

Propagation Effects in Optical Waveguides, Fibres and Devices

A thesis submitted for the degree of Doctor of Philosophy
of the Australian National University

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Canberra,
13 January 2003



Declaration

This thesis is an account of research undertaken in the Laser Physics Centre and Applied Photonics Group within the Research School of Physical Sciences and Engineering at the Australian National University between June 1999 and January 2003 while I was enrolled for the Doctor of Philosophy degree.

The research has been conducted under the supervision of Prof. J. D. Love, Dr. Adrian Ankiewicz and Dr. Martin Elias. However, unless specifically stated otherwise, the material presented within this thesis is my own.

None of the work presented here has ever been submitted for any degree at this or any other institution of learning.

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January, 2003

Publications

Journal papers:

- [1] S. Tomljenovic-Hanic, J. D. Love, and A. Ankiewicz: "Low-loss single mode waveguide and fibre bends", *Electronics Letters*, 2002, vol.38, pp. 220-222.
- [2] S. Tomljenovic-Hanic, J. D. Love, and R. B. Charters: "Cut-off wavelength and transient effects in asymmetrically clad single-mode buried-channel waveguides", *IEE Proc.-Optoelectronics*, 2002, vol. 149, pp 51-57.
- [3] S. Tomljenovic-Hanic, J. D. Love, and A. Ankiewicz: "Effect of Additional Layers on Bend Loss in Buried Channel Waveguides", *IEE Proc.-Optoelectronics*, 2002, accepted for publication.
- [4] S. Tomljenovic-Hanic, J. D. Love: "Planar waveguide add/drop wavelength filters based on segmented gratings"-submitted to *Microwave and Optical Technology Letters*, #20653.
- [5] S. Tomljenovic-Hanic, and W. Krolikowski: "A new design of variable optical attenuator based on bent waveguide"-submitted to *Applied Physics B*.

Patents:

- [1] Australian provisional patent, Reg. No: PR8642
title: 'Optical waveguides and fibres with reduced bend loss'
authors: S. Tomljenovic-Hanic, J. D. Love, and A. Ankiewicz
- [2] Australian provisional patent, Reg. No: PS0831
title: 'Curved Waveguide-based variable optical attenuator'
authors: G. R. Atkins, R. B. Charters, W. Krolikowski, and S. Tomljenovic-Hanic
- [3] Australian provisional patent, Reg. No: PS2262
title: 'Optical filter structure'
authors: J. D. Love, and S. Tomljenovic-Hanic

Conference proceedings:

- [1] S. Tomljenovic-Hanic, J. D. Love, and R. B. Charters: "Fundamental Mode Cutoff in Buried Channel Waveguides", *25th Australian Conference on Optical Fibre Technology*, Canberra, Australia, 2000, pp 48-50.
- [2] S. Tomljenovic-Hanic, J. D. Love, and A. Ankiewicz: 'Low-loss single-mode waveguide and fibre bends', *Australian Conference on Optics, Lasers and Spectroscopy*, Brisbane, Australia, 2001, pp 82.
- [3] S. Tomljenovic-Hanic, J. D. Love, and A. Ankiewicz: 'Optical waveguides and fibres with reduced bend loss', *10th International Workshop on Optical Waveguide Theory and Numerical Modeling*, Nottingham, UK, 2002, pp 74.
- [4] S. Tomljenovic-Hanic, J. D. Love, A. Ankiewicz, and W. Krolikowski: "Effect of added layers on bend loss in buried channel waveguides", *4th International Conference on Transparent Optical networks*, Warsaw, Poland, 2002, pp 16-19 (Invited).
- [5] S. Tomljenovic-Hanic, and J. D. Love: "Planar Waveguide Add/Drop Filter based on Segmented Gratings", *27th Australian Conference on Optical Fibre Technology*, Sydney, Australia, 2002, pp 19-22.
- [6] S. Tomljenovic-Hanic, W. Krolikowski, R. B. Charters, and G. R. Atkins: "New design of Variable Optical Attenuator based on a Bent Channel Waveguide", *27th Australian Conference on Optical Fibre Technology*, Sydney, 2002, pp 29-31.

Abstract

This thesis consist of a theoretical study of propagation effects in optical waveguides, fibres and photonic crystals, with some comparison with experiment.

Chapter 1 gives a brief introduction with the current view of optical components in photonic integrated circuits and issues related to the loss mechanism.

In **Chapter 2** the characteristics of single-mode propagation and transient effects in practical square- and rectangular-core buried channel planar waveguides are quantified, assuming a cladding which is unbounded in one transverse dimension and bounded in the other. The wavelength cut-off condition for the fundamental mode is determined when the cladding index is asymmetric and composed of step-wise, uniform index regions.

In **Chapter 3**, the application of segmented reflection gratings in planar devices that can function as either a single- or two-wavelength add/drop filter is investigated and a numerical technique developed in Chapter 2 is applied to the waveguides with high extinction ratio. The role of the segmented gratings is analogous to that of a blazed grating, but they can provide a higher reflectivity level at the Bragg wavelength, eliminate back reflection into the fundamental mode and provide arbitrarily small channel spacing in the two-wavelength case.

Chapters 4 address the problem of bend loss in a single-mode slab waveguide. A new theoretical strategy for reducing bend loss is presented and compared to existing designs. The results obtained in this chapter are the basis for the following two chapters.

Chapter 5 deals with bend loss in single-mode buried channel waveguides and demonstrates that the new strategy can lead to significant bend loss reduction when compared to other strategies, and, conversely, can be used to enhance bend loss for a fixed bend radius for application to devices such as optical attenuators.

In **Chapter 6**, a novel design of a variable optical attenuator based on a bent channel waveguide is proposed, realized by applying a new strategy for bend loss control in a polymer buried channel waveguide.

Chapter 7 investigates effects of the additional rings in a single mode step-index fibre on bend loss. It is supported with the experimental results of Ron Bailey from Optical the Fibre Technology Centre, University in Sydney.

In **Chapter 8**, bend loss of a one-dimensional photonic crystal is quantified and compared to bend loss of a standard single-mode slab waveguide and a bend-resistant waveguide.

Acknowledgments

Firstly I wish to thank Ross Williams who soon after my arrival in Australia suggested and organized an introduction for me at the Australian National University. If she had not been so kind as to take me under her wing I would have probably accepted the position of Science teacher in a girl school and be there still.

Having included Optical Fibres in my undergraduate studies it was natural to be introduced to Professor John Love at the ANU. John became my supervisor and arranged for me to obtain a PhD scholarship, partly supported by ADC Pty Ltd Australia. Professor Love encouraged me to develop my research skills and introduced me to the Scientific Community at various conferences. Despite my intruding at any hour or day into his busy schedule he took it in good humour.

I am most grateful to my second supervisor Dr Adrian Ankiewicz whose door was always open to discuss problems. He provided invaluable constructive feedback and guidance almost throughout my entire studies. His sense of humour never failed to lift my spirit.

I also wish to acknowledge the encouragement of my third supervisor Dr Martin Elias.

I thank Dr Wieslaw Krolikowski for his helpful effective suggestion and his input on the VOA project.

Dr Darren Edmundson introduced me to IDL saving me many hours of self teaching nightmare.

I thank Dr Elena Ostrovskaya for the initial help with UNIX system, the numerical technique and her constant support.

Dr Andrey Sokohurov, thank you for keeping my computer happy despite my effort to the contrary.

Valuable input was given by Mr Ron Bailey at the Optical Fibre Technology Centre at the University of Sydney in making my imagination of the fibres into reality.

I gratefully acknowledge the support of the Australian Photonics Cooperative Research Centre and RPO Pty Ltd, in particular, Professor Barry Luther-Davies, Dr Robbie Charters, Piter Lightbody and many others.

Finally I would like to mention Keith, Tristram, Sam, Ruth, Stephanie, Maryla, Vicky, Megan, Elliot, Darryl, Mihajlo, Anton and other friends who have in their own way supported me. In particular I wish to thank my dearest friend Ken Cubbage who had enough courage and patience to review my written work.

Further more I like to thank my family for all the love and support through out the years.

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CHAPTER 1

Introduction

The demand for data traffic has initiated the development of optical telecommunications. Since 1960, when the first laser was built, it was recognized that the coherence properties of laser light, and its frequency of the order of 2×10^{14} Hz provide enormous potential bandwidth. The next step was finding an appropriate optical carrier and in 1966 the first glass fibre was made, with an attenuation range of 20 dB/km. Since then the losses have been reduced below 0.2 dB/km at a wavelength of 1550 nm and optical fibre technology has become the standard for long-distance data communication. With the introduction of Wavelength Division Multiplexing (WDM) fibre network link has become a high-capacity advanced telecommunication link.

The concept of integrated optics started in 1969 and has led to the development of more sophisticated devices needed for the modern telecommunication, such as optical switches, multiplexers, demultiplexers, add/drop filters, etc. The integration of many components on a single substrate permits the fabrication of chips which have a size of several square centimetres. These devices are now commercially available and offer reliable and cost-effective solutions to device requirements.

However, the thirst for faster, cheaper, more reliable data communication, with smaller device features is still not satisfied. State-of-the-art optics and photonic band gap material-based optics may in future answer these demands.

1.1 Waveguides and devices

In a modern optical communications network, data is encoded and transported in streams of light that must be generated, transported, split, amplified, switched and detected. Optical fibre has become the standard transmitter for long-distance data communication. A powerful aspect of an optical fibre is that many different wavelengths, carrying independent channels can be sent along a single fibre. Amplification can be also done with fibre optics, whereas all other functions in the network are mainly performed by integrated circuits, based on the planar waveguides. They are more efficient and cheaper than the fiber elements performing the same functions. These devices contribute dramatically to

improvements in network speed, capacity and reliability. However, there is a limitation in packing density, ruled by the bend loss mechanism. This is where photonic crystals come into play, with their ability to efficiently control light, with, at the present stage a six order higher packing density than conventional waveguides.

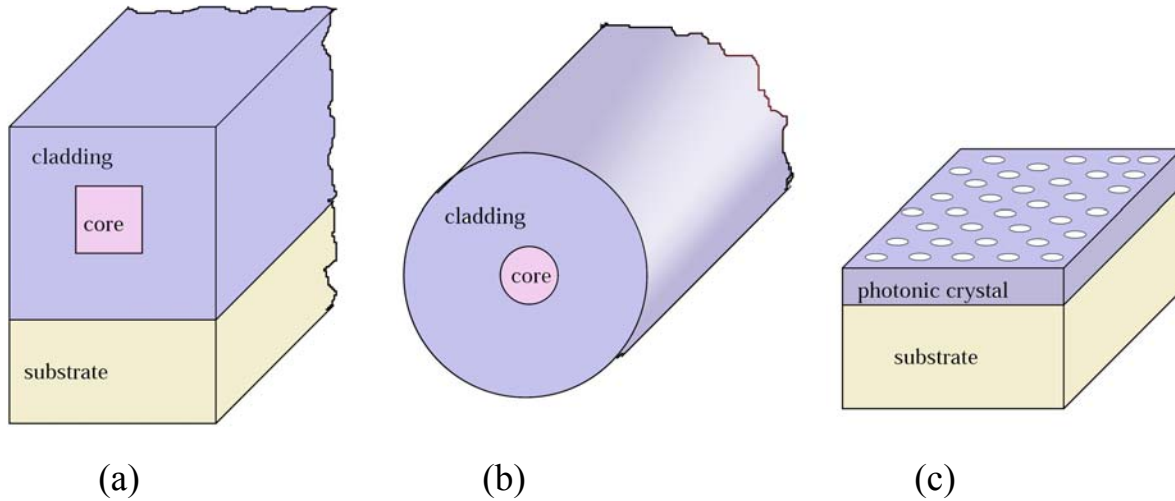


Fig. 1.1 *Illustration of some optical guiding structures: (a) buried channel waveguide, (b) fibre, (c) photonic crystal slab*

1.2 Loss mechanism

The loss problem can be formulated as follows. If a mode or a linear combination of modes has been excited in a guide, how much power is still guided in the last guide cross-section relative to the input power? What causes the losses and how they can be minimized? In straight waveguides the scattering and absorption are the major losses, whereas in curved guides the control of bend loss is the main issue. The important issue related to fibre-waveguide, fibre-photonic crystal coupling is insertion loss that accounts for a percentage of power transmitted from one guide to another.

The power which does not enter the fundamental mode is lost to the radiation field, and the latter accounts for the spatial transient. The radiation loss from the fibre core occurs in a relatively short length (within a few metres) and is absorbed by the fibre coating, whereas in a single-mode planar waveguide, the role of the radiation field can be quite important when the whole waveguide is only a few centimetres long, as is the case with planar devices. Spurious modes, modes that propagate close to the core, have been experimentally observed and they can be related to the leaky modes of the waveguide.

The field that is well confined in straight waveguides and fibres becomes leaky when the guide is bent. Bending loss can be avoided by making the bend radius larger or by increasing the confinement of the modal field. Unfortunately, these changes increase either the size of the device or insertion loss. Therefore many strategies have been investigated in order to minimize bend loss in curved waveguides.

In practical applications, the coupling efficiency between devices and a standard single-mode telecommunication fibre is an important issue. The order of the insertion loss is determined by the index difference and difference in dimension of elements that couple. The practicality of photonic crystals has been questioned mainly due to these issues.

1.3 Photonic and Optoelectronic integrated circuits

Photonic Integrated Circuit (PIC) includes passive and active components having multiple functions on a single substrate and is usually called a chip, implying that light is manipulated on a small scale.

Conventional components can be fabricated using silica, polymer, silicon-oxynitride, and silicon. Silica-on-silicon is very common material used for PIC, due to the low coupling loss to standard optical fibre and low fabrication cost. The disadvantages of silica waveguides are the small range of index difference available; concerns over the slow thermo-optic effect and small response to the temperature changes, and limits over the bend radius that increase the size of the devices. On the other hand polymer waveguides have fast and significant thermal response but higher propagation and insertion losses. Silicon-oxynitride and silicon-based waveguides can have higher index contrast than silica based waveguides, allowing tighter bends and therefore smaller device. However, it is hard to couple these high index reduced-core waveguides to a standard single-mode fibre. Additionally, higher propagation losses due to scattering appear in these devices.

Light is manipulated not only at the beginning and the end of a fibre link. In order to extract one or more channels and insert new information into these channels along the transmission add/drop wavelength filters are used. There are many different realizations of these devices, both as passive, e.g. Bragg grating devices and active, e.g. thermo-optic effect based devices.

Active components can be a part of optoelectronic integrated circuits (OEIC) where a thermo-optic effect controls the waveguide refractive index. For devices that use this effect, such as a variable optical attenuator thermo-optic, the response time of the material, insertion loss and the power that is required to create a significant level of attenuation are the most important issues. VOA's have been used extensively for several years for the optical power equalization between channels in WDM transmission systems before they are combined into a fibre. Another important application of VOA's is channel balancing that is needed at add/drop nodes, because optical signals arrive independently from different points in a network.

A common concern for all components is the overall size, and that is limited in particular by the bend radius that increases the density of the components but on the other hand it introduces bend loss. Future devices will require structures that are much smaller. In terms of packaging density, photonic crystal devices promise a revolution in photonics as semiconductors led to a revolution in electronics. Their ability to confine and manipulate photons may result in the creation of all-optical integrated circuits with a high order packing density.

1.4 Scope of the thesis

This thesis investigates a wide range of propagation effects in waveguides, with a particular emphasis on application to photonic integrated circuits. Guiding structures that are considered include slab waveguides, buried channel waveguides, fibres and photonic crystal slab waveguides. In the investigation of different models different approximations and numerical methods are used, the results of two methods compared to ensure accurate results.

The first part of the thesis deals with propagation effects in straight buried channel waveguide and devices, developing a new technique for the modal analysis of asymmetric-clad buried channel waveguides and applying it to the analysis of segmented grating based add/drop filters. Demands in modern network for the channel spacing of 0.8 nm has been a motivation for considering this new kind of grating, since it can replace blazed gratings in similar devices.

The second part of the thesis addresses the bend loss problem, starting with bend loss minimization in slab waveguides and buried channel waveguides. Further on, a similar strategy is applied for the increase of bend loss in a variable optical attenuator, additionally including the thermo-optic effect. Bend loss has been a subject of study since 1969. Nevertheless, new strategies are needed, as demand for the tighter bends increases.

The new strategy is also applied to fibres and theoretical results are supported with measurement results of bend loss for a fibre made according to my design. At the end, a new class of materials, that operate differently from the conventional waveguides, is investigated with an emphasis on bend loss.

CHAPTER 2

Cut-off Wavelength and Transient Effects in Asymmetric-Cladding Single-Mode Buried Channel Waveguides

Single-mode buried channel waveguides are commonly excited by the fundamental mode of a pigtailed, single-mode fibre. Pig-tailing involves the splicing of fibre to the waveguide by one of a variety of active or passive techniques currently used in practice. If the fibre spot size is well-matched to that of the waveguide, and also optimally aligned with the waveguide, then there is minimal mismatch between the fundamental modes of the fibre and waveguide, with transmission losses typically around 0.1dB or less. However, if the fibre and waveguide spot sizes are not well-matched, or if the fibre and waveguide axes are offset or tilted, the transmission loss will be considerably higher. Apart from the small fraction of reflected power originating from any index variation across the splice, typically 50dB down or better, any power not entering the fundamental mode of the waveguide will be lost through excitation of the forward-propagating radiation field. This situation is analogous to the excitation of the fundamental mode of a single-mode fibre by a source, such as a laser.

The power, which does not enter the fundamental mode, is lost to the radiation field, and the latter accounts for the spatial transient in the fibre. Since the radiation loss from the fibre core occurs in a fairly short length (within a few metres) and is absorbed by the fibre coating, it has not usually been of significant interest in long-distance fibre transmission involving tens of kilometres or more of fibre.

In a single-mode planar waveguide, however, the role of the radiation field can be quite important when the whole waveguide is only a few centimetres long, as is the case with planar devices. If one assumes that the cladding of the waveguide is unbounded in the cross-section, then the radiation field can be represented as an integral superposition of the continuum of radiation modes [1,ch25]. However, the numerical evaluation of this superposition is non-trivial because of the presence of a rapidly oscillating modal phase dependence in the integration. Since the frequency of the oscillations increases with distance along the fibre, it rapidly becomes impractical to evaluate these integrals with sufficient accuracy.

2.1 Leaky modes

An alternative, approximate description of the radiation field relies on a superposition of leaky modes [1, ch24]. This description is also difficult to implement quantitatively because each leaky mode formally carries infinite power, but the physical properties of leaky modes can provide significant insight into the nature of the radiation field. By analogy with the corresponding situation for the excitation of a single-mode fibre, the radiation field of the waveguide will have physical characteristics associated with the leaky modes of the waveguide. There is a significant body of material on the properties and determination of the leaky modes of a fibre [1,ch24], but, as yet, their significance for buried channel waveguides has not been investigated.

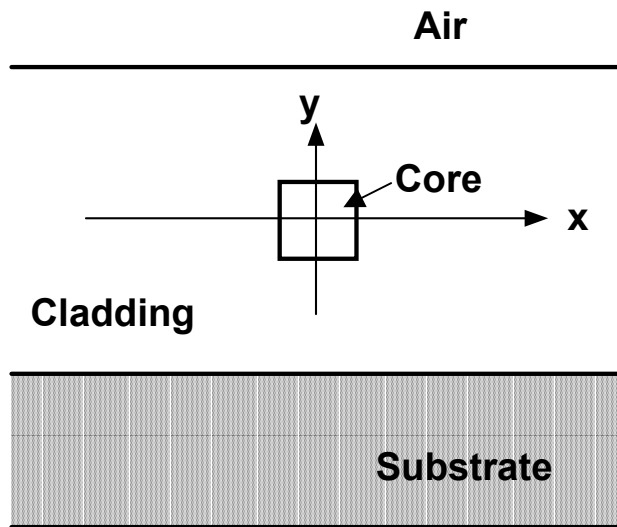


Fig. 2.1 *Schematic of the cross-section of a buried channel waveguide, showing the geometry of the core, cladding and substrate.*

The motivation for this study stems partly from the need to quantify the complete guided and radiation fields associated with the excitation of the relatively short lengths of buried channel waveguide used in photonic integrated circuits, normally of the order of a few centimetres. In so doing, a new numerical technique, the Hybrid Fourier Decomposition Method/Modified Fourier Decomposition Method (H-FDM/MFDM), is introduced for analysing waveguides where the cladding is unbounded in one dimension, but finite in the orthogonal dimension. A single-mode buried channel waveguide with a typical cross-section for a buried channel waveguide is shown schematically in Fig. 2.1.

In this analysis, any material absorption and scattering are ignored within the waveguide structure; these effects can be quantified separately. Provided the buffer layer between the core and the substrate is sufficiently thick, there will be negligible tunnelling of optical power into the substrate when it is composed of a higher-index material. A silicon wafer is commonly used in practice [2]. Taken together with the large index difference between the cladding and the air on the top surface of the waveguide, the radiation field is essentially totally confined in the vertical y -direction in Fig. 2.1. However, the radiation field can spread horizontally (in the x -direction) into the cladding, as it is unbounded in that direction.

One consequence of the relatively short lengths of waveguides used in planar lightwave circuits is that any leaky mode excited by the source can remain relatively close to the core, especially if the leaky mode is only marginally above the cut-off wavelength of the corresponding bound mode. Characterization of single-mode waveguides has therefore resulted in a number of observations of what appear to be spurious modes propagating close to the core. These modes can be related to the leaky modes of the waveguide. In general, it would be expected that modes would still propagate (as leaky modes) below their cutoff V -values and that their field profiles would be similar to those of the bound mode, but gradually move laterally away from the waveguide core. For short guides, no abrupt changes occur when going from below to above the cutoff wavelength.

Accordingly, one purpose of this study is to exhibit leaky mode propagation for the particular case described below. This approach essentially follows the procedure for determining the spatial transients of fibres using the supermodes of the complete structure [3]. The analysis is also generalized to those waveguides where the cladding index is not uniform. This situation can arise due to the nature of the deposition of discrete layers e.g. in plasma enhanced chemical vapour deposition (PECVD) fabrication processes, where there can be variations between the buffer and cladding material indices. This situation can also arise in direct-write waveguides comprising a tri-layer of deposited materials sandwiching a higher-index photosensitive layer.

It is well-known that the fundamental mode in a fibre with a depressed cladding can be cutoff [4]. Here, a consequence of a non-uniform cladding is that the fundamental mode of a buried channel waveguide can also have a cutoff wavelength. In Section 2.2, the physical model is defined, and in Section 2.4, the new method of analysis is described. Results are presented and interpreted in Section 2.5.

2.2 Physical model

A number of different configurations is considered, where each consists of a square- or rectangular-core buried channel waveguide of uniform refractive index n_{co} surrounded by a cladding of lower and piecewise uniform index. The cross-section is bounded above by a horizontal planar interface between the cladding and air, and below by a second interface between the cladding and the silicon substrate, as shown in Fig.2.1. Thus, with reference to Cartesian axes orientated so that the z direction is parallel to the axis of the waveguide, the

x - and y -axes are in the horizontal and vertical directions, respectively, and the cladding is unbounded in the $\pm x$ -directions. The vertical separation between the core and the silicon wafer is assumed to be sufficiently large so that there is negligible tunnelling from the waveguide fundamental mode and radiation field into the silicon substrate.

The relative variation in index between the core and the cladding is assumed to be small, as with practical waveguides, so that the weak-guidance approximation can be invoked. Thus each bound mode has a propagation constant and a single scalar component of electric field that satisfy the scalar wave equation. Because of the asymmetry of the cross-section in Fig.2.1, the electric field will be polarized parallel to either the x or y axis. Because of the large index difference between the cladding and air on the upper interface, it is assumed that the modal field there is approximately zero, and, similarly, because of the large index difference between silica and silicon, the field on the lower interface is also taken to be zero.

This approximation for the silica-silicon interface is justifiable over short distances along the waveguide, as the leaky mode radiation field diverges slowly. This divergence corresponds to a superposition of cladding modes with effective indices that are below but close to that of the cladding index. At the interface, each cladding mode field can be approximated by a local plane wave whose direction of propagation makes a small angle relative to this interface, and is virtually reflected with only a small component of optical power being refracted into the silicon.

2.3 Method of analysis

2.3.1 Bound modes

There are no known analytical solutions of the scalar wave equation for the bound modes of square- or rectangular-core step-profile dielectric waveguide. Accordingly, a variety of numerical and approximation methods has been developed, each one of them with its own advantages and limitations [2]. Here we concentrate on two such methods that are appropriate for analysing the class of waveguides described above. The Fourier Decomposition Method (FDM) [5] is a fast and accurate procedure for determining modal fields and propagation constants of waveguides away from the cutoff wavelength of a mode, while the Modified Fourier Decomposition Method (MFDM) [6], is applicable both close to and at the mode cutoff wavelength. Thus the field and propagation constant of the waveguide fundamental mode can be determined, if necessary, up to cutoff using the MFDM.

2.3.2 Radiation field

The radiation field of a waveguide can be evaluated using a supermode analysis

involving a superposition of the supermodes of the complete waveguide cross-section. This approach has been previously applied to the analysis of propagation along fibres [3] and determines the radiation field in the cross-section in terms of a superposition of supermodes, i.e. the discrete modes of the complete fibre cross-section, including the core, cladding and coating. For short planar waveguides, it is important to consider all excited modes, particularly at the beginning of the device there can be a significant fraction of the source power entering the radiation field. A discrete bound-supermode technique, using the modal field solutions obtained with the H-FDM/MFDM, describes propagation by a discrete summation over all the supermodes of the whole structure. In an experiment it could be seen that the fundamental mode also has a cutoff. In this chapter, the aim is to examine and provide explanations for this and the contribution of low-order leaky modes for guides which are only a few centimetres long.

2.4 Numerical methods

In the weak guidance approximation, each mode has only a single electric field component E_t . It is transverse to the waveguide axis and has the separable form:

$$E_t = \psi(x, y)e^{i\beta z}, \quad (2.1)$$

where β is the propagation constant and $\psi(x, y)$ determines the transverse field dependence. Taken together, these quantities form the solution of the scalar wave equation:

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k^2 n^2(x, y) - \beta^2 \right] \psi(x, y) = 0 \quad (2.2)$$

subject to appropriate boundary conditions, where $n(x, y)$ is the refractive index profile of the waveguide, $k=2\pi/\lambda$ is the free space wavenumber and λ is the source wavelength. Due to the weakly-guiding waveguide structure, polarization effects are small [1, ch13].

2.4.1 Fourier Decomposition Method (FDM)

With the FDM technique, the waveguide is enclosed within a rectangular bounding box. The vertical dimension L_y is taken to be the total thickness of the cladding, and the upper and lower boundaries of the rectangle coincide with the cladding-air and cladding-substrate interfaces, respectively, because of the zero-field assumption made above. The horizontal domain L_x needs to be large enough to ensure that (i) the field and propagation constant of the bound fundamental mode can be accurately determined and (ii) the superposition of the FDM modes of the box reproduce the radiating field within the region

of interest. The latter condition ensures that the radiating field is not influenced by the perfect reflectance (zero field) condition at the vertical boundaries of the rectangle.

The unknown field distribution $\psi(x,y)$ is then expanded in terms of a complete set of the orthonormal, sinusoidal eigenfunctions $\phi_{mn}(x,y)$ of the rectangle box of dimensions L_x and L_y :

$$\psi(x,y) = \sum_{m_i=1}^M \sum_{n_i=1}^N a_{m_i n_i} \phi_{m_i n_i}(x,y) \quad , \quad \phi_{m_i n_i}(x,y) = \frac{2}{\sqrt{L_x L_y}} \sin\left(\frac{m_i \pi x}{L_x}\right) \sin\left(\frac{n_i \pi y}{L_y}\right), \quad (2.3)$$

where the index i is related to indices with:

$$\begin{aligned} m_i &= (i-1) \text{div} M + 1 \\ n_i &= (i-1) \text{mod} N + 1 \end{aligned} \quad (2.4 \text{ a,b})$$

and the $a_{m_i n_i}$ are amplitude coefficients and $m=1,2,\dots,M$, and $n=1,2,\dots,N$. On substituting this expansion into the scalar wave equation, together with the appropriate refractive index profile, integrating over the area of the box, and using the orthogonality of the eigenfunctions:

$$\int_0^{L_x} \int_0^{L_y} \phi_i(x,y) \phi_j(x,y) \, dx dy = \delta_{ij}, \quad (2.5)$$

where δ_{ij} is the Kronecker delta function, this expansion reduces the scalar wave equation to a standard matrix eigenfield and eigenvalue problem. The FDM is useful for modes that are not near cutoff, so that their fields need to be confined to a relatively small area away from the horizontal and vertical boundaries.

2.4.2 Modified Fourier Decomposition Method (MFDM)

The Fourier Decomposition Method can be used to calculate modal field distributions that are sufficiently far from cutoff. To improve the analysis, we can use the MFDM to determine the fields and propagation constants of the modes of the waveguide both close to and at cutoff, by mapping the whole of the Cartesian x - y plane onto the unit square in u - v space, $0 < u, v < 1$ via the transformation functions:

$$x = \alpha_x \tan\left[\pi\left(u - \frac{1}{2}\right)\right] \quad , \quad y = \alpha_y \tan\left[\pi\left(v - \frac{1}{2}\right)\right], \quad (2.6 \text{ a,b})$$

where α_x and α_y are scaling parameters in the x - and y -directions, respectively. In order to achieve satisfactory convergence, these parameters have to be chosen judiciously [6]. The field is now forced to be zero along the boundary of the unit square, in u - v space which maps back to the x - y plane and gives the correct boundary conditions at infinity, $x, y = \pm\infty$.

Near the cutoff the field spreads further into the cladding and this kind of the infinite boundaries are more appropriate than the artificial bounding box used in FDM. This additionally means that an unbounded medium of uniform refractive index, n_{cl} , will result in ‘free-space’ radiation modes [1, ch25]. Solving the eigenvalue problem in the unit square in u - v space results in a discrete set of radiation modes, that are included in this study.

In similar manner as in FDM the scalar wave equation is reduced to a standard eigenvalue problem. The eigenvalues and eigenvectors give the unknown modal propagation constants and the field, which is mapped back to the x - y space with the inverse transformation functions of (2.6 a,b).

A question that has not been addressed to date is the analysis of the radiation field of the infinite cladding waveguide using the MFDM. The radiation field of the waveguide can be represented as an integral over the continuum of radiation modes [1,ch25]. Each radiation mode has an effective index, n_{eff} , that is below the cladding index, so $1.0 < n_{eff} < n_{cl}$. In the transformed domain of the unit square, only discrete eigenfunctions are solutions of the transformed scalar wave equation, together with its boundary conditions. In other words, both the bound mode field and the radiation mode field are represented by a superposition of the complete set of eigenfunctions of the unit square.

2.4.3 Hybrid Fourier Decomposition Method/Modified Fourier Decomposition Method (H-FDM/MFDM)

As mentioned earlier, for the buried channel waveguides in Fig. 2.1, it is assumed that the modal field at the cladding/air upper interface and on the lower interface between the silica buffer layer and the silicon wafer are both approximately zero. Therefore it is appropriate to apply the FDM in the y -direction of the waveguide. On the other hand, the MFDM should be applied in the x -direction, because the cladding is unbounded in the horizontal direction. This means that the modal field, which is not well-confined to the core region, will spread further into the cladding in the x -direction when near to and at cutoff.

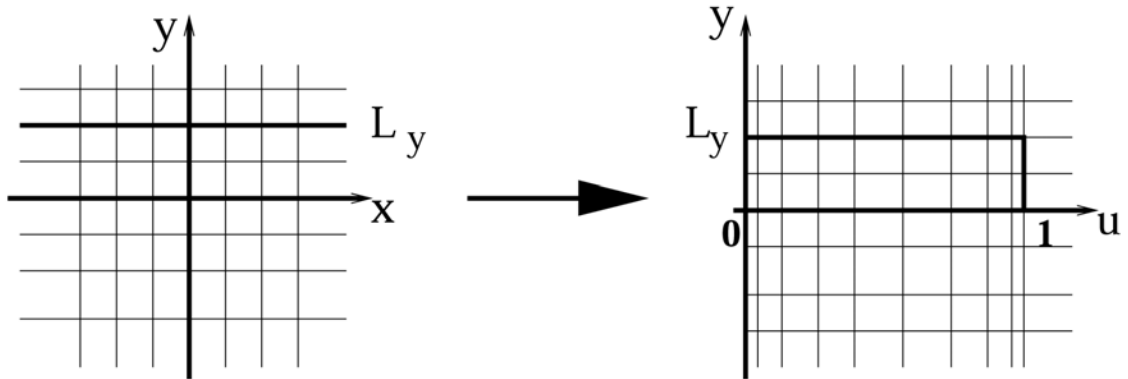


Fig. 2.2 Graphical representation of the unit line mapping.

Therefore we propose a new approach for analysing these types of buried channel waveguides. It is a hybrid combination of the FDM in one direction and the MFDM in the orthogonal direction. The Hybrid FDM/MFDM maps the x -axis onto a unit line in u -space with the transformation function (2.6a), see Fig. 2.2, and defines an artificial bound in the y -direction of length L_y .

With the x - u transformation of (2.6(b)), the scalar wave equation (2.2) becomes:

$$\left[\left(\frac{du}{dx} \right)^2 \frac{\partial^2}{\partial u^2} + \frac{d^2 u}{dx^2} \frac{\partial}{\partial u} + \frac{\partial^2}{\partial y^2} + k^2 n^2(u, y) - \beta^2 \right] \psi(u, y) = 0, \quad (2.7)$$

where the transverse field component, $\psi(u, y)$, is expanded as a set of orthogonal basis functions:

$$\psi(u, y) = \sum_{m_i=1}^M \sum_{n_i=1}^N a_{m_i n_i} \phi_{m_i n_i}(u, y). \quad (2.8)$$

Each basis function is of the form:

$$\phi_{m_i n_i}(u, y) = \frac{2}{\sqrt{L_y}} \sin(m_i \pi u) \sin\left(\frac{n_i \pi y}{L_y}\right). \quad (2.9)$$

The basis functions obey the orthonormality relation:

$$\int_0^1 \int_0^{L_y} \phi_i(u, y) \phi_j(u, y) du dy = \delta_{ij}. \quad (2.10)$$

The scalar wave equation can then be transformed into a series of coupled, algebraic equations by using the orthonormality of the $\phi_{mn}(u, y)$ in a similar manner as in the FDM and MFDM. Inserting the expansion (2.8) into (2.7), multiplying by $\phi_j(u, y)$ and integrating over the domain $u \in [0, 1]$ and $y \in [0, L_y]$ gives:

$$\sum_{i=1}^{MN} (V^2 A_{ji} + B_{ji} - W^2 \delta_{ij}) a_i = 0. \quad (2.11)$$

where V and W are the waveguide and cladding-mode parameters respectively, defined by:

$$V = k\rho(n_{co}^2 - n_{cl}^2)^{1/2}, \quad W = \rho(\beta^2 - k^2 n_{cl}^2)^{1/2}. \quad (2.12a,b)$$

The core-halfwidth ρ is defined as $\rho = \sqrt{\rho_x \rho_y}$, see Fig. 2.3.

The Galerkin matrix elements, $V^2 A_{ij} + B_{ji}$ are calculated from:

$$A_{ji} = \int_0^1 \int_0^{L_y} g(u, y) \phi_j(u, y) \phi_i(u, y) du dy \quad (2.13a)$$

$$B_{ji} = \rho^2 \left(I_1 + I_2 + \left(\frac{n_i \pi}{L_y} \right)^2 \delta_{ji} \right), \quad (2.13b)$$

where:

$$g(u, y) = \frac{n^2(u, y) - n_{cl}^2}{n_{co}^2 - n_{cl}^2} \quad (2.14)$$

and

$$I_1 = -m_i^2 \pi^2 \int_0^1 \int_0^{L_y} \left(\frac{du}{dx} \right)^2 \phi_i(u, y) \phi_j(u, y) du dy \quad (2.15a,b)$$

$$I_2 = m_i \pi \int_0^1 \int_0^{L_y} \left(\frac{d^2 u}{dx^2} \right) \frac{1}{\tan(m_i \pi u)} \phi_i(u, y) \phi_j(u, y) du dy$$

The integrals I_1 and I_2 can be calculated analytically:

$$I_1 = -\frac{m_i^2}{2\alpha_x^2} \left(\frac{3\delta_{m_i, m_j}}{4} - \frac{\delta_{m_i, m_j-2}}{2} - \frac{\delta_{m_i, m_j+2}}{2} + \frac{\delta_{m_i, 2-m_j}}{2} + \frac{\delta_{m_i, m_j-4}}{8} + \frac{\delta_{m_i, m_j+4}}{8} - \frac{\delta_{m_i, 4-m_j}}{8} \right) \delta_{n_i, n_j}$$

$$I_2 = -\frac{m_i}{\alpha_x^2} \left(\frac{\delta_{m_i, m_j-2}}{4} - \frac{\delta_{m_i, m_j+2}}{4} + \frac{\delta_{m_i, 2-m_j}}{4} - \frac{\delta_{m_i, m_j-4}}{8} + \frac{\delta_{m_i, m_j+4}}{8} - \frac{\delta_{m_i, 4-m_j}}{8} \right) \delta_{n_i, n_j} \quad (2.16a,b)$$

The scalar wave equation is thus reduced to a standard eigenvalue problem which is solved by using numerical routines [7]. The matrix is real and asymmetric and its eigenvalues determine the propagation constants for the bound and radiation modes. Also, the eigenvectors will give the coefficients $a_{m_i n_i}$ in the series expansion (2.8). In general, there are also complex eigenvalues when solving an asymmetric eigenmatrix problem, but they are ignored, since only real eigenvalues are of interest in this analysis.

The modal fields are mapped back to x-y space with the inverse transformation function of (2. 6a).

At modal cutoff, the propagation constant $\beta = kn_{cl}$, so $W=0$. Therefore the expression (2.10) is simplified to:

$$\sum_{i=1}^{MN} \left(V_{coff}^2 A_{ji} + B_{ji} \right) a_i = 0. \quad (2.17)$$

Multiplying (2.17) with B_{ji}^{-1}/V_{coff}^2 , the matrix becomes:

$$\sum_{i=1}^{MN} \left(B_{ji}^{-1} A_{ji} + \delta_{ji} \frac{1}{V_{coff}^2} \right) a_i = 0. \quad (2.18)$$

Solving (2.18) gives the eigenvalues, $1/V_{\text{cutoff}}^2$, and then using (2.12a) the corresponding cutoff wavelengths, λ_{cutoff} are obtained.

This new method has several advantages over the existing FDM and MFDM. Firstly, it incorporates the symmetry of the waveguides, which means that the waveguide is mapped onto the unit line in the direction of symmetry, while in the vertical direction it accommodates the asymmetry without a mapping. Secondly, it takes into account radiation from the waveguide in the x -direction.

2.4.4 Source of excitation

Once the modal fields are obtained, a superposition describes propagation along the waveguide using the bound modes of the entire waveguide:

$$E_{\text{sup}} = \sum_p a_p E_p(x, y, \beta_p) e^{i\beta_p z}. \quad (2.19)$$

A non-symmetrically-placed focused source on the end-face of the guide, such as the fundamental mode of a single-mode fibre is modelled by assuming a coherent source with a planar phase front and an approximately Gaussian transverse electric-field E_s , with distribution:

$$E_s = A \exp\left(-\frac{(x \pm \sigma_x)^2 + (y \pm \sigma_y)^2}{s^2}\right), \quad (2.20)$$

where A is the amplitude, s the spot size, and σ_x and σ_y are the offsets in the x - and y -directions, respectively. The corresponding amplitude, a_p , of the p th excited mode of the waveguide is determined by [3]:

$$a_p = \frac{A \int_{-\infty}^{\infty} \int_0^{L_y} \exp\left(-\frac{(x \pm \sigma_x)^2 + (y \pm \sigma_y)^2}{s^2}\right) E_p(x, y, \beta_p) dx dy}{\int_{-\infty}^{\infty} \int_0^{L_y} |E_p|^2 dx dy}. \quad (2.21)$$

2.5 Examples and results

A number of different structures of buried channel waveguides with non-uniform claddings, in terms of the refractive index of the cladding or dimensions, are considered here.

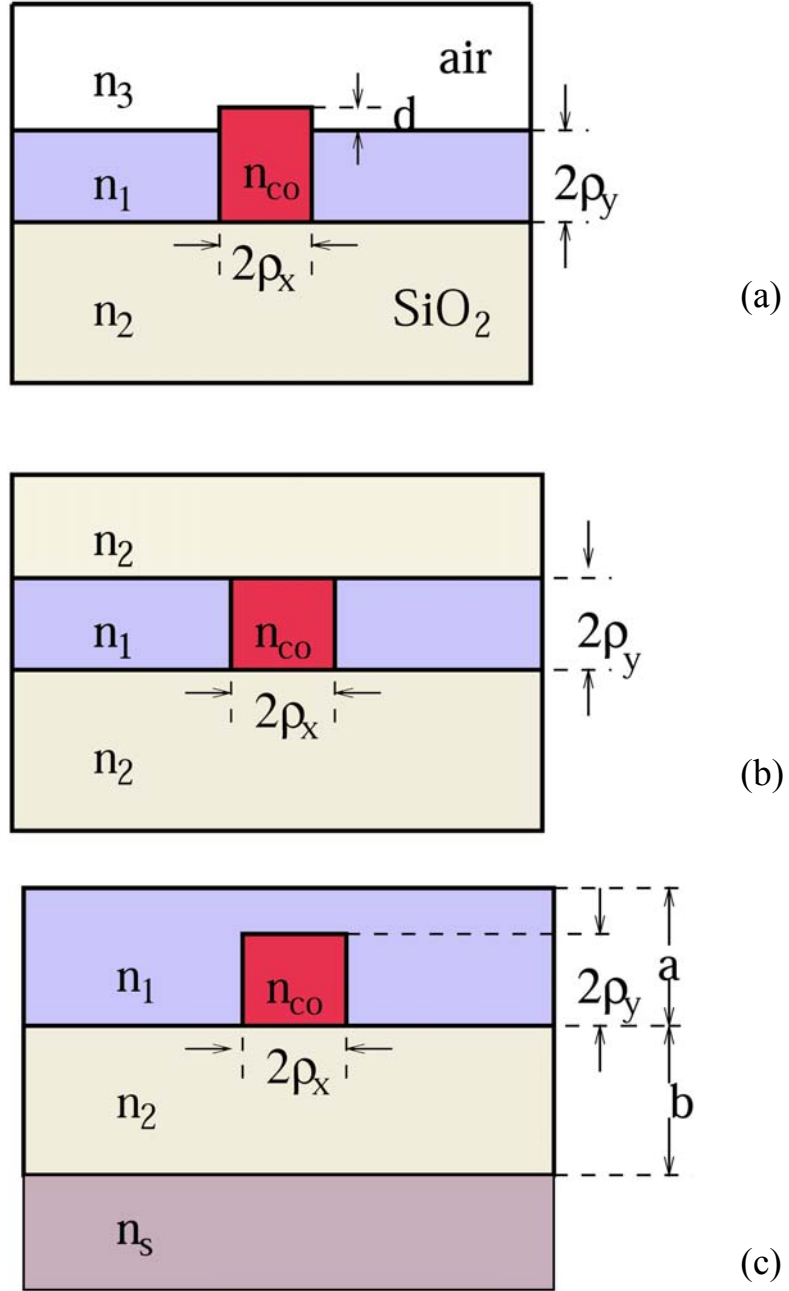


Fig. 2.3 Cross-sections of various buried channel waveguides.

A polymer-silica buried channel waveguide structure with a non-uniform cladding has been used as a practical application for the analysis. The cross-section of the waveguide is shown in Fig. 2.3(a). It consists of a silica buffer layer of index $n_2=1.4531$, a core composed of UV-exposed photosensitive polymer of mean index $n_{co}=1.515$, a cladding

layer on either side of the core composed of polymer with index $n_l=1.5089$. A source wavelength of $\lambda=820\text{nm}$ is assumed. The core protrudes a slight distance, $d=0.2\mu\text{m}$, above the cladding and the region above the core and cladding is air (with index $n_3=1.0$). The core has width $2p_x=5\mu\text{m}$ and the cladding on either side is of thickness $2p_y=5\mu\text{m}$.

The cross-section in Fig. 2.3(b) relates to a buried channel waveguide that is produced by a combination of plasma-enhanced chemical vapour deposition/ reactive ion etching (PECVD/RIE) and direct writing. The buffer and cladding layers have an index of $n_2=1.444$ at 1550nm if composed of pure silica. The core layer consists of germanosilicate to introduce photosensitivity and has a slightly higher index, $n_{co}=1.446$, than the other two layers. The core region is produced by scanning a high intensity laser, such as an Excimer laser, across the top of the tri-layer. In the absence of detailed information about the index profile induced by the beam, we assume for convenience that the index change is uniform under the beam. The net result is a step-wise continuous profile that is non-uniform in the buffer and cladding regions.

The final practical application is shown in Fig.2.3(c). In the fabrication of buried channel waveguide using PECVD/RIE, the buffer layer is laid directly onto a silicon substrate with a particular index, say $n_2=1.446$. The layers are deposited, masked and etched with height of $b=16\mu\text{m}$, and finally a top cladding layer is deposited over the core, as shown, with height $a=16\mu\text{m}$. Here we address the issue of the possibility that the top cladding layer may have an index value different from the buffer layer. We also investigate the effect of including the silicon substrate in the analysis, compared to the zero-field approximation assumed on the buffer layer-substrate interface.

In the propagation analysis, we assume that each waveguide is excited by a Gaussian-shaped source with a spot size radius of $s=2.5\mu\text{m}$.

2.5.1 Fundamental-mode cutoff wavelength

The fundamental mode of the waveguide shown in Fig. 2.3(a) will have a finite cutoff wavelength when $n_{eff}=n_l$, because of the large index difference between the core and air at the top and the core and silica below. The situation is similar to that for a W-shaped fibre, where the deep depression surrounding the core accounts for a finite cutoff wavelength of the fundamental mode. Using the MFDM method on the whole cross-section, as outlined in Section 4.1, the fundamental-mode cutoff wavelength is plotted as a function of the core index n_{co} as the dotted curve in Fig.2.4.

As the core index increases, the cutoff wavelength also increases, as would be expected. The horizontal line in Fig. 2.4 denotes the operating wavelength for the single-mode waveguide, from which it is clear that a core index greater than 1.5118 is required for the mode to remain bound to the core. In other words, the design core index of 1.515 ensures that the fundamental mode is not cut off.

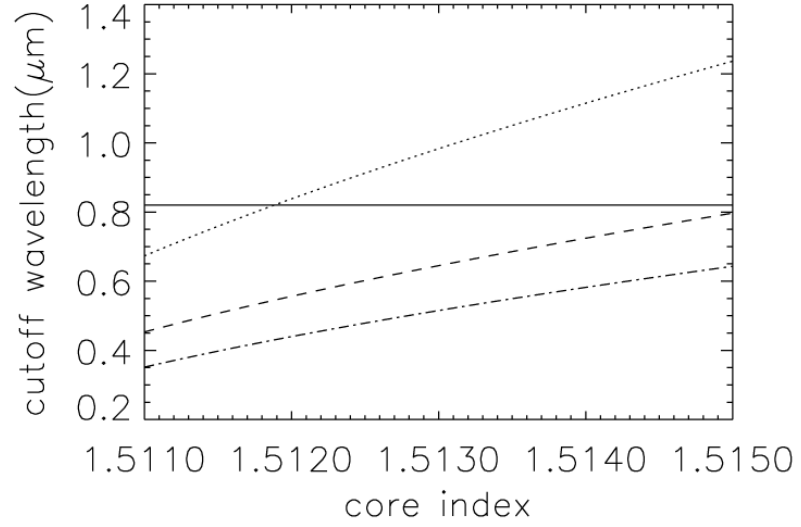


Fig. 2.4 Cutoff wavelength as a function of core index for fundamental (dotted line), first leaky mode (dashed line) and second leaky mode (dash dotted line). Full line shows the operational wavelength of 820nm.

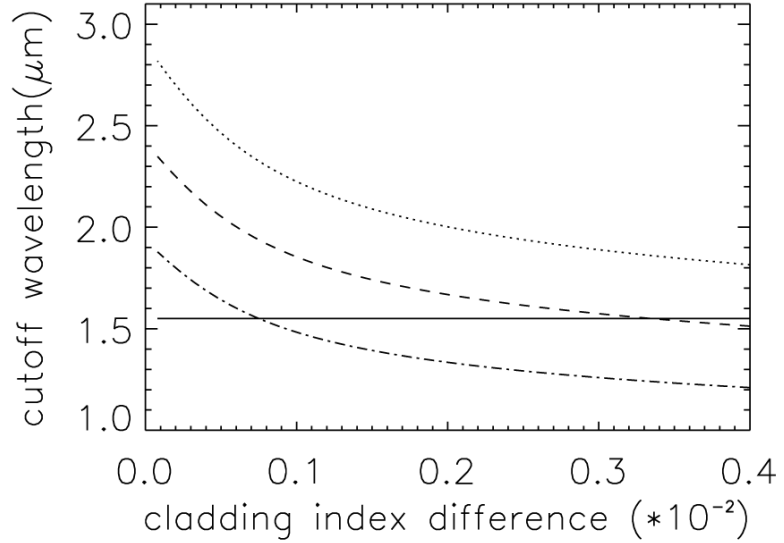


Fig. 2.5 Cutoff wavelength as a function of cladding index difference for the fundamental mode: $2\rho=6\mu\text{m}$ -dotted line; $2\rho=5\mu\text{m}$ -dashed line and $2\rho=4\mu\text{m}$ -dash dotted line). Full line shows the commonly used wavelength of 1550nm.

The cutoff wavelength for the fundamental mode for the square waveguide cross-section in Fig. 2.3(b), which occurs when $n_{\text{eff}}=n_l$, is calculated using the MFDM and is plotted in Fig. 2.5 for a number of values of the core size. Each core size also defines the

width of the cladding on either side of the core. In this situation, the cutoff wavelength of the fundamental mode decreases as the core size decreases.

This trend is to be expected, as the degree of confinement across and close to the core will increase with an increase in the overall area of the core. Similarly, for a given core area, each curve decreases with increasing cladding index difference ($n_1 - n_2$), with n_1 fixed. This trend occurs because the index of the upper and lower layers is decreasing and thereby reducing the effective index of the fundamental mode. This is analogous to the effect of a deepening and /or widening of the depressed region in a W-shaped profile single-mode fibre. For the operating wavelength of 1550nm, it is clear that the reduction can be offset if the core area is increased.

The plots in Fig.2.6 show how the cutoff wavelength of the fundamental mode varies with the index difference between the upper cladding and the buffer layer- Fig.2.3(c). The cutoff wavelength for the fundamental mode occurs when $n_{eff} = n_2$, and is calculated using the H-FDM/MFDM. The dotted curve is based on the zero-field assumption on the buffer layer-substrate interface and the dot-dashed curve includes this region.

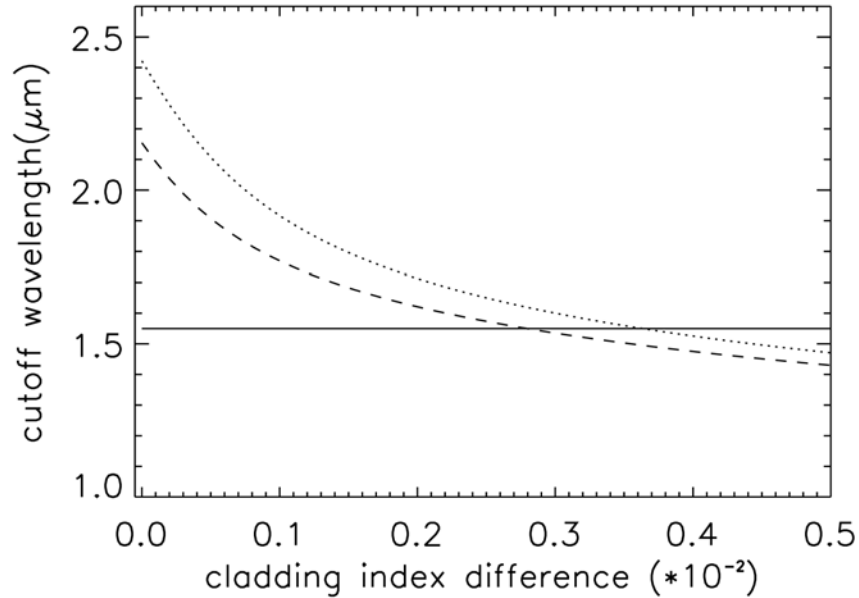


Fig. 2.6 *Cutoff wavelength for the fundamental mode with substrate (dashed line) and without substrate (dotted line).*

Both curves show the same characteristic trend in that the cutoff wavelength decreases with increasing index difference. In the limit of a uniform cladding, the cutoff wavelength in both cases remains finite, consistent with the well-known result that the fundamental mode of a slab waveguide with a cladding of finite thickness has a finite cutoff wavelength.

For the normal operating wavelength of 1550nm, the curves show that the index difference in the cladding should be kept below 0.003; this is not a difficult constraint to achieve in practical PECVD systems.

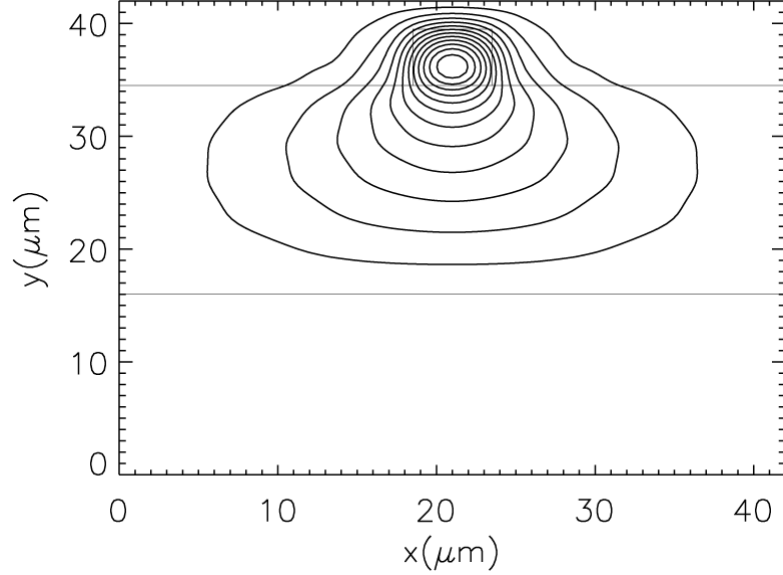


Fig. 2.7 *Contour plot of fundamental mode field ($\Delta n_{cl}=0.005$)*

The plot in Fig. 2.7 show contours of constant field for the fundamental mode when the buffer layer index is 0.005 higher than the upper cladding. Note how the higher-index region contains a much larger fraction of the total field.

2.5.1.1 Comparison of H-FDM/MFDM and MFDM

Here the results obtained with the H-FDM/MFDM are compared with the results obtained with the MFDM for the case of high aspect ratio step profile rectangular waveguides, see Fig. 2.8(a). Using the same number of basis elements in each method, $N=10$ and $M=10$, the cutoff wavelengths of the eigensolutions of (2.18) are plotted as a function of the core half-width, ρ_x . The core height is $\rho_y=\rho_x/3.33$, so the characteristic modal field shapes are similar to those of a slab waveguide. In Figs. 2.8(b) and (c), cutoff wavelengths are plotted as a function of the core dimension using the MFDM and H-FDM/MFDM methods, respectively.

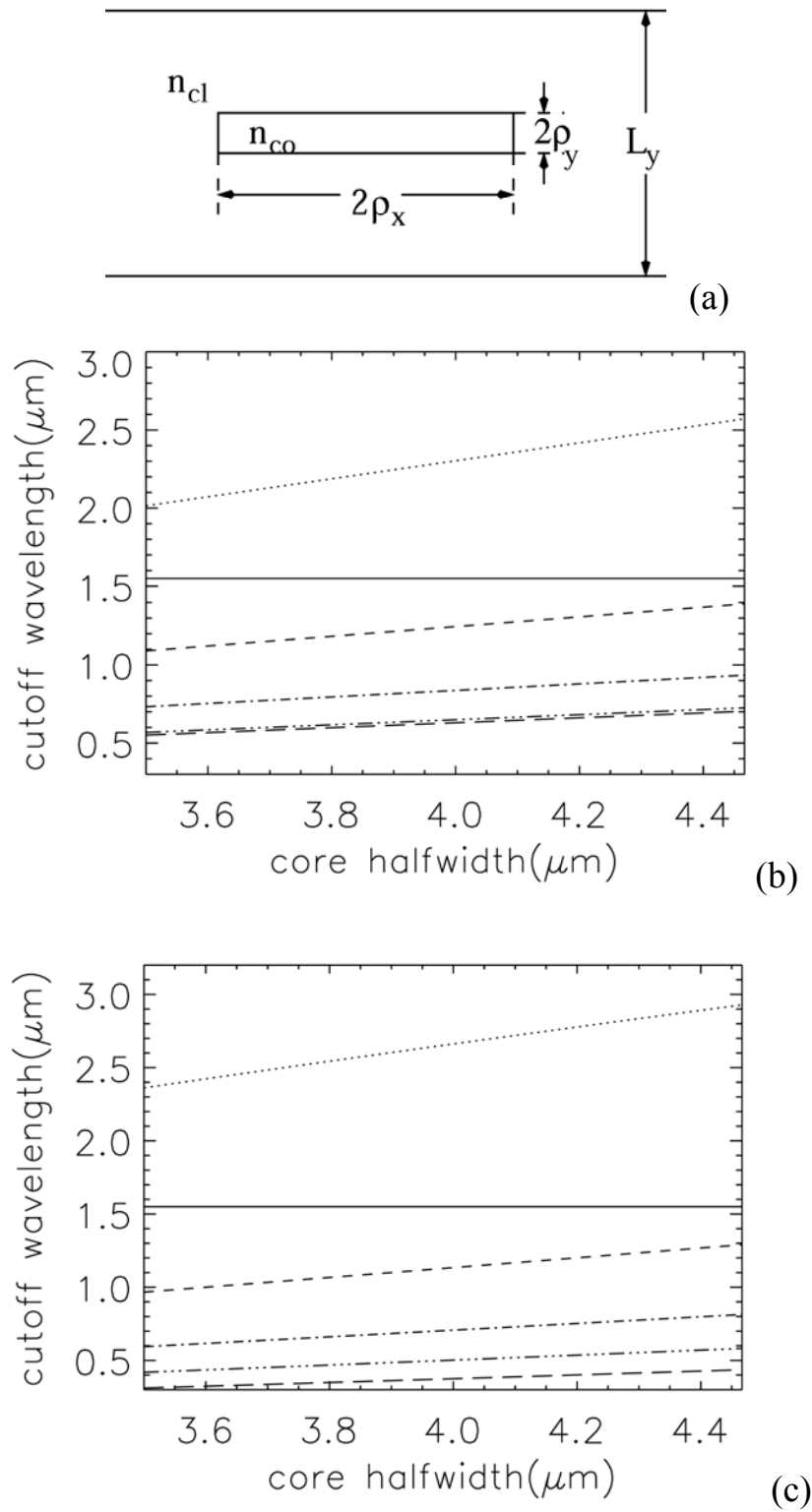


Fig. 2.8(a) Cross-section of the waveguide. Cutoff wavelengths(sloping lines) as a function of core dimension (b) calculated using MFDM and (c) calculated using H-FDM/MFDM. The horizontal line is operational wavelength of 1550nm.

Spurious modes can be seen in Fig. 2.8(b) after the second mode, whereas they do not appear in Fig. 2.8(c), corresponding to the dashed and dash-dot-dot lines. Thus the H-FDM/FDM avoids the problem of spurious modes introduced by the MFDM for waveguides with an asymmetry. The H-FDM/MFDM technique is also applied in chapter 3, when analyzing propagation along segmented gratings.

2.5.2 Spatial transient

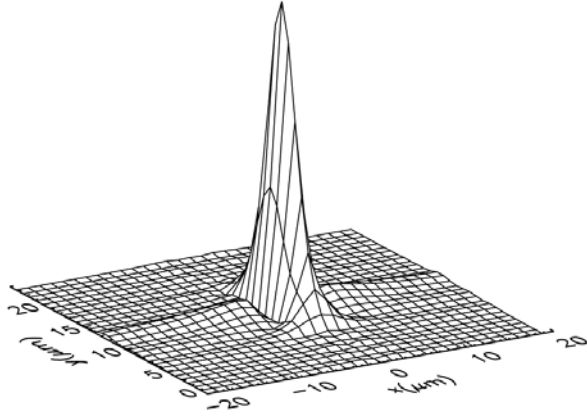
When a single-mode waveguide is excited, not all of the power of the source enters the fundamental mode. The unguided field slowly diverges from the core as it propagates, and its evolution can be quantified using a superposition of the eigensolutions of (2.7). Superposition (2.19) describes propagation along the waveguide using the bound modes of the entire waveguide.

To demonstrate the use of the H-FDM/MFDM technique, the spatial transient field for the single-mode waveguide presented in Fig. 2.3(a) is determined. It has a core index $n_{co}=1.515$ and successive offsets of 0, 1.25 and $2.5\mu\text{m}$ in the x -direction, with an operational wavelength of 870nm and a spot size of $2.5\mu\text{m}$. Surface plots of the spatial transient show intensity of the field given by the superposition in (2.19).

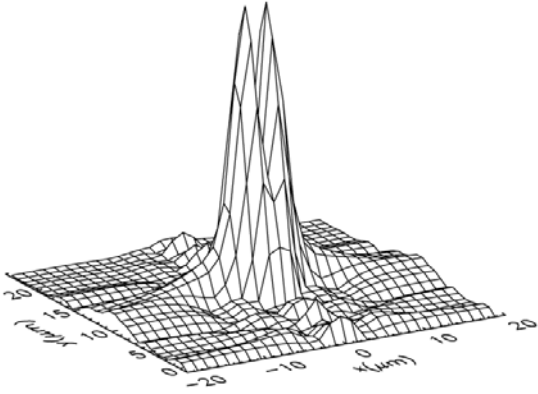
Fig.2.9 shows 3-dimensional plots of the spatial transient electric field at various distances along the waveguide from the source with zero offset of the Gaussian source relative to the waveguide axis. The electric field of the fundamental mode does not match the Gaussian source field exactly, and hence there is a small fraction of power entering higher-order leaky modes in Fig. 2.9(a). The equivalent fundamental mode is elliptical with a width of $3\mu\text{m}$ in the x -direction and $4\mu\text{m}$ in the y -direction. It is clear from Figs. 2.9(a)-(d) that there is a leakage of power in the horizontal direction due to the excitation of leaky modes. Note that, because of the interference between the fundamental and leaky modes, the power distribution in the waveguide cross-section varies significantly along its length. In practice, the fundamental-mode field of an exciting single-mode telecommunications fibre will never exactly match the fundamental mode field of the waveguide, and hence the analytical technique used here can provide a useful detailed analysis of the transient field in the waveguide.

Fig. 2.10(a) and 2.10(b) show 3-dimensional plots of the transverse electric field with a source offset of $1.25\mu\text{m}$ in the x -direction for distances of 1.58cm and 2.46cm along the waveguide, respectively. Compared with on-axis excitation, the field along the waveguide is clearly more asymmetric as the bound mode and leaky modes beat with one another.

Fig.2.11 shows the evolution of the spatial transient with a source offset of $2.5\mu\text{m}$ in the x -direction. The effect of the increased spread of the leaky modes in the x -direction with distance along the waveguide is clear from the 3-dimensional plots and corresponding contour plots. However, the spread in the x -direction is relatively slow when compared to the length of practical buried channel waveguides, which is normally only a few centimetres.

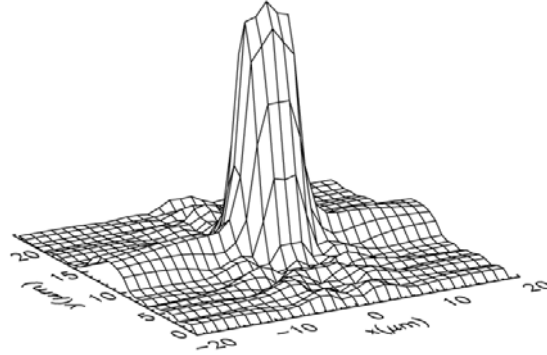


(a)



(b)

(c)



(d)

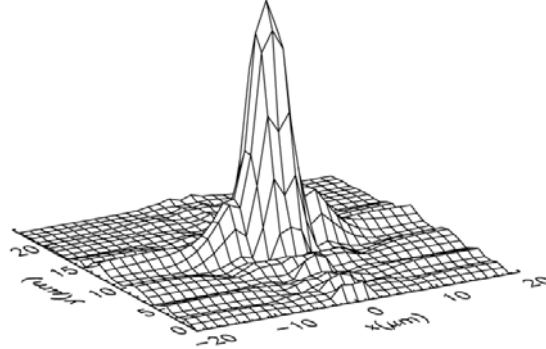


Fig. 2.9 Transverse electric field at four points along the waveguide: (a) $z=0$, (b) $z=3\text{mm}$, (c) $z=2.1\text{cm}$ and (d) $z=2.69\text{cm}$ with zero offset of the source.

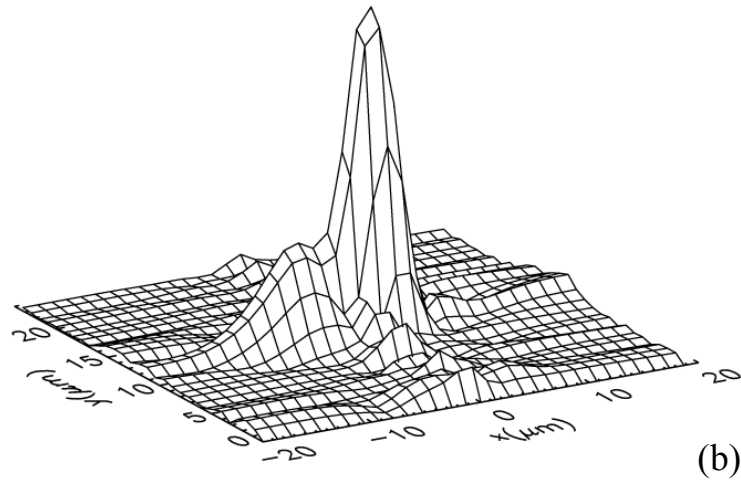
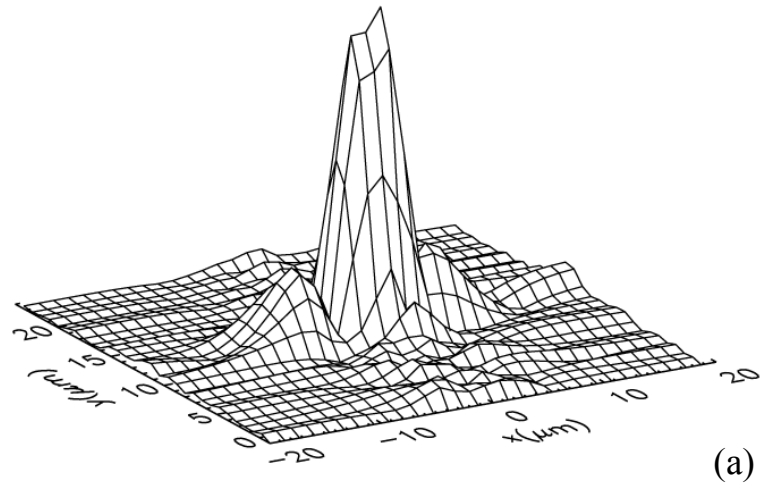
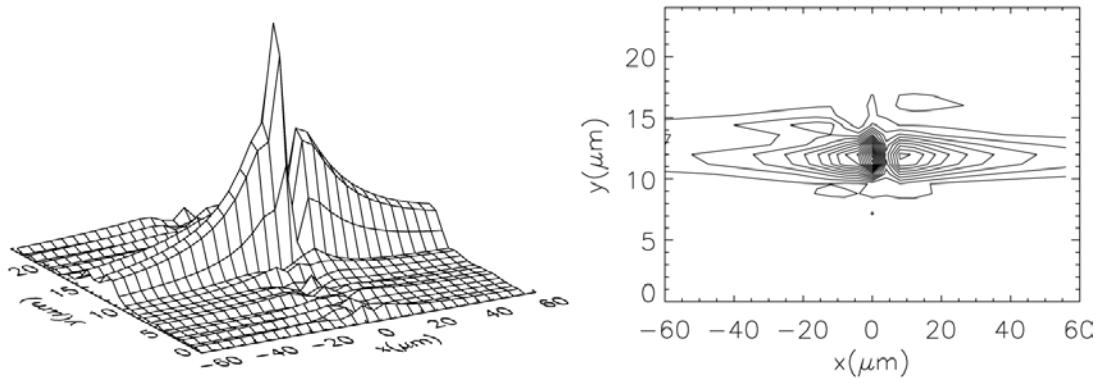
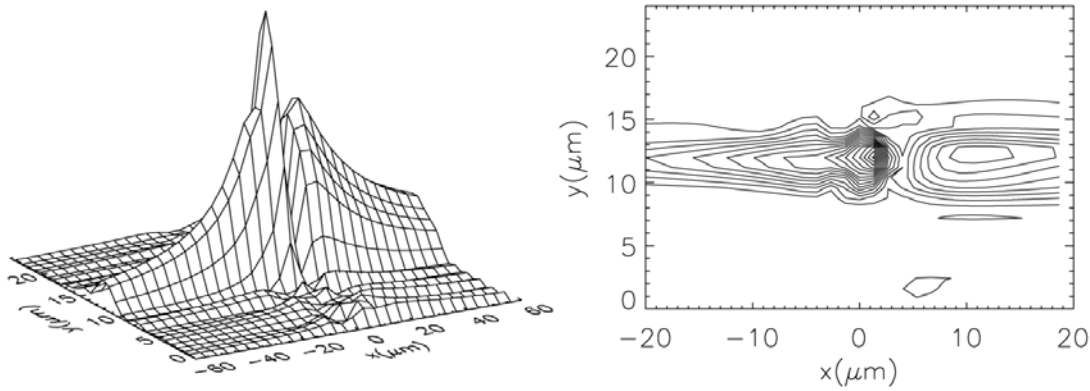


Fig. 2.10 *Spatial transient with the offset of $1.25\mu\text{m}$ at (a) $z=1.58\text{cm}$ and (b) $z=2.46\text{cm}$.*



(a)



(b)

Fig. 2.11 *Spatial transient at two positions along the waveguide: (a) $z=3.9\text{mm}$ and (b) $z=1\text{cm}$.*

2.5.2.1 Comparison of FDM and Hybrid FDM/MFDM

One advantage in using the H-FDM/MFDM over the MFDM in calculating cutoff wavelengths has been presented in 2.4.1.1. Here the results of the FDM and H-FDM/MFDM are compared. In Fig. 2.9(a), the field at the beginning of the waveguide, $z=0$, with zero offset is plotted using the H-FDM/MFDM method. The same field is plotted in Fig. 2.12 using the FDM method and the same parameters values. The FDM method clearly does not account for the horizontal spread of the field that exists in this kind of asymmetric

waveguide. Therefore the spatial transient is not adequately described using the FDM method, because it cannot take into account higher-order leaky modes. Additionally, the FDM boundaries in the horizontal direction are reflective, and thus will not allow radiation to leak from the unbounded waveguide in the x -direction.

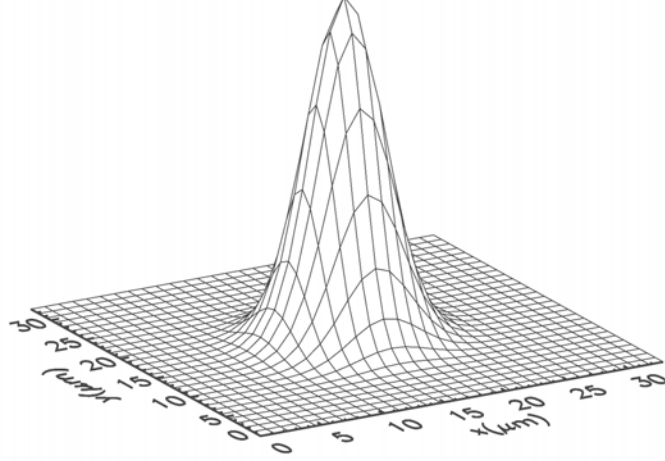


Fig. 2.12 *Transverse electric field at the beginning of the waveguide, $z=0$, with zero offset calculated using the FDM.*

2.6 Conclusions

In this chapter, the cutoff condition and propagation characteristics in non-symmetric rectangular waveguides have been determined. The results suggest the existence of a modal cutoff for the fundamental mode. Therefore, the design parameters of these waveguides must be chosen carefully to ensure the desired single-mode guidance.

A new technique, the Hybrid FDM/MFDM has been derived, to quantify the spatial transient of the complete asymmetric buried channel waveguide when excited by a single-mode fibre source. The results confirm that, for devices which are only a few centimetres long, the spatial transient is important, so that the contribution of higher-order modes, even if they are leaky, must be taken into account.

The results presented here are in keeping with observations in a number of experiments involving the excitation of a variety of single-mode buried channel waveguides, which have observed higher-order modes which appear to cling closely to the core of the waveguide. Our results, when combined with these observations, suggest that close alignment of a single-mode optical field to a buried channel waveguide is necessary in order to avoid the excitation of unwanted leaky modes. In practice, even if these leaky modes are excited, they can be detached from the core by introducing, for example an S-bend into the

waveguide path. However, the detached leaky modes will continue to propagate, and could thus interfere with other components within the wafer.

CHAPTER 3

Planar Waveguide Add/Drop Wavelength Filters based on Segmented Gratings

Demand for high-capacity telecommunication links has resulted an increase in the use of wavelength-division multiplexing (WDM), which is the technology of combining a number of wavelengths onto the fundamental mode of the same fibre. Even though the concept for WDM has been explored for more than two decades, there is still a demand for new solutions for WDM devices that offer the advantage of compactness. There is a need for more compact devices that provide adding or dropping one or more wavelengths (channels) at the interconnected nodes. Therefore a key component still needed for WDM system is an add/drop filter.

There has been widespread application of Bragg reflection gratings to optical fibre waveguiding problems, following from the demonstration of grating writing into fibres with a photosensitive core [8]. A major application of reflection gratings has been to fibre-based devices that add or drop a single wavelength from a set of closely-spaced wavelengths in a WDM or DWDM transmission system within the amplification spectrum of erbium-doped fibre amplifiers (EDFA's). Virtually all of these devices involve gratings that are written approximately uniformly over the core cross-section of a single-mode fibre and at right angles to the fibre axis. They may also be apodized and chirped along their length. In each case, the grating provides virtually 100% reflection of the forward-propagating fundamental mode into the backward-propagating fundamental mode at the design Bragg wavelength provided the grating is sufficiently long.

As well as wavelength-selective reflection of the fundamental mode by such a grating, a reflection grating can also be used to couple light between the fundamental mode and backward-propagating, higher-order modes in a few-mode fibre. For example, a slightly blazed or tilted grating written into the core of a two-mode fibre can reflect light from the fundamental mode into the second, i.e. first odd mode, of the fibre at the Bragg wavelength. Whilst this intermodal coupling property of blazed gratings has been quantified and demonstrated [9], its application to add/drop wavelength filters is not straightforward. One reason is the difficulty in separating the fundamental and second modes of the fibre in a

simple and efficient manner. Ironically, it is the cylindrical symmetry of the fibre that inhibits an effective solution to this separation.

3.1 Planar blazed gratings

If the above discussion of blazed gratings is considered in terms of two-mode planar waveguides instead of fibres, the rectangular geometry of the core and the nature of the waveguide fabrication technique enable mode separation to be readily achieved with minimal cross-talk. Consider the two-mode waveguide core illustrated in Fig. 3.1, with 2-mode asymmetric Y-junctions at each end and a blazed grating written across the core.

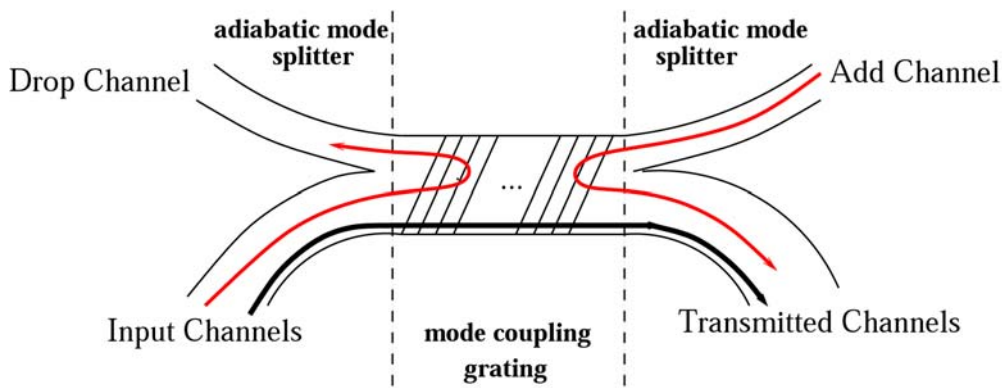


Fig. 3.1 *Planar add/drop wavelength filter.*

Light from the fundamental mode enters the device through the wider lower port of the Y-junction on the left and evolves to become the fundamental mode of the core region. For wavelengths different from the Bragg wavelength, this mode passes through the blazed grating without attenuation and exits the device approximately adiabatically through the lower port of the right hand Y-junction. The functionality of these asymmetric Y-junctions in terms of cross-talk between the arms has been quantified [10]. At the design Bragg wavelength, the fundamental mode reflects from the blazed grating and couples into the backward-propagating first odd mode, which then exits the device through the narrower left-hand upper arm of the Y-junction [11].

It is important to note that, at any longitudinal position along the waveguide, the blazed grating has a refractive index profile that is not anti-symmetric about the waveguide axis in the core cross-section. Consequently, the grating can also couple light from the forward-

propagating fundamental mode into the backward-propagating fundamental mode, but at a wavelength longer than that for coupling to the odd mode. This effect could be a problem for WDM systems with many wavelength channels, but by judicious choice of the blaze angle, the back reflection effect can be minimized [12]. However, there is an alternative type of grating to the blazed one that totally avoids back-reflection into the fundamental mode. Additionally, the minimum channel spacing of around 1.2nm obtained using the blazed grating is larger than the standard channel spacing for dense WDM of 0.8nm.

3.2 Segmented gratings

The basic idea behind a segmented grating is to replace a grating written over the entire core cross-section of a fibre or waveguide, such as the normal and blazed gratings above, with a grating that is written over only part of the core. The greater flexibility and compactness in device design that can be achieved using this approach is illustrated using the following two examples based on the blazed grating planar devices discussed above.

For the case of high aspect-ratio step profile rectangular waveguides, the characteristic modal field shapes in the centre of the waveguide are similar to those of a slab waveguide. Therefore the modes are of even or odd symmetry in the horizontal direction, as for the slab waveguide. In the y-direction there is space for only one maximum and therefore, in that direction, the waveguide is single mode. In this case, use of gratings with even or odd symmetry enables selectivity in terms of the mode symmetry. Gratings with certain symmetry in the horizontal direction will be symmetry-selective, reflecting the modes of particular symmetry.

3.2.1 Anti-symmetric segmented grating

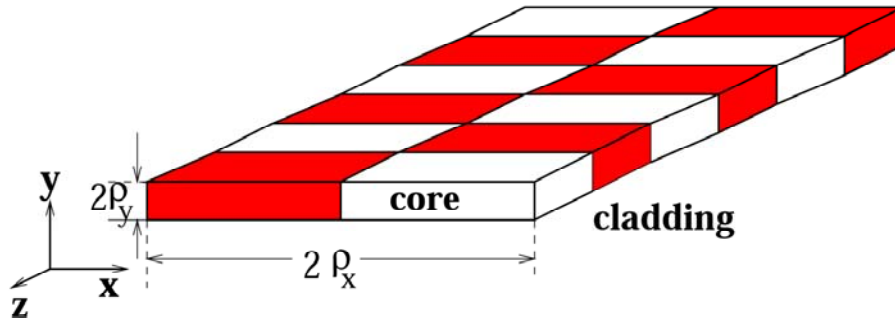


Fig. 3.2 Schematic of the anti-symmetric segmented grating.

An anti-symmetric segmented grating has the property that its refractive index distribution is anti-symmetric in the waveguide cross-section about a vertical axis, corresponding to the y-axis in the schematic in Fig. 3.2. Here the darker and lighter sections correspond to regions of higher and lower index, respectively. Alternatively, the segmented grating can be thought of as two identical gratings offset longitudinally by half a grating period.

This kind of grating reflects the mode of **odd** symmetry at the Bragg wavelength and transmits all modes of even symmetry, providing absolutely zero reflection of even modes.

3.2.2 Symmetric segmented grating

The even segmented grating consists of three equal-period gratings written across the core, such that the two outer gratings of equal width, t , are in phase longitudinally, while the third grating, of width $2s$, is centrally located and out of phase with the outer gratings by half a period as illustrated in Fig.3.3.

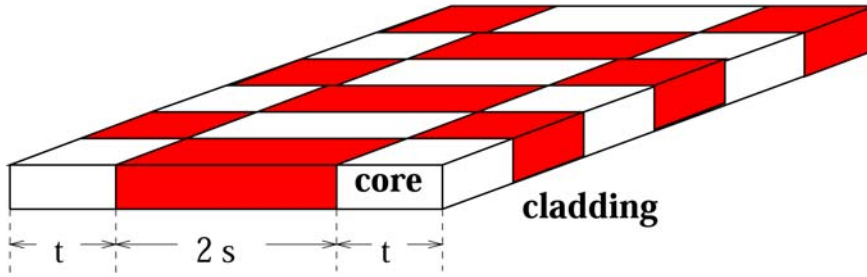


Fig. 3.3 *Schematic of the symmetric segmented grating.*

This kind of grating is also symmetry selective, reflecting only modes of even symmetry and transmitting all odd modes.

3.3 Device design

3.3.1 Single wavelength add/drop filter

Fig. 3.4 shows a schematic of the 4-port add/drop wavelength filter with an anti-symmetric, segmented grating, illustrated in Fig. 3.2, written into the core.

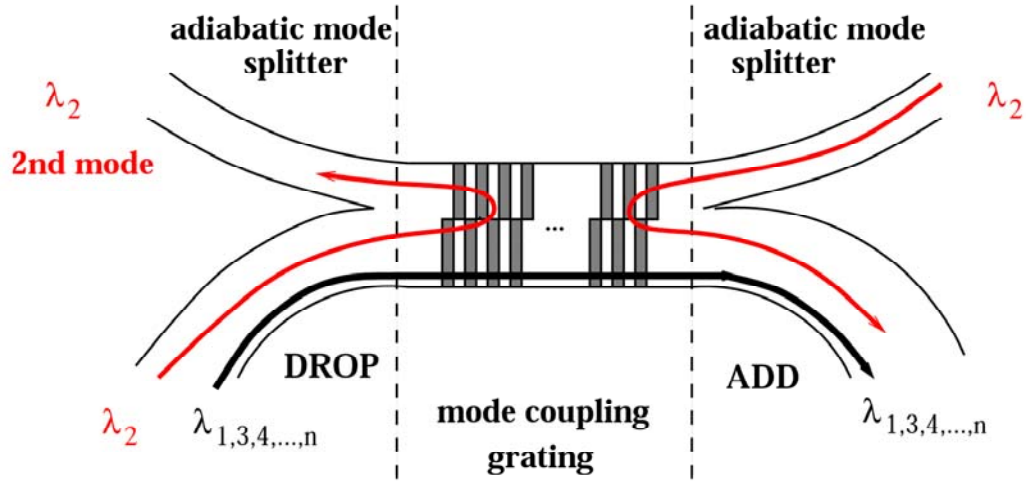


Fig. 3.4 Schematic of the 4-port add/drop wavelength filter with anti-symmetric segmented grating in the coupling region.

The anti-symmetry enables the forward-propagating fundamental mode to couple into the backward-propagating first odd mode at the appropriate Bragg wavelength, and vice-versa, but also ensures that there is no reflection into the backward-propagating fundamental (first even) mode. The 2 input and 2 output ports of the 2-mode rectangular step-profile core have sufficiently dissimilar core widths to ensure that the fundamental mode enters and leaves the device approximately adiabatically through the wider ports, while the first odd mode enters or leaves through the narrower ports. This phenomenon has been analyzed in detail and the cross talk between ports quantified [10].

3.3.2 Two wavelength add/drop filter

More recently, a 6-port, 3-mode single core device, also incorporating a blazed grating, has been designed to add or drop two closely spaced wavelengths simultaneously [12]. The functionality of this 6-port device, like the 4-port device above, relies on having 3 input and 3 output ports that are sufficiently dissimilar to enable approximately adiabatic evolution of the second and third core modes into the fundamental mode of the corresponding input or output ports [10]. Both gratings are written into the 3-mode core and, in drop mode they couple power from the forward-propagating fundamental mode into the backward-propagating first anti-symmetric mode and the backward-propagating second even mode at the respective coupling wavelengths. In add mode, the coupling process is simply reversed.

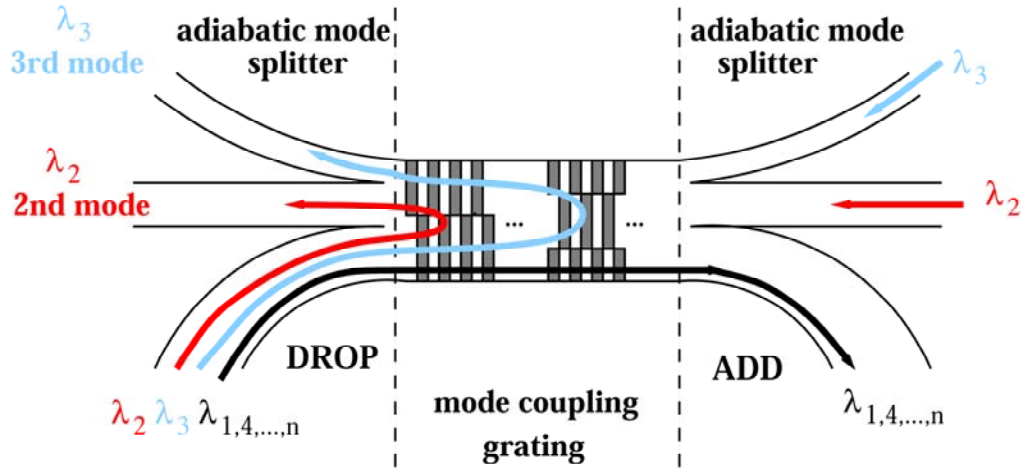


Fig. 3.5 *Schematic of the 6-port add/drop wavelength filter incorporating both symmetric and anti-symmetric segmented gratings in the coupling region.*

A second device that enables two wavelengths to be dropped or added simultaneously comprises 3 input and 3 output ports and a 3-mode core, as illustrated in Fig. 3.5. The desired functionality is achieved by writing two segmented gratings – one anti-symmetric and symmetric - into the core. The anti-symmetric segmented grating couples the forward-propagating fundamental mode to the backward-propagating first odd mode, as in the 4-port device, and the symmetric segmented grating couples to the backward-propagating second even mode. The 2 wavelengths at which coupling occurs can be made arbitrarily close by a judicious choice of the grating periods. In the case of the symmetric segmented grating, reflection into the backward-propagating fundamental mode can be virtually eliminated by appropriate choice of the grating widths, $2s$ and t , respectively, in the core cross-section.

3.4 Method of analysis

The analysis of propagation through the segmented gratings is based on the standard coupled mode theory approach [13]. First, the propagation constants and modal fields are

determined for the waveguide without the grating present [14]. Standard coupled-mode equations are then solved for the waveguide with the grating included.

3.4.1 Modal analysis

In chapter 2, the Hybrid FDM/MFDM was introduced and shown to be a more appropriate method for modal analysis of the waveguides with high aspect ratio than the Modified Fourier Decomposition Method. In particular, the H-FDM/FDM avoids the problem of spurious modes introduced by the MFDM for waveguides with asymmetry. The waveguide is mapped onto the unit line in the horizontal x -direction, while in the vertical y -direction, the boundaries are at a finite distance from the core. In this way, any radiation from the waveguide in the horizontal direction is taken into account. The scalar wave equation (2.2) is solved and the superposition of the modal fields obtained as in (2.17).

3.4.2 Coupled-mode theory

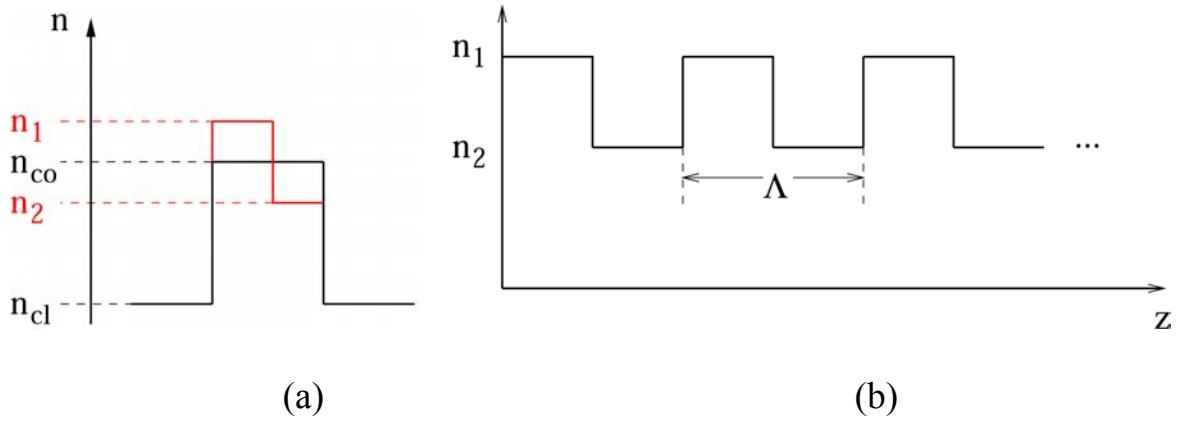


Fig. 3.6 (a) transverse and (b) longitudinal refractive index profiles of the step-profile waveguide with an anti-symmetric segmented grating written into the core.

The index modulation, $\Delta n = n_1 - n_{co} = n_{co} - n_2$, of the grating is assumed to be small in all the cases examined here, and therefore perturbation theory can be used. The periodic variation of the refractive index, n , is considered as a perturbation of the waveguide and the complete refractive index is written as:

$$n^2(x, y, z) = n_o^2(x, y) + \Delta n^2(x, y, z) , \quad (3.1)$$

where n_0 is the unperturbed part of the index and $\Delta n(x,y,z)$ is the small perturbation, that is periodic in the propagation z -direction. The modal fields and propagation constants of the unperturbed waveguide without the grating, are obtained using the H-FDM/MFDM. These results are used to express the field in terms of the superposition of equation (2.17), but the coefficients a_p in the expansion are now functions of z :

$$E_{\text{sup}} = \sum_p a_p(z) E_p(x, y, \beta_p) e^{i(\omega t - \beta_p z)}, \quad (3.2)$$

where ω is the source frequency. Substituting (3.2) into the scalar wave equation (2.2) and using (3.1), the scalar wave equation becomes:

$$\sum_p \left[\frac{d^2}{dz^2} a_p(z) - 2i\beta_p \frac{d}{dz} a_p \right] E_p(x, y) e^{-i\beta_p z} = -k^2 \sum_s \Delta n^2(x, y, z) a_s(z) E_s(x, y) e^{-i\beta_s z}. \quad (3.3)$$

By neglecting the second derivative in (3.3), multiplying (3.3) with $E_p(x,y)$, using the orthogonality of the modes and expanding the refractive index perturbation as a Fourier series:

$$\Delta n^2(x, y, z) = \sum_{m \neq 0} n_m^2(x, y) e^{-im \frac{2\pi}{\Lambda} z} \left[= \sum_m \frac{i(1 - \cos m\pi)}{m\pi} e^{-im \frac{2\pi}{\Lambda} z} \right] \quad (3.4)$$

leads to:

$$\frac{d}{dz} a_p = -i \frac{\beta_p}{|\beta_p|} \sum_s \sum_m \kappa_{ps}^m a_s e^{i\left(\beta_p - \beta_s - m \frac{2\pi}{\Lambda}\right)z}, \quad (3.5)$$

where κ_{ps}^m is a coupling coefficient, representing the magnitude of coupling between the p - and s -th mode due to the m -th Fourier component of the refractive index perturbation, that for a uniform grating, this can be expressed in the form given by the part enclosed within brackets in (3.4). The integrals over regions with different refractive indices are calculated separately and added together. For the anti-symmetric grating:

$$\kappa_{ij} = \int_{-\rho_x}^0 \int_0^{2\rho_y} E_i^*(x, y) n^2_1(x, y, z) E_j(x, y) dx dy + \int_0^{\rho_x} \int_0^{2\rho_y} E_i^*(x, y) n^2_2(x, y, z) E_j(x, y) dx dy, \quad (3.6)$$

where $*$ denotes complex conjugate.

For the symmetric grating, the coupling coefficients are calculated by:

$$\begin{aligned} \kappa_{ij} = & \int_{-\rho_x}^{-\rho_x+t} \int_0^{2\rho_y} E_i^*(x, y) n_1^2(x, y, z) E_j(x, y) dx dy + \int_{-s}^s \int_0^{2\rho_y} E_i^*(x, y) n_2^2(x, y, z) E_j(x, y) dx dy + \\ & + \int_s^{\rho_x} \int_0^{2\rho_y} E_i^*(x, y) n_1^2(x, y, z) E_j(x, y) dx dy \quad . \end{aligned} \quad (3.7)$$

At and close to a particular coupling wavelength, it is assumed that only two modes are strongly coupled. The system of coupled-mode equations can then be solved analytically for an unapodized grating [13]. With the boundary conditions $a_f(z=0)=a_f(0)$ and $a_b(z=L)=0$ the solution for the mode amplitudes are:

$$\begin{aligned} a_f(z) = a_f(0) e^{i\frac{1}{2}\Delta\beta z} & \left[\frac{s \cosh s(L-z) + i\frac{1}{2}\Delta\beta \sinh s(L-z)}{s \cosh sL + i\frac{1}{2}\Delta\beta \sinh sL} \right], \\ a_b(z) = a_b(0) e^{-i\frac{1}{2}\Delta\beta z} & \left[\frac{-i\kappa^* \sinh s(L-z)}{s \cosh sL + i\frac{1}{2}\Delta\beta \sinh sL} \right], \end{aligned} \quad (3.8)$$

where:

$$s = \sqrt{\kappa^* \kappa - \left(\frac{1}{2}\Delta\beta\right)^2} \quad (3.9)$$

and

$$\Delta\beta = \beta_1 + \beta_2 - m\frac{2\pi}{\Lambda} \quad , \quad (3.10)$$

where $m=1,2,3,\dots$, Λ is the period of the grating and β_1 and β_2 are the propagation constants of the forward-propagating and backward-propagating modes, respectively. Reflectivity is therefore given by:

$$R = \left| \frac{a_b(0)}{a_f(0)} \right|^2 = \frac{\kappa^* \kappa \sinh^2 sL}{s^2 \cosh^2 sL + \left(\frac{1}{2}\Delta\beta\right)^2 \sinh^2 sL} \quad (3.11)$$

Including a sine-squared apodization, the coupled mode equations become:

$$\frac{da_f}{dz} = i\kappa \sin^2\left(\frac{\pi z}{L}\right) a_b(z) e^{i\Delta\beta z} \quad , \quad \frac{da_b}{dz} = -i\kappa^* \sin^2\left(\frac{\pi z}{L}\right) a_f(z) e^{-i\Delta\beta z} \quad (3.12)$$

where a_f and a_b are amplitudes of the forward- and backward-propagating fundamental and second modes, respectively, L is the length of the grating and $\Delta\beta$ is given by (3.10)

By defining the local reflection coefficient:

$$r(z) = \frac{a_b}{a_f} \quad (3.13)$$

then differentiating:

$$\frac{dr}{dz} = \frac{1}{a_f} \frac{da_b}{dz} - \frac{a_b}{a_f^2} \frac{da_f}{dz} \quad (3.14)$$

and substituting into (3.8) the differential equation:

$$\frac{dr}{dz} = -i \sin^2\left(\frac{\pi z}{L}\right) \left[r^2 \kappa e^{i\Delta\beta z} + \kappa^* e^{-i\Delta\beta z} \right] \quad (3.15)$$

is obtained.

This equation is of the form of Riccati's equation, and it can be reduced to a linear equation if any one particular solution is known. Since a particular solution is not available, the solution to the differential equation (3.15) is obtained by the numerical Runge–Kutta method [7], using the initial condition $r(L)=0$.

3.5 Analysis and results

3.5.1 Physical model

For two-, three- and four-mode propagation, a waveguide with core index 1.46, cladding index 1.452, common core thickness $2\rho_y=4.7\mu\text{m}$, core width $2\rho_x$, and aspect ratios $\rho_x/\rho_y=2.1, 3.33$, and 4.5 respectively, were assumed, see Fig 3.7.

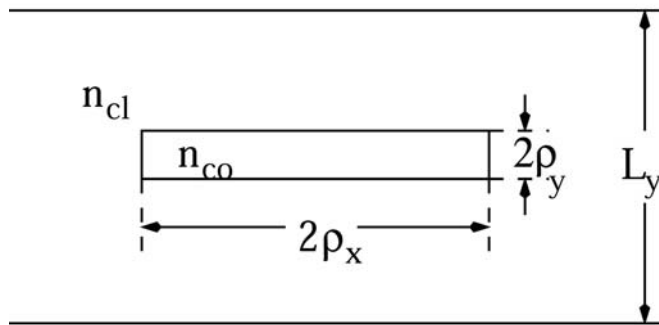


Fig. 3.7 Cross-section of the waveguide.

Here L_y is sufficiently large compared with the core dimension that the field is approximately zero on the boundaries $y=0$ and $y=L_y$. With a sufficient number of the basis elements in (2.8) convergence of the solution for the propagation constant is obtained. Ten to twelve basis elements, see (2.8), and a width six times longer than the core width are mainly used in calculations. In the x-direction, there are no marked boundaries, as the whole x-axis is mapped onto the unit line $x=[0,1]$.

3.5.2 Anti-symmetric segmented grating

The first structure to be analysed using the coupled mode equations is the anti-symmetric, unapodised, segmented grating illustrated in Fig.3.2 with the index modulation shown in Fig.3.6. The fundamental mode of the core in Fig.3.7 enters the grating at one end $z=0$. The transmittance T , i.e. the fraction of fundamental mode power that emerges from the far end of the grating length L is calculated from (3.11) for the situation when the source wavelength matches the Bragg condition between the forward-propagating fundamental mode and the backward-propagating second, or first odd mode of the waveguide, i.e. $\Delta\beta=0$ or $s=\kappa$, and $T=1-R$.

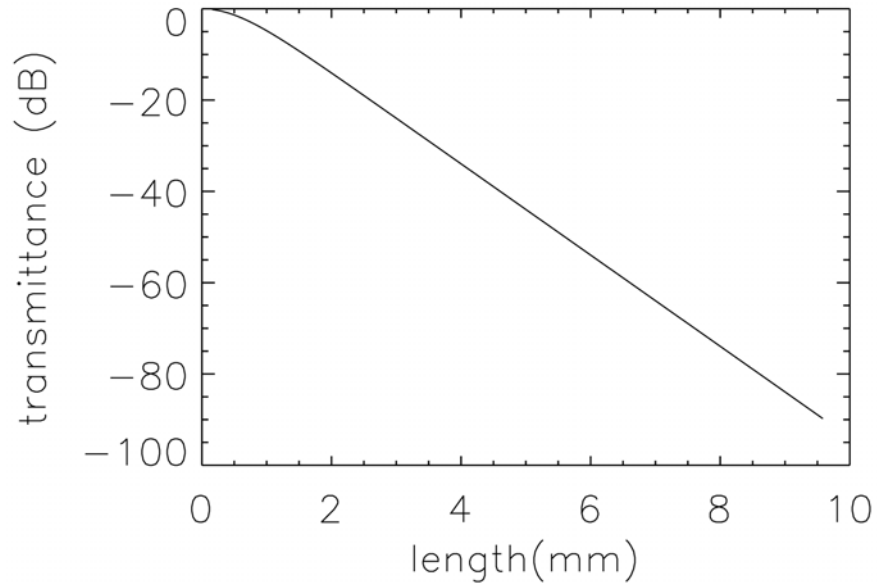


Fig. 3.8 Transmittance of the fundamental mode through the anti-symmetric grating as a function of grating length.

In Fig. 3.8, the transmittance of the first odd mode is plotted as a function of the grating length for the two mode waveguide, with a core aspect ratio of 2.1. The index modulation is $\Delta n = n_1 - n_{co} = n_{co} - n_2 = 0.002$ for the unapodized grating and the source wavelength is $\lambda = 1.55 \mu m$.

It can be seen that transmittance is reduced to -50dB for just 5mm length of the anti-symmetric grating, with zero reflection into the fundamental mode. This continues to decrease linearly (in dB) with increasing grating length, as the theory predicts. On a dB scale this is equivalent to:

$$T = -20\log_{10}\{\text{sech}(\kappa L)\} \sim 20\kappa L\log_{10}e \text{ for } |\kappa L| \gg 1 \quad (3.16)$$

The linear part of the curve is predicted by the asymptotic form of the expression in (3.16) for large argument.

Assuming an unapodized grating of fixed length 1cm , the transmittance of the fundamental mode is plotted as a function of the index modulation of the grating in Fig. 3.9. The plot shows that with an index modulation of only 0.002 , transmittance of the first odd mode is less than -90dB and continues to decrease linearly with increasing index modulation, as predicted by the asymptotic form of (3.16).

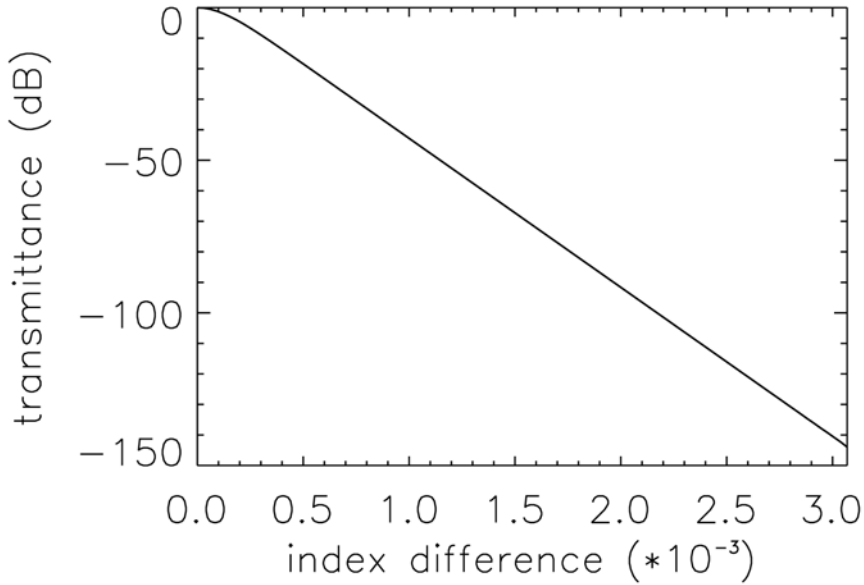


Fig. 3.9 *Transmittance of the first odd mode anti-symmetric grating as a function index modulation.*

The transmission spectrum, on a logarithmic scale, for the 4-port device of Fig.3.4 is plotted in Fig. 3.10, assuming an unapodised grating of length 1cm and core index modulation $\Delta n=0.001$. The results exhibit a maximum reflectance of -53dB at 1.5494 microns , with a maximum width of 0.35nm .

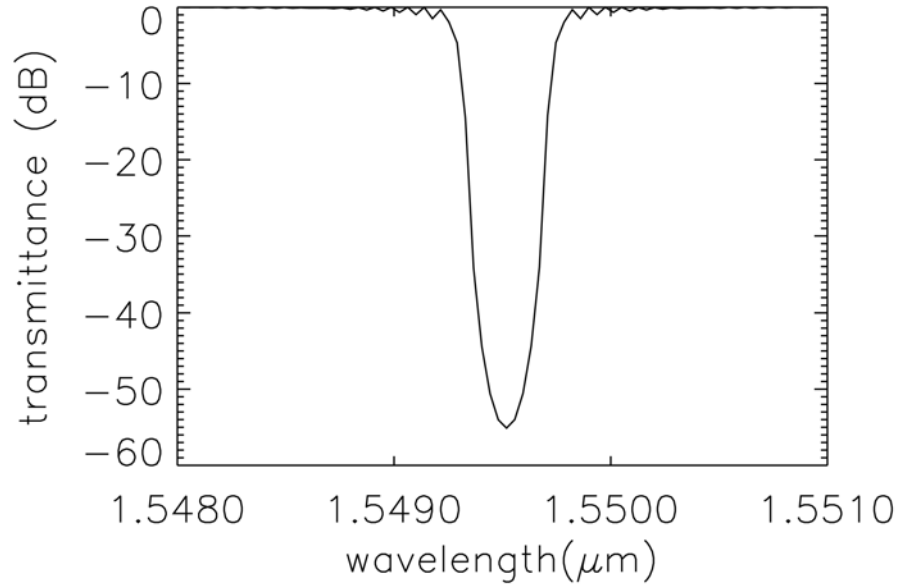


Fig.3.10 *Transmittance spectrum for coupling from the forward-propagating fundamental mode into the first backward-propagating odd mode, for the 4-port device of Fig. 3.4.*

Aside from the maximum reflectance at and close to the resonant point, $\Delta\beta=0$, the spectrum includes a series of sidelobes on both sides of the peak, that will be discussed in Section 3.5.6.

3.5.3 Symmetric segmented grating

For reflection of the fundamental mode into backward-propagating modes with even symmetry, a grating with appropriate even symmetry, such as that illustrated in Fig. 3.3, can be used instead of the blazed grating employed for the 6-port device in Fig. 3.4. Since the fundamental mode is of even symmetry, it will also be reflected. Thus the aim is then to minimize this reflection, while not adversely affecting significantly the reflection of higher-order even modes. Power reflected into the backward-propagating fundamental mode can propagate back through the input channel and may give rise to cross-talk. In Fig. 3.11, the coupling coefficients for the coupling between the forward- and backward-propagating fundamental mode and the backward- propagating second even mode are plotted as a function of the grating dimension $2s$. This dimension determines the width of the central symmetric part of the grating in Fig. 3.3.

The coupling coefficient is zero when $2s=4.8\mu\text{m}$, and thus there is then no reflectance of the forward-propagating fundamental mode into backward-propagating fundamental mode. Similarly, there is no reflection from the fundamental mode into the backward-propagating second even mode when $2s=0.6\mu\text{m}$, and a maximum when $2s=6.8\mu\text{m}$.

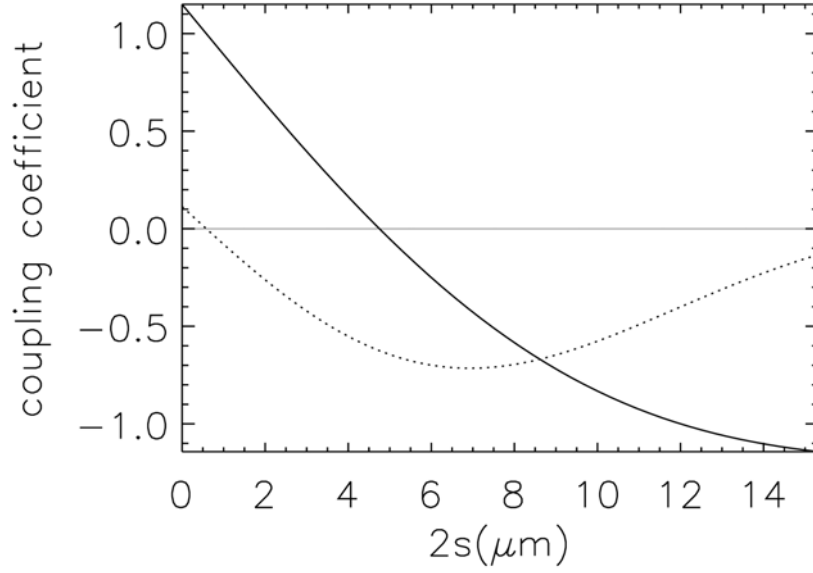


Fig. 3.11 Coupling coefficient as a function of the width $2s$ of the central grating region for coupling of the forward-propagating fundamental mode into the backward-propagating fundamental mode (solid line) and backward-propagating second even mode (dotted line).

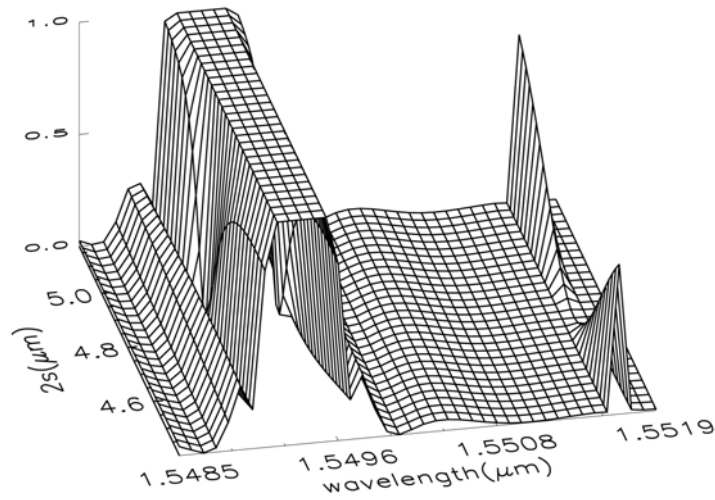


Fig. 3.12 Reflectivity of the first two even modes as a function of the wavelength and width of the centrally-located grating.

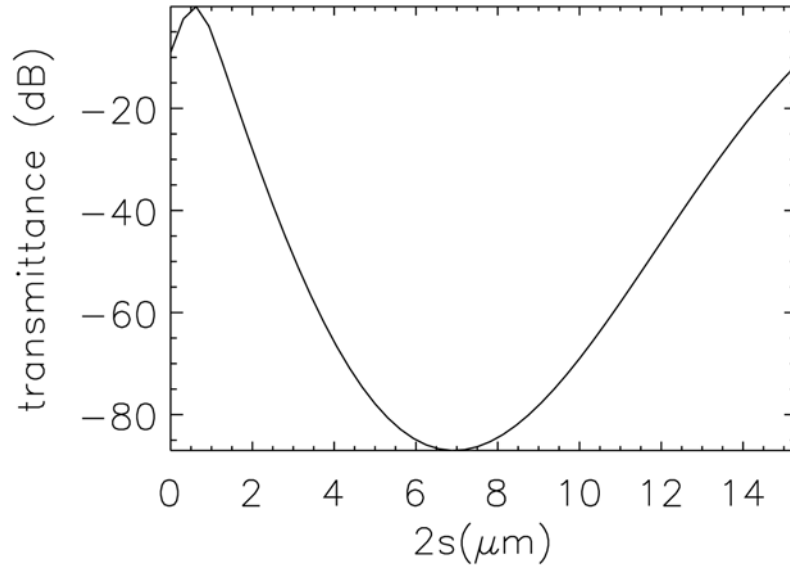


Fig. 3.13 *Transmittance of the second even mode as a function of the width of the centrally-located grating at the Bragg wavelength.*

Fig. 3.12 plots a composite two-dimensional surface for the reflectivity from the fundamental mode into the back-ward propagating fundamental and second even modes as a function of both the source wavelength and the central grating width $2s$.

The reflectivity of the second even mode is extremely close to 100% and shows little variation with change in the grating central width $2s$, as expected from the results for the coupling coefficient plotted in Fig. 3.11. In terms of transmittance, at the Bragg wavelength, the very slight variation in reflectivity in Fig. 3.12 is magnified in the dB scale in Fig. 3.13. It is clear that there is a minimum in transmittance of -87dB when $2s=6.8\mu\text{m}$. However, it is desirable to minimize the reflectance into the backward-propagating fundamental mode, Fig. 3.12, shows that a zero reflectance occurs when $2s=4.8\mu\text{m}$. This leads to a slight reduction in transmittance to -70dB in Fig. 3.13. From the same figure, it can be seen that there is zero reflectance of the second even mode when $2s=0.6\mu\text{m}$. This is to be expected, as the coupling coefficient for coupling of the forward-propagating fundamental mode into the backward propagating second even mode is zero for $2s=0.6\mu\text{m}$, as seen in Fig. 3.11.

In Fig. 3.14 transmittance (in dB) is plotted as a function of the grating length. The index modulation is $\Delta n=0.002$, the period of grating is $\Lambda=1.59\mu\text{m}$ and the Bragg wavelength is $1.549\mu\text{m}$. The inner grating dimensions have been chosen to minimize reflectance into the fundamental mode at $2s=4.8\mu\text{m}$. The transmittance shows the same trend as for the anti-symmetric grating and decreases linearly in dB with increasing grating length.

In Fig. 3.15, the length of the grating is fixed, $L=1\text{cm}$, and the index modulation is varied. On increasing the index modulation, the transmittance of the second even mode (for a three mode waveguide) decreases, as expected. The grating length and index modulation for a given transmittance can be determined from Figs. 3.14 and 3.15 when the symmetric grating is incorporated into the 6-port two-wavelength add/drop filter discussed below.

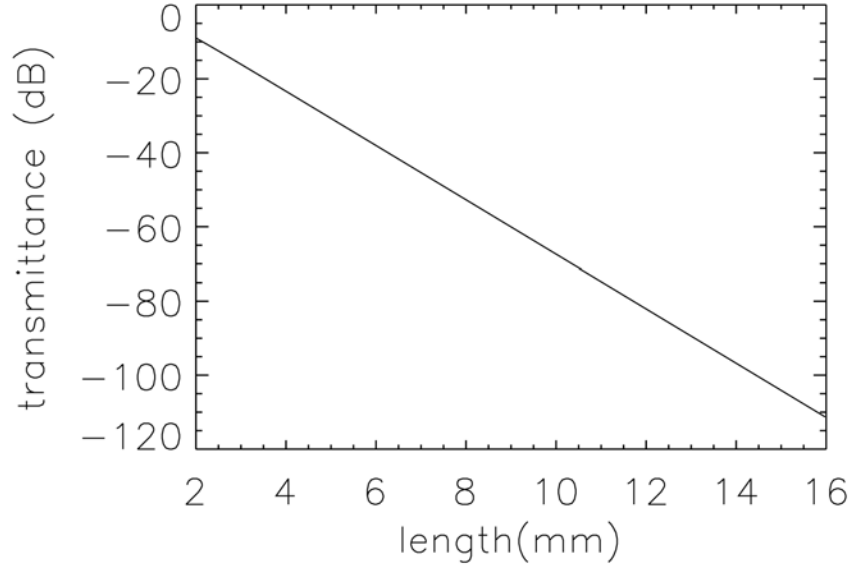


Fig. 3.14 Transmittance of the symmetric grating as a function of the grating length.

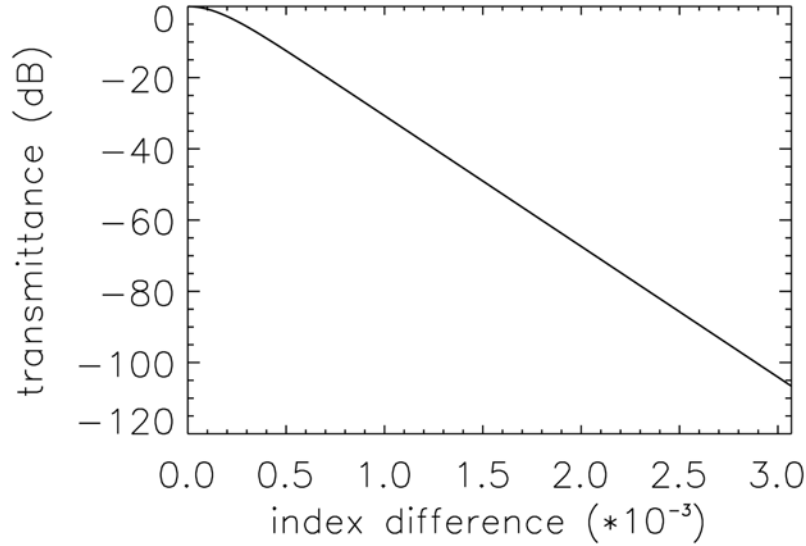


Fig. 3.15 Transmittance of symmetric grating as a function of the index modulation.

3.5.4 Two wavelength add/drop filter

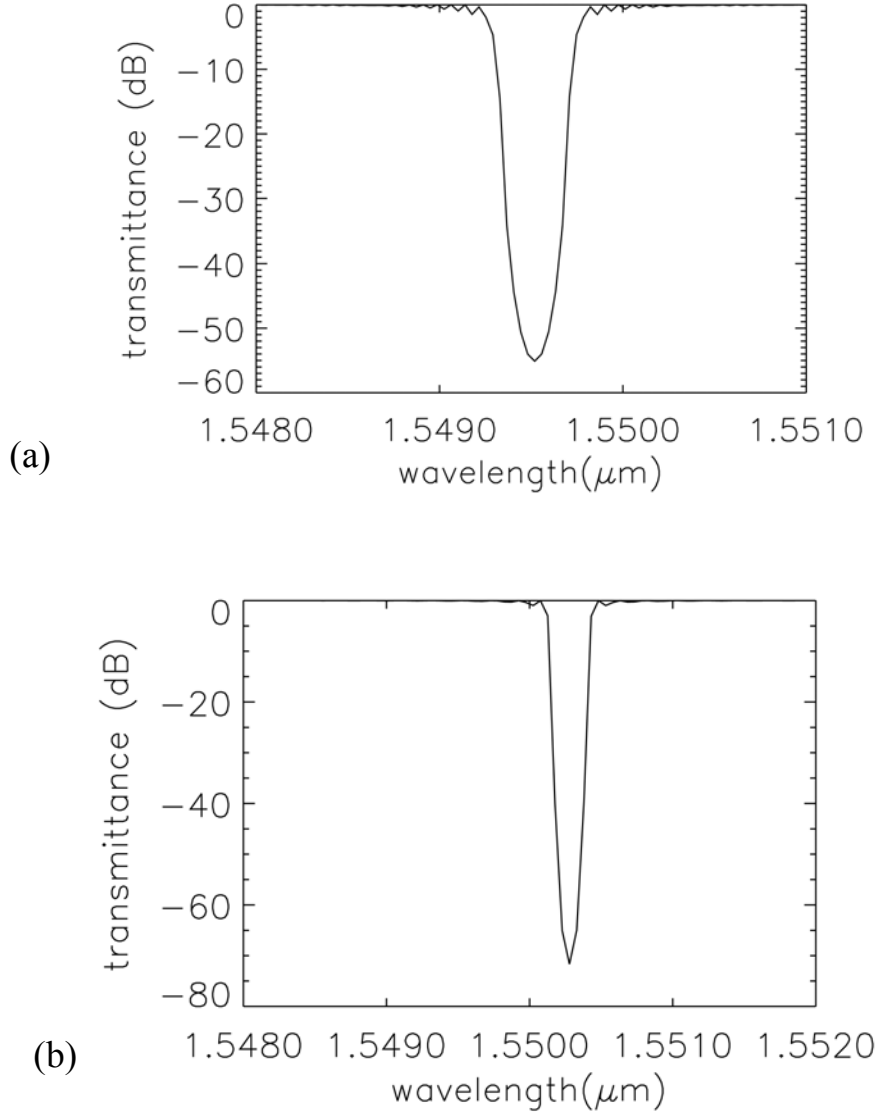


Fig. 3.16 *Transmittance spectra for coupling from the forward-propagating fundamental mode into (a) the first backward-propagating odd mode for a 1cm long segmented anti-symmetric grating and (b) the second backward-propagating even mode for a 2cm long segmented symmetric grating, for the 6-port device.*

The results for the 6-port device in Fig. 3.5, with a 1cm long anti-symmetric grating and 2cm long symmetric grating and index modulation $\Delta n=0.001$, are plotted in Figs.3.16(a) and (b). They display maximum reflectances of 56dB and 63dB, respectively,

and a maximum width of $0.4\mu\text{m}$. The widths of the inner and outer parts of the symmetric grating are $2s=4.8\mu\text{m}$ and $t=5.4\mu\text{m}$, respectively, which ensure that there is zero reflection into the backward-propagating fundamental mode.

The two kinds of segmented grating are used in the 6-port device, so it reflects both the first odd mode and the second even mode. Therefore the channel wavelength spacing can have any required value.

3.5.5 Three wavelength add/drop filter

Segmented gratings can be used for an 8-port device, written into the waveguide core with an aspect ratio of 4.5. It can support four guided modes. Using a 1cm long unapodized anti-symmetric segmented grating with the index modulation of 0.002, transmittance of the first odd mode is less than 10^{-12} and transmittance for the second odd mode is 10^{-5} , as Fig. 3.17 indicates. Reflectivity of the second odd mode is smaller than for the first odd mode, as expected, because the higher-order modes are less confined to the core and spread more into the cladding.

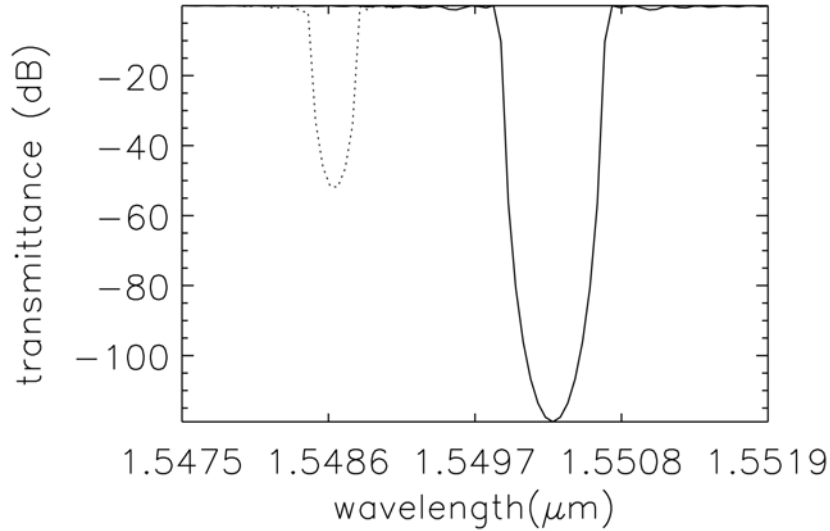


Fig. 3.17 Transmittance spectra for coupling from the forward-propagating fundamental mode into the first backward-propagating odd mode (solid line) and the second backward-propagating odd mode (dotted line) for a 1cm long anti-symmetric segmented grating with index modulation of 0.002, for the 8-port device.

In order to drop the second even mode, it is necessary to have a symmetric segmented grating. Results for a 1cm long symmetric segmented grating with an index modulation of 0.002 are plotted in Fig. 3.18. Again, the channel spacing can be adjusted because two different gratings are used, but the channel spacing between the first and second odd mode

can be slightly changed by varying the waveguide parameters, such as the index of the core and cladding, width or height.

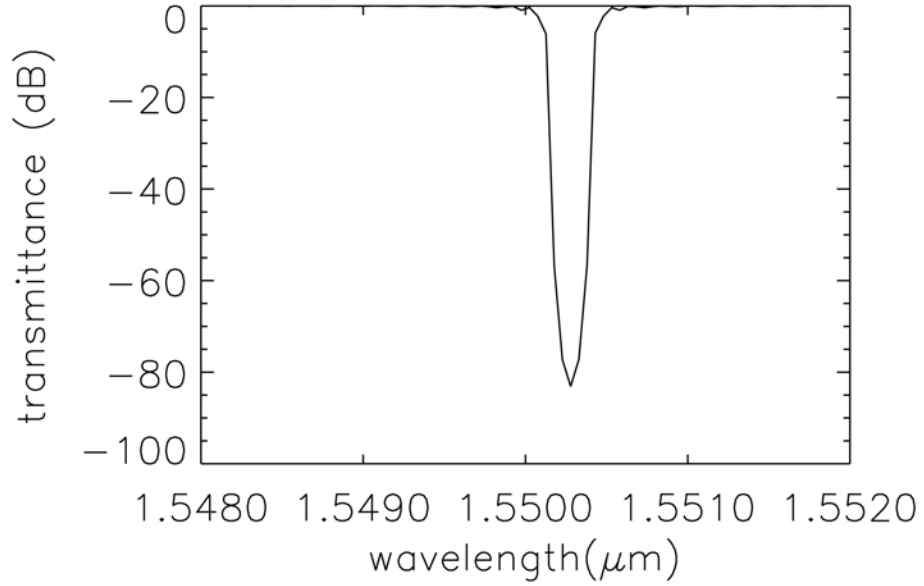


Fig. 3.18 *Transmittance spectrum for coupling from the forward-propagating fundamental mode into the second backward-propagating even mode for a 1cm long symmetric segmented grating with index modulation 0.002, for the 8-port device.*

The minimum reflection into the fundamental mode is obtained for $2s=5.93\mu\text{m}$, and it is less than -0.001 dB . If the dimension of the central grating is varied in the range $2s=5.09\text{--}6.25\mu\text{m}$ the reflection of the fundamental mode is less than -0.5dB .

The results of the study of the adiabatic mode splitter [10] suggest that cross-talk below -30dB can be achieved with 15 mm long arms for the 6-port device, whereas for the 8-port device the arms need to be 50mm long. Therefore, this kind of device can be applied only for adding/dropping a few wavelengths from a WDM network.

3.5.6 Effects of apodization

Gratings are finite in length, so they have an abrupt change in modulation at the beginning and end. The multiple reflections of the field from ends of the grating will affect the strength of the reflection outside of the reflection band, i.e. the strength of the sidelobes [15]. Sidelobes can be suppressed by gradually increasing the index modulation from the beginning of the grating, and gradually decreasing it on exiting from the grating. This process is called apodization.

The cross-talk in the mode-coupling grating arises from the reflectance of the modes outside their reflection band. Therefore decreasing the magnitude of the sidelobes should reduce cross talk in the mode-coupling grating. For the application to wavelength filters, the sidelobes should be well below -30dB [16]. From Fig. 3.19, it is clear that the unapodized anti-symmetric segmented grating does not satisfy this condition, due to the presence of fine detail on either side of the centre Bragg wavelength of $1.55025\mu\text{m}$. Therefore it is necessary to apply apodization.

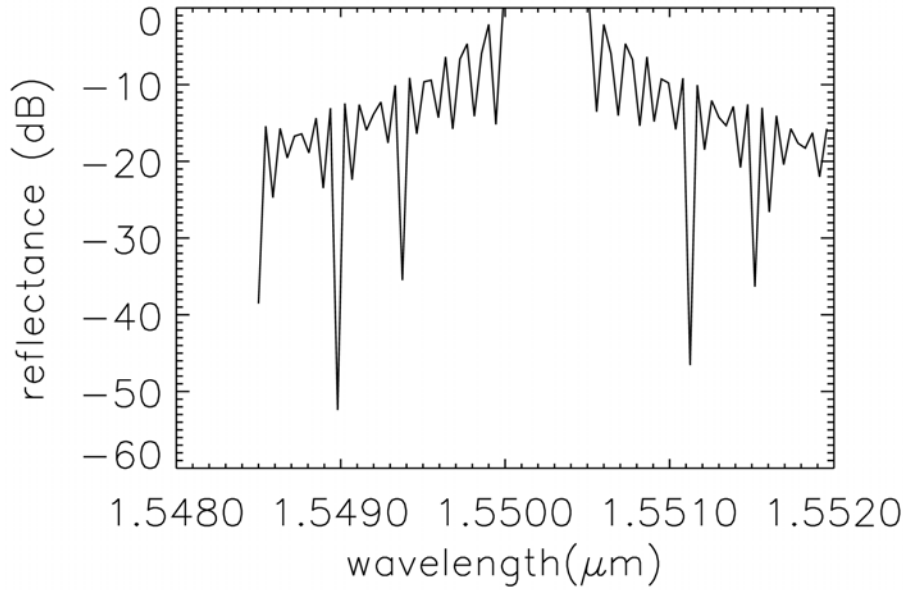


Fig. 3.19 *Reflection spectra of unapodized anti-symmetric segmented grating.*

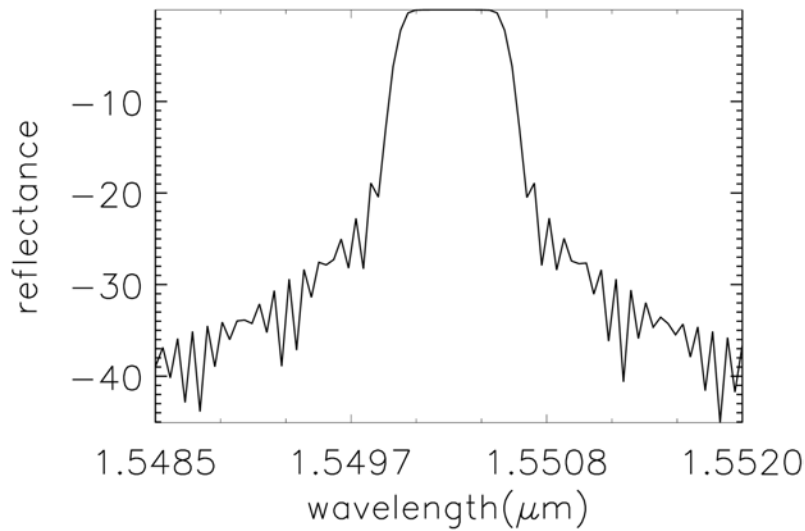


Fig. 3.20 *Reflection spectra of apodized anti-symmetric segmented grating.*

Many different apodization functional forms have been investigated. Here a sin-squared apodization is used for the anti-symmetric segmented grating, and results are presented in Fig.3.20.

However, the sidelobe suppression comes at the cost of a decrease in the grating's reflectivity [17]. For example, the transmittance of the first odd mode using an unapodized anti-symmetric grating is -90dB , whereas using the same parameters for the apodized grating results in only -40dB transmittance of the second mode.

3.5.7 Comparison with blazed grating

The 4-port segmented grating device illustrated in Fig.3.4 has a number of advantages over the blazed grating-assisted asymmetric-coupler in Fig. 3.1 in that: (i) there can be no power reflected back into the fundamental mode, and (ii) the need to optimize the blaze angle to minimize this reflection is avoided.

For the 6-port device, the reflectivities of 30dB and 62dB from the fundamental mode into the first odd and second even backward-propagating modes, respectively, require a 2cm long blazed grating with an index modulation of 0.002 . Comparable results can be achieved using only a 7mm long anti-symmetric segmented grating for the first odd mode and a 1.2mm long symmetric segmented grating for the second even mode, both with the same index modulation as the blazed grating.

Using a single blazed grating in a 6-port device, there are restricted channel spacing, whereas, using the segmented grating, any desired spacing is possible. Further, coupling to leaky modes could be more significant problem with the blazed grating because the minimum for coupling from the backward- to forward-propagating fundamental mode occurs when the coupling coefficients to higher-order modes increases with mode order. Therefore it could be expected that higher-order leaky modes will be excited by the fundamental mode, thereby raising the cross talk. The results presented in Fig. 3.17 suggest that the coupling coefficients for higher-order modes decrease with mode order, suggesting that coupling to higher-order leaky modes in segmented grating will be less than that in blazed gratings.

3.6 Fabrication

The writing of standard and blazed reflection gratings over part or all of the cross-section of an optical fibre, and, to a lesser extent, over the cross-section of planar waveguides, has matured during the last decade to a high level of sophistication and accuracy. Segmented gratings present a new challenge to their successful incorporation into fibre or waveguide cores, because of the departure from uniformity of the grating cross-section. Here two approaches are suggested for the fabrication of anti-symmetric segmented

gratings in fibres and waveguides, respectively, that can be generalised from the fabrication of symmetric segmented gratings.

Reflection gratings are commonly written into optical fibres and waveguides using the photosensitivity property of germanium-doped silica. When exposed to intense UV-light, a slight increase in the refractive index of this material occurs. Two standard techniques are employed, using either a UV-beam passing through a phase mask or two coherent interfering UV-beams. An important feature of both methods is that a number of grating periods is written simultaneously and essentially uniformly across the photosensitive region of the fibre or waveguide. Neither method appears to offer the potential for the accurate writing of segmented gratings.

Point-to-point writing techniques are not normally appropriate for reflection gratings with their very short period of the order of a micron or less, but are applicable for the writing of long-period or forward-coupling gratings where the period is of the order of several hundred microns. Long-period segmented gratings could be written this way, but because of the spot size of the laser beam used for writing, typically a few microns, it might prove difficult to have sufficient control and accuracy to produce anti-symmetric or symmetric gratings with the characteristic cross-sectional dimensions described above.

3.6.1 Fibre fabrication

A more promising approach might be to introduce regions of photosensitive and non-photosensitive material into the fibre or waveguide core during the respective fabrication process, such that both regions have a common refractive index prior to UV-exposure. A schematic of the cross-section of such a fibre is shown in Fig. 3.21

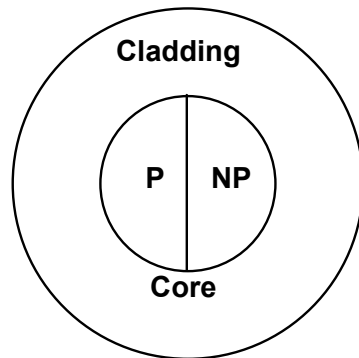


Fig. 3.21 *Schematic of the cross-section of a fibre with a core of uniform index comprising semi-circles of photosensitive (P) and non-photosensitive (NP) materials, surrounded by a cladding of uniform and lower index material.*

In the case of fibre fabrication, the technique used for the fabrication of silica-based Hi-Bi fibre based on the Modified Chemical Vapour Deposition (MCVD) process could be adopted and modified as follows. The starting point for the MCVD process is a pure silica glass tube. Layers of silica and doped silica are deposited on the inside of the glass using thermal heating of an appropriate admixture of gases flowing within the tube. Normally the tube is rotated and the heater translated along the length of the tube to ensure that each deposited layer is uniform both longitudinally and azimuthally. If the rotation of the tube is suppressed, layers of the photosensitive material can be deposited on the left-hand side of the tube and, likewise, layers of non-photosensitive material can be deposited on the right hand side. By appropriate choice of dopant gases, the index of both regions can be made to be the same.

3.6.2 Waveguide fabrication

In the case of waveguide fabrication, the Plasma Enhanced Chemical Vapour Deposition (PECVD)/ Reactive Ion Etching (RIE) process commonly used to fabricate silica-based buried channel waveguides could be modified as follows. Instead of writing two gratings into the waveguide core, the same reflectivity can be obtained if the index of one half is raised, whereas the other part stays unchanged, see Fig. 3.22.

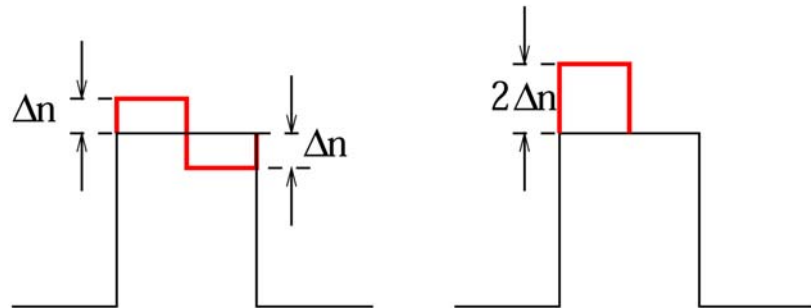


Fig. 3.22 Step-index profile of the grating (a) written over cross-section of the core and (b) written only over half of the core.

By analogy with the fibre a waveguide is fabricated that is photosensitive only in one half or third of the core. The procedure is based on a variant of the standard procedure the PECVD/RIE [2]. After depositing buffer layer on a silicon wafer, a photosensitive core layer is deposited, and then a standard core layer is deposited, Fig. 3.23 (a). A predesigned mask is deposited on the top of the core layers and the core layers are etched, see Fig.3.23 (b). The mask is removed and finally the cladding layer is deposited, Fig. 3.23(c).

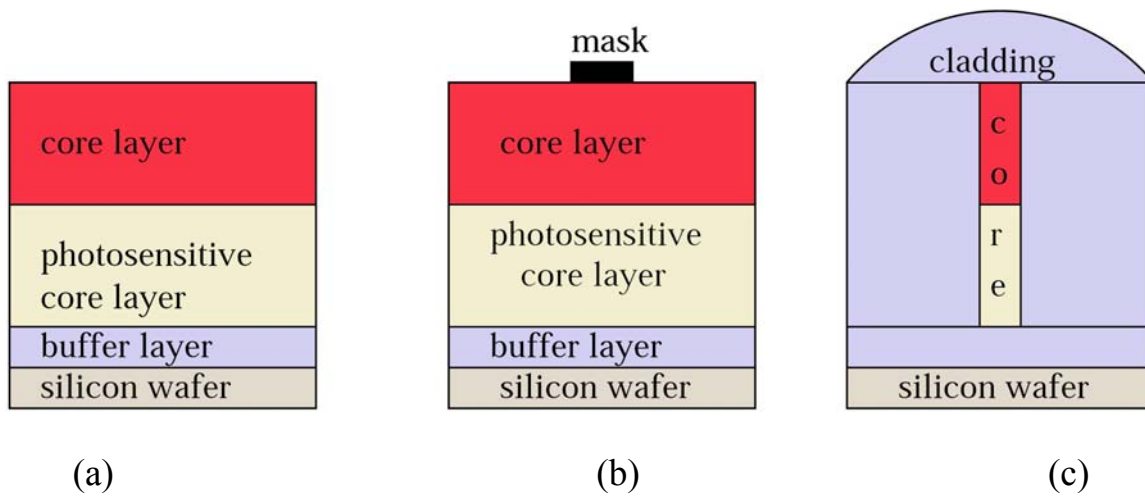


Fig. 3.23 Fabrications steps for deposition and etching of buried channel waveguide.

3.6.3 Grating writing

The phase mask and interfering beam techniques for writing gratings result in an index modulation that is of the form shown in Fig.3.24, where the sinusoidal-like variation is a positive index increase relative to the uniform unperturbed index, denoted by the horizontal line.

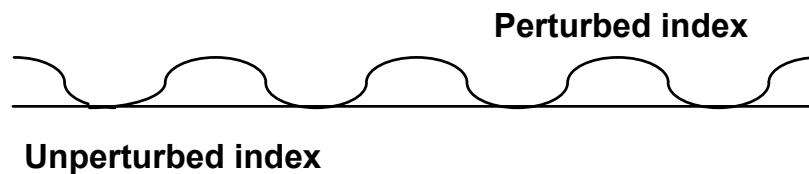


Fig. 3.24 Index perturbation within the photosensitive region of the core.

For either the fibre or waveguide with split cores shown in Figs.3.21 and 3.24, exposure to intense UV using either writing technique will result in an anti-symmetric grating that schematically has the form shown in Fig.3.25.

Compared to the anti-symmetric segmented grating of Fig. 3.2, the above grating has only half its strength for a given period and index modulation, and accordingly would need to be twice as long in order to have the same reflectivity at the Bragg wavelength for reflection into the backward-propagating first odd mode in either the fibre or the waveguide.

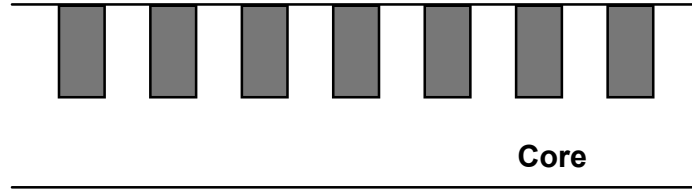


Fig. 3.25 *Anti-symmetric segmented grating written into the two-region core of a fibre or waveguide.*

3.7 Conclusions

In this chapter, a new type of grating, the segmented grating, and its application to single-, two- and three-wavelength add/drop wavelength filters have been proposed and their performances have been quantified.

Segmented gratings are symmetry selective, so an anti-symmetric grating reflects only modes of odd symmetry, so the reflection of modes of even symmetry, and, in particular, the fundamental mode, is zero. Therefore, an anti-symmetric segmented grating, when used within a 4-port device, has two major advantages over the comparable blazed grating. It exhibits higher-order reflectivity than a blazed grating of the same length and index modulation, and there is no reflection of the fundamental.

By employing two different layers of segmented gratings with the 6-port device, enables any channel spacing to be chosen, whereas the blazed grating it is less flexible.

Additionally, for comparable 6 and 8-port devices, results suggest that coupling to leaky modes could be less significant than for the blazed grating.

The possibility of fabrication of segmented gratings has been discussed and a method using deposition and etching has been proposed.

CHAPTER 4

Low-loss Single-Mode Slab Waveguide Bends

Curved single-mode planar waveguides are important components in photonic integrated circuits and will become even more important in the development of platforms and subsystems as photonic and electronic components are jointly integrated, and compactness becomes a critical issue. Curved waveguides are commonly used to connect input and output ports on the edge of a silicon wafer substrate with the optical processing devices in the circuit, and also between and within these devices. The compactness of individual devices, such as Y-junctions, is often dictated by the minimum waveguide bend radius. It is also advantageous to minimise bend radius as much as possible, without introducing significant bend loss, in order to achieve a high packing density of optical components, and so make best use of the available wafer area. Single-mode optical fibres that are bend-tolerant are also of interest in certain applications, such as within fibre organisers and fibre-based platforms.

However, curved waveguides and fibres are necessarily lossy, and the fraction of propagated power in the waveguide that is radiated increases very rapidly as the radius of curvature is decreased. There are two main contributions to overall bend loss: transition loss and pure bend loss. Transition loss appears at both the beginning and end of a curved waveguide, because of the mismatch in the fields of the straight and bent waveguides due to the abrupt change in curvature, as illustrated in Fig. 4.1.

There are a number of strategies for reducing transition loss. In one approach, the curvature of the bend is increased continuously from zero, for the straight waveguide, to the required value for the bend. However, this approach necessarily introduces extra length into the waveguide, thereby taking up more space on a wafer. A second approach that avoids this disadvantage is to laterally offset the bent waveguide core from the straight waveguide core at the beginning of the bend by a distance that is equal to the field shift of the bent waveguide [18].

Even if transition loss can be offset, the reduction of pure bend loss from the fundamental mode still remains a major challenge, notwithstanding the plethora of loss-reduction strategies that have been suggested.

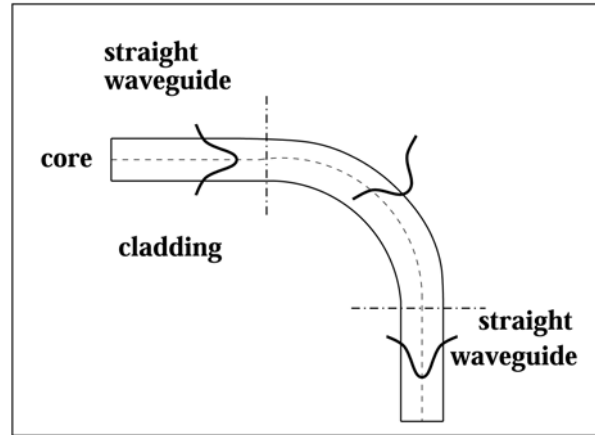


Fig. 4.1 *Illustration of the fundamental mode field mismatch between the straight and bent waveguides at the beginning and end of a bent waveguide denoted by the dot-dash lines.*

The main difficulty with pure bend loss is that it increases almost exponentially with decreasing radius of curvature. This continuous radiation of mode power as light travels around a bend appears because the modal phase front rotates about the centre of curvature and thus the local phase front velocity increases with increasing distance from the centre of curvature. At a position where the local phase velocity is equal to the speed of light in the cladding, the field detaches from the mode and radiates away tangentially.

This critical distance, where the field starts to radiate, is sometimes called the radiation caustic. Beyond the radiation caustic, the fundamental mode field in the cladding has an oscillatory behaviour instead of the exponential decay that occurs on the straight waveguide, as illustrated in Fig. 4.2.

To illustrate the radiation field due to both transition loss and pure bend loss, Fig. 4.3 shows a plot of a BPM simulation of the field intensity along a bent slab waveguide, with a bend radius of 4mm. At the beginning of the waveguide there is a straight part, followed by a curved waveguide. In this way, both transition and pure bend loss are taken into account. There is obvious radiation in the outer cladding is due to the waveguide bend. Horizontal fringes occur because of the transition loss, whereas the angled fringes are mainly due to pure bend loss. Such beams have been demonstrated experimentally in a bent fibre surrounded by index-matching liquid [19,20].

The radiation loss from bent waveguides or fibres is essentially confined to the plane of the bend, and decreases rapidly outside of this plane because of the increase in effective bend radius. Accordingly, it is often sufficient to use a slab model of these bent structures

in order to quantify bend loss. In Chapters 5 and 6, buried channel waveguides and fibre bend losses in Chapter 7 will be analysed, using the technique introduced in this chapter as a basis.

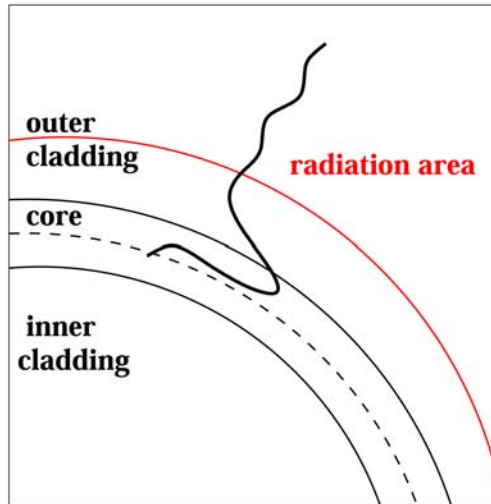


Fig. 4.2 Schematic of the fundamental mode field on a bent waveguide, showing the oscillatory behaviour of the field in the cladding beyond the radiation caustic.

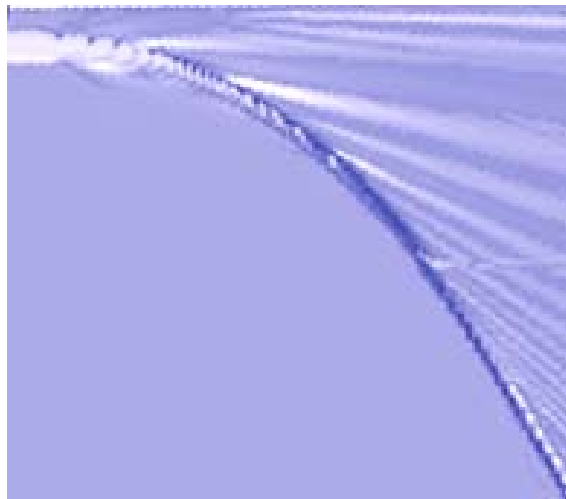


Fig. 4.3 Simulation of the radiation field of a bent slab waveguide. with a bend radius of 4mm.

4.1 Method of analysis

Theoretical modelling of bend loss in waveguides and fibres has been a source of research activity for many years. As a result, a wide range of analytical and semi-analytical methods have been developed. Many of these approaches are based on treating a bent waveguide as a perturbation of the corresponding straight waveguide. For example, Marcatili uses Bessel functions and their first-term approximation in a way similar to straight waveguide analysis [21]. Marcuse analyses loss from a bent fibre by regarding it as the cross-section of a cylinder and uses an asymptotic expansion in terms of Bessel functions [22], while Snyder and Love use the Kirchhoff type perturbation technique [1].

A bent slab waveguide can be transformed into an equivalent straight waveguide with the same core dimension, where the effect of the curvature is included by using a transformed index that modifies the step profile into a graded-index profile. This method is used by Heiblum and Harris [23] in the form of a conformal mapping and by Thayagarajan, Shenoy and Ghatak [24,25] using the transfer-matrix method.

There are many other methods that have been developed for the analysis of loss from curved waveguides, including purely numerical techniques, such as the method of lines [26], and the beam propagation method (BPM) [27]. The two-dimensional BPM is discussed and applied to bent slab waveguides in this chapter, and a three-dimensional BPM is applied in chapter 5 and chapter 6. In the present chapter, the analysis of loss from curved slab waveguides follows the Airy function method introduced by Goyal, Gallawa and Ghatak [28].

4.1.1 Airy function method

Using the Airy function method, it is possible to solve the scalar wave equation for the bent waveguide equivalent profile on a straight waveguide and obtain an analytical solution for the pure bend loss for the case when the bend radius is large compared with the core width.

Fig. 4.4 shows the parameters of a bent waveguide, with core width 2ρ , bend radius R , radial coordinate r and azimuthal angle ϕ . A cylindrical coordinate system (r, ϕ, z) is used with the origin at the centre of the arc and the z -axis out of the plane of the bend through the origin. For a mode propagating along the bend, the scalar electric field in the cross-section of the bent waveguide has the form:

$$\Psi(r, \phi) = \psi(r) e^{-i\beta R \phi}, \quad (4.1)$$

where β is the propagation constant and $\psi(r)$ is a solution of the scalar wave equation:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{d\psi}{dr} \right) - \frac{\beta^2 R^2}{r^2} \psi + k^2 n^2(r) \psi = 0, \quad (4.2)$$

where $n(r)$ denotes the radial refractive index profile, $k=2\pi/\lambda$ is the free space wave number and λ is the source wavelength.

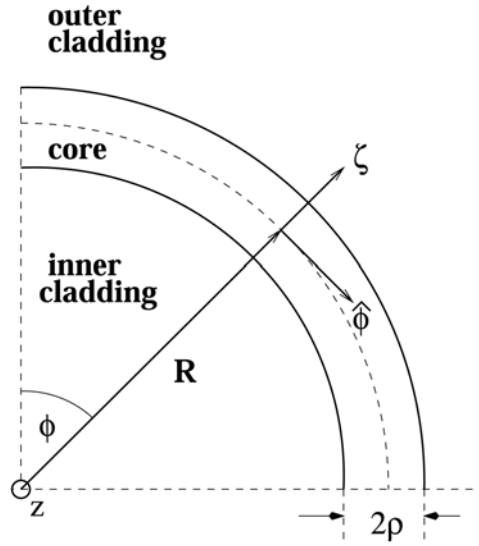


Fig. 4.4 Geometry of bent slab waveguide.

If the radial wave function is further transformed into $u(r)$:

$$\psi(r) = \frac{u(r)}{\sqrt{r}}, \quad (4.3)$$

then by writing $\zeta = r - R$ and assuming that $R \gg \rho$, the scalar wave equation (4.2) becomes:

$$\frac{d^2 u}{dX^2} + (n_e^2(X) - b)u(X) = 0, \quad (4.4)$$

where:

$$\begin{aligned} n_e^2(X) &= n^2(X) + \frac{1}{4}K^{-2} + S^3 X, \\ S^3 &= 2\left(b - \frac{1}{4}K^{-2}\right)K^{-1}, \\ X &= \zeta k, \\ b &= \frac{\beta^2}{k^2}, \\ K &= Rk. \end{aligned} \quad (4.5)$$

Through these transformations, the square of the actual index profile of the bent waveguide, n^2 , is replaced with the square of the equivalent index profile of the straight waveguide, n_e^2 , which is linear if $R \gg \rho$, as illustrated in Fig. 4.5.

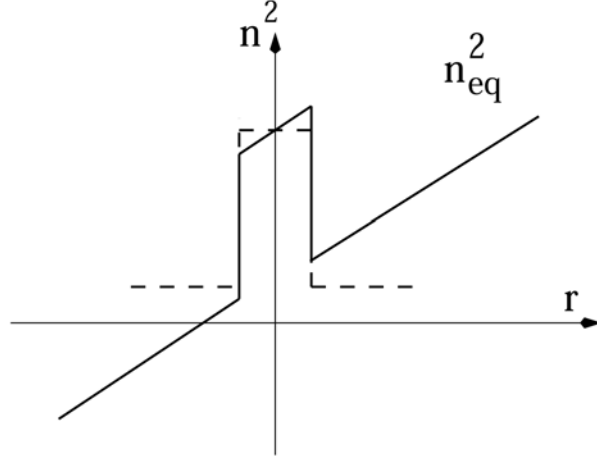


Fig. 4.5 *Equivalent (solid line) and actual (dashed line) refractive index profile for the step profile slab waveguide.*

The scalar wave equation can be further simplified to:

$$\frac{d^2 u}{dZ_i^2} - Z_i u(Z_i) = 0, \quad (4.6)$$

where:

$$Z_i = \left(\frac{KS^3}{2} - n_i^2 - XS^3 \right) S^{-2} \quad (4.7)$$

and i denotes regions with different actual index.

The governing equation (4.6) is the Airy equation and its solution is a linear combination of Airy functions:

$$u(Z_i) = C_i Ai(Z_i) + D_i Bi(Z_i), \quad (4.8)$$

where C_i and D_i are coefficients and Ai and Bi are Airy functions of the first and second kinds, respectively.

The number of layers in the analysis is determined by the refractive index profile that is assumed piecewise constant within and close to the core. For the profile shown in Fig. 4.5, there are 3 layers, but in general there will be N layers, with the right hand outermost cladding layer labelled “1” and progressing to the left hand innermost cladding layer

labelled “ N ”. Since $Z \rightarrow \infty$ in the N th layer it is necessary that: $D_N = 0$ since $Bi(Z_N)$ is singular in this limit. Since the power carried by the mode is not relevant to the present analysis, it can be assumed that $C_N = 1$. The values of the other coefficients C_i and D_i in the intervening layers can be determined matching boundary conditions at the interfaces of layers, assuming continuity of u and its first derivate. Finally in the first layer, since $Z_1 \rightarrow \infty$ and $Ai(Z_1)$ is singular in this limit:

$$C_1(b) = 0 \quad (4.9)$$

for the right-most region should be satisfied. The solution of the equation (4.9), which is an eigenvalue equation, gives the propagation constants of the quasi-modes that have real values. The continuity of u and du/dZ at the N layer boundaries will yield $2N$ equations for $2N$ coefficients C_i and D_i in (4.8), giving the field of the quasi-modes. A bent waveguide does not support guided modes, every mode is a leaky mode. Therefore a bent waveguide can support a finite number of so called quasi-modes.

Now, when the propagation constant and fields in each layer are obtained the bend loss can be calculated analytically [28]. A bent structure is a leaky structure and the leakage is obtained from the ratio of the incident and guided power, which represents the fractional power that remains inside the core [29]. Therefore the ratio between the incident plane wave field, the field in the right most region of the bent structure, and the field in the guiding layer (core), denoted by E_i is the excitation efficiency of the wave in the bent structure. $|E_i/E_1|^2$ is a function of the propagation constant β and has the resonance peak at the particular solution which is Lorentzian in shape, as illustrated in Figure 4.6.

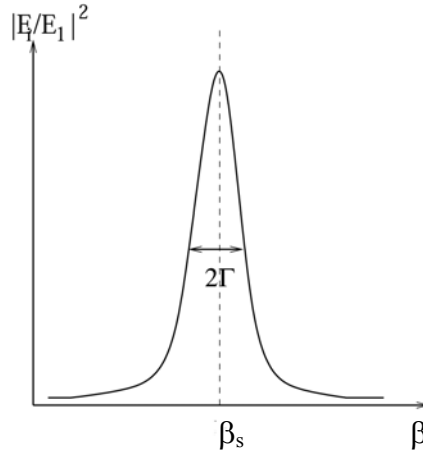


Fig. 4.6 *Excitation efficiency as a function of propagation constant.*

The value of β_s , obtained by solving (4.9), is the real part of the propagation constant and the full width at half maximum represents the power attenuation coefficient, which is twice the imaginary part of the propagation constant.

By fitting a Lorentzian function to each peak the attenuation coefficient Γ can be obtained by the following procedure. If a particular solution is denoted by the subscript s , C_l can be expanded in a Taylor series:

$$C_1 \cong \frac{dC_1}{db} \big|_{b=b_s} (b - b_s) = \dot{C}_{1s} (b - b_s). \quad (4.10)$$

Then $|E_i/E_l|^2$ is calculated in the neighbourhood of b_s . Correct to first order in the difference $b-b_s$:

$$\left| \frac{E_i}{E_l} \right|^2 = \frac{C_i^2 + D_i^2}{C_1^2 + D_1^2} \cong \frac{C_i^2(b_s) + D_i^2(b_s)}{\dot{C}_1^2} \frac{1}{(b - b_s)^2 + \Gamma^2}, \quad (4.11)$$

where

$$\Gamma^2 \cong \frac{D_1^2(b_s)}{\dot{C}_1^2(b_s)}. \quad (4.12)$$

Γ is the halfwidth of the Lorentzian and it gives an analytical expression for the bend loss. The modal power $P(L)$ that is guided by the core at the end of curved waveguide of length L is:

$$P(L) = P(0)e^{-2\Gamma kL}, \quad (4.13)$$

where $P(0)$ is the power at the beginning of the bend and k is free-space wavenumber. The attenuation per unit length γ is usually expressed in units of dB/unit length by using the relation:

$$\gamma = -\frac{10}{L} \log \left[\frac{P(L)}{P(0)} \right]. \quad (4.14)$$

The only approximation in this method is the assumption that the effective index of the bent waveguide is linear in each of the various regions. This is a very good approximation in the practical case where $R \gg \rho$ [28].

An advantage of this method is that it considers only layers where there is a difference in actual index and avoids the problem of convergence that exists when the transform matrix and conformal mapping methods are used. However, this method may not be appropriate for very tight bends because the linear approximation to the transformed profile is no longer valid.

The value of an analytical expression for bend loss is that it gives some insight and approximate quantification of bend loss and thereby avoids the extensive computational time required for purely numerical methods to make the same deductions. However it can only calculate pure bend loss because only the modes of the curved waveguide are calculated and used in the calculation of the bend loss. Using this method transition loss could be calculated by using an overlap integral of fields of the straight and curved waveguides [1,ch36].

The Airy functions method will be used in Chapter 5 too. When applied with the effective index method it enables quantification of bend loss of buried channel waveguides. However, this method has a limitation on bend radius, so we additionally use conformal mapping combined with a two-dimensional beam propagation method (BPM).

4.1.2 Conformal mapping and BPM

Firstly, the conformal mapping is applied, transforming a curved waveguide into an equivalent straight waveguide, of length $L_c = R\phi$ (see Fig. 4.7), but with a transformed index profile. Then for the two-dimensional BPM is used. A ‘straight’ waveguide of length L_s is placed at the beginning of the curved section in order to calculate transition loss.

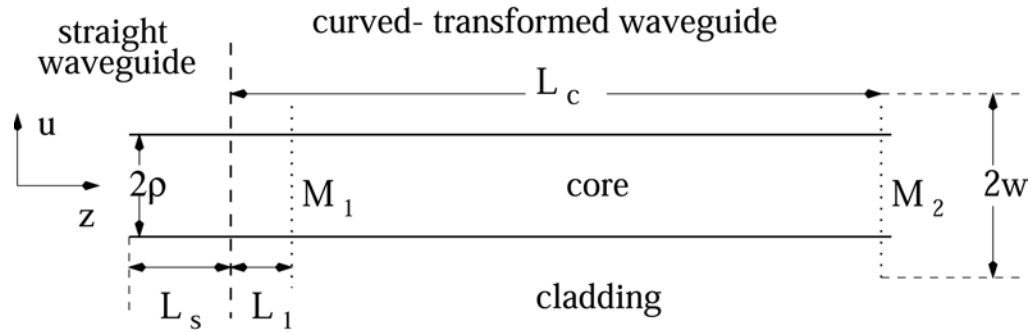


Fig. 4.7 *Geometry of transformed curved waveguide.*

There are two cross-sections at which bend loss has been calculated. At the first one, denoted by M_1 in Fig. 4.7, mainly transition loss contributes to bend loss, whereas the second one, denoted by M_2 , at the end of the curved part, includes both transition loss and pure bend loss.

4.1.2 Conformal mapping

The plane of curvature (r, ϕ) is mapped into the (u, v) plane via the conformal transformations:

$$u = R \ln \frac{r}{R} \quad , \quad v = R\phi \quad . \quad (4.15)$$

With this transformation, the piecewise constant index profile in a two-dimensional circular guide geometry is transformed to an exponential profile in a straight guide:

$$n(u) = n(r) e^{\frac{u}{R}} \quad . \quad (4.16)$$

When the radius of curvature is much larger than the width of the fields confined to the waveguide the profile becomes approximately a linear function of u as in the previous section, as is clear from expanding the exponential term in (4.16) for small argument [23].

4.1.2.2 Beam propagation method

The BPM is a very powerful numerical technique for investigating lightwave propagation phenomena along waveguides and through devices. There are many variations of the BPM available, and here an implicit FD-BPM is used [30]. Here a ‘straight’ slab waveguide is considered with the equivalent index profile given by (4.16). Therefore the equation to be solved is the one-dimensional scalar wave equation that is solved numerically and details are given in Appendix A.

To include the transition loss between the straight and curved waveguide, the starting field is the fundamental mode of the straight waveguide launched at the beginning of the structure and propagated through the structure.

Planes at M_1 and M_2 where the power fraction is calculated are just four microns wider than the core, denoted by w in Figure 4.7, so $w = \rho + 2\mu\text{m}$. At these planes, the fraction of power that is guided by the core region relative to the input power at the same cross-section is calculated.

4.2 Strategies for bend loss reduction

As mentioned in the introduction, there are two main contributions to bend loss. A plot of the fundamental-mode field intensity profile on a bent step-profile slab waveguide is given in Figure. 4.8. It is clear that there is a shift in the field maximum towards the outer cladding, which can result in transition loss, as explained above, and there is oscillatory behaviour of the field in the outer cladding, which is the origin of pure bend loss.

There exist a number of tested strategies for reducing bend loss [31-35]. Each of these strategies has its advantages and limitations. It is known that increasing the relative index difference between the core and the cladding of a waveguide allows tighter low-loss bends [2, Sec.10.6]. The reason for this strategy is evident by examining the following formula for the attenuation of the fundamental mode of a bent, single-mode fibre [1,ch23]

$$\gamma = \sqrt{\frac{\pi\rho}{R}} \frac{V^2 W^{1/2}}{2\rho U^2} \exp\left(-\frac{4}{3} \Delta \frac{R}{\rho} \frac{W^3}{V^2}\right), \quad (4.17)$$

where V is the fibre parameter, U and W are the core and cladding mode parameters, respectively, ρ is the core radius, R is the bend radius and Δ is the relative index difference. On examining the definition of V :

$$V = \frac{2\pi}{\lambda} \rho \sqrt{n_{co}^2 - n_{cl}^2} \quad (4.18)$$

it is clear that the value of V can be held constant if the index difference between the core and cladding is increased and core radius is decreased such that their product remains constant. However, on examining the exponential dependence in Equation (4.17), simultaneously increasing Δ , and decreasing ρ makes the exponent more negative and hence reduces the power attenuation coefficient. However, as the index difference increases, the waveguide size decreases, which makes it more difficult to couple such a waveguide efficiently to a standard telecommunications fibre [34]. Additionally, a large index difference can produce higher propagation losses due to scattering.

Pure bend loss can also be significantly reduced through the introduction of a depression into the outer cladding adjacent to the core, since this effectively increases the NA of the waveguide and hence the modal confinement. On the other hand, elevating the inner cladding index will confine the field more to the core region and will reduce the transition loss [31], as well pure bend loss. The field of the curved waveguide is shifted towards the outer cladding, as can be seen in Fig. 4.8 that represents a plot of the field of the curved waveguide with bend radius of 5mm.

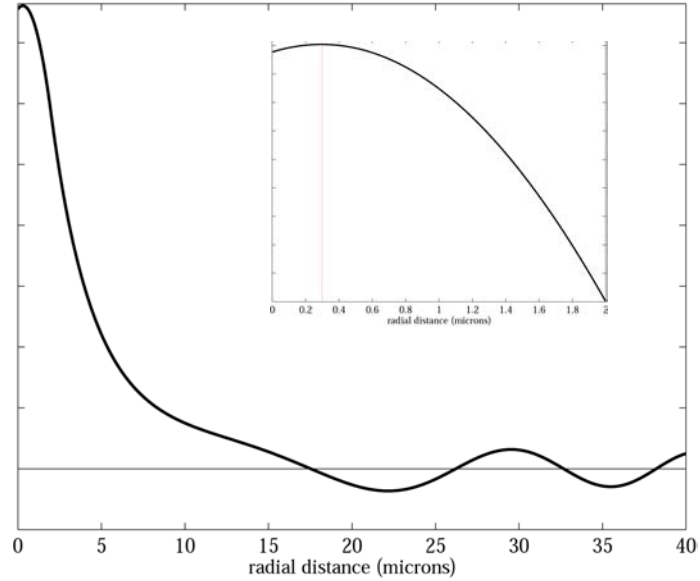


Fig. 4.8 *Fundamental field profile of the bent slab waveguide with 5 mm bend radius.*

The red line indicates the shift of the field for a bend radius of 5mm. The elevated index region in the inner cladding shifts the field back towards the centre of the core and consequently reduces the bend loss. Transition loss can be minimized by using an offset wherever there is an abrupt change in curvature. In that way the field of the straight and bent guides can be better matched.

The introduction of an isolation trench, or depressed region, on the outside of the bent core makes the evanescent modal field decrease more rapidly in the region between the waveguide core and the apparent origin of radiation, so that pure bend loss is also reduced [35].

Results for both depressing the outer cladding and introducing a trench are presented in section 4.5 and discussed in section 4.7.

4.3 New strategy

Here a new strategy is proposed for reducing bend loss. It is based on the introduction of two regions of increased and depressed index, respectively, into the cladding on the outer side of the core of the waveguide, as shown in Figure 4.9.

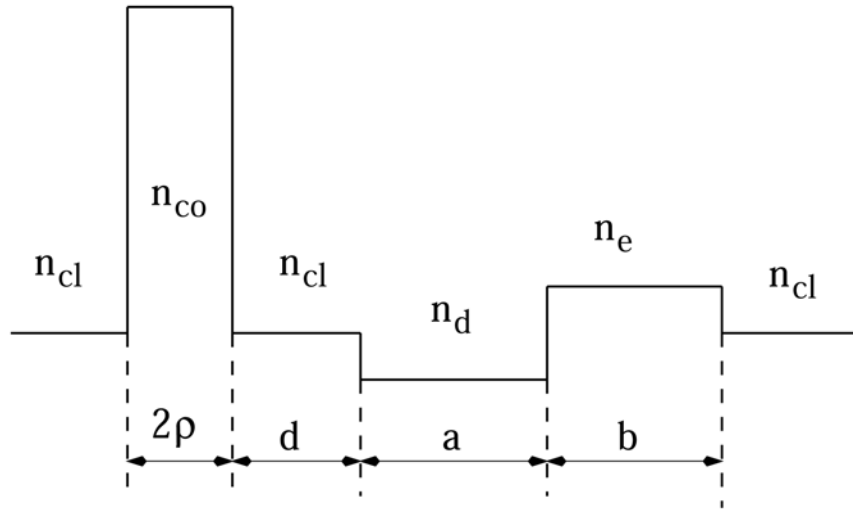


Fig. 4.9 Refractive index profile of the waveguide.

This strategy is going to be applied to buried channel waveguides and fibres as well in chapter 5, chapter 6 and chapter 7, respectively.

4.4 Physical model

A slab step profile 90 degree bent waveguide is considered in all cases represented in the following section.

The piece-wise, step-index profile for the bent slab waveguide is shown in Fig.4.9 Both depressed and elevated index regions are on the outer side of the bent core. The core width is $2\rho=4\mu\text{m}$, core index $n_{co}=1.467$ or 1466 and cladding index $n_{cl}=1.46$, assuming a wavelength of 1550nm . Two different core indices are considered depending whether

transition loss is taken into account, which means wherever the BPM is used the core index is $n_{co}=1.466$.

In order to optimise bend loss reduction the remaining parameters, the widths, a and b , and indices, n_d and n_e , of the additional layers are varied. The value of the width, d , of the region adjacent to the core is decreased with decreasing bend radius.

When the conformal mapping and BPM are applied the length of the straight waveguide is $L_s=400\mu\text{m}$. The loss is first calculated at the cross-section M_1 that is $L_I=700\mu\text{m}$ along the bent waveguide from the straight part, see Fig. 4.7.

This structure has two propagating modes when $n_e \geq 1.4605$. Although two modes can propagate in the structure, resonant coupling between the higher index regions does not occur because the modes have propagation constants that are sufficiently different. In other words, the coupling between the two higher index regions is very close to zero due to the mismatch.

4.5 Results

4.5.1 Airy function method

A plot of bend loss, in dB/m, as a function of bend radius (in mm) relative to the centre of the core, is given by the dashed curve in Fig.4.10.

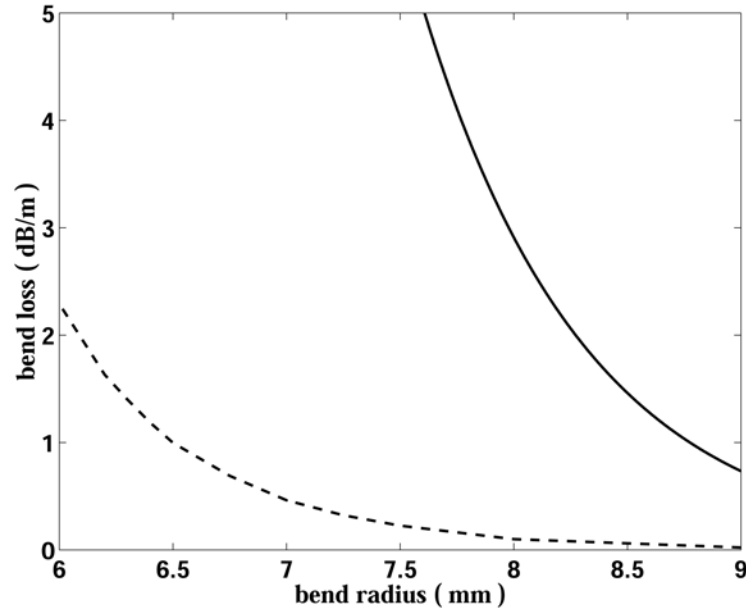


Fig. 4.10 Bend loss of the matched cladding slab waveguide (full line) and bend loss of the modified waveguide with depressed and raised regions in the outer cladding (dashed line).

The choice of d for a particular bend radius corresponds to minimum bend loss, with all other parameters fixed in value. In this plot, the width d of the region adjacent to the core in Fig. 4.9 is decreased continuously from $13.8\mu\text{m}$ at a bend radius of 9mm , to $4.2\mu\text{m}$ at a bend radius of 6mm . The indices of the depressed and raised regions are $n_d=1.459$ and $n_e=1.461$, respectively, and their widths are taken to be $a=15\mu\text{m}$ and $b=11.6\mu\text{m}$, respectively. For comparison, the solid curve represents the bend loss for the matched-cladding, step-profile slab waveguide using an approximate formula [36,Sec.9.6], and clearly demonstrates the reduced loss using the modified profile.

There are a number of parameters that can be varied in order to optimise bend loss reduction. Firstly, the bend loss is examined as a function of the refractive index difference between the cladding and additional layers, $\Delta n=n_e-n_{cl}=n_{cl}-n_d$. The results are presented in Fig. 4.11 with bend loss expressed in dB/m. The bend loss decreases with increasing the index difference between the layers and the cladding. Once it reaches the index difference of 0.0025 the bend loss increases again. However the biggest change, from 68dB/m to 5dB/m is obtained when the index difference changes from 0 (no layers at all) to 0.001 .

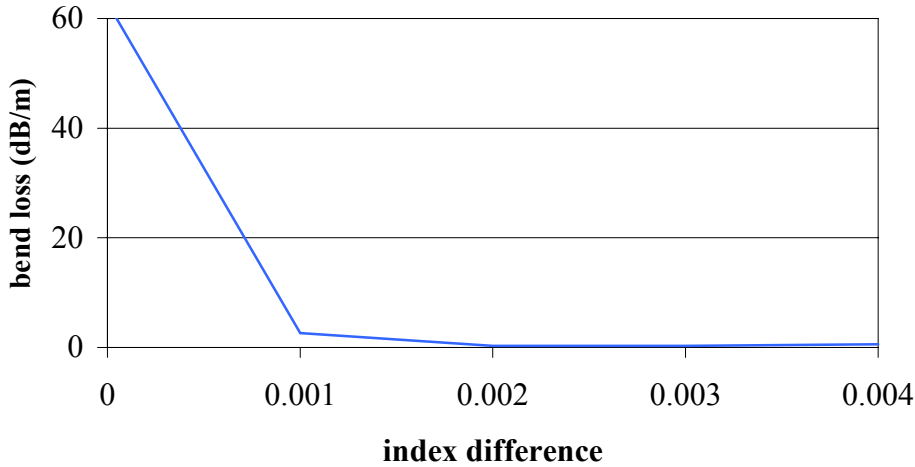


Fig. 4.11 Bend loss as a function of the index difference of the additional layer for the waveguide with the core index $n_{co}=1.467$ and the bend radius of 6mm .

Secondly, the bend loss reduction can be optimised by changing the widths of the additional layers, a and b . Results are plotted in Fig. 4.12, using an index difference of 0.001 . The widths of the depressed and elevated index region are related by $b=a-3.4\mu\text{m}$. It is clear from Fig. 4.12 that variation in this parameter is not as sensitive to bend loss minimization as the index difference between the cladding and layers. The optimal width, for given indices of the core, cladding and layers, is $15\mu\text{m}$, but the loss does not change significantly if the layers are changed by a few microns, as it is clear from the figure.

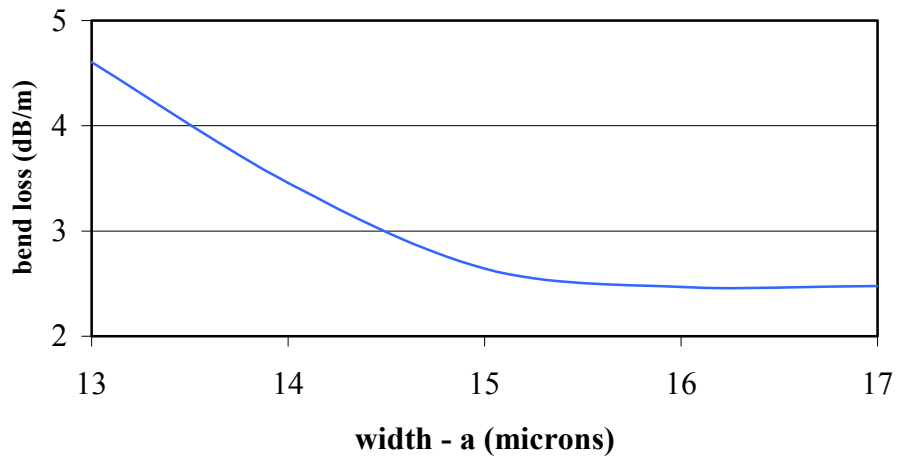


Fig. 4.12 *Bend loss as a function of width of the additional layers.*

Thirdly, in Fig. 4.13, bend loss is plotted as a function of the distance between the core and the layers and it can be seen that there is an optimal separation of $d=4.2\mu\text{m}$. It is important again that this parameter is not very crucial in terms of bend loss reduction, but it still can be optimised.

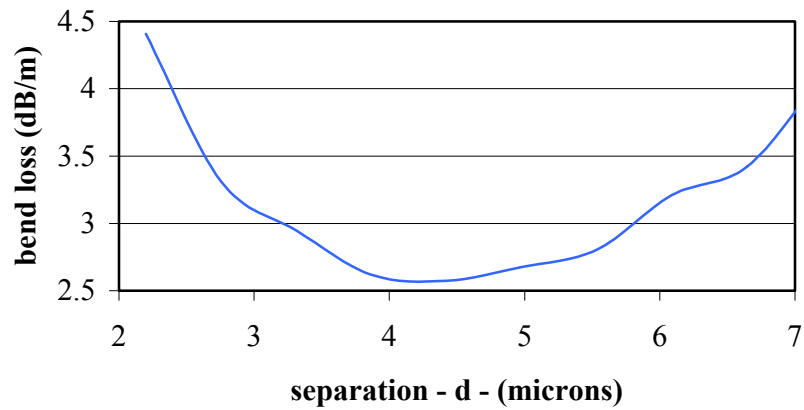


Fig. 4.13 *Bend loss as a function of distance between the core and depressed layer.*

Finally, the optimum minimum bend loss is wavelength-dependent. At a bend radius of 6.5mm, the loss increases from 0.67dB/m at 1520nm to 1dB/m at 1550nm (see Fig.4.10) and to 1.4dB/m at 1580nm.

There are a number of additional layer parameters that can be varied in order to minimize the bend loss. These are: (1) the index difference between the cladding and additional layers, $n_i - n_{cl} = n_{cl} - n_d$, (2) the widths of the extra layers, a and b , and (3) the distance between the core and the layers, d . With the results obtained in this section, a new strategy can be applied to tighter bends in the next section. The conclusions of this part is that the index of the additional layers is the most important parameter, whereas the other parameters such as width of the layers and their distance from the core are not very crucial, but can still be optimised. Simultaneous optimisation of all additional layers parameters is not practical. Firstly, the index of the layers should be optimised, and then each remaining parameter varied separately until optimal reduction of bend loss is obtained.

4.5.2 Application to tighter bends using conformal mapping and BPM

Expressing bend loss in dB/cm is a more suitable loss unit for PIC purposes and therefore a waveguide with a smaller core index $n_{co}=1.466$ is considered. The minimum bend radius has a limitation when the Airy function method is used, but now with the combination analysis of the conformal mapping and the BPM, bend loss can be accurately calculated for tighter bends. Again, dimensions and location of the additional layers depend on the bend radius and for representative bend radii they are presented in Table 4.1.

R [mm]	d [μ m]	a [μ m]	b [μ m]
5	2.2	16	8.6
4	2.2	12	8.6
3	1.2	10	7.6

Table 4.1 *Parameters values for different bend radius.*

The values presented in Table 4.1 are optimised values for an index difference of 0.002 between the cladding and additional layers. There are no large changes in the parameter values for different bend radius, which means even if the same values for these parameters had been used in each calculation the results would not show much variation.

In the previous section only pure bend loss could be calculated, therefore firstly transition loss is considered as a function of the index difference between the cladding and additional layers in Fig. 4.14 (a), and in Fig. 4.14(b) overall loss is plotted, both for a 5mm bend with parameters values given in the Table 4.1. It is clear that not only do the additional layers not increase transition loss, more significantly the transition loss is decreased with increasing index difference, from 16% of loss with no layer to less than 2% when the index difference is 0.002. If the index difference is further increased, transition loss will start to increase for an index difference larger than 0.0035, because if the index difference is too large, the field shift becomes too large to match the field of the straight waveguide.

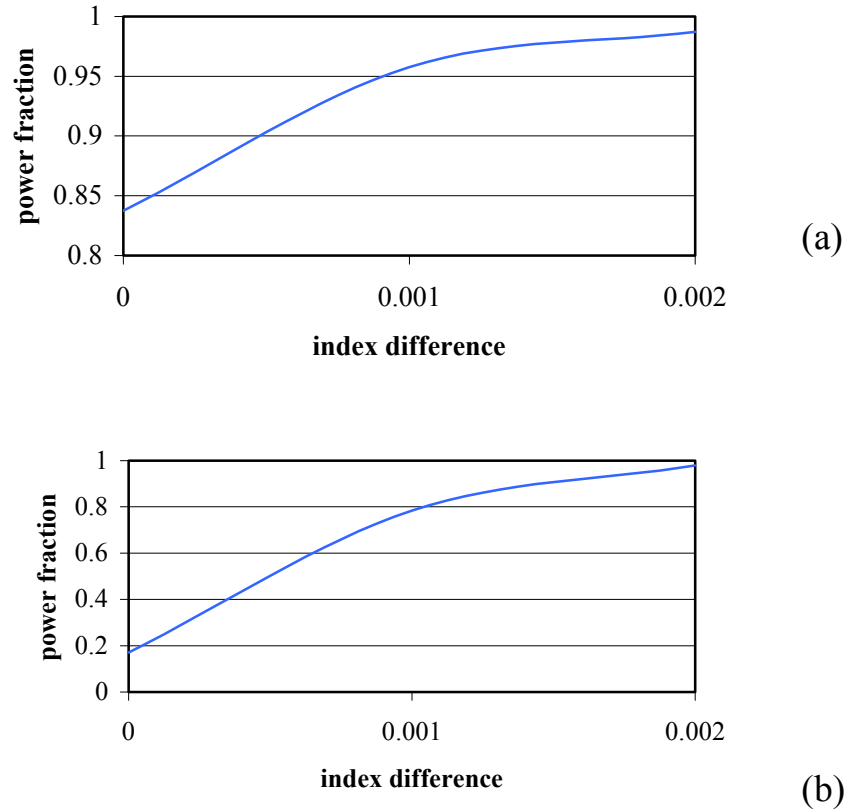


Fig. 4.14 *Fraction of transmitted power (a) at plane M_1 and (b) at plane M_2 as a function of index difference between the core and additional layers*

As expected, overall losses are going to be reduced significantly as presented in Fig. 4.14(b). Without any layers, $\Delta n=0$, less than 20 percent of mode power is transmitted along a 90 degree bend, whereas with the additional layers having 0.002 higher/lower index than the cladding almost 100 percent of mode power is transmitted along a bend. This means

that the new strategy not only reduces the pure bend loss, additionally it also reduces transition loss.

The role of the additional elevated index region to the right of the depressed region in Fig.4.9 can be quantified using the results presented in Fig. 4.15.

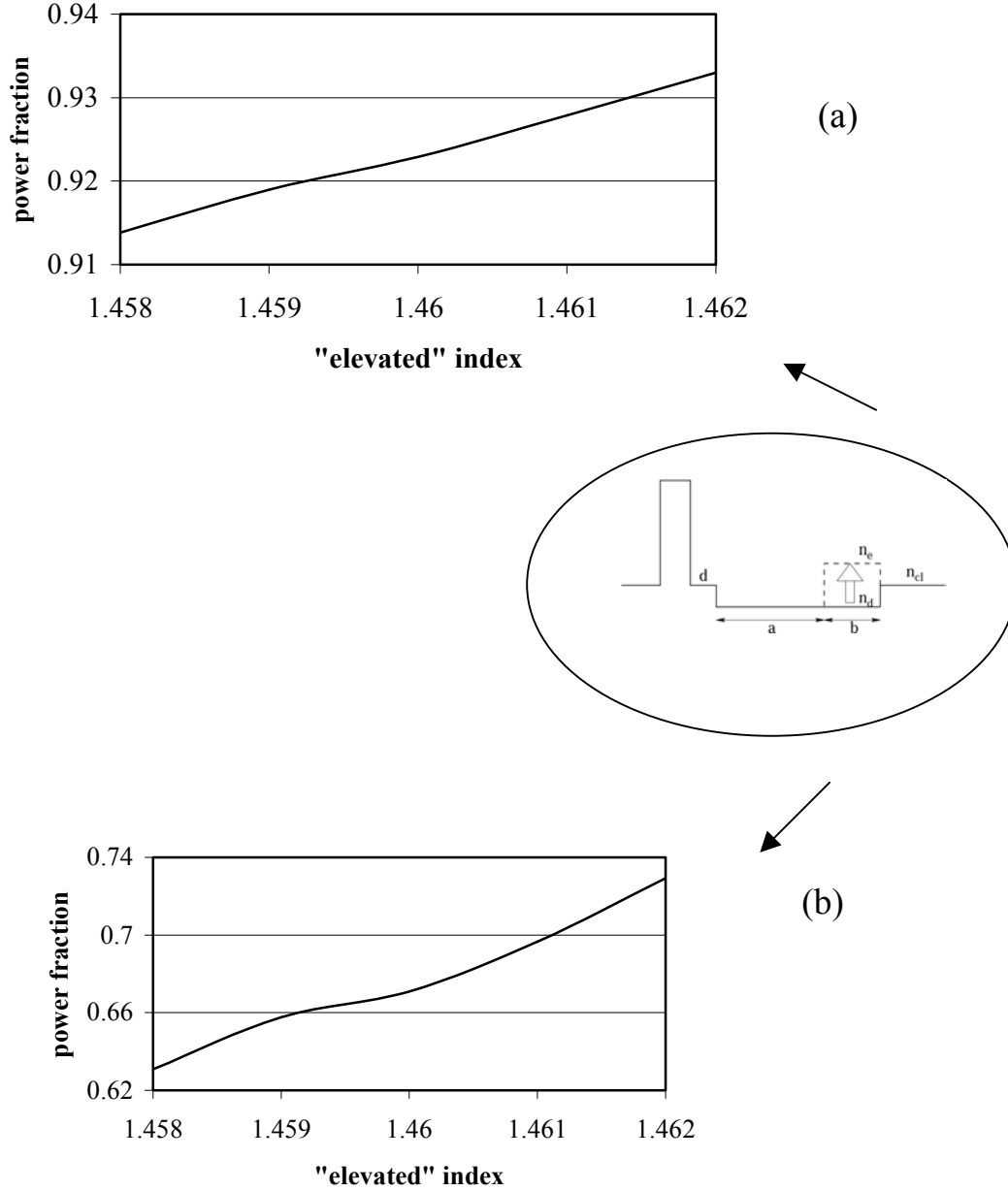


Fig. 4.15 Transmitted power fraction (a) at plane M_1 and (b) at plane M_2 as a function of the index of the index region next to the trench.

The transmitted core power fraction is plotted as a function of the index difference between the cladding and the elevated index region. When $\Delta n = -0.002$, this represents the situation where the depressed region is extended further into the cladding; $\Delta n = 0.0$ means there is no additional layer next to depressed one; and $\Delta n = 0.002$, represents the effect of a layer of increased refractive index, which means both trench and elevation are included. The bend radius is 3mm and corresponding parameter values are given in Table 4.1.

The power is calculated at two different cross-sections along the bend. As explained at the beginning of the section, M_1 provides a means of transition loss, while the M_2 , accounts both losses. It can be seen that extending the depressed region ($\Delta n = -0.002$) increases both transition and pure bend loss, but there are reduced losses from introducing the elevated index region ($\Delta n = 0.002$). The change of index in the region next to the trench is illustrated in the inset of Fig. 4.15. More than 10 percent of the core power is retained by introducing the elevated index region instead of extending the depressed region.

4.6 Comparison with other strategies

4.6.1 Pure bend loss - Airy function method

Bend loss for the new profile is compared with the optimised design of (i) a waveguide that has only a depressed region in the outer cladding, and (ii) a waveguide which has an increased index region in the inner cladding and a depressed region in the outer cladding.

The results obtained using the new strategy are compared with the results obtained using existing strategies. For example, with a bend radius of 6mm and only a depressed cladding region with a width of $52\mu\text{m}$ on the outside of the bend, the bend loss is 6.6dB/m, compared to 2.2dB/m in Fig. 4.10. For a waveguide with a depressed index in the outer cladding, for which $a = 13.3\mu\text{m}$ and $n_d = 1.459$, and a raised index in the inner cladding, for which $b = 13.3\mu\text{m}$ and $n_e = 1.461$, the bend loss for a radius of 6mm is found to be 6.7dB/m.

4.6.2 Bend loss – Conformal mapping and BPM

The insertion of a trench in the profile, as compared to a depressed region starting at the core boundary is justified by the results presented in Fig. 4.16. Pure bend loss is plotted as a function of the distance between the core and depressed region/trench for a 4mm bend radius. It is clear that introducing a trench is more successful than depressing the outer cladding. A simple physical explanation for this result will be given in the discussion section.

However overall bend loss is due both to pure bend loss and transition loss, therefore the magnitudes of both losses with the new strategy are compared with bend loss when other strategies are applied. Results from the previous paragraph indicate that introducing

only a trench can be competitive a strategy when compared with the new strategy. Therefore in this section only these two strategies are compared.

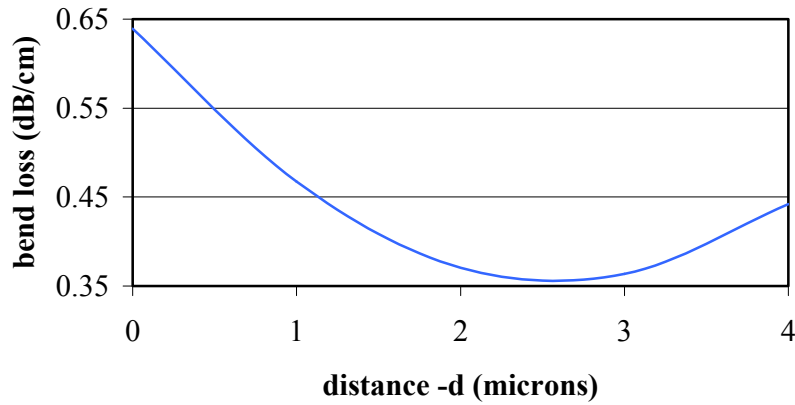


Fig. 4.16 Pure bend loss as a function of the distance, d , between the core and the trench.

Pure bend loss is smaller when the trench is applied instead of depressing the cladding from the core. In Fig. 4.17 overall losses for these two strategies are compared and plotted as a function of a distance between the core and the trench. The bend radius has the same value $R=4\text{mm}$ with corresponding values given in Table 4.1. When $d=0$, a depression to the cladding is applied; when $d \neq 0$, this is equivalent to introducing a trench. It can be seen that by moving the depressed region further from the core will improve bend loss reduction but increasing the distance by more than the optimal $d=1.5\mu\text{m}$ will cause the bend loss start to increase again. Therefore, for both transition and pure bend loss a trench placed at the optimal distance from the core is better then depressing the cladding from the core.

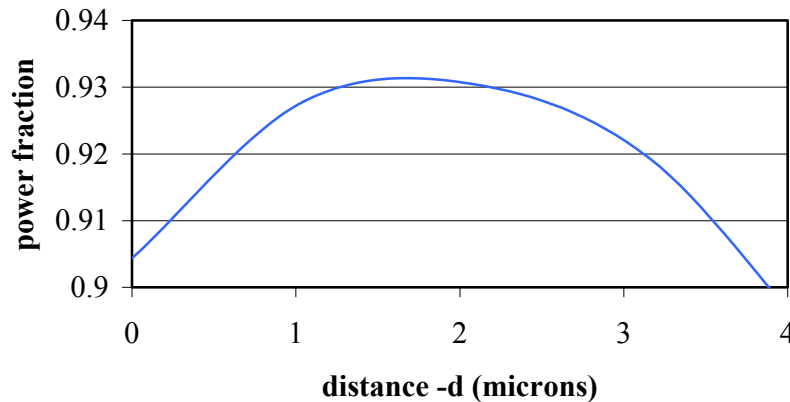


Fig. 4.17 Transmitted core power fraction as a function of a distance between the core and depressed region for the bend radius of 4mm .

Now the new strategy and the introduction of a trench can be discussed using the results presented in Fig. 4.15. It appears from Fig. 4.15(a) that the transition loss is smaller when both the trench and elevated regions are applied compared to when only the trench is applied, and therefore the overall losses in Fig. 4.15(b) are also consequently smaller when both layers are introduced.

4.7 Discussion

Insight into the reduced bending loss due to the new profile is gained by examining the transformed index profile in Fig. 4.18, denoted by the sloping lines, and the fundamental mode effective index, denoted by the horizontal lines. The transformed index accounts for the effects of the bend in terms of propagation along an equivalent straight waveguide. The apparent origin of radiation due to bending is located at the intersection of the modal effective and transformed index lines at position A in Fig. 4.18 for the matched cladding profile. The bend loss decreases if this position moves farther from the core.

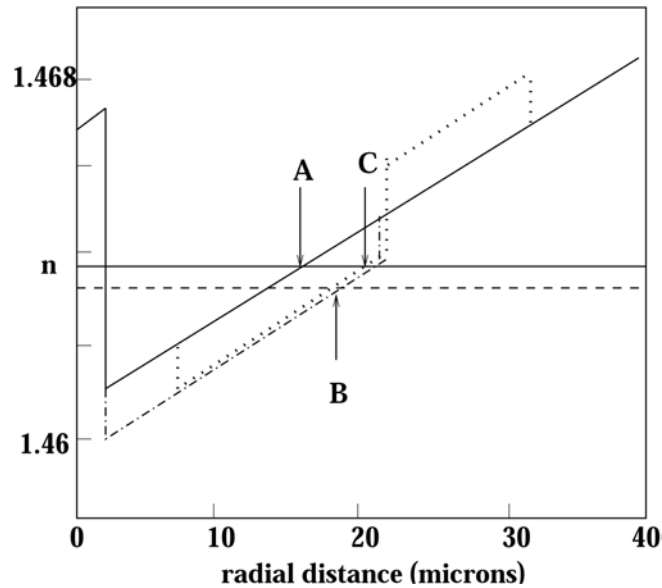


Fig. 4.18 *Effective index profile of the bent waveguide. The effective index of the fundamental mode is denoted by the horizontal lines, and the transformed index profiles by the sloping lines.*

The introduction of a depressed region, denoted by the dash-dotted lines below the solid line in Fig.4.18, decreases the effective index, and moves the intersection from A to

B, farther from the core, and decreases the bend loss accordingly. At the same time the effective index of the guided mode decreases, denoted by the dashed horizontal line in Fig. 4.18. If we can shift the effective index of guided mode back to its original value, that will reduce bend loss even more. In Sec. 4.7 it was shown that the introduction of a trench is the better option compared to depressing the cladding from the core. Therefore if we now introduce the trench and an elevated index region, denoted by the dotted sloping line in Fig. 4.18, the result is to raise the effective index and move the intersection from B to C, and hence further decrease the bend loss.

When only a trench is introduced, this changes the effective index of the quasi-mode and almost retrieves the original value. Numerical calculations confirm that the presence of the additional elevated index layer has a negligible effect on the value of the fundamental mode effective index because the cladding field is well attenuated at this distance from the core. Physically, the role of this additional layer of higher index might be a potential well to the radiated power from the curved waveguide, whilst the depressed region acts as a potential barrier [37]. The situation is similar to the theory of resonant tunnelling in a variably spaced multiquantum well structure, using an Airy function approach [38]. As already discussed in our case resonant effects do not appear.

Layers can be placed on either side of the core but the bend loss reduction will be of smaller order. On the other hand transition loss will be slightly higher when both layers are in the outer cladding. When calculated at the end of the curved waveguide, overall losses are smaller for the waveguide with both layers on the same side. However in all the cases considered here, transition loss has been included only once at the beginning of the 90 degree curved waveguide. In the case of an S-bend waveguide, transition loss appears four times, at the beginning and end of the curve and twice when the sign of the curvature changes. Additionally, the bends are not 90 degree bends and therefore in the case of an S-bend, it might be more appropriate to apply the option of placing the layers on either side of the core, as is applied to the buried channel waveguide in chapter 5.

4.8 Conclusions

A new strategy for reducing bend loss in slab waveguides has been proposed. It has been shown that, by introducing both depressed and raised index regions into the cladding on the outside of the bent core, bending loss can be reduced significantly compared to existing designs. The analysis has shown that with the new strategy both transition and pure bend loss are reduced.

All layer parameters have been analyzed and optimal values have been found for certain bend radii, showing that there is no one parameter that provides a sharply resonant behaviour at bend loss minimum.

It has to be emphasised again that both methods used in this chapter are approximate methods and they are not appropriate for designing very tight bends. However the conclusions from this chapter provide the basis for the analysis indicators for the next three chapters. When compared with numerical solutions using the BPM for much smaller angle bends these results differ only slightly from the results obtained with the two approximate methods, and both show the same trend in bend loss reduction.

CHAPTER 5

Effect of Added Layers on Bend Loss in Single-mode Buried Channel Waveguides

Bent planar single-mode waveguides are important components in any layout of optical processing devices in photonic integrated circuits. They are used to connect input and output ports linking waveguides and fibres on the edge of a chip, and they also provide connections between successive devices. The level of acceptable overall loss in such circuits limits the smallest bend radius that can be employed, and this in turn dictates the overall size of the circuit. At a time when there is a trend towards more complex and compact optical circuitry, reduction of bend radius without increase in bend loss is becoming a major issue.

Here a new strategy is adopted that moves the apparent origin of bend loss radiation even farther from the core. This is achieved by introducing a subtle arrangement of additional layers of different indices in the cladding on either or both sides of the core, but at the same time maintaining a relatively small core-cladding relative index difference to ensure spot size compatibility with standard single-mode fibres. The advantage of this strategy in terms of reduced bend loss has already been modelled using a simple one-dimensional slab model in Chapter 4.

In this chapter, its application is extended to the more practical two-dimensional problem of bend loss in silica-based buried channel waveguides (BCW's). Compared with other planar waveguides, such as rib guides and high-index contrast semiconductor material waveguides, BCW's are much more sensitive to bend loss at sub-centimetre radii, due to their small relative core-cladding index difference, typically below 1%.

5.1 Model

A structure consisting of a square-core buried channel waveguide of uniform refractive index, n_{co} , and side length $2p$, is considered. The core is surrounded by a nominally

unbounded cladding of uniform index, n_{cl} , with an additional layer or layers whose indices differ slightly from the cladding index, such as the two layers illustrated schematically in Fig. 5.1 (a). These layers are transverse to the plane of the bend, distance d from the core-cladding boundary and have a common height h . The layers have indices n_d and n_e , and thickness a and b , respectively.

The bent waveguide and cladding layers in Fig. 5.1(b) are sandwiched between two straight waveguides, and subtend an angle ϕ at the centre of the bend, i.e. the bend has length $R\phi$, where R is the bend radius of the waveguide axis. Although the layers are shown as occupying only the bent part of the waveguide, in practice they would extend onto the straight waveguides.

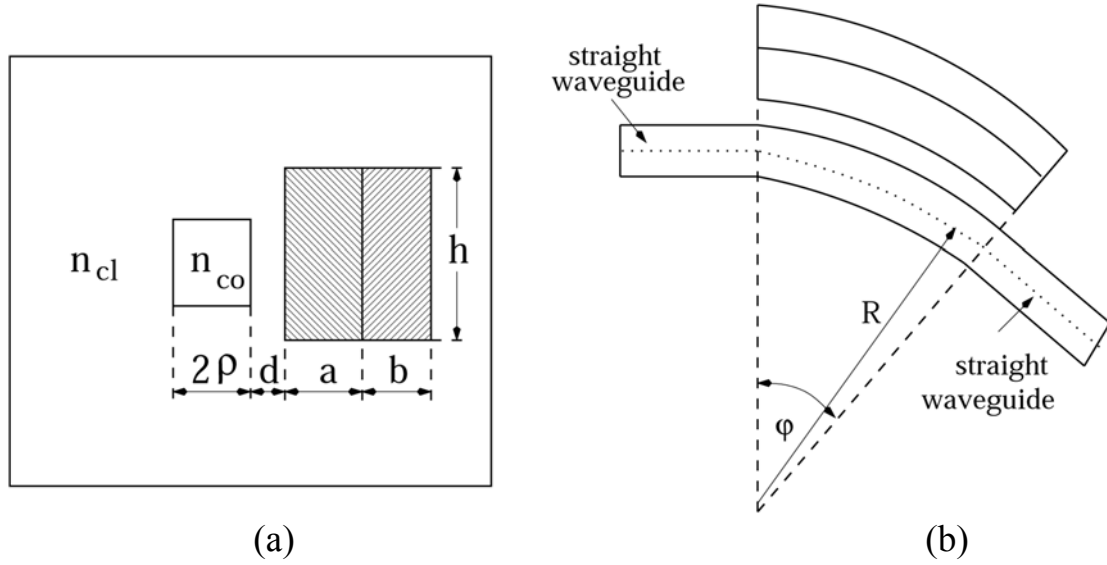


Fig. 5.1 (a) Cross-section of the waveguide and (b) top view of the structure.

5.2 Method of analysis

There is no exact analytical method for determining bend loss from a square-core buried channel waveguide, but there are a number of numerical and semi-numerical techniques available. Here we employ two of them, one is conformal mapping [23] in combination with 2D BPM [30], as was done for slab waveguides in chapter 4, but first the effective index method (EIM) [39] is applied reducing the 3D-problem to a two-dimensional one.

The other method is a bi-directional 3D-BPM. For the former, we apply an effective index method to the scalar wave equation for the 3-dimensional structure in the direction orthogonal to the plane of the bend, thus reducing it to a two-dimensional problem, and then apply the conformal mapping method, further simplifying it to 1 dimension by including a corresponding equivalent index profile. Using these two analytical methods is convenient in terms of computing time required and they also provides some physical insight into the problem. After that, 2D-BPM is used for the propagation in the equivalent straight waveguide.

In the second approach, we use a 3-dimensional finite difference beam propagation method (FD-BPM).

5.2.1 Effective index method, conformal mapping and 2D-BPM

When the index variation across the waveguide cross-section is small, as occurs in silica-based buried channel waveguides, the EIM has been found to be an accurate method for analysing curved waveguides [40].

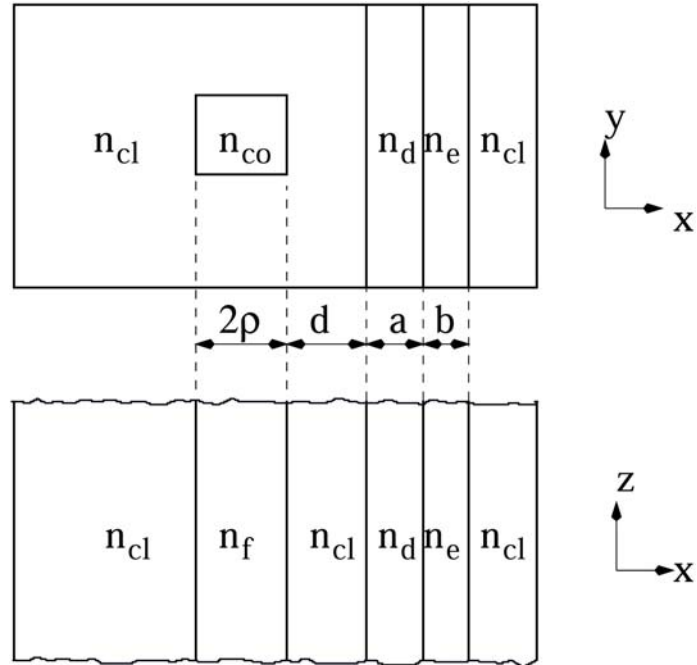


Fig. 5.2 Transformation of 3D buried channel waveguide to 2D slab waveguide with use of effective-index method.

If there are additional layers present in the cladding, then the analysis remains straightforward if the additional layers are assumed unbounded perpendicular to the plane of the bend.

The EIM reduces the number of dimensions by one, so the curved BCW is then replaced by a bent slab waveguide, see Fig. 5.2. The effective index of the slab guide, n_f , is calculated by letting the vertical dimension of the original waveguide approach infinity.

It is sufficiently accurate to use the equivalent slab model of these bent structures to quantify the bend loss. Then, the bent slab waveguide is transformed into an equivalent straight waveguide by introducing a modified refractive index profile by using the conformal mapping method. The modal field of this equivalent straight slab waveguide is then propagated with the 2D-BPM.

This approach quantifies both pure bend loss and transition losses.

5.2.2 3D BPM

The BPM is a very powerful numerical technique for investigating lightwave propagation phenomena along fibres. There are many variations of the BPM available, and here we use a vectorial, bi-directional, implicit FD-BPM, as it allows a 3-dimensional full vectorial formulation of Maxwell's equations within the paraxial approximation [41]. Mesh sizes used were sufficiently small, so that no significant discretization errors were introduced. When the mesh and step size were small enough, it was found that results remained the same when the mesh size was reduced further.

There are two main remaining issues regarding the use of this BPM. One issue concerns the location of the numerical boundaries of the computational space, and the other relates to possible reflections of modal power from any interfaces.

Transparent boundary conditions have already been introduced into the BPM [42]. This treatment of boundary conditions allows the electric field to freely 'escape' the computational domain without reflection. The standard BPM cannot account for reflections back along the direction of propagation because its unidirectional formulation accounts only for 1-way transmission. Accordingly, we have used a bi-directional BPM, where the transfer matrix method is used at the interfaces, in order to allow for any reflections from the additional layers in the cladding, even though such reflections will be minute because of the small core-cladding index difference and the exponentially decreasing modal field away from the core [43]. In the uniform regions, forward- and backward-traveling waves are propagated independently using the BPM. Therefore, the bi-directional BPM analyses coupled forward- and backward-travelling waves, and can account for reflection phenomena, including resonant effects.

The BPM offers a further advantage, in addition to accuracy, when compared with the matrix method, in that transition losses are automatically accounted included in the determination of bend loss in the complete straight-bent-straight waveguide structure in Fig. 5.1(b). However, because of the paraxial approximation, there is an upper limit on the arc angle ϕ . If the paraxial approximation breaks down, there is a sudden loss of guided

power, which is clearly not due to bend loss. This does not occur in examples presented here.

5.3 New strategy

Fig. 5.3 shows, schematically, three essentially different arrangements of the additional layers relative to the core for bend loss control. Depressing the outer cladding or introducing a trench, as in Fig. 5.3(a), are known methods for bend loss reduction, since both lead to a more rapid decrease in the fundamental mode evanescent field outside the cladding. However, the introduction of a trench relative to the uniform cladding is more effective when compared to slightly depressing the cladding index, since the former attenuates the evanescent field more rapidly, as discussed in the following section.

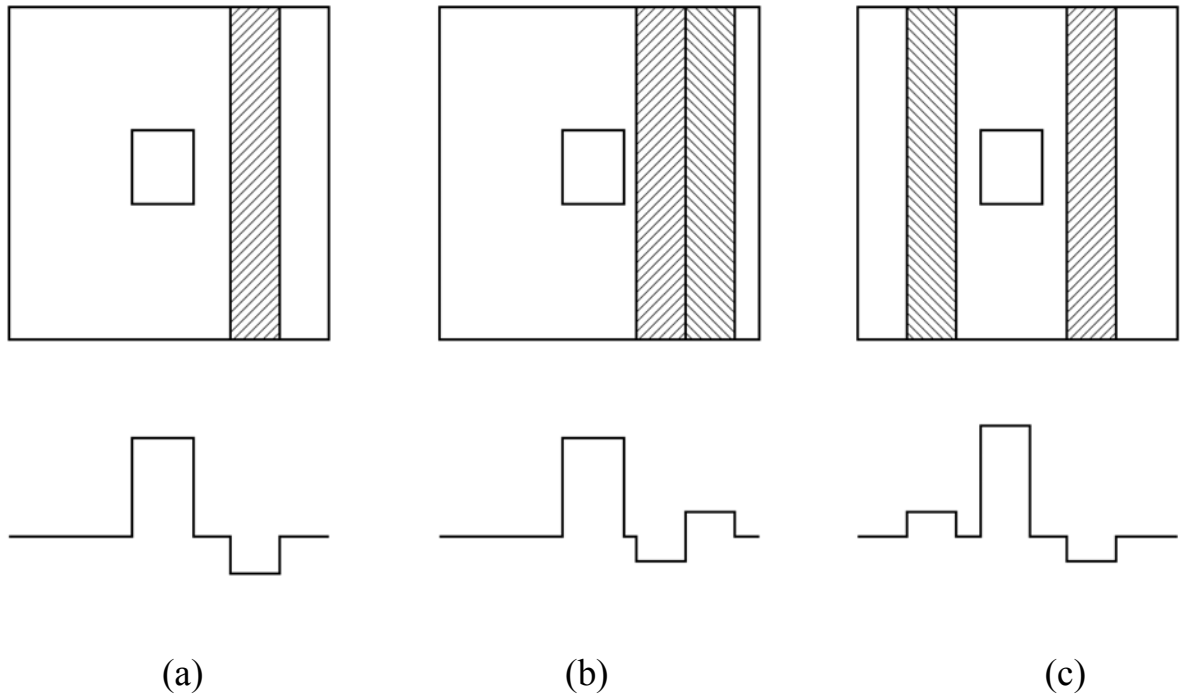


Fig. 5.3 *The cross-section of the waveguide (top) and corresponding index profiles (bottom) for three different geometries (a) with an additional depressed index layer in the outer cladding, (b) with two additional layers of depressed and raised index in the outer cladding and (c) with an additional layer on each side of the core.*

The new strategy for reducing bend loss is based on the introduction of a region of increased and depressed index, respectively, into the cladding on the outer side of the core, as shown in Fig. 5.3(b) [44,45]. The introduction of these regions on opposite sides of the core, as in Fig. 5.3(c), has a similar effect.

In some applications, such as switching or sensing, it may be important to increase the bend loss in the active (e.g. heated) state of the device, without any loss increase in the passive (e.g. unheated) state. In this case the positions of the depressed and elevated index regions are interchanged [46].

5.4 Results and discussion

The top view of the structure used in the BPM calculations is illustrated in Fig. 5.1(b). An arc of 20 degrees, with an axial bend radius of 5mm, is considered in all the cases presented here (unless otherwise stated). At the beginning of the structure there is a section of straight waveguide; this is followed by a curved waveguide, and at the end there is another straight section. The transmitted waveguide power is calculated at the end of the curved part, which means that transition loss has been taken into account at the beginning of the bent section. The optimum values of the widths of the additional layers in Fig. 5.1(a) are found to be $a=10\mu\text{m}$ and $b=8\mu\text{m}$ for the given bend radius.

The optimum value of the distance, d , from the core to the depressed index region, and the widths, a , of the depressed index region and b , of the elevated region will depend on the bend radius. If the bend is tighter, then the additional layers have to be placed closer to the core. The common height of the layers, h , used in the calculations is taken to be the height of the waveguide that produces the optimum results in terms of bend-loss reduction. Significant bend-loss reduction or increase only occurs when the height of these layers is greater than the core height.

5.4.1 Depressing the outer cladding

As noted above, introducing a trench is more successful than depressing the outer cladding index. There is a simple physical explanation for this result. The effective index profile of the waveguide is shown in Fig. 5.4, denoted by the sloping lines, while horizontal lines denote the fundamental mode effective indices.

The intersection of the mode effective index and effective refractive index profile indicates the apparent origin of bend loss radiation from the bent waveguide in the plane of the bend, see Fig. 5.4. For a simple step-profile BCW with a uniform cladding, this corresponds to the intersection of the solid lines at A. The distance from the core axis to A is indicative of

the magnitude of the bend loss. When A is closer to the core, the bend loss is higher, and, conversely, if A moves farther from the core, the loss decreases.

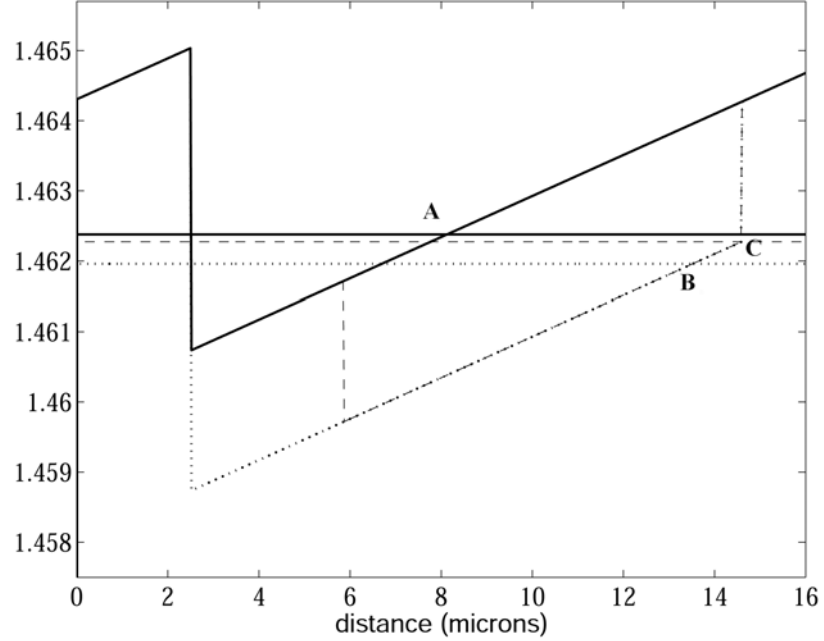


Fig. 5.4 *Effective index profile of the waveguide with only depressed index region (sloping lines) and the fundamental mode effective index (horizontal lines) as a function of the radial distance.*

If part of the outer cladding is depressed, as denoted by the dotted lines in Fig.5.4, this shifts point A further into the cladding and thus bend loss is reduced. However, the mode effective index decreases slightly and this partially offsets the reduction loss, leading to the intersection at point B. If a trench of equal depth is introduced into the cladding, as denoted by the dashed lines in Fig. 5.4, the mode effective index decrease is reduced and therefore the intersection moves even further into the cladding to C, so the bend loss reduction is enhanced.

In Fig. 5.5 the overall bend loss is plotted as a function of the separation, d , between the core and depressed region.

There is an optimal distance between the core and trench which depends on bend radius and waveguide parameters. For a 90 degree bend with bend radius of 4.5mm and index difference $\Delta n=0.002$ between the cladding and trench, as can be seen in Fig. 5.5, the optimal separation is $1.2\mu\text{m}$.

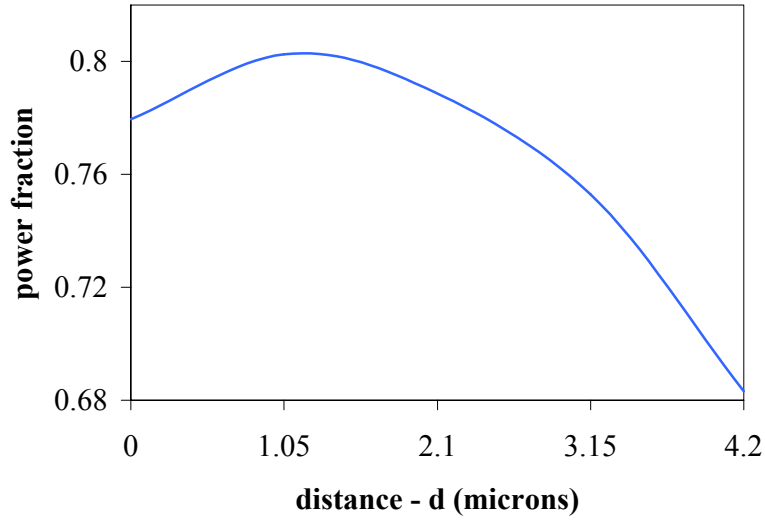


Fig. 5.5 Fraction of transmitted power as a function of distance between the core and depressed index region.

5.4.2 Depressed and elevated regions

Here, bend loss is quantified when layers of raised and depressed index, respectively, are present in the cladding on the outside of the bend, as illustrated in Fig. 5.1(b).

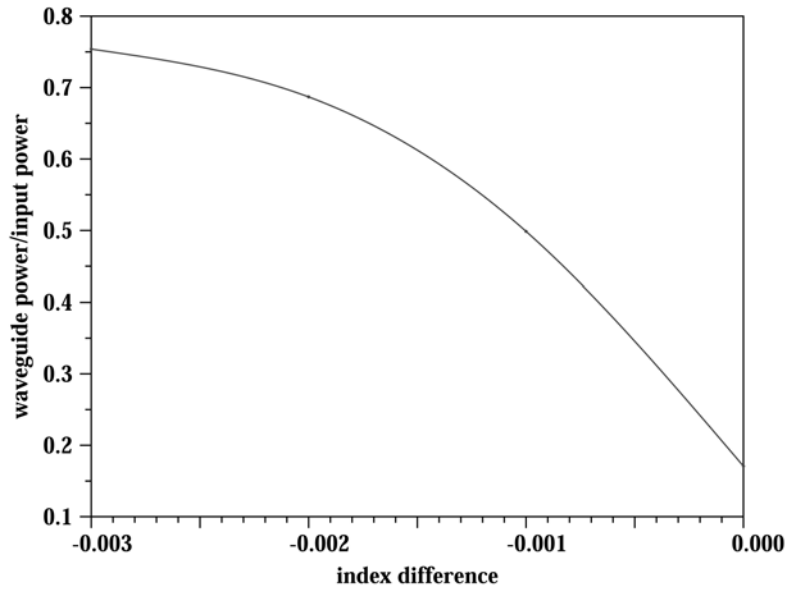


Fig. 5.6 Fraction of transmitted power as a function of index difference, $n_d - n_{cl} = n_{cl} - n_e$.

In Fig. 5.6, the transmitted fundamental mode power in the core, normalized to the input power, is plotted as a function of the index difference between the cladding (n_{cl}) and the lower index (n_d) additional layer, assuming that the height of the elevated index layer is equal to the depth of the lower index layer, i.e. $n_d - n_{cl} = n_{cl} - n_e$, where n_e is the elevated index. The bend radius is 5mm and the arc angle is 20 degrees.

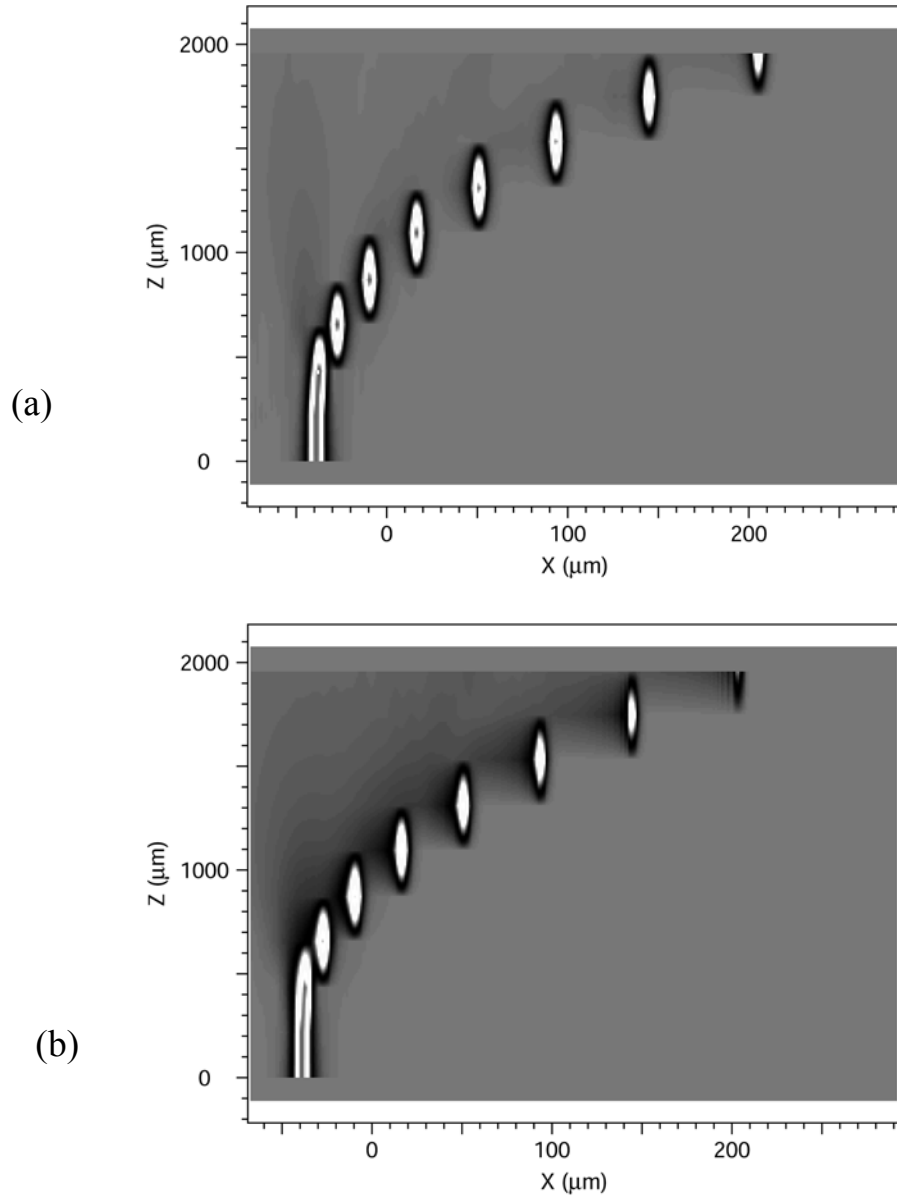


Fig. 5.7 Contour plots of the field of the bent waveguide (a) with the additional layers and (b) without the additional layers.

As would intuitively be expected, the transmitted power fraction increases rapidly from the uniform cladding result of 19% (no additional layers-zero index difference), as the index differences in the layers increases. When the index difference in Fig.5.6 is below -0.003, there is virtually no bend loss, as the initial fundamental mode power in the core is 75 percent of the input power.

The reduction in bend loss is also shown qualitatively through the introduction of the two layers by plotting the field intensity of the bent waveguide without the layers in Fig. 5.7(a), and with the layers in Fig. 5.7(b). The waveguide is bent in the x - z plane and the plots are contour plots in the cross-section for $y=0$. The former shows a series of loss plumes peeling off the bent waveguide, which is characteristic of the superposition of transition and pure bend losses. With two layers present, there is only a small amount of radiation present in Fig. 5.7(b) and it appears to be due predominantly to the mismatch between the straight and curved waveguide, i.e. transition loss.

It should also be noted that there is negligible reflection of fundamental mode power from the additional layers along the bend. This is due to a combination of the relatively small index difference between these layers and the cladding, and the fundamental mode field in the cladding that decreases exponentially in the region between the core and the apparent origin of radiation in Fig.5.4. Any reflected power is accounted for quantitatively by the transform matrix method.

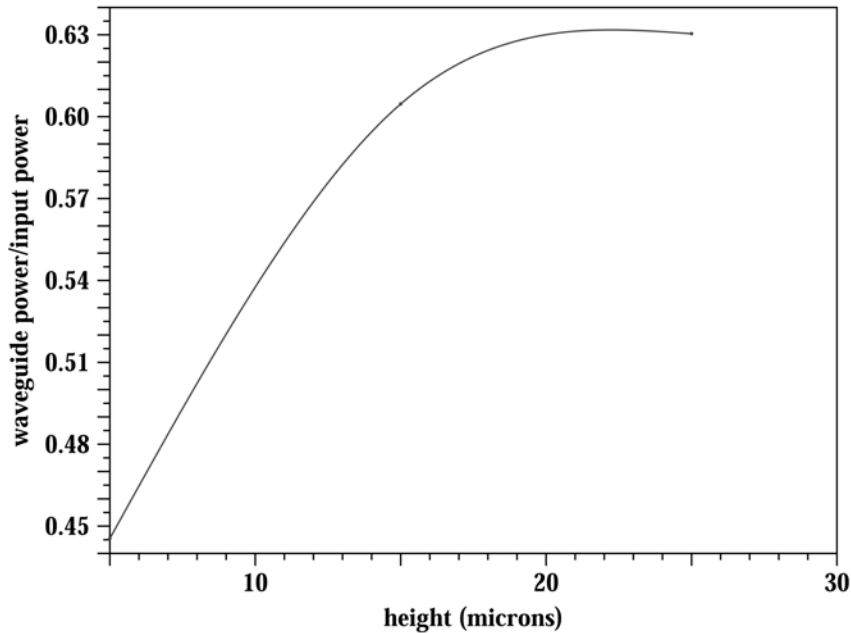


Fig. 5.8 *Fraction of transmitted power as a function of the height, h , of the additional layers.*

The minimisation (or maximisation) of bend loss for a given bend radius and source wavelength is a 4-parameter problem depending on: (1) the widths a and b of each layer; (2) the common height h of the layers, and; (3) the distance d between the core and the layers. In all figures, except Fig. 5.6, the height of the layers is much greater than that of the waveguide core, and these layers extend in the vertical direction across the whole cladding layer. Fig. 5.8 provides a justification for this choice. When the layers are the same height as the core, i.e. $h=5\mu\text{m}$, less than 45 percent of power remains in the waveguide core at the end of the bend, whereas if $h=20\mu\text{m}$ or greater, there is an improvement in transmitted power of about 40 percent.

There is a few percent difference in loss when the distance between the core and the layers is varied, as is quantified in Fig. 5.9. Improved bend loss reduction is obtained if these layers are closer to the core when the bend is tighter, but it is evident that this parameter is not as crucial to overall loss as the height of the layers. There still exists an optimum distance, d , that depends on the bend radius. Other parameters need to be optimized as well, since there is no one parameter that provides a sharply resonant behaviour at loss minimum. Optimization of the layer parameters is undertaken in the same way as in section 4.5.1 for slab waveguides.

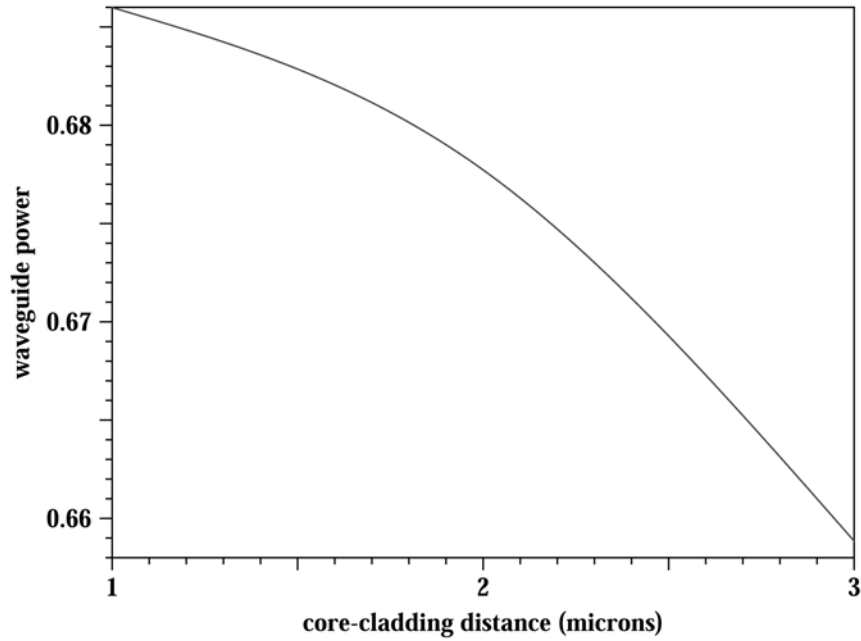


Fig. 5.9 *Fraction of transmitted power as a function of the distance, d , between the core and the additional layers.*

Two modes can exist in the modified profile, even if the elevated index region is slightly above the cladding index, e.g. $n_e=1.4606$ when $n_{cl}=1.46$. Although two modes can exist, resonant coupling between the high-index regions does not occur because the two ‘cores’ thus formed have sufficiently different effective index values for their fundamental modes. In the other words, the coupling fraction is very close to zero due to the mismatch.

There is no simple relation that provides a way to obtain optimal values for bend loss reduction. Firstly, the EI method should be applied for a straight waveguide, thus reducing the three-dimensional problem of the curved waveguide to a two-dimensional problem.

Secondly, we use the Airy Function Method in order to obtain an effective index profile and the effective index of the guided quasi-mode. (Conformal mapping, in combination with the transfer matrix method, or some other approximation method, can be used.) When plotted, as in Fig. 5.4, the intersection of the effective index of the guided mode and effective index profile, point A, gives the point where the waveguide starts to radiate. If bend loss reduction is required, then our aim is to shift that point further into the cladding.

Thirdly, placing a trench in such a way that the right-most point of the trench index intersects the effective index of the quasi-mode will result in optimal bend loss reduction.

Finally, putting the elevated index region right next to the trench, with the same index difference as that between the trench and the cladding, with a width which is a few microns less than the trench width, should improve bend loss control.

5.4.3 Justification for the increased index layer

There remains the question of the effect of the additional layer with the increased index. As we showed above, the insertion of a trench in the profile, as compared to a depressed region starting at the core boundary, has the effect of both decreasing the effective refractive index and increasing the modal effective index, and therefore it significantly reduces bend loss. The role of the additional elevated index region to the right of the depressed region in Fig.5.3 can be quantified using the results presented in Fig. 5.10.

The results presented in Fig. 5.10 are calculated for a 90 degree bend with a bend radius of 4.5mm, so the Airy function method, in combination with the EI method, is used. The transmitted core power fraction is plotted as a function of the index of the raised index region. When $n=1.458$, this represents the situation where the depressed region is extended further into the cladding. Further, $n=1.46$ means there is no additional layer next to the depressed one, while $n=1.462$ represents the effect of a layer of increased refractive index. Therefore, the index of the extended part of the trench, of width b , is gradually increased from $n=1.458$ to $n=1.462$, as illustrated in the inset in Fig. 5.10. It can be seen that extending the depressed region ($\Delta n=-0.002$) increases bend loss to 5dB/cm, but there is reduced loss if we introduce an elevated index region ($\Delta n=0.002$). The plotted curve changes shape when the sign of the index difference between the layer and the cladding changes at $n=1.46$. This represents the point where only an optimized trench of width a exists in the outer cladding.

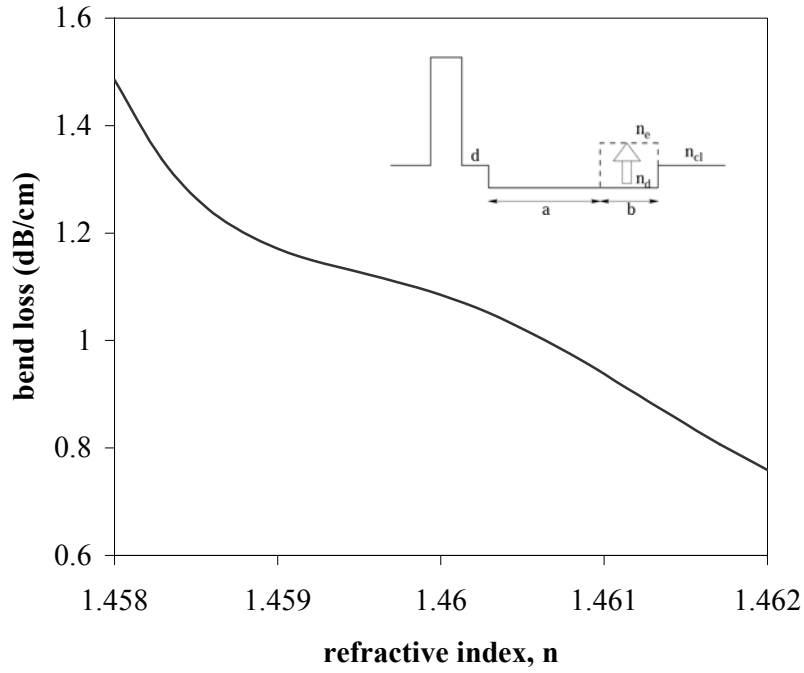


Fig. 5.10 Pure bend loss as a function of index n of outer layer (width b). Here $n=n_d$ when $n < n_{cl}$ and $n=n_i$ when $n > n_{cl}$.

Numerical calculations confirm that the presence of the additional layer has negligible effect on the value of the fundamental mode effective index because the cladding modal field is well-attenuated at this distance from the core.

5.4.4 Alternative strategy

An alternative strategy is to place the elevated index region in the inner cladding, as illustrated in Fig. 5.3(c). However the minimum in bend loss is found to be slightly higher than for the case illustrated in Fig. 5.3(b), unless the layer is adjacent the core. The layer placed next to the core has an increased or decreased index compared to the cladding index, depending on whether bend loss reduction or increase, respectively, is needed. For example, the placement of the layers on opposite sides of the core is appropriate for application to the thermal variable optical attenuator, based on waveguide bending, that will be presented in chapter 6.

A comparison is made for a 90 degree bend with a bend radius of $R=4.5\text{mm}$ and an index difference between the cladding and additional layers of $\Delta n=0.002$. Placing the elevated index region in the inner cladding, next to the core will result in 0.66dB/cm pure bend loss, whereas for a layer placed in the outer cladding bend loss is 0.76 dB/cm. For an

estimation of the effectiveness of both methods for bend loss reduction, the bend loss without any layer would be 37.2dB/cm.

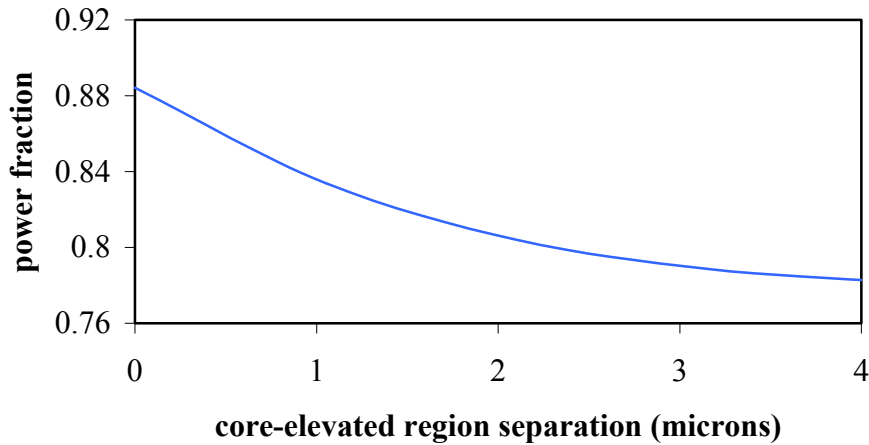


Fig. 5.11 *Fraction of transmitted power as a function of distance between the core and elevated index region.*

When choosing where to place an elevated index region, if it is not possible to increase the index immediately next to the core, it is better to place it after the trench. In Fig. 5.11, bend loss is plotted as a function of separation between the core and the elevated index region that is placed in the inner cladding. It is obvious that there is an increment in bend loss reduction when the layer is closer to the core.

5.4.5 Comparison with other strategies

It is useful to compare the results of the two-layer strategy with previous bend-loss strategies. The introduction of a trench instead of depressing the cladding immediately beyond the core has already been justified by Fig. 5.4 and the discussion in Section 5.4.1. Further, it has already been shown, via Fig. 5.10 and the discussion in section 5.4.2, that introducing the elevated index region further improves bend loss reduction when compared with the introduction of the single depressed trench.

Using the results presented in Fig. 5.10, we justify the choice of the small index difference between the additional layers and the cladding, and compare the results with the strategy of putting in an isolation trench of much deeper index than we have used.

Accordingly, the index of the depressed region is decreased, and at the same time we keep the elevated index, $n_i = n_{cl} + 0.002$, unchanged. An arc angle of 12 degrees has been used for the calculation to produce the plots in Fig. 5.12. The transmitted waveguide power

is calculated after the beginning of the curved section as a function of the index of the depressed index in Fig. 5.12(a), and at the end of the curved section in Fig. 5.12(b).

In Fig. 5.12(a), the loss is due to the transition only, and it can be seen that there is an optimum for the index difference between the cladding and the depressed region in terms of minimizing the transition loss. This arises because the effect of deepening the index is to shift the modal field on the bend inwards and thus counteract the outward shift caused by the bend in the absence of the depressed layer. If the depressed index is too low, the field shift becomes too large to match the field of the straight waveguide.

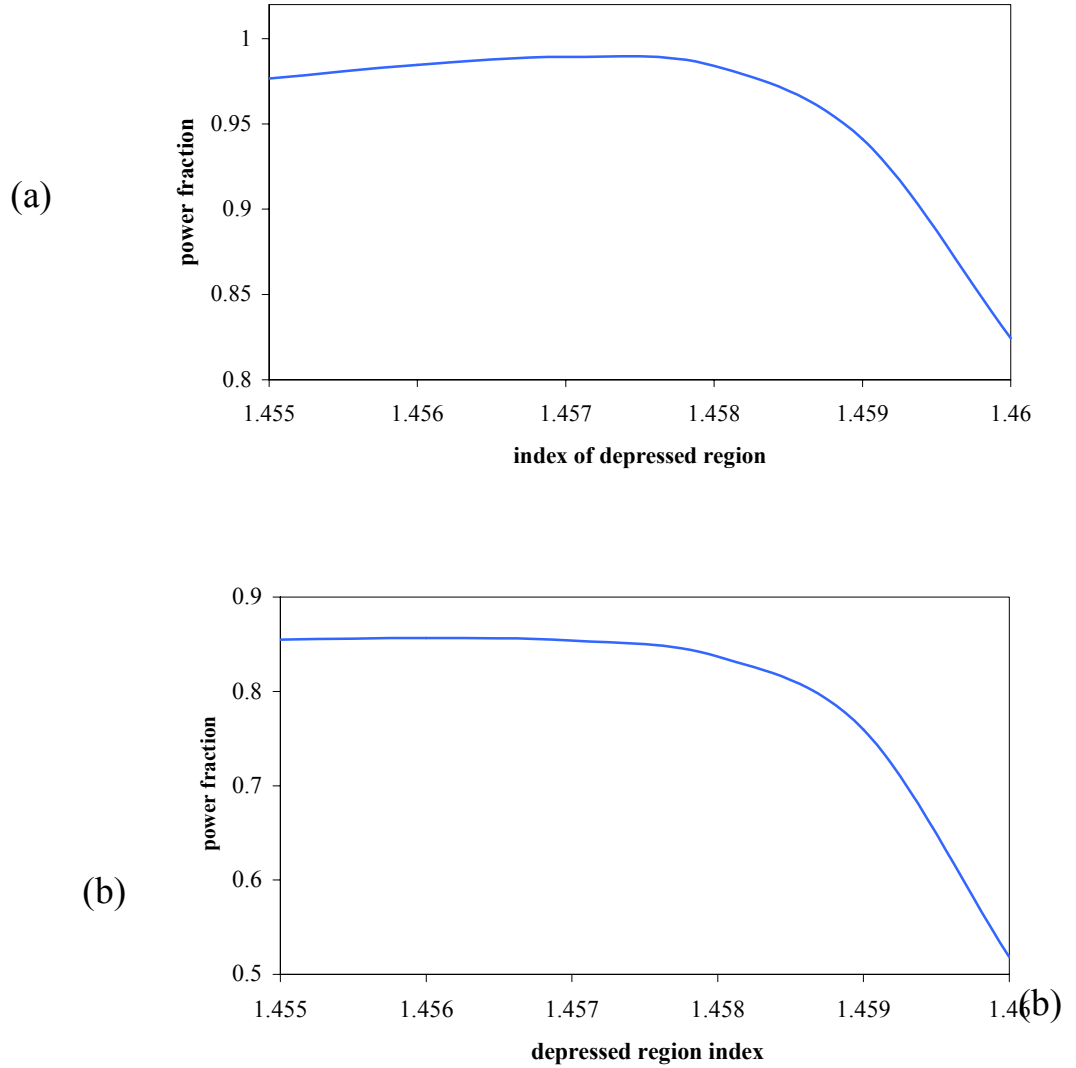


Fig 5.12 Fraction of transmitted power as a function of the index of the depressed region, n_d , (a) at the beginning of the curved section and (b) at the end of the curved section.

The loss curve plotted in Fig. 5.12(b) is dominated by pure bend loss and shows that, when decreasing the index of any depressed region from its initial value of $n_d=1.46$, which is equal to the cladding index, down to $n_d=1.4575$, the maximum increase in transmitted power is reached, and that any further decrease in index does not lead to any further increase in transmitted power. This saturation effect demonstrates that the new strategy works more effectively than introducing just an isolation trench for buried channel waveguides.

In order to quantify the order of bend loss reduction, we compare three different strategies (depressing the outer cladding from the core, using a trench and our strategy) by using the Airy Function Method, in combination with the EI method for a 90 degree bend. The results are presented in Table 5.1 for two different bend radii and index differences. The tighter the bend, the higher the index difference that is needed for efficient bend loss reduction.

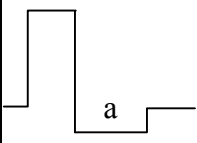
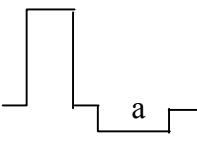
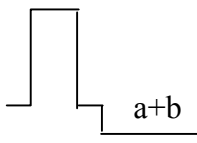
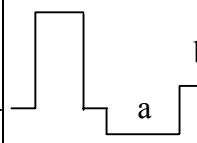
profile parameters				
R=4.5mm $\Delta n=0.002$	1.42dB/cm	1.08dB/cm	1.49dB/cm	0.75dB/cm
R=3.5mm $\Delta n=0.003$	1.66dB/cm	1.18dB/cm	1.62dB/cm	0.77dB/cm

Table 5.1 *Pure bend loss for two combinations of bend radius and index difference for various index strategies.*

It has to be emphasized again that this method is approximate, and should not be used for bend design. However, the aim is to compare different strategies and the differences between the bend loss reductions.

5. 5 Conclusions

A new strategy for reducing bend loss in bent waveguides has been applied to buried channel waveguides. It has been shown that, by introducing both depressed and raised index regions into the cladding on the outside of the bent core, bending loss can be reduced significantly when compared to related existing profile designs.

The index differences between the cladding and the additional layers are small, and therefore no significant problem should occur when introducing them into the cladding, using a direct writing technique. The fact that the values of the layer parameters are not particularly critical when close to the optimum minimum bend loss design should make the fabrication procedure fairly tolerant. Furthermore, their presence should not have a significant effect on the efficiency of coupling from the waveguide to a standard single mode fibre.

CHAPTER 6

Variable Optical Attenuator based on a Bent Channel Waveguide

Variable optical attenuators (VOAs) are expected to play an important role in wavelength-division multiplexed systems and long-haul transmission lines. Their applications include dynamic channel-power and/or gain equalization in wavelength division multiplexed cross-connect nodes and transmission systems. With regard to optical performance, the most important characteristics needed in a VOA are large dynamic range of attenuation, flat wavelength characteristic, low polarization-dependent losses (PDL), low driving power, small size and low insertion loss.

Several practical realizations of VOAs have been proposed so far. They include, for example, micro-mechanical systems [47], Faraday rotators [48] and those based on thermal switching [49-52]. Recent advances in polymer waveguide technology [53-58] favour the use of VOAs utilizing thermo-optical switching. Such switching can be very effective in waveguide structures made of polymers, due to their high thermo-optic coefficients, low thermal conductivity and easy integration with other optical and electronic components [59,60]. Well-developed adhesion schemes permit the use of polymers on a wide range of substrates.

A few configurations of VOAs utilizing thermo-optical switching have been proposed. These range from straight waveguide geometry [61] to more elaborate designs involving Y-junctions [49] and S-bends [62]. The simplest geometry involves a straight length of a channel waveguide with a thermal actuator (heater) placed directly above it at a distance that ensures low polarization-dependent losses. When the heater temperature increases (due to electric current), the core index decreases below the cladding index, in the case of a polymer waveguide and forces the guided light out of the waveguide, leading to its attenuation. Recently Kowalczyk *et al.* [59] have given a practical realization of this design, offering a high extinction ratio of better than 30dB with heating power below 10mW.

Another promising VOA design is based on a bent channel waveguide. Its principle of operation exploits the effect of thermally-enhanced radiation of light from the curved section of the channel waveguide. This type of VOA has already been studied in [62,63].

6.1 Standard VOA based on a bent channel waveguide

A standard VOA, based on a bent channel waveguide, consists of a buried channel polymer waveguide in the form of an S-bend structure, followed by a straight segment. The cross-section of the waveguide is shown in Fig. 6.1(a) and the top view of the device in Fig. 6.1(b). A square core with side 2ρ and a refractive index n_{co} , is surrounded by a cladding of lower index, n_{cl} .

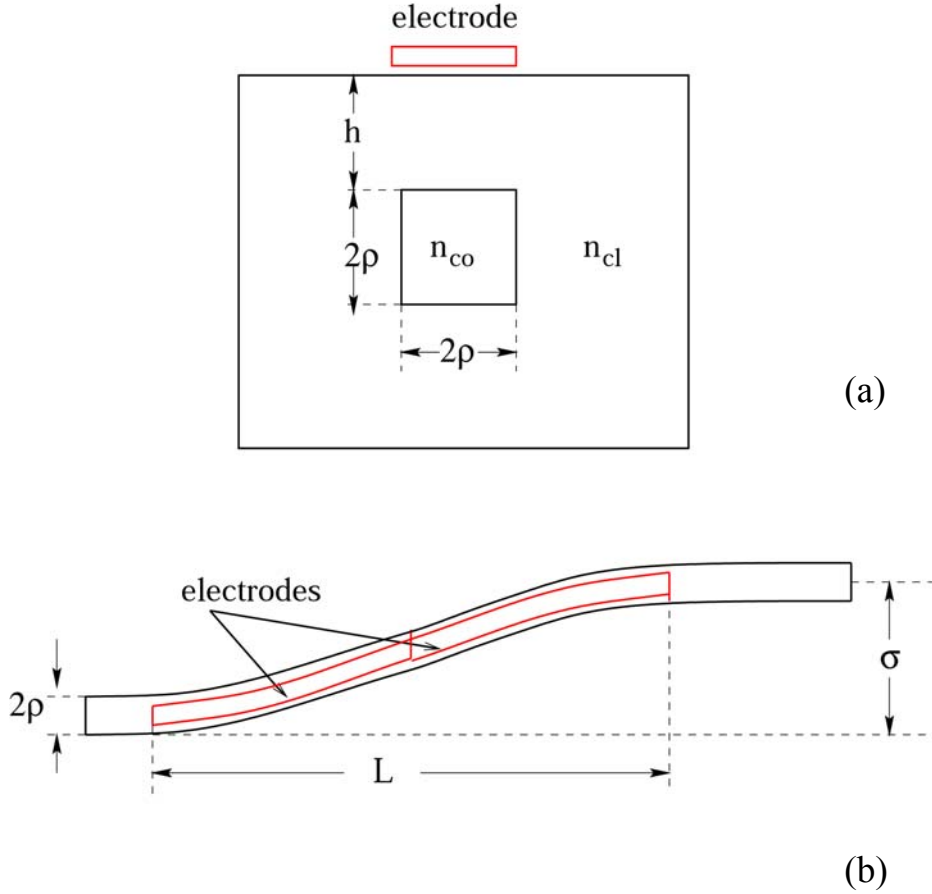


Fig. 6.1 Schematic of the S-bend-based variable optical attenuator: (a) cross-section, and (b) top view of device.

The device length, L , is related to the bend radius, R , and the bend offset, σ , by:

$$L = 2R \arccos\left(1 - \frac{\sigma}{2R}\right). \quad (6.1)$$

Attenuation can be induced by creating a change in the effective refractive index of parts of the waveguide, and this can be implemented by activating the heater electrodes that are placed above the waveguide. The distance between the core and the top surface of the cladding is denoted by h . The heating electrodes are parallel to the guiding channel and their widths and locations are determined by the requirement of low power consumption and low PDL.

6.1.1 Bend loss

S-shaped bends have been widely used in integrated optical circuits because they provide low-loss transitions between parallel waveguides with a lateral offset and are relatively easy to fabricate. In Chapters 4 and 5 the control of bend loss and the role of the additional layers in the cladding have already been discussed. However, all bends considered there were based on bends that do not reverse. Here an S-bend is considered, as illustrated in Fig. 6.1(b).

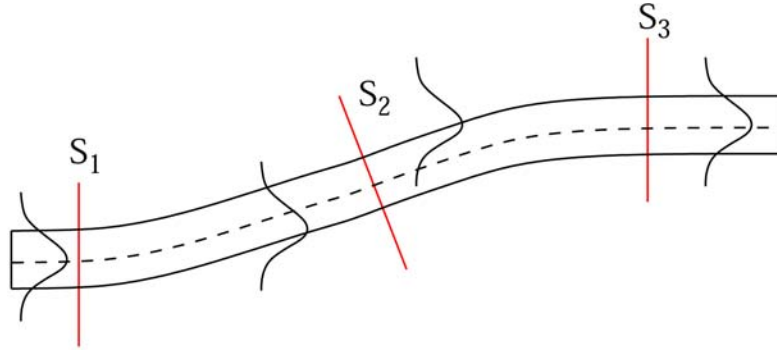


Fig. 6.2 *Illustration of transition loss in a S-bend waveguide.*

As already mentioned, in Chapter 4, there are two contributions to bend loss, transition and pure bend loss. The mechanism of pure bend loss is the same for different shaped bends, but transition loss occurs three times in the S-shaped bend. In Fig. 6.2 the mismatch of the fields of the straight and curved waveguide is illustrated, and it can be seen that the transition losses appear at the beginning (the plane denoted by S_1) of the S-bend, in the middle of the bend, S_2 , and at the end of the bend, S_3 . A double transition loss occurs at S_2 , since the sign of the curvature changes. However, the main contribution to bend loss is still pure bend loss. Therefore the choice of bend radius is important for both passive and active regime bend loss.

6.1.2 Material thermal properties

The change in refractive index of a material is due to a combination of the physical expansion of the material and the change of the index of refraction with temperature, T . The thermo-optic coefficient can be expressed as:

$$\frac{dn}{dT} = \left(\frac{\partial n}{\partial \rho} \right)_T \left(\frac{\partial \rho}{\partial T} \right) + \left(\frac{\partial n}{\partial T} \right)_\rho, \quad (6.2)$$

where n is refractive index, ρ is density.

When the coefficient of volume expansion, γ , is used, then (6.2) becomes:

$$\frac{dn}{dT} = - \left(\rho \frac{\partial n}{\partial \rho} \right)_T \gamma + \left(\frac{\partial n}{\partial T} \right)_\rho \quad (6.3)$$

In most silica based integrated-optic materials the second term in (6.3) is the more significant and its value is of order:

$$\frac{dn}{dT} \approx \left(\frac{\partial n}{\partial T} \right)_\rho \approx 10^{-5} / ^\circ C \quad (6.4)$$

On the other hand, for glassy polymers the physical expansion of the material will be dominant factor when the temperature change occurs. The first term for these materials is of order [60,64]:

$$\frac{dn}{dT} \approx - \left(\rho \frac{\partial n}{\partial \rho} \right)_T \gamma \approx - 10^{-4} / ^\circ C \quad (6.5)$$

If this result is compared with that for silica based materials in (6.3), the conclusion is that the thermo-optic coefficient in glassy polymers is, in absolute value, an order of magnitude larger than in silica. There is also a difference in the sign, so with an increase in temperature, the refractive index of polymer decreases, whereas for silica it increases.

Activating the electrode that is placed above the waveguide cladding, as illustrated in Fig. 6.1, induces the temperature change. The response time is inversely proportional to the thermal conductivity of the waveguide material. The thermal conductivity is seven times higher for silica-based than for polymer-based waveguides. Therefore, for the same temperature change and the same response time, seven times more power is needed for the silica-based waveguides.

Taking into account the differences, both in conductivity and thermo-optic coefficient, it takes about two orders of magnitude more power to induce the same refractive index change in silica-on-silicon than in glassy polymers.

6.1.3 Principle of operation

The aim is to have as small as possible bend loss in the passive regime, where attenuation is not needed, whereas in the active regime, when the attenuation is on, to have as high a loss as possible. The difference between the passive and active losses is usually called the extinction ratio.

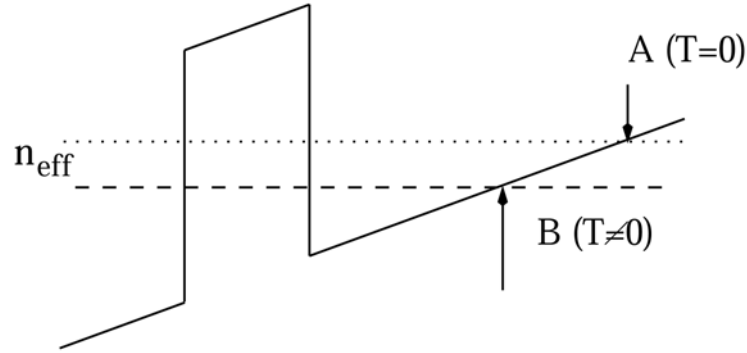


Fig. 6.3 *Illustration of operation of the VOA.*

For an appropriate fixed bend radius, taking into account the refractive index difference between the core and the cladding, and the core dimensions, virtually all the light is guided by device. The effective index profile of the curved waveguide is illustrated in Fig. 6.3. The dotted horizontal line corresponds to an effective index of the guided fundamental mode in the passive regime. The intersection of this line with the effective index of the bent structure (point A) indicates the origin of radiation of the guided energy into the cladding. Point A has to be sufficiently far from the core to provide low passive loss.

The switching operation relies on the thermo-optic effect. When the electrodes are on, the temperature rises in the polymer below the electrodes. The increase in temperature results in a lower refractive index, because glassy polymers have a negative thermo-optic coefficient. Decreasing the effective index of the guided mode brings the effective index down and moves the intersection point closer to the guiding channel (point B), leading, in effect, to higher losses. This is basis of operation of a standard thermal VOA. The temperature change below the electrodes is simplified in Fig. 6.3 for the present discussion. The actual change in the refractive index that is induced but the temperature gradient is plotted in Fig. 6.6 of section 6.3.1.

The thermo-optic effect occurs in straight waveguides as well, but the power stays in the high index substrate if some other radiation effect is not introduced. Therefore the S-bend is introduced in order to provide radiation of power.

6.1.4 Device requirements

As mentioned in the introductory part of this chapter, there are certain requirements for attenuators. These include low power consumption, millisecond switching time, polarization and wavelength independence, small size, reliability and high extinction ratio.

Polymer waveguides are used for these devices because their thermal response time is faster than silica, they have better thermo-optic characteristics in terms of higher thermo-optic coefficients and lower thermal conductivity. However, transmission losses and insertion losses are higher for polymer waveguides than for silica-based waveguides. Material loss is not of major concern for a device which is a few millimeters long. Insertion loss for polymer waveguides is still of some concern, as it is sufficiently larger compared to silica waveguides.

The PDL value represents the difference in losses between TE and TM polarizations. The PDL of a single-mode waveguide at 1550nm wavelength can be reduced to 0.01dB/cm [65]. A VOA based on a bent waveguide is almost wavelength-independent, as it does not rely on any resonant effect.

A common concern is the overall size of the device, because the size limits attempts to lower cost, as a result of device yield per wafer. The possibility for an S-bend VOA to be of the order of few millimeters long makes it more economical than other devices which are a few centimeters long.

Extinction ratio depends on device characteristics, power used and the temperature variation. Unfortunately, increasing heating power affects cross-talk between devices. All of these characteristics determine the extinction ratio which is an important characteristic of the device.

In conclusion, thermo-optic VOA's using silica-based technology provide good connectivity with optical fibres, but their extinction ratio is inadequate and their cross-talk is too high, whereas polymer-based VOA's provide higher extinction ratio using less power, due to their thermo-optic characteristics.

6.2 New design of VOA

In this chapter, a modified VOA design, based on a bent channel waveguide, is proposed. It features an asymmetric refractive index profile of the waveguide structure, and this leads to significant improvement in the extinction ratio when compared with the conventional design. Changes are based on the introduction of additional layers that control bend loss, which has already been discussed in Chapters 4 and 5. One of the conclusions of section 4.7 was that for bends with a high contribution from transition loss, it is more appropriate to apply a strategy of using additional layers on each side of the core. This strategy works better than introducing the additional layers in the outer cladding if a layer in the inner cladding can be introduced next to the core. The cross-section and index profile of the waveguide with introduced layers on each side of the core is presented in Fig. 6.4.

Depressing the index of the cladding on the outer side of the waveguide bend and increasing it on the inner side reduces the bend loss [31]. In the device discussed here, the goal is to achieve exactly the opposite effect. The index of the cladding in the inner area of the bend is decreased with appropriately-placed heating electrodes, while the index in the outer part of the bend is increased by introducing an extra layer with an elevated refractive index [44,45].

In contrast to a standard VOA, on the outer side of each bend there is an additional narrow layer with a refractive index slightly higher than that of the cladding, but lower than that of the core. The height of this layer is much greater than that of the guiding channel. It extends in the vertical direction across the whole cladding layer. The cross-section of the whole device is illustrated in Fig. 6.4(a).

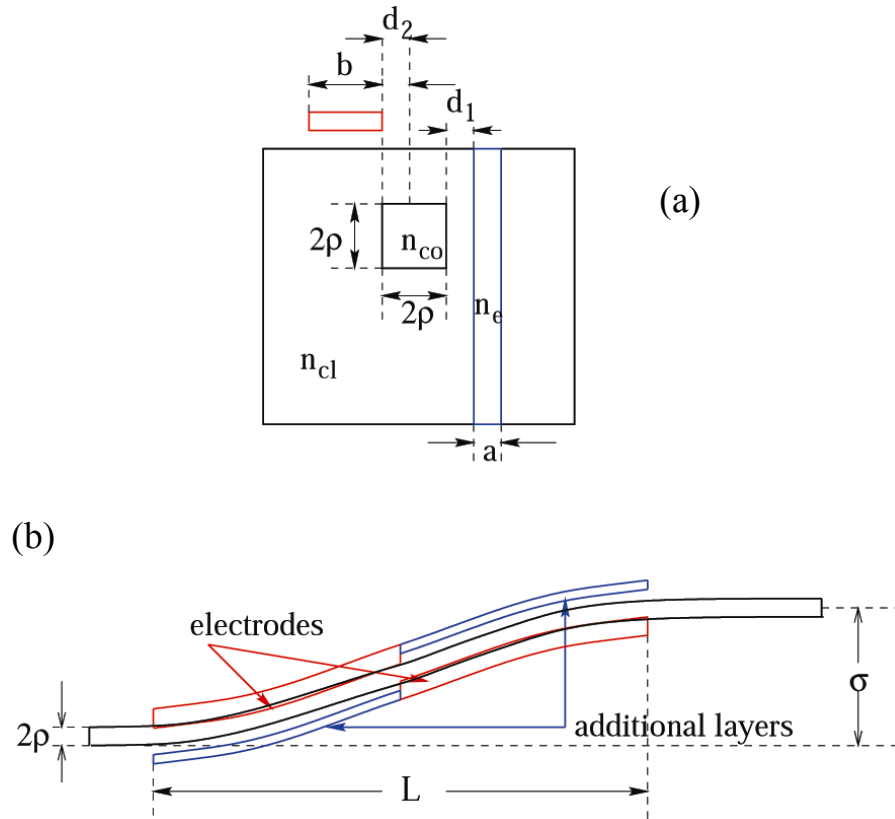


Fig. 6.4 Schematic of S-bend-based variable optical attenuator: (a) cross section, and (b) top view of device.

The width of the additional layer of thickness a , its distance from the guiding channel, d_1 , and its refractive index n_e are variable parameters. Their exact values depend on the parameters of the S-bend structure whose top view is illustrated in Fig. 6.4(b). The width of each electrode, b , is equal to that of the guiding region and they are placed on the inner side

of the bent guiding channel. The distance between the electrodes and the core vertical axis is denoted by d_2 in Fig. 6.4(a).

The physical explanation of the underlying phenomenon is illustrated in Fig. 6.5, where the equivalent index profile of the slab waveguide, whose indices are of the channel waveguide, is plotted. The actual change of the refractive index due to the temperature change is plotted in Fig. 6.6. Here, only an illustration of the basic operation is considered.

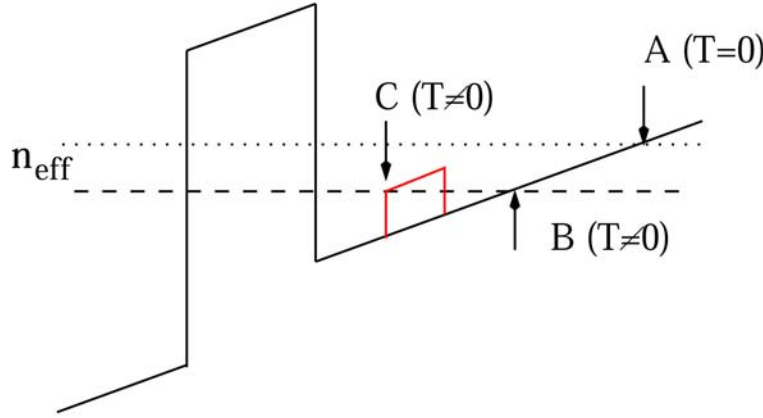


Fig. 6.5 *Effective index profile of the equivalent bent waveguide structure.*

The distinct feature of the design lies in the presence of the narrow layer in the cladding with a slightly elevated refractive index. By moving the heating electrode towards the inner region of the bend and away from the additional layer, the heating will decrease the refractive index mainly in the region immediately below the electrode and in its vicinity, including the core and part of the cladding. If this index change is sufficiently large, then the horizontal line representing the effective index of the guided mode will move down, intersecting the effective index distribution in the region of the location of the additional layer (point C). Since this point is situated much closer to the core than points A or B, the tunnelling, and subsequent bend losses, will be correspondingly higher. Additionally, decreasing the inner cladding index shifts the field of the fundamental mode further away from the core centre thus providing higher transition loss in the active regime.

6.3 Method of analysis

The refractive index changes due to the thermo-optic effect can be calculated by using the heat equation.

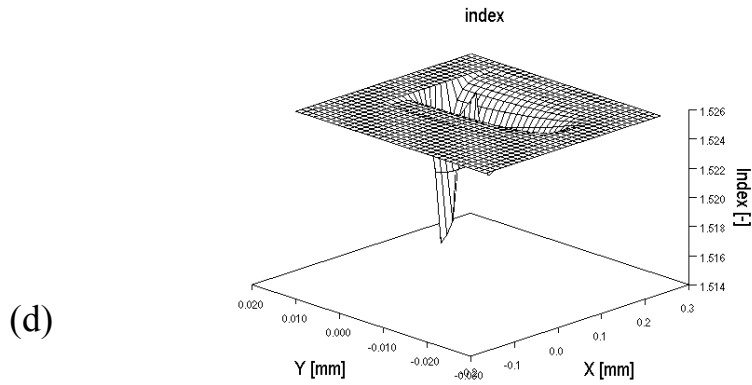
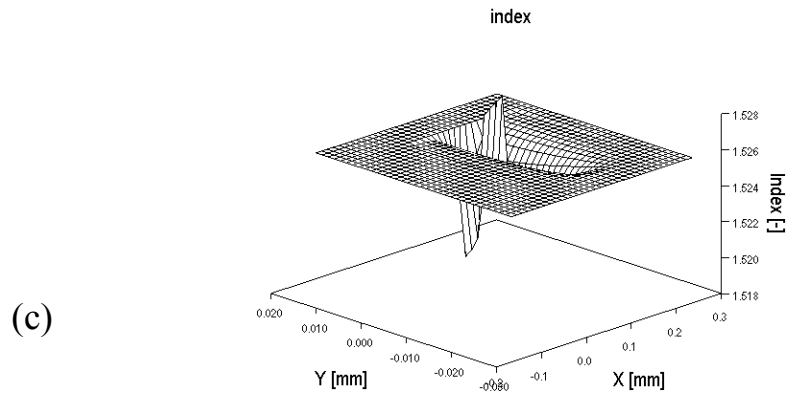
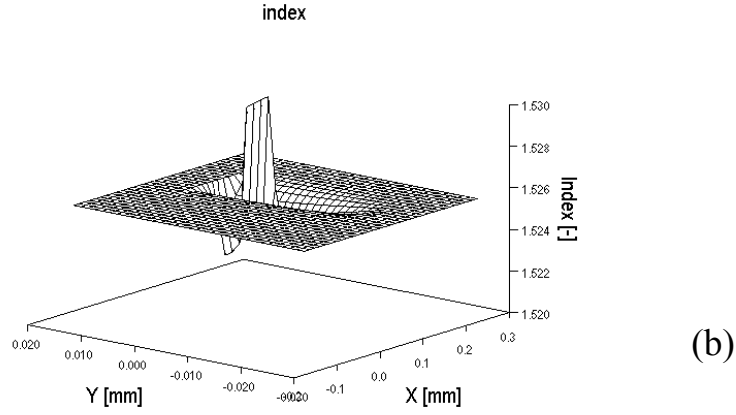
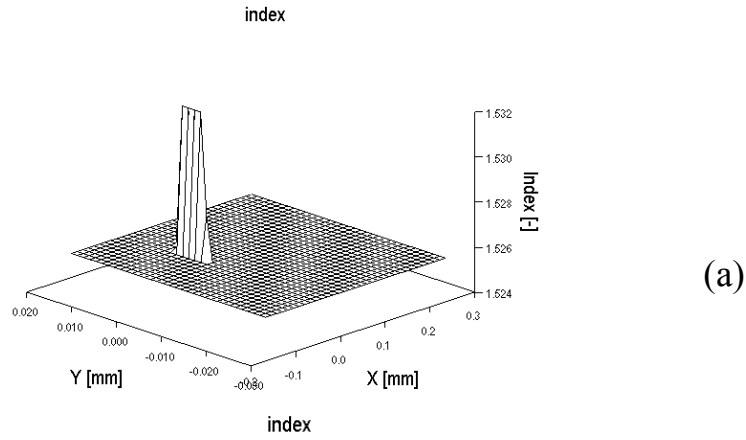


Fig. 6.6 Refractive index profile of the device for temperature changes of: (a) $\delta T=0^{\circ}\text{C}$; (b) $\delta T=15^{\circ}\text{C}$; (c) $\delta T=30^{\circ}\text{C}$, and (d) $\delta T=45^{\circ}\text{C}$.

The changed refractive index profile can be used later for light propagation through the structure by use of the beam propagation method (BPM). The BPM used in the numerical analysis of the device has already being discussed in the previous chapters. The exact mode profile of the straight waveguide was used as the initial condition.

6.3.1 Heat equation

The temperature profile, which results from electrodes being added to the design can be obtained solving the heat equation:

$$\nabla^2 T - \frac{1}{D} \frac{\partial T}{\partial t} = - \frac{Q(x, y, z, t)}{C} , \quad (6.6)$$

where T is the temperature increase, D is the thermal diffusivity, Q is heat generated per unit volume and time, t is time and C is the thermal conductivity. The thermal gradient along the propagation direction, z , is neglected and therefore the conductivity in the x and y -directions is used for solving (6.6). The boundary conditions used for numerical solution of (6.6) are zero temperature change at the bottom and perfect insulators at the top, right and left boundary of the calculation window.

By solving the heat equation the temperature gradient in a steady state $T(x, y)$ is obtained numerically.

The refractive index change is obtained by multiplying the temperature change by the thermo-optic coefficient of the material. These refractive index changes are saved and then used in the BPM simulations. An illustration of the refractive index change is presented in Fig. 6.6 for different temperature changes, ranging from $\delta T=0$ to $\delta T=45^\circ\text{C}$. As temperature increases, the reduction in refractive index also increases and spreads further away from the heater, the latter is indicated with the straight line of zero index change parallel to the x -axis.

6.4 Results

The results presented below are obtained for an S-bend with a bend radius of 7mm and an offset $\sigma=80\mu\text{m}$. For this case, the total length of the device is 2.6mm and its passive bend losses do not exceed 0.5dB. The single-mode requirement is satisfied by choosing a square core with side length $2p=6\mu\text{m}$, core index $n_{co}=1.5319$ and cladding index $n_{cl}=1.5254$, assuming a wavelength of $\lambda=1550\text{nm}$.

The refractive index difference between the cladding and the additional layer is of the order of $\Delta n = n_e - n_{cl} = 0.001$ (unless stated otherwise), while its width is $a=3\mu\text{m}$ (unless stated

otherwise). For instance, when the bend radius is 7mm, the additional layer is placed $2\mu\text{m}$ from the core. The layer can be introduced by use of a direct UV-writing technique [66,67].

The core and cladding are assumed to have the same thermo-optic coefficient $\alpha = -2.7 \times 10^{-4} / ^\circ\text{C}$. The response time for the particular material is 2-10ms and electrical power consumption is 30mW.

In Fig. 6.7, the loss (in dB) of the fundamental mode propagating through the device is plotted as a function of temperature change above ambient for a standard S-bend waveguide. The blue line is for a standard device and the red curve indicates a device with the additional layer. The improvement in device performance is obvious, and, for the parameters presented above, the extinction ratio has increased considerably. The results presented in Fig. 6.7 could be improved in different ways, such as by using materials for the core and the cladding with different thermo-optic coefficients.

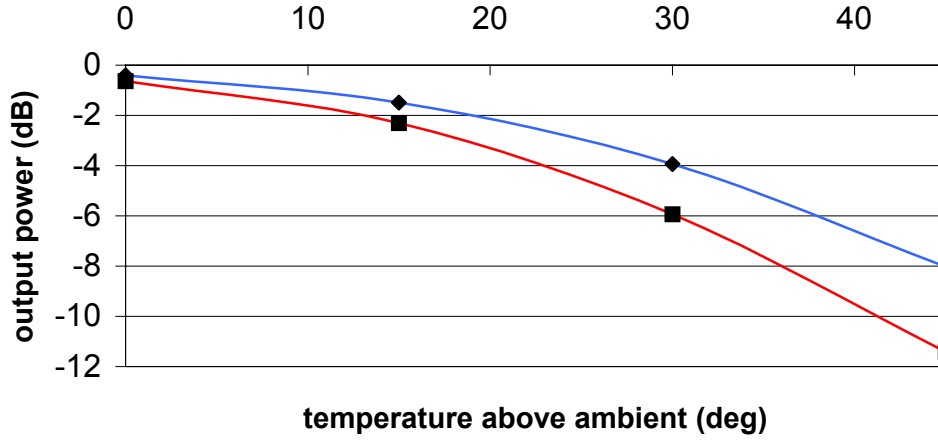


Fig. 6.7 Transmitted power, indicating heat-induced bend loss of the waveguide vs. electrode temperature. Blue line-traditional design without the additional layer; red line-proposed modified arrangement with the additional layer. Additional layer parameters: $a = 2.5\mu\text{m}$, $d_1 = 2\mu\text{m}$, $d_2 = 2.5\mu\text{m}$.

Obviously, the presence of such the additional layer increases the bend loss even when the device is in the passive regime (no heating). While disadvantageous, this effect is small compared to the benefits achieved in the active regime, i.e. when the heating is on. For a heating temperature of 45 degrees above ambient, the induced power loss reaches almost -11dB with an additional layer, compared to the -7.7dB obtained without it.

There are a number of waveguide parameters that can be varied in order to maximize the bend loss. These are: (1) the index of the additional layer, n_i , (2) the width of the extra layer, a , (3) the distance between the core and the layers, d_1 ; and (4) the electrode offset, d_2 .

In Fig. 6.8 the output power (in dB) is plotted as a function of the index difference between the additional elevated index layer, n_e , and the cladding, n_{cl} . Clearly, the improvement in the performance of the VOA is greater with a higher index difference. Increasing this index difference will increase the radiated power (red line). One limitation on its value is the need to avoid a high passive loss (blue line).

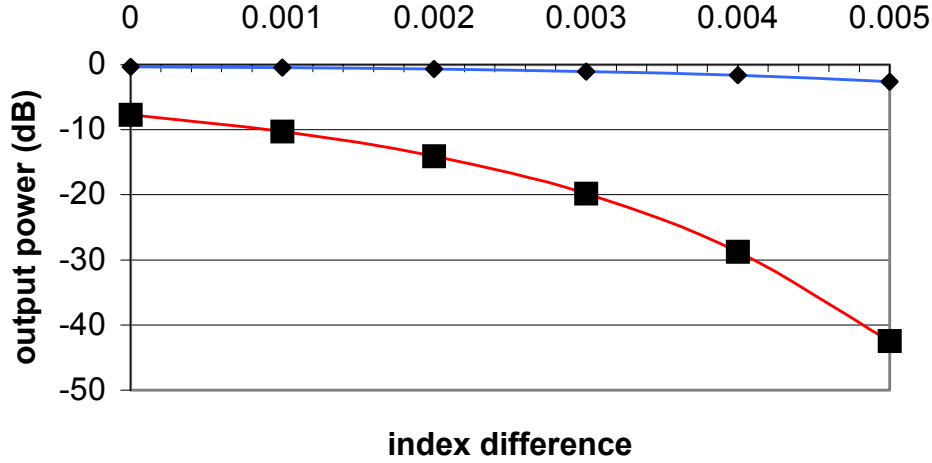


Fig. 6.8 Output power as a function of the refractive index difference between the additional layer and the cladding. Blue line-passive($\delta T=0$) and red line-active regime of operation($\delta T=45^\circ\text{C}$). Additional layer parameters: $a=2\mu\text{m}$, $d_1=2\mu\text{m}$, $d_2=2.5\mu\text{m}$.

The optimum width of the additional layer depends on its index. The layer has to be wider if the index difference between the layer and the cladding is smaller. The index difference used for Fig. 6.9 is only 0.001 and therefore the layer has to be wider than layers used for the bigger index difference. There is an optimum width of $5\mu\text{m}$, beyond which the loss is reduced. Having a layer wider and so close to the core means that a significant amount of power is guided by the layer, thus increasing the effective index of the fundamental mode and therefore reducing the bend loss. This is the opposite of the aim, which is to increase the bend loss.

Fig. 6.10 plots transmitted power (in dB) as a function of the additional layer width. It can be seen that a greater bend loss increase is obtained if the layer ($a=3\mu\text{m}$) is closer to the core. However, it is evident that this parameter is not crucial, but there still exists an optimum distance, d_1 . The optimum value for this parameter is mainly determined by the bend radius, so that the tighter the bend, the smaller the distance between the core and the layer.

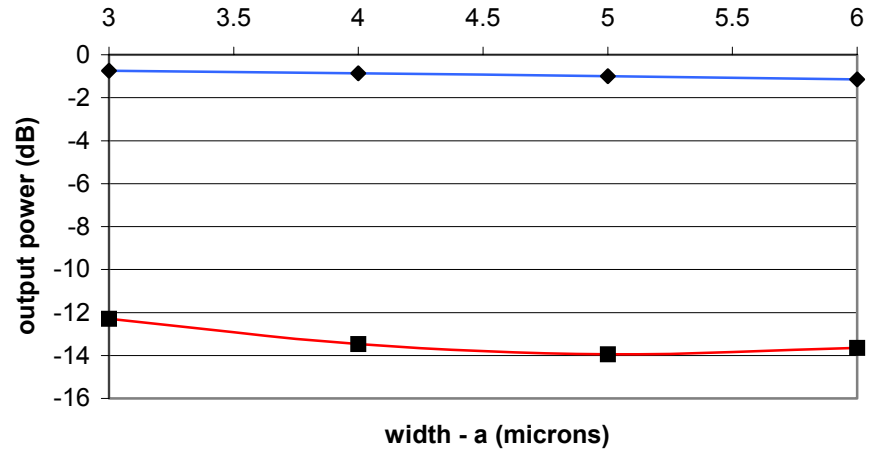


Fig. 6.9 Transmitted power as a function of the width of the additional layer, a . Blue line-passive($\delta T=0$) and red line-active regime of operation($\delta T=45^\circ\text{C}$). Additional layer parameters: $d_1=2\mu\text{m}$, $d_2=2.5\mu\text{m}$.

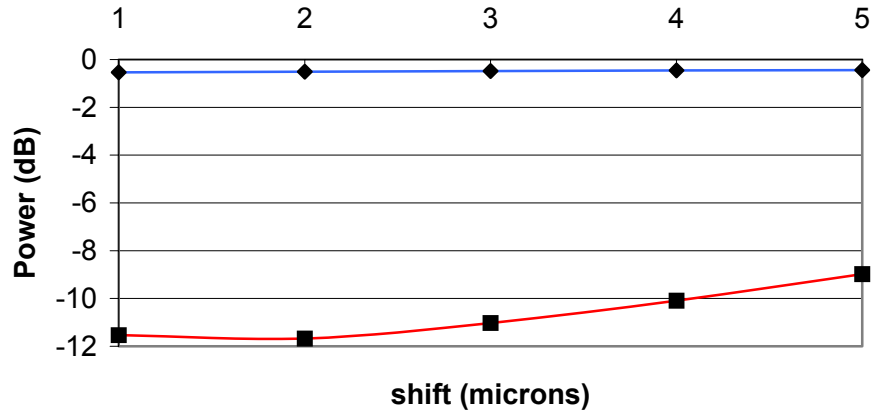


Fig. 6.10 Transmitted power as a function of the distance between the core and the additional layer, d_1 . Blue line-passive($\delta T=0$) and red line-active regime of operation($\delta T=45^\circ\text{C}$). Additional layer parameters: $a=3\mu\text{m}$, $d_2=2.5\mu\text{m}$.

The use of the electrode offset is, in some sense, equivalent to introducing an additional layer with a depressed index on the inner side of the waveguide bend, and it too can be optimized. This is evident from Fig. 6.11 where the output power of the device is shown as a function of the electrode offset. The blue line represents the bend loss without an additional layer and the red line represents the results for a waveguide with the additional layer. In both cases, calculations show the existence of an optimum offset of approximately 3 to 4 microns.

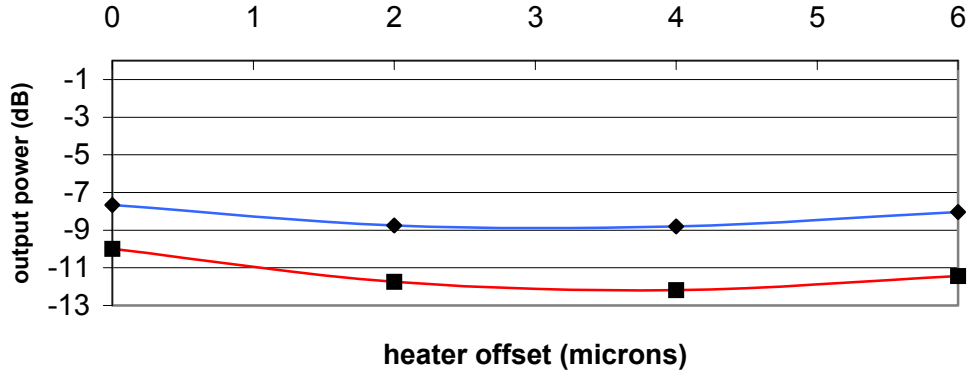


Fig. 6.11 *The effect of an offset of the heating electrode on the output power of the attenuator ($\delta T = 45^\circ\text{C}$). Blue line-standard design; red line-novel design with the additional layer. Additional layer parameters: $a = 3\mu\text{m}$, $d_l = 5\mu\text{m}$.*

6.5 Conclusions

A new strategy for bend loss control in polymer buried channel waveguides has been applied to design a VOA. It has been shown that, by introducing depressed and raised index regions into the cladding on each side of the bent core, respectively bending loss can be enhanced significantly.

Transition loss has been adjusted using a refractive index decrease, realized with an appropriate electrode placement, while pure bend loss has been increased by introducing an additional layer in the outer cladding. The overall result is that bend loss has increased.

This strategy has been applied to design of a variable optical attenuator based on a bent channel waveguide. It has been shown that the introduction of an asymmetric refractive index distribution and non-central location of the heating electrodes leads to a higher

extinction ratio and lower driving power relative to conventional designs. In addition, the proposed device is compact (2.6mm in length).

It should be emphasized that the proposed waveguide structure can be realized in practice. Crucial in the design is the presence of an auxiliary layer of slightly elevated refractive index. In practice, such a structure can be fabricated with relative ease using a direct laser writing technique [66,67]. This method involves the formation of optical circuitry by using optically-induced photopolymerization of spin-on polymers. Low loss, narrow (5 micron) waveguide channels have been fabricated with this technique. Moreover as reported in [67] controllable index change can be achieved by varying the ultra-violet exposure of the films.

CHAPTER 7

Bend Loss Resistant, Multiple-Clad, Single-Mode Fibres

The design and fabrication of single-mode fibres for application to long-haul optical transmissions systems has traditionally focused on the two key properties of low transmission loss and zero, or close to zero, dispersion. As a result, a range of low-loss fibres is available tailored for specific dispersion at the system operating wavelength. The bend loss property of these fibres has not been of primary concern, since cabled fibre is not normally bent to sufficiently small radii, of the order of a few centimetres, when such loss can become significant. However, certain fibre designs have incorporated features in their refractive index profiles which, as well as achieving the desired dispersion value, help mitigate bend loss.

Here the reverse approach is investigated by focussing on the minimizations of bend loss in single-mode fibres for applications involving relatively short lengths of fibre where the fibre dispersion is not the prime issue. Applications of bend-resistant fibres include miniature delay lines, fibre organizers, Sagnac interferometers, and fly-by and pay-out systems where the ability to contain looped fibre within a limited area is an important issue [68,69].

By adopting the strategy used for bend loss minimization in single-mode planar waveguides to fibre geometry, a highly bend resistant single-mode fibre refractive index profile design can be realised. A fibre based on this design was fabricated and characterized as a first step towards achieving this goal.

7.1 Existing fibre designs

Many types of multiple clad fibres have been studied, and, for some of them comparisons with experiments have been made in terms of bend loss reduction. For instance, bending losses were examined experimentally for dispersion-flattened single-mode (DFSM): triple-clad fibres and quadruple clad fibres [70]. For the latter, bend losses were calculated by using the volume current method, in combination with a variational

approach, and compared with experimental values. It has been shown that agreement between theory and experiment exists only for relatively small bend radius. The refractive index profiles for these kinds of fibres are illustrated in Fig. 7.1. The triple-clad fibre profile, Fig. 7.1 (a), consists of a graded core and uniform claddings. Two profile designs of DFSM, illustrated in Figs. 7.1(b) and (c), consist of a uniform core and multiple cladding layers. In each of these three examples, a depressed ring is introduced adjacent to the core.

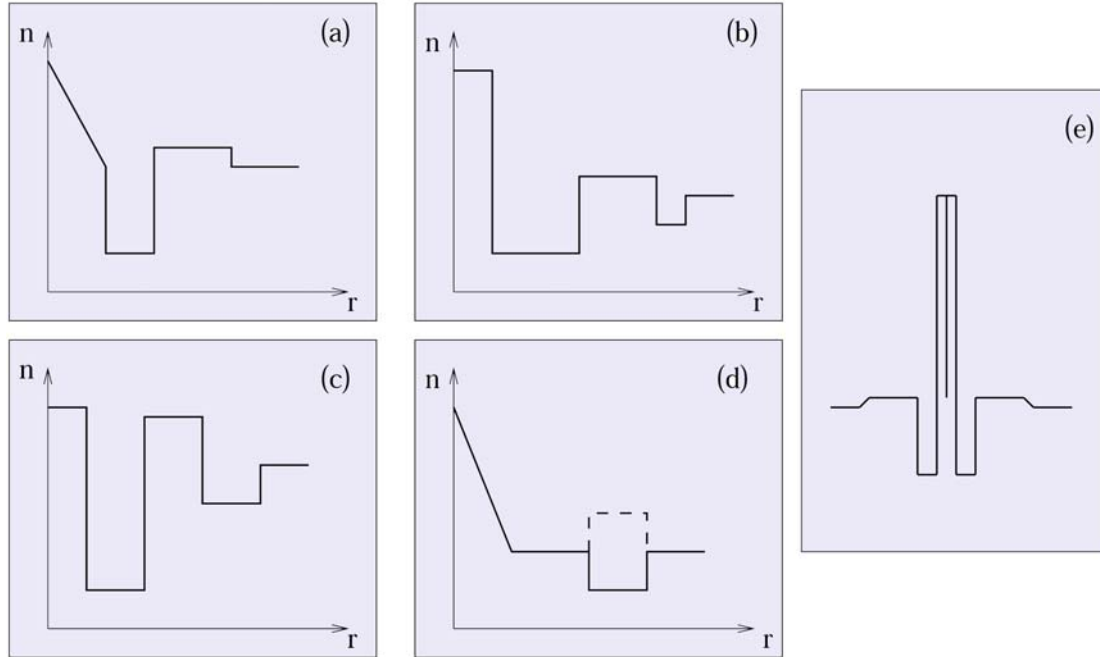


Fig. 7.1 *Refractive index profiles of various types of single-mode dispersion-compensating fibres.*

Triangular-index fibres with a depressed or elevated ring are primarily used to obtain either a dispersion-shifted or a dispersion-flattened characteristic. Their bending properties have been studied [71] for a bend radius of 2 cm. The index profile for this kind of fibre is illustrated in Fig. 7.1(d). It has been found that the presence of an elevated ring (shown dashed) produces better bending-loss properties when compared to a trench. However, the presence of the elevated ring shifts the dispersion curve. Consequently, the operational wavelength moves closer to the cutoff wavelength of the second-order mode.

High numerical aperture, reduced-core single mode fibres are available commercially [72]. The refractive index profile of this kind of triple-clad dispersion compensating fibre (DCF) is illustrated in Fig. 7.1(e). A depressed cladding, followed by a slightly elevated ring, surrounds a narrow high-index core. The purpose of the increased index core is to

produce a large, negative dispersion, but decreasing the core diameter results in increasing bend loss. Therefore an elevated ring is introduced beyond the depressed ring to decrease bend loss. However, this is an undesirable feature as it also increases the cut off wavelength of the second mode. Additionally, a special intermediate fibre is necessary in order to reduce the splice loss between this high NA-fibre and a standard fibre. Even though its micro-bending resistance is better than that of standard fibres, macro-bending resistance is comparable with that of standard fibre.

In this chapter, the main emphasis is on bend loss reduction. We suggest a new strategy that has already been applied to slab waveguides in Chapter 4 and buried channel waveguides in Chapters 5 and 6. Since bend loss in fibres occurs predominantly in the plane of the bend, the strategy applied to a slab waveguide in Chapter 4 has immediate application to the bent fibre.

7.2 New strategy

The strategy for reducing bend loss in single-mode fibres is based on a refractive index profile corresponding to a rotation of the profile of Fig. 4.9 about the core axis, as in Fig. 7.2. Reduction of bend loss in a fibre due to the introduction of a depressed ring or elevated ring into the profile is known [70,71]. However in both cases, it is necessary in the design to avoid the possibility of the introduction of the second mode. This suggests that the introduction of an additional raised index ring immediately beyond the depressed ring would result in a similar reduction in bend loss for the waveguides as that quantified earlier.

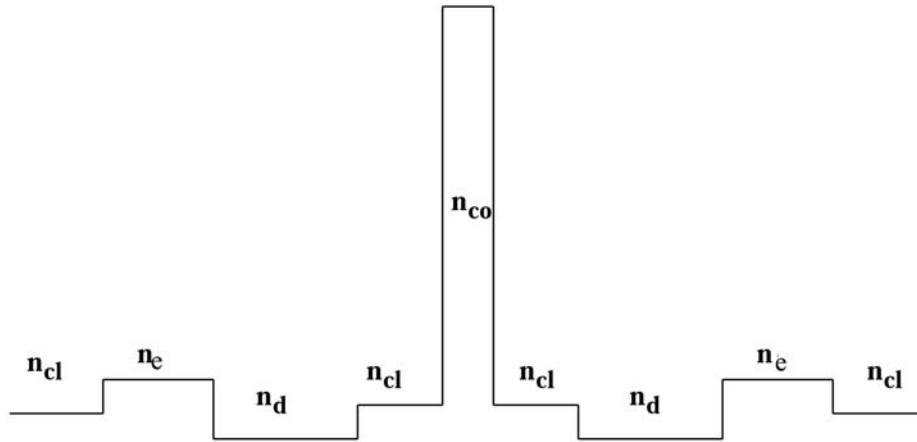


Fig. 7.2 *Refractive index profile of the fibre.*

7.3 Theoretical model and method of analysis

A 3D beam propagation method has been used in the theoretical optimization of the profile and related parameters, in the same way as was done for the BCW in chapter 5. It is explained in detail in Chapter 5 and Appendix A.

We consider a fibre of uniform core refractive index, $n_{co}=1.467$, and diameter $p=8\mu\text{m}$, surrounded by a cladding of lower and piecewise-uniform index, $n_{cl}=1.46$, with additional rings with indices which differ slightly from the cladding index (see Fig. 7.2). In the absence of the ring, i.e. a matched-cladding profile, $V=2.32$ at a wavelength of 1550nm, ensuring that the fibre is single moded. The cross-section of the fibre is illustrated in Fig. 7.3. The additional depressed ring is not introduced immediately next to the core, and its diameter, p_{cl} , depends on the bend radius. The elevated ring is placed outside the depressed ring. The index differences are set to be equal, so that $\Delta n=n_e-n_{cl}=n_{cl}-n_d$.

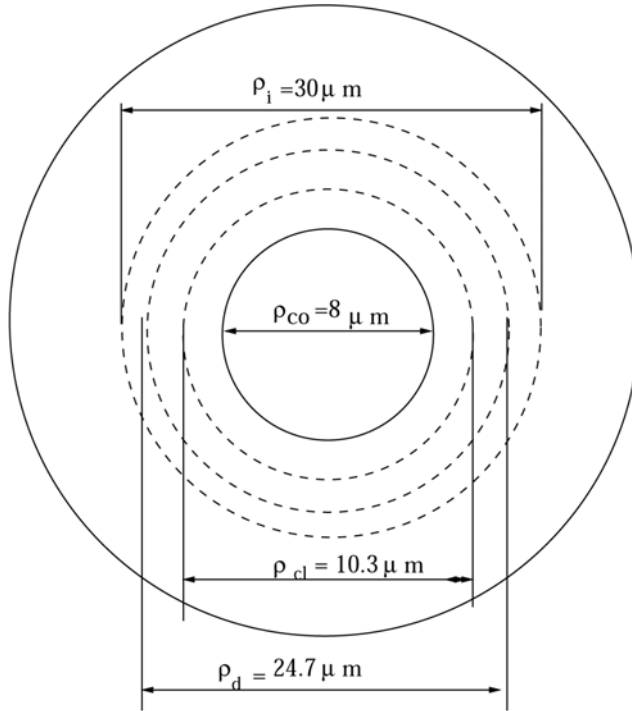


Fig. 7.3 *Cross-section of the fibre with depressed ring and elevated ring.*

To quantify the fibre bend loss, it is assumed that there is a length of straight fibre followed by a curved fibre of constant bend radius, and at the end of the curved section

there is another length of straight fibre. Fundamental mode power is calculated in the second straight length of the fibre, so that both pure bend loss and transition loss are accounted for. The structure is of the same type as the one plotted for the BCW in Fig. 5.1(b). The arc angle used in numerical analysis is 20 degrees. A fibre based on the above parameters values was fabricated and characterized by Mr Ron Bailey at the Optical Fibre Technology Centre at the University of Sydney.

7.4 Results and discussion

There are several parameters that can be varied in order to optimise bend loss reduction. The most important of these is the index difference between the cladding and the additional rings. In previous chapters, it has been shown that there is an optimal index difference between the cladding and depressed or elevated index region, see sections 4.5.2 and 5.4.2. There is a major change in bend loss from zero index difference to an index difference of $\Delta n = n_i - n_{cl} = n_{cl} - n_d = 0.001$, beyond which bend loss still decreases with an increase in index difference, reaching saturation at $\Delta n = 0.003$. However, any further increase in the index difference would increase the transition loss.

The positions of the additional rings can be optimised relative to the bend radius and fibre parameters. However, this parameter is not as crucial as the index difference between the cladding and rings. The depressed ring should not be introduced adjacent to the core. It is better to introduce a ring of index equal to that of the original cladding before introducing the depressed ring, because of the possibility of introducing the second mode.

The bend loss reduction also can be changed by varying the widths of the additional layers. It appears that increasing the width of the depressed and the elevated rings improves bend loss reduction. There is no significant change when the widths of the rings are changed by a few microns, so this helps with fabrication tolerance.

Presenting numerical results for the fibre would be essentially repeating the results presented in chapters 4 and 5. Therefore, the fibre profile has been optimised for a tight bend radius, $R \approx 3\text{mm}$, using the parameters presented in the previous section, fabricated and measured for different bend radii. In order to compare results of the new profile with a standard fibre, measurements of bend loss have been made for an SMF28 fibre with the same bend radii as the multi-clad fibre. The results are discussed in section 7.4.2 below.

7.4.1 Fabricated fibre refractive index profile

The refractive index profile of the fibre perform is presented in Fig. 7.4. The core exhibits a central index depression common for germanium-doped cores, fabricated using the MCVD technique, when the germanium core dopant diffuses out of the core during the collapse phase of perform fabrication. It is difficult to precisely produce a prescribed

profile. Accordingly the profile in Fig. 7.4 should be regarded as a first attempt in a process. Thus the conclusions drawn below represent an interpretation of the properties of the first iterate and form the basis for modifying the design for a second iterate.

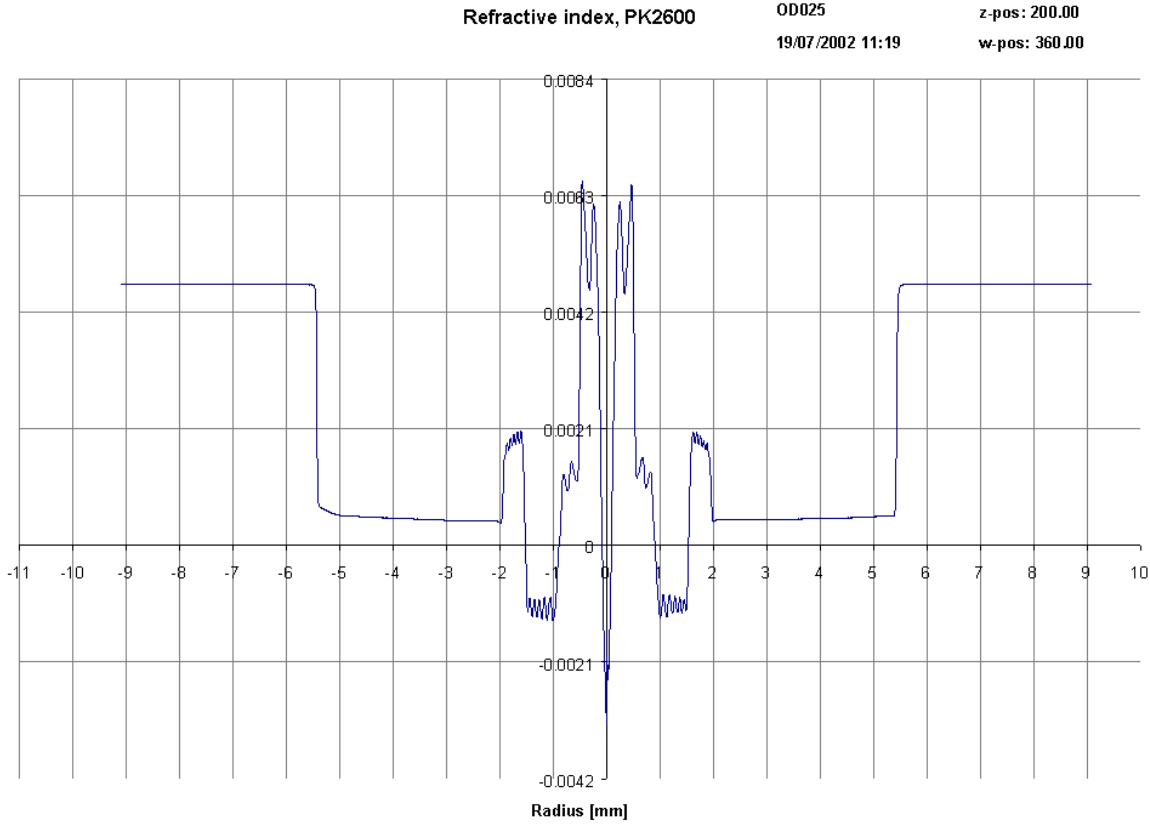


Fig. 7.4 Preform refractive index profile.

Clearly, the refractive index in Fig. 7.4 has detailed features which preclude any simple analytical solution. In the numerical calculations, it is sufficient to replace the actual core radius with the effective core radius for an equivalent step-profile fibre, assuming that both fibres have equal volume profiles [1, pp. 70,330]. The equivalent step-index profile is illustrated in Fig. 7.5. The purpose of these calculations is to help explain the experimental results.

The profile volume is obtained by rotating the profile shape about the fibre axis:

$$\Omega = 2\pi \int_0^{\rho_h} rS(r)dr \quad , \quad (7.1)$$

where $S(r)$ is the square of the profile shape:

$$S(r) = n^2(r) - n_{cl}^2, \quad (7.2)$$

$n(r)$ is the profile and ρ_h is the core radius.

A function that approximately describes the core profile in Fig.7.4 is:

$$n(r) = n_0 \sin^2\left(\frac{\pi r}{\rho_h}\right), \quad (7.3)$$

where n_{co} is the maximum value in Fig. 7.4, $n_{co}=1.4657$. Replacing $n(r)$ with (7.3) in (7.1) and solving the integral in (7.1) for the actual profile, an effective radius for the equivalent step-index profile can be obtained assuming the two profile have the same volume profile:

$$2\pi \int_0^{\rho_h} [n^2(r) - n_{cl}^2] r dr = 2\pi [n_{co}^2 - n_{cl}^2] \int_0^{\rho_{eff}/2} r dr. \quad (7.4)$$

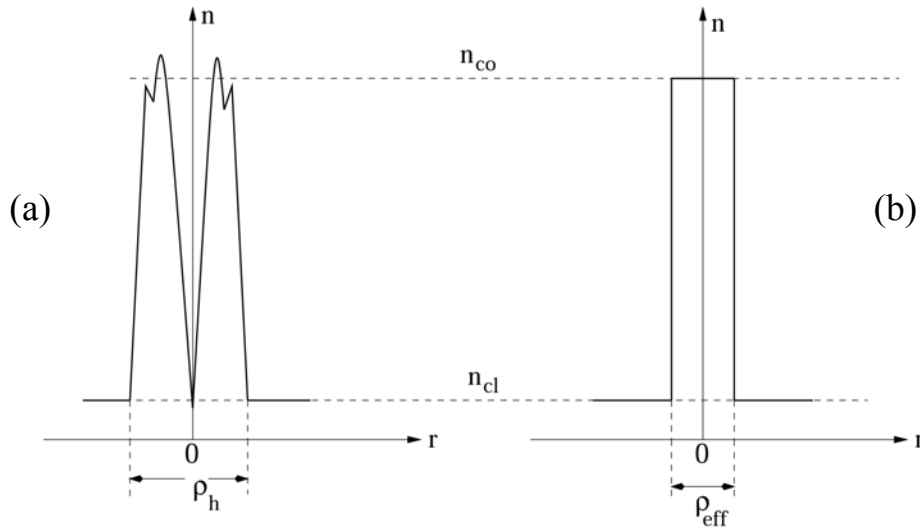


Fig. 7.5 Equal volume fibres: (a) graded and (b) step-index fibre.

For the values given in the previous section the effective radius is calculated using (7.4). With the cladding index next to the core being $n_{cl}=1.4607$ and using the parameters above, it is found the effective diameter of the step profile fibre is $\rho_{eff}=11.3\mu\text{m}$. Consequently, the V parameter is larger than 2.41 and the fabricated fibre is not single-moded at a wavelength of 1550nm. The fact that core is too wide means that energy can easily be launched into the second ‘core’ mode and thence radiated at longer wavelength.

The widths of the additional rings did not match the design. The depressed ring of the fabricated fibre is twice as thick as the depressed ring of the design fibre. This applies for the elevated ring thickness, as well. Despite these differences, the fabricated fibre is useful for getting some insight in terms of the effects of the additional rings in a fibre.

7.4.2 Bend loss measurements

Bend loss measurement for the SMF28 and bend-loss resistant (BLR) fibres were taken using a York S14 machine that is designed to determine the cutoff wavelength of the second mode. For each measurement two turns of fibre were wound around a mandrel of a given diameter and a loss scan as a function of wavelength is performed. Each such measurement accounts for both pure bend loss and any transition loss at each end of the two turns.

In order to extract as much information as possible, scans were performed for both fibres with mandrel diameters of 8,10,12,14,16,18,20,38, and 60mm. The bend loss measurement for SMF28 fibre predicts a cutoff wavelength for the second mode of 1200nm. Beyond this wavelength, bend loss increases with decreasing bend radius at any given wavelength. Fig. 7.6 plots the measurement bend loss in dB against wavelength for SMF28 fibre. The increase in the loss for the standard fibre above 1200nm is due to the bend loss effect. Increasing the wavelength decreases the fibre V parameter and therefore the fundamental mode is less confined to the core-consequently bend loss is higher.

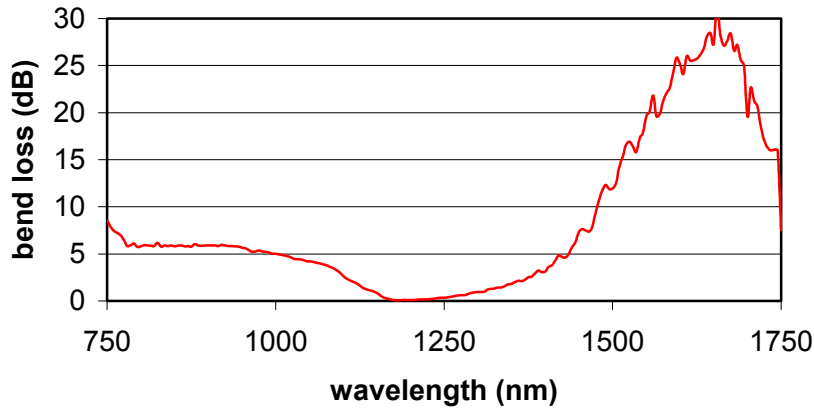


Fig. 7.6 *Experimental measurement of bend loss with a bend radius of 4mm for the SMF28 fibre.*

Measurement data for the BLR fibre with bend radius of 4mm are plotted in Fig. 7.7. SMF28 fibre has the same index difference as the fabricated BLR fibre, $\Delta n=0.005$. However, the SMF28 is single-moded but the fabricated fibre is not. Higher-order modes are more susceptible to bend loss because they are less confined to the core region, and therefore the fabricated fibre has higher bend loss than the designed BLR fibre. Even so, when compared to the SMF28, this fibre still exhibits smaller bend loss. The bend loss for the wavelength of interest, $\lambda=1550\text{nm}$, is 1.1 dB/cm for the fabricated fibre, whereas for the SMF28 fibre, it is 5dB/cm.

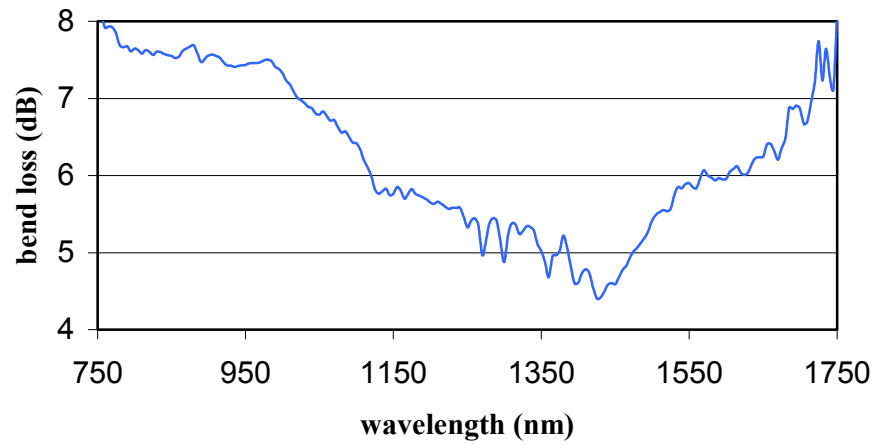


Fig. 7.7 Experimental measurement of bend loss with a bend radius of 4mm for the BLR fibre.

There is no zero loss range in Fig. 7.7 for the BLR fibre, while there is such a range in Fig. 7.6 for the SMF28 fibre beyond the second mode cutoff around 1200nm. This occurs because the fabricated fibre is not single-moded. The second core mode field is plotted in Fig. 7.8 and the ring mode intensity is plotted in Fig. 7.9.

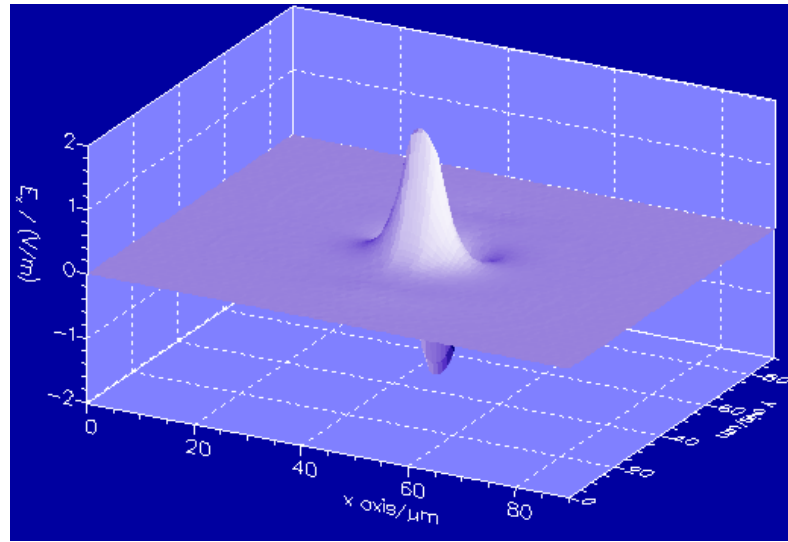


Fig. 7.8 Second core mode field profile of the fabricated fibre at 1570nm.

The second core mode is located in the core region and therefore it can easily be excited when the fibre is illuminated. It is not likely that the ring mode is excited, since the illumination is concentrated on the core region, while the ring is located in the outer region.

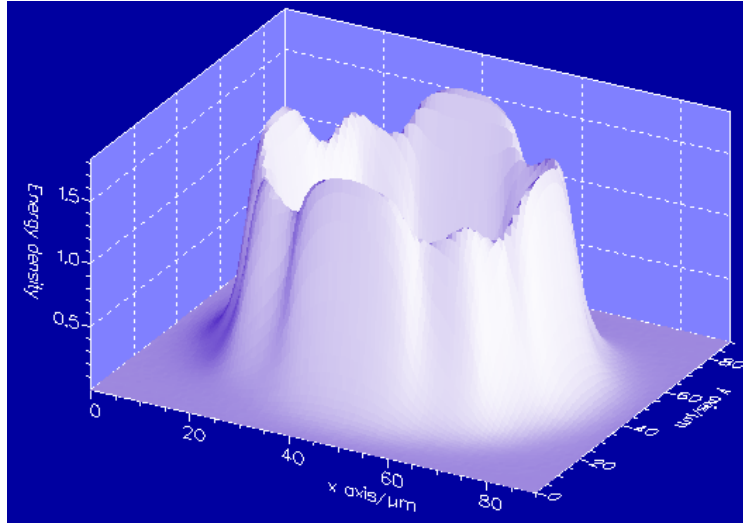


Fig. 7.9 Intensity of the ring mode of the fabricated fibre at 1570nm.

The contribution of this mode could be significant only when the effective index of the fundamental mode is below the ring index, $n_e=1.4615$ and the fibre is long. This case will be considered at the end of this section. Numerical calculations of mode profiles have been undertaken using commercial software [73]. The slightly non-circular appearance of the ring mode is due to a limitation of the software resulting from the use of a square box numerical window.

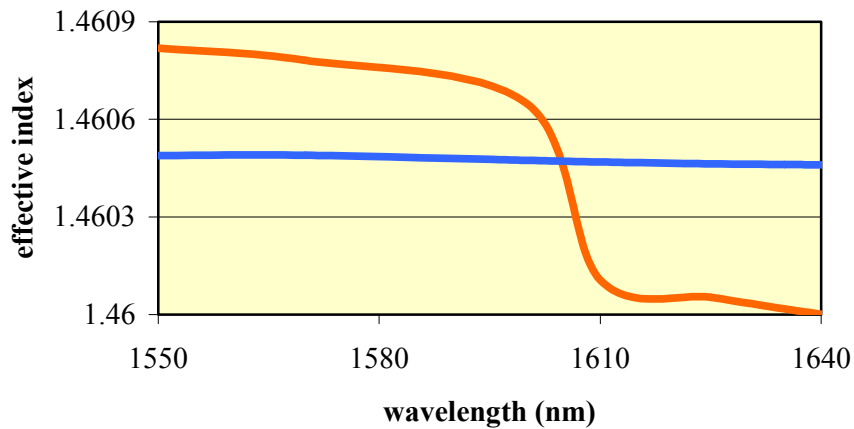


Fig. 7.10 Calculated effective indices of the second core mode (red) and ring mode (blue).

The second core mode cutoff for the fabricated fibre is around 1640 nm, as can be seen from Fig. 7.10. In the same figure, the effective index of the ring mode is plotted as a

function of wavelength. Whilst the effective index of the ring mode changes slightly with wavelength, the second core mode effective index drops at 1610 nm. The second core mode is cutoff before the ring mode because the ring mode is located in the outer part. Each of these modes could have an effect on transition loss.

We now investigate the effect of making the core less significant relative to the outer part of the structure. This occurs if the core index is reduced or its diameter is reduced. In the example presented here, the core diameter is reduced to 5.65 microns.

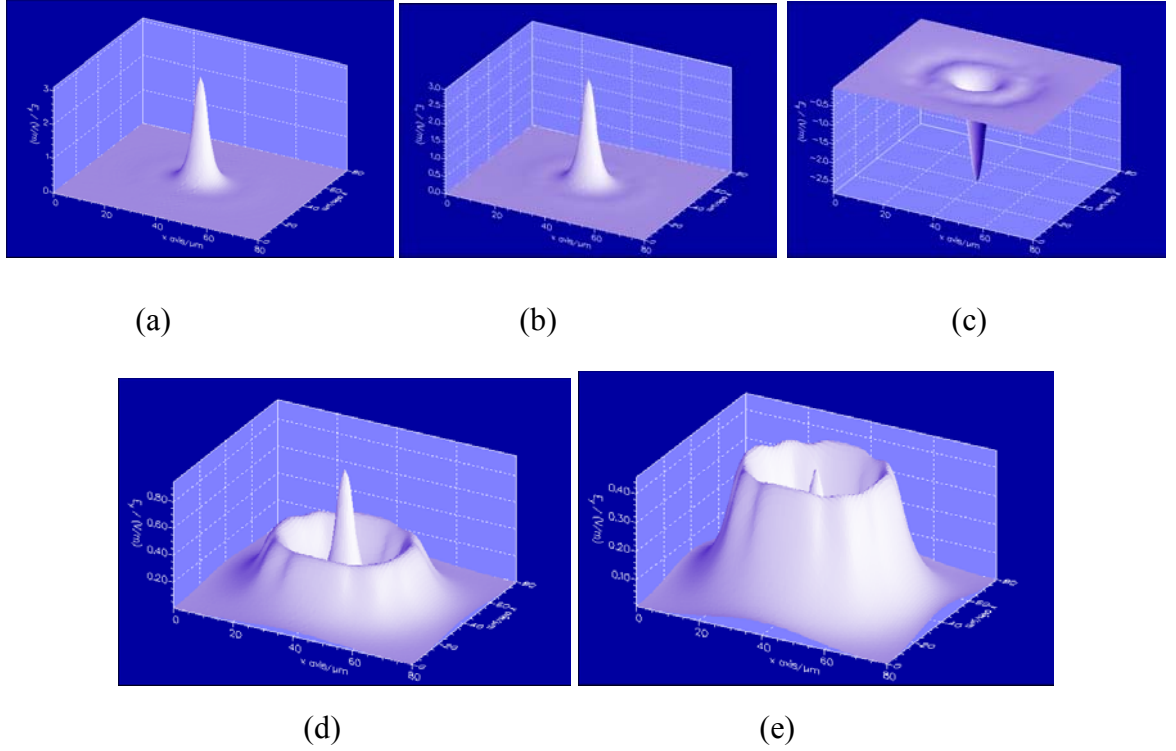


Fig. 7.11 The field of the fundamental mode of the “BLR” fibre for wavelengths: (a) 1450nm, (b) 1500nm, (c) 1550nm, (d) 1600nm, and (e) 1650nm.

With the reduced core dimension the effective index of the fundamental mode falls to a value below the outer ring index, $n_e=1.4615$, at wavelength around 1500nm. Surface plots of the fundamental mode for this fibre are presented in Fig. 7.11. In the wavelength range $1500\text{nm} < \lambda < 1650\text{nm}$ the modes are two modes. The ring contribution is greater for the wavelength above 1600nm, and therefore it may suffer more bend loss.

As noted above, the structure fundamental mode becomes basically a summation of the core (spot) mode and the ring (annulus) mode. Then the intensity features a peak at the center and another at the ring radius. Hence the propagation constant flattens out as wavelength increases, so the fundamental mode is not cutoff. Depending on the manner of

source excitation, it is thus possible that significant power can propagate in the ring above 1550nm. This fraction of the power is more susceptible to transmission loss.

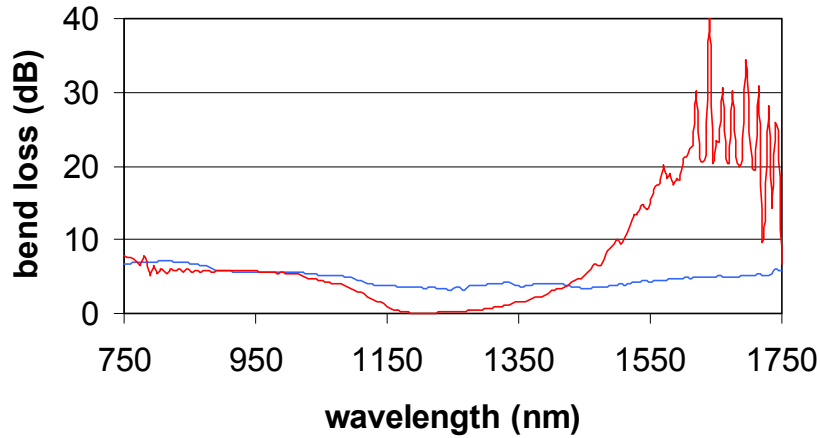


Fig. 7.12 *Experimental measurement of bend loss with a bend radius of 5mm for the multiple-clad fibre (red line) and for SMF 28 fibre (blue line).*

In Fig. 7.12, there are plots of measured bend loss for a bend radius of 5mm, for the both BLR fibre (blue line) and the SMF28 fibre (red line). Above 1400nm, there is a significant bend loss reduction due to the introduced fibre rings in the multiple-clad fibre. In the region from 1150nm to 1400nm, the standard fibre has the smaller bend loss because the second mode is cutoff at 1200nm, whereas for the BLR fibre, the second core mode is cutoff around 1640nm.

An increase in loss beyond 1400nm, due to bend loss, occurs for the standard fibre. For the multiple-clad fibre the same effect appears but with a much smaller change, for tight bends. However, the same effect exists in the multiple-clad fibre, even when the fibre should exhibit zero bend loss, for bend radii greater than 1 cm. In Fig. 7.13, measured bend loss for each fibre with a bend radius of 1.9 cm is plotted as a function of wavelength. The red curve represents the standard fibre bend loss, and it has the expected zero bend loss value around 1500nm. On the other hand, the BLR fibre shows an increase in bend loss after 1500nm. Some increase appearing after 1700nm is due to molecular (SiO_2) vibrational absorption.

The increase in loss of the almost straight fibre with wavelength is an unexpected effect. The first thought was that the fundamental mode was cutoff, because the effective index volume, calculated by (7.1) including the depressed and elevated ring, appeared to be negative. Therefore it was natural to expect that the fundamental mode could be cutoff at sufficiently long wavelengths. However, the fundamental mode is not cutoff here, and even for $\lambda=2000\text{nm}$, it still has an effective index above the cladding index. The answer was found after examining the second core mode cutoff, which appears around 1640nm, as

indicated by the results presented in Fig. 7.10. Close to cutoff, this mode spreads further into the cladding, thus causing the higher transition loss of the BLR fibre.

The fabricated fibre profile is not quite the same as the design profile. However the features are similar. In particular, the fundamental mode is strongly guided by the core alone around the communication wavelength of 1550nm. The outer ring has virtually no effect on this mode, and its effective index is approximately 1.463 in both cases. This is above the outer ring index.

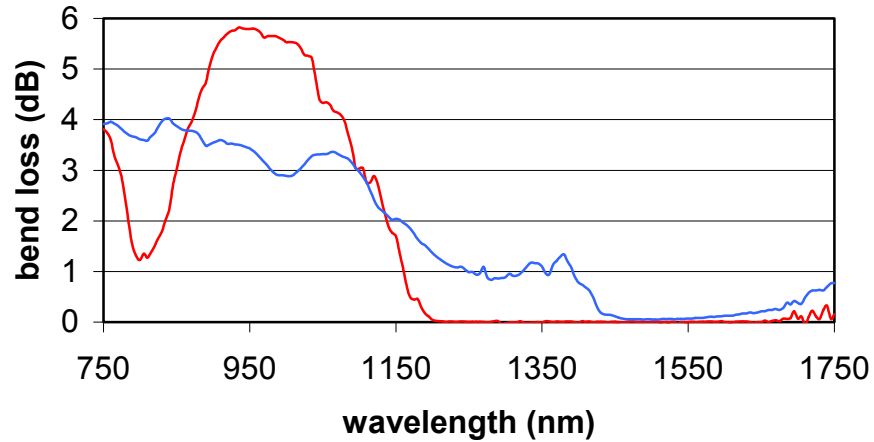


Fig. 7.13 *Experimental measurement of bend loss with a bend radius of 1.9cm the standard SMF28 fibre (red curve) and the multiple-clad fibre (blue curve).*

The final comparison for the standard and fabricated fibre bend loss is presented in Fig. 7.14. Bend loss in dB/cm is plotted as a function of bend radius in the range from 4 to 9 mm, based on measured values for the both fibres. The wavelength is 1550nm. At this wavelength, the BLR fibre is at least two-moded and still has smaller bend loss than the single-moded SMF28 fibre.

There are big dimension deviations in the fabricated fibre compared to the designed BLR fibre. Even so, for tight bends, this kind of fibre shows smaller bend loss than the standard fibre. However, final statement on the usefulness of this fibre design can only be made when future fabrication attempts meet fibre design dimensions better.

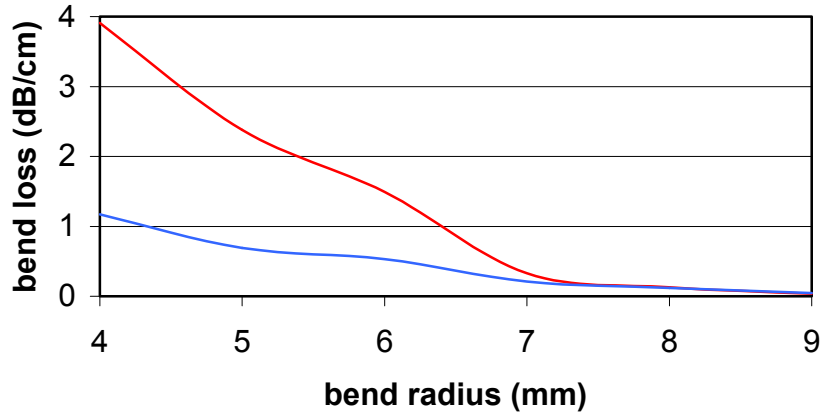


Fig. 7.14 Measured bend loss of SMF28 fibre (red curve) and BRL fibre (blue curve) as a function of bend radius.

7.5 Conclusions

A new strategy for controlling bend loss has been applied to fibres. It has been shown, by introducing both depressed and elevated rings into the cladding, that bending loss can be reduced significantly.

A fibre with additional rings has been fabricated and characterized, and the results have been compared with the bend loss measurement of a standard SMF28 fibre. According to the measurements results, the multi-clad fibre has a relatively smaller bend loss at the wavelength of interest, $\lambda=1550\text{nm}$, even though the fabricated fibre did not exactly match the design for the minimum bend loss. A smaller core diameter would provide a single-mode operation and the bend loss would be much smaller. Additionally, if the index difference between the cladding and the additional layers can be increased from 0.0015 to 0.003, it would decrease bend loss, and for a bend radius of 3mm, the fibre would have bend loss below 1dB/cm. Even with a smaller index difference, bend loss results confirm the advantage of this type of fibre over a conventional fibre in terms of bend loss reduction.

CHAPTER 8

Bend Loss in Photonic Crystal Waveguide

Photonic crystals are structures with a periodic modulation of dielectric constant that can control light through the effect of a photonic band-gap in a similar way as a periodic potential can control electron propagation in a crystal lattice. This periodicity can be in one, two or three dimensions, providing a confinement of light in one, two or the full three dimensions. In Fig. 8.1, there are illustrations of one-dimensional periodic structures. In Fig. 8.1(a), the multilayer stack is periodic in the horizontal direction, while in Fig. 8(b), the Bragg fibre is periodic in the radial direction. These structures can provide a photonic band-gap in one dimension if the index difference between the layers is sufficiently large.

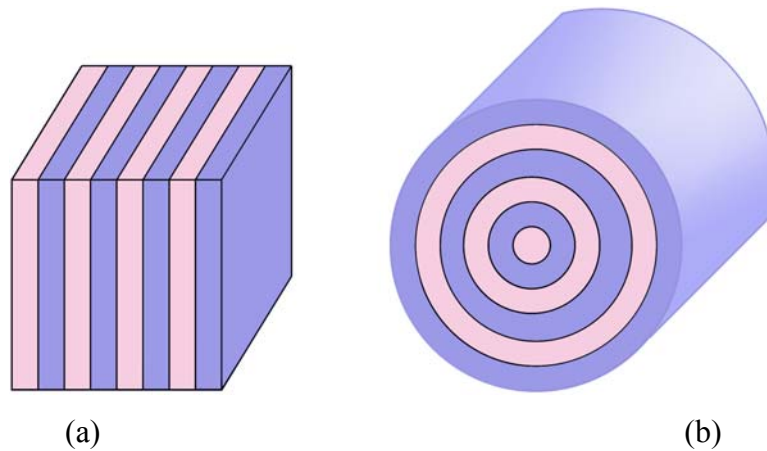


Fig. 8.1 *Illustration of one-dimensional photonic crystal structures:*
(a) *multi-layer slab waveguide and (b) Bragg fibre.*

In recent years, there have been many publications on photonic crystals [74-77]. There have also been a number of papers claiming good bend loss reduction results [78-85].

However, there has not been a comparison between bend loss-resistant waveguides, or conventional waveguides, and photonic crystals. In this chapter, the main aim is to examine bend loss properties of a band gap-guided periodic structure, and compare it with bend loss in conventional waveguides and bend resistant waveguides.

8.1 Method of analysis

There are many different approaches and methods in the study of photonic crystals. These include the transfer matrix method [86], plane wave method, multiple scattering technique and finite difference method time domain [76,87].

Here the Bloch theorem and transfer matrix method are used for the photonic band gap calculation and a modal analysis of the straight periodic structure. When this structure is curved, conformal mapping is applied and then, for the equivalent index profile, the Beam Propagation Method (BPM), including second order Padé approximation, is used for the propagation in a similar manner to that applied in Chapter 4.

8.1.1 Transfer matrix method

The transfer matrix method is a powerful and versatile tool that can be applied for any index difference between different layers. It relates the transverse fields of one layer to those of the next. A periodic structure with alternating layers of high index, n_2 , and low index, n_1 , material is considered, as illustrated in Fig. 8.2.

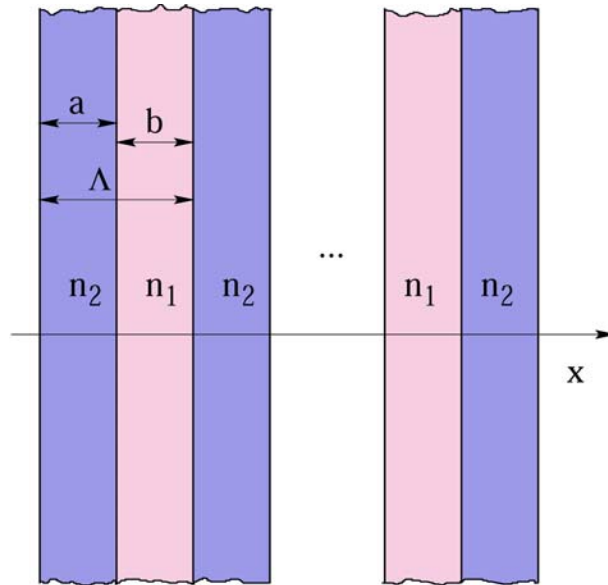


Fig. 8.2 Parameters of 1D periodic structure.

The period is denoted by Λ , so $\Lambda=a+b$, and the refractive index profile satisfies:

$$n(x + \Lambda) = n(x) \quad (8.1)$$

where the x -axis is normal to the interfaces.

The electric field in each layer can be expressed as a linear combination of an incident and a reflected plane wave:

$$E(x, z) = \left(c_n^\alpha e^{-ik_\alpha(x-n\Lambda)} + d_n^\alpha e^{ik_\alpha(x-n\Lambda)} \right) e^{i\beta z}, \quad (8.2)$$

where:

$$k_\alpha = \left[(k_0 n_\alpha)^2 - \beta^2 \right]^{1/2}, \quad \alpha = 1, 2, \quad (8.3)$$

and c_n^α, d_n^α are the complex amplitudes in the layer α of the n th unit cell.

The boundary matching condition at each interface can be written in matrix form, relating the coefficients in two neighbouring cells with the same index:

$$\begin{pmatrix} c_{n-1}^\alpha \\ d_{n-1}^\alpha \end{pmatrix} = T \begin{pmatrix} c_n^\alpha \\ d_n^\alpha \end{pmatrix}. \quad (8.4)$$

where the translation matrix $T = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$ relates the higher and lower index coefficients.

The elements of the matrix T are different, relating the higher and lower index coefficients, and are also different for different polarizations. However the trace of the translation matrix for different indices is the same, and it is directly related to the condition for having a band gap for the structure. The matrix elements of T , relate the amplitudes of the same index, here n_1 , and TE polarization are:

$$\begin{aligned} A &= e^{-ik_1 a} \left[\cos k_2 b - \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin k_2 b \right], \\ B &= -i \frac{1}{2} e^{ik_1 a} \left(\frac{k_2}{k_1} - \frac{k_1}{k_2} \right) \sin k_2 b, \\ C &= \frac{1}{2} e^{-ik_1 a} \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin k_2 b, \\ D &= e^{ik_1 a} \left[\cos k_2 b + \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin k_2 b \right]. \end{aligned} \quad (8.5)$$

8.1.2 Bloch waves

The periodic structure is invariant under cell translation in the direction of the symmetry, x , and consequently the field $E(x)$ in these cells satisfies:

$$TE(x) = E(T^{-1}x) = E(x - n\Lambda), \quad (8.6)$$

where n is an integer and T is a lattice translation operator defined by $Tx = x + n\Lambda$. The translation matrix derived in section 8.1.1 is a representation of the unit cell translation operator. According to Bloch's theorem [74], the fields in different cells with same refractive index differ only in phase:

$$E(x + \Lambda) = e^{iK\Lambda} E(x), \quad (8.7)$$

where K is the Bloch wave number. Therefore, from (8.2) and (8.7), the coefficients in the neighbouring cells are related by:

$$\begin{pmatrix} c_n \\ d_n \end{pmatrix} = e^{iK\Lambda} \begin{pmatrix} c_{n-1} \\ d_{n-1} \end{pmatrix}. \quad (8.8)$$

Consequently, $e^{-iK\Lambda}$ is an eigenvalue of the translation matrix, T :

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} c_n \\ d_n \end{pmatrix} = e^{-iK\Lambda} \begin{pmatrix} c_n \\ d_n \end{pmatrix}, \quad (8.9)$$

and, because the translation matrix is unimodular (i.e. $\det T = 1$), it is given by:

$$e^{-iK\Lambda} = \frac{1}{2}(A + D) \pm \left\{ \left[\frac{1}{2}(A + D) \right]^2 - 1 \right\}^{1/2}. \quad (8.10)$$

From (8.10), when $|(A+D)/2| < 1$ the Bloch wave number, K , is real and the Bloch wave is oscillatory, whereas when $|(A+D)/2| > 1$ the Bloch wave number is complex, $K = m\pi/\Lambda + iK_i$, and therefore the Bloch wave is evanescent and the structure is in the so-called 'band gap'.

8.1.3 Defect modes

In the photonic band gap, propagation is forbidden and a point or line defect introduced into the structure is able to localize light. By making a line defect in a periodic structure, it is possible to propagate light confined to the defect if its frequency falls in the photonic band-gap regime. Here we consider a defect of lower refractive index, so propagation can only occur in the band gap regime [88]. The refractive index of the structure is illustrated in Fig. 8.3. It is clear that guidance by total internal reflection is not possible.

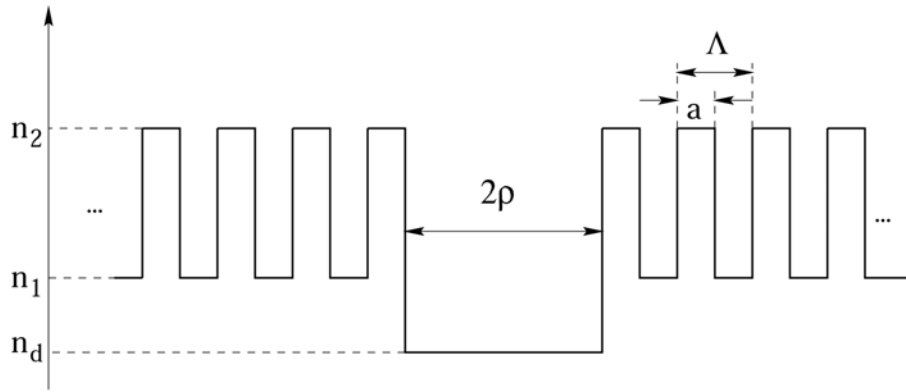


Fig. 8.3 Refractive index of a structure with a defect.

The propagating field is of the form:

$$E(x) = \begin{cases} C_1 \cos(k_d x) & \text{even, } |x| \leq \rho \\ C_2 \sin(k_d x) & \text{odd, } |x| \leq \rho \\ E_K(x) e^{iK|x|} & , |x| \geq \rho \end{cases} \quad (8.11)$$

where

$$k_d = \left[(k_0 n_d)^2 - \beta^2 \right]^{1/2}, \quad (8.12)$$

C_1 and C_2 are constants and E_K is the Bloch wave in the periodic structure, given by (8.2). By matching the fields and their derivatives at the boundary $x=\pm\rho$, the eigenvalue equation is obtained:

$$-ik_1 \left(\frac{e^{-iK\Lambda} - A - B}{e^{-iK\Lambda} - A + B} \right) = \begin{cases} -k_d \tan(k_d \rho), & \text{even} \\ k_d \cot(k_d \rho), & \text{odd} \end{cases} \quad TE \text{ modes}, \quad (8.13)$$

where A and B are given by (8.5).

The right-hand-side of equation (8.13) is real, so the equation will have a solution only when the left-hand-side of the equation is also real. That happens when the Bloch wave number has an imaginary value, which means that the structure is in the forbidden band gap. In this way, the propagating wave is localized to the defect.

8.2 Physical model

The evanescent decay in the transverse direction becomes extremely small after only several periods, and therefore ten cells on either side of the defect is a good approximation to the semi-infinite structure [86]. Therefore it is sufficient to consider ten layers on each side of the defect. In all the results presented in the next section, the width of the layers is assumed to be equal, $a=b=0.5\mu\text{m}$, and wavelength is $\lambda=1.55\mu\text{m}$. The defect dimension is a multiple of the period, $2\rho=n\Lambda$, where n is integer. The refractive indices are variables, except within the defect, which is always taken to be air, so $n_d=1.0$.

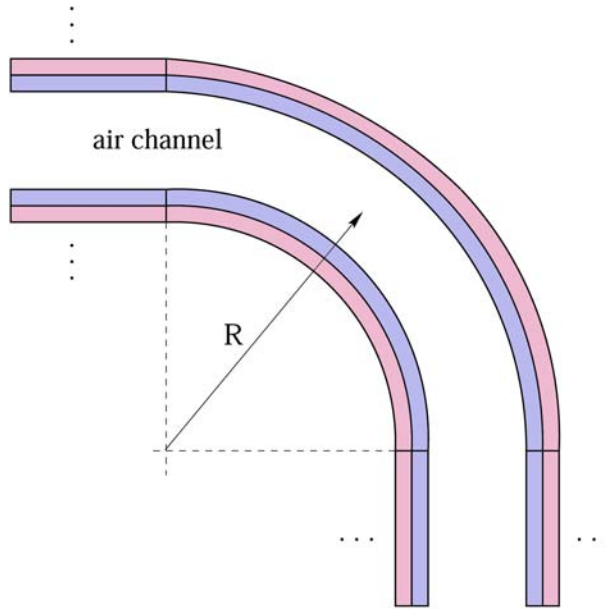


Fig. 8.4 *Top view of the curved periodic structure with the air channel as a defect.*

The straight waveguide of Fig. 8.3 leads into a bent waveguide of Fig. 8.4. At the beginning and end of 90 degree curve, there is a $350\mu\text{m}$ long straight part of the periodic structure as illustrated in Fig. 8.4. The bend radius, R , is 3mm , both for the periodic structure and conventional waveguides. As noted above, we use ten cells on either side of the defect [86].

For the periodic structure, a Gaussian field is chosen for the input field. The exact mode of the periodic structure can be calculated in some cases by solving (8.13) and using (8.11). However, it is more convenient to use a matched Gaussian as the input, because any change of index, dimension or wavelength changes the matrix elements in 8.11 and 8.13, and thus requires a new input file. The best fit of a gaussian with the exact mode is obtained when the transmission is maximized.

8.3 Results

8.3.1 Photonic band gap

Photonic band gap (PBG) calculations are performed for the straight structure, as well as root finding for the defect (impurity or localized) modes. In Fig. 8.5, the higher index material has an index of $n_2=1.5$, whereas the lower index, n_1 , is increased from 1.0 to 1.2, thus decreasing the index difference between the layers. Green regions represent the band gap regions. They satisfy the condition $|(A+D)/2| > 1$. From the figure, it is obvious that, for $n_1=1.2$, there is no possibility of band gap guidance, whereas for the lower index, there is a possibility of band gap effect guidance. That means that, for this structure, the index difference has to be higher than 0.3 in order to be able to control light.

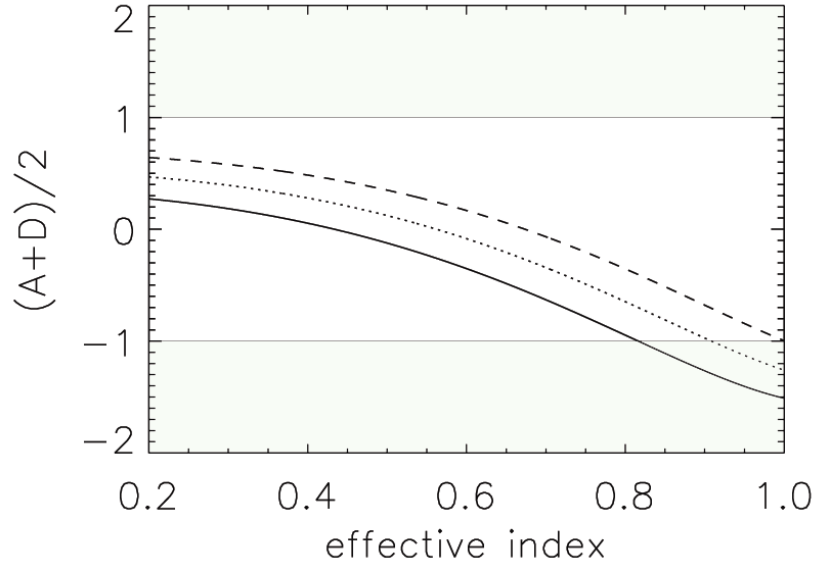


Fig. 8.5 Photonic band gap (shaded green) for different lower index- n_1 : solid curve- $n_1=1.0$, dotted curve- $n_1=1.1$, dashed curve- $n_1=1.2$, as a function of air-guided mode effective index, $n_e=\beta / k$. The higher index (n_2) is 1.5.

The index difference can be increased further by changing the higher index, n_2 , from 1.5 to 2.5, while keeping the lower index fixed at $n_1=1.0$. For $n_2=1.5$, there is a PBG in the higher index region, whereas for index $n_2=2.0$ there is a PBG in the lower index region. For index $n_2=2.5$, the whole frequency range is in the PBG. Therefore, the index difference, $\Delta n=n_2-n_1$, has to be larger than 1.5 to have a full band gap for this particular structure.

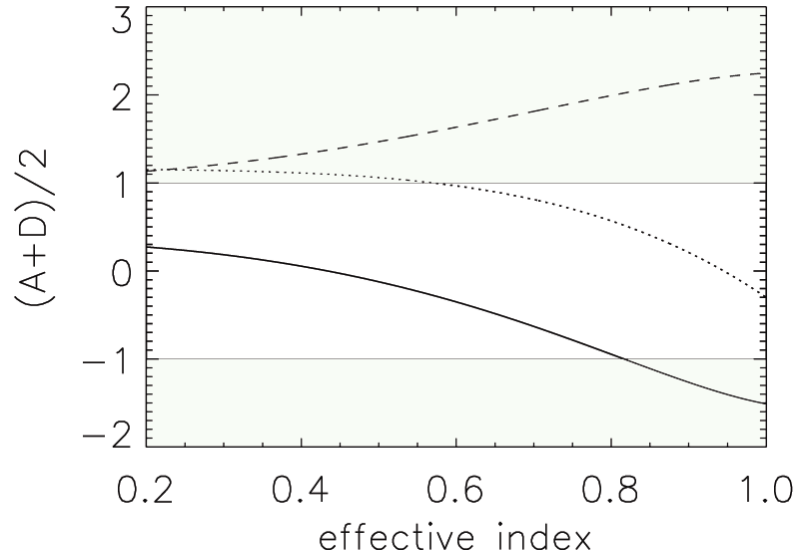


Fig. 8.6 Photonic band gap (shaded green) for different higher index- n_2 : solid curve- $n_2=1.5$, dotted curve- $n_2=2.0$, dashed curve- $n_2=2.5$, as a function of air-guided mode effective index, $n_e=\beta/k$. The lower index (n_1) is 1.

Therefore, the index difference between the layers has to be chosen carefully. There is an assumption that higher index difference should lead to better confinement. However, the results plotted in Fig. 8.6 show that, even with an increase in index difference, in some cases the light is less confined to the guiding region. When the index difference is 1.0 ($n_1=1$, $n_2=2$), the light is less confined than when the index difference is 0.5 ($n_1=1$, $n_2=1.5$), as will be discussed in the next section.

8.3.2 Bend loss

A structure with the defect index below or equal to the cladding index can have guidance only through band gap effect. If there is no band gap, as occurs for a small index difference, the input field cannot be guided, and it leaks out of the structure, as is illustrated in Fig. 8.7, where the modal field after the straight structure is plotted as a function of the index n_2 . The length of the straight structure, l , is taken to be the same as that of the curved structure, $l=5\text{mm}$. For values of n_2 lower than 1.2, the field is guided, whereas for higher indices, it is no longer guided.

According to these results and the results presented in Fig. 8.5, there is no PBG and so no air-guidance for structures having an index difference, n_2-n_1 , lower than 0.3. Therefore, in Fig. 8.7, bend loss is plotted as a function of the lower index within the guided range. It can be seen that bend loss increases drastically when the index difference is low. The higher index is taken to be $n_2=1.5$ and defect width is $2\rho=3\mu\text{m}$.

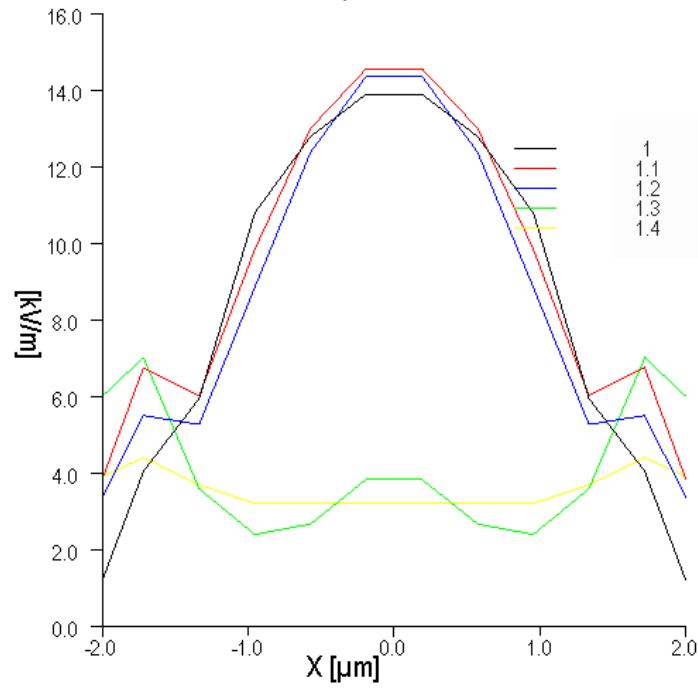


Fig. 8.7 *End field of the straight structure for different values of the lower index, n_1 . Legend gives index n_1 . The higher index is 1.5.*

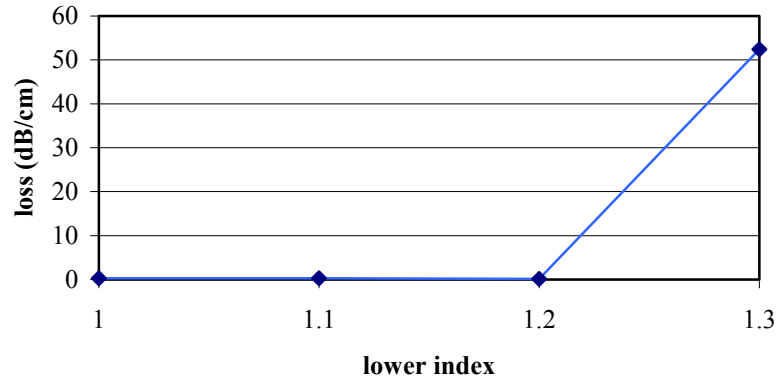


Fig. 8.8 *Loss as a function of the lower index, n_1 .*

In the next two figures, loss is examined as a function of the layer widths, see Fig. 8.9, and as a function of the defect width, see Fig. 8.10, for a silica-air structure. The bend loss included in the calculations is pure bend loss. The different contributions to overall loss, *viz.* bend loss and intrinsic loss, will be discussed in the next section. The choice of lower index defect has been made because, if a higher index is introduced, the field is guided by

the high index difference, and not by band gap effect [88]. Also, the defect has to be extremely small (less than a micron) in order to maintain the single-mode condition, whereas for air-guidance, the defect can be of order of a few microns.

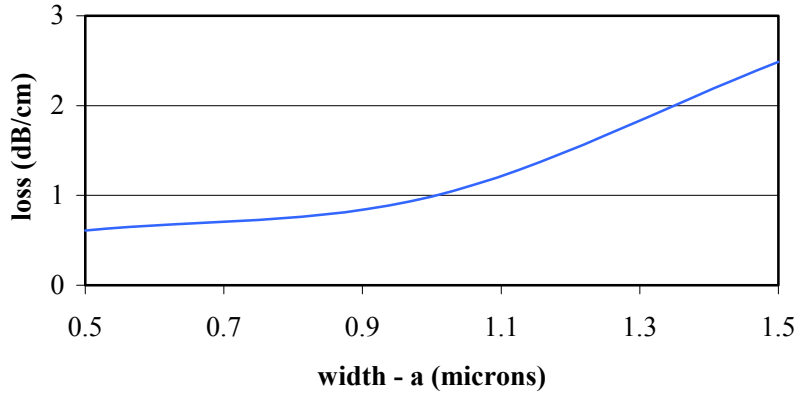


Fig. 8.9 Loss as a function of the layers widths, a and $b=a$.

When the period of the cells is increased, the loss also increases, as the results in Fig. 8.9 indicate. Periodic structures with dimensions on the scale of microns are less likely to support higher-order modes [86]. However, when the period of the structure is increased, the second mode appears and for a width of $a=b=1.6\mu\text{m}$, it is well-guided. At the same time, the band gap broadens, leading to conditions for the support of the second mode.

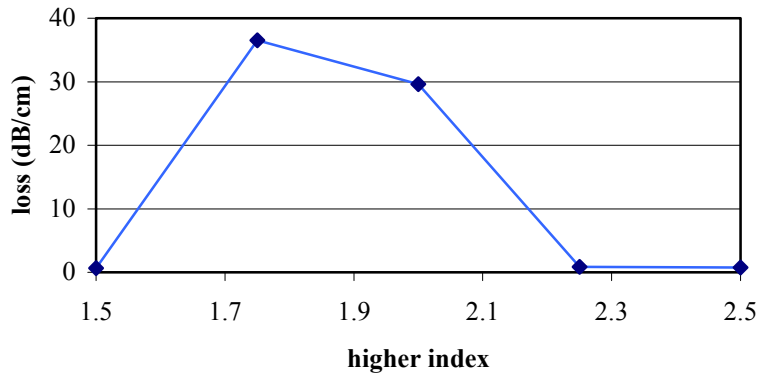


Fig. 8.10 Loss as a function of the higher index. The lower index is 1.

If the lower index defect becomes wider, the loss increases because the defect is single-moded for a width, 2ρ , of $3\mu\text{m}$, but when it widens, the second mode appears, according to the solution of eigenvalue equation (8.13), and it is then radiated when the structure is curved. Fitting the input Gaussian to the actual mode is important. It should be optimized for any defect width.

Finally, the loss is plotted as a function of the higher index, for $1.5 < n_2 < 2.5$ in Fig. 8.10. The results presented in Fig. 8.7 indicate that loss changes within this index range.

When the higher index changes from 1.5 to 2.0, the range of the band gap changes from the high index to the lower index region, and therefore loss increases within this range. If the higher index is further increased to 2.25, the loss decreases, but, to satisfy the single-mode condition, the waveguide width, 2ρ , according to the results of the eigenvalue equation (8.13), has to be changed from $3\mu\text{m}$ to $1.8\mu\text{m}$. In each case, when the structure is bent with a bend radius of 3mm, the total loss is around 0.4dB/cm.

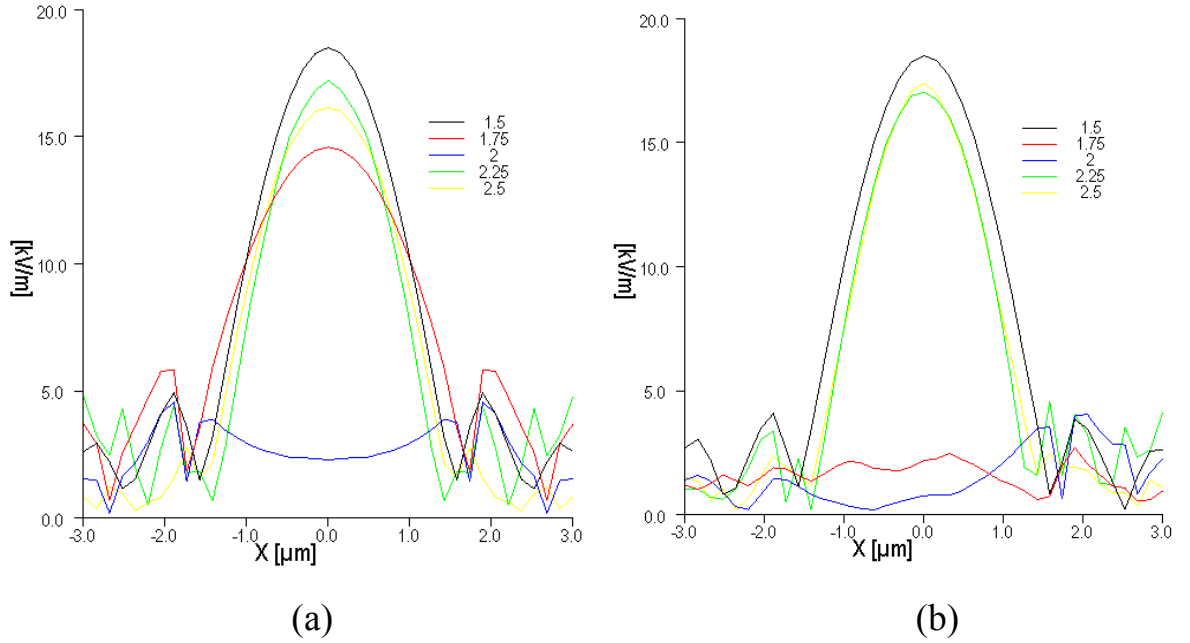


Fig. 8.11 End field of (a) the straight and (b) curved periodic structure with a lower index defect for various values of the higher index, n_2 , from 1.5 to 2.5.

However, these losses are mainly due to the intrinsic losses that exist for the straight structure, as will be discussed in the following section. For comparison, the end fields of the curved and straight periodic structure are plotted in Fig. 8.11. Bend loss becomes significant only when the effective index of the guided mode has a low value. The field is still guided for $n_2=1.75$ for the straight structure whereas for the curved structure, it leaks. On the other hand, when the PBG is in the high effective index region, the bend loss contribution is very small compared with the intrinsic loss.

8.3.3 Comparison with conventional waveguides

There are not many common parameters for conventional waveguides and periodic structures, as the mechanism of guidance is completely different. However, bend loss results can be compared in terms of different parameters that are common for the particular

structure. The aim of this section is not to favour any of these structures, as there is still plenty of room for additional comparisons, such as for the density of PIC packing and coupling to conventional sources.

Firstly, the bend loss of a conventional single-mode slab waveguide is plotted as a function of the core-cladding index difference, with results presented in Fig. 8.11(a). The core width is $5\mu\text{m}$ and the cladding index is $n_{cl}=1.46$. The core index is changed from $n_{co}=1.464$ to $n_{co}=1.467$, always assuming a wavelength of $\lambda=1.55\mu\text{m}$.

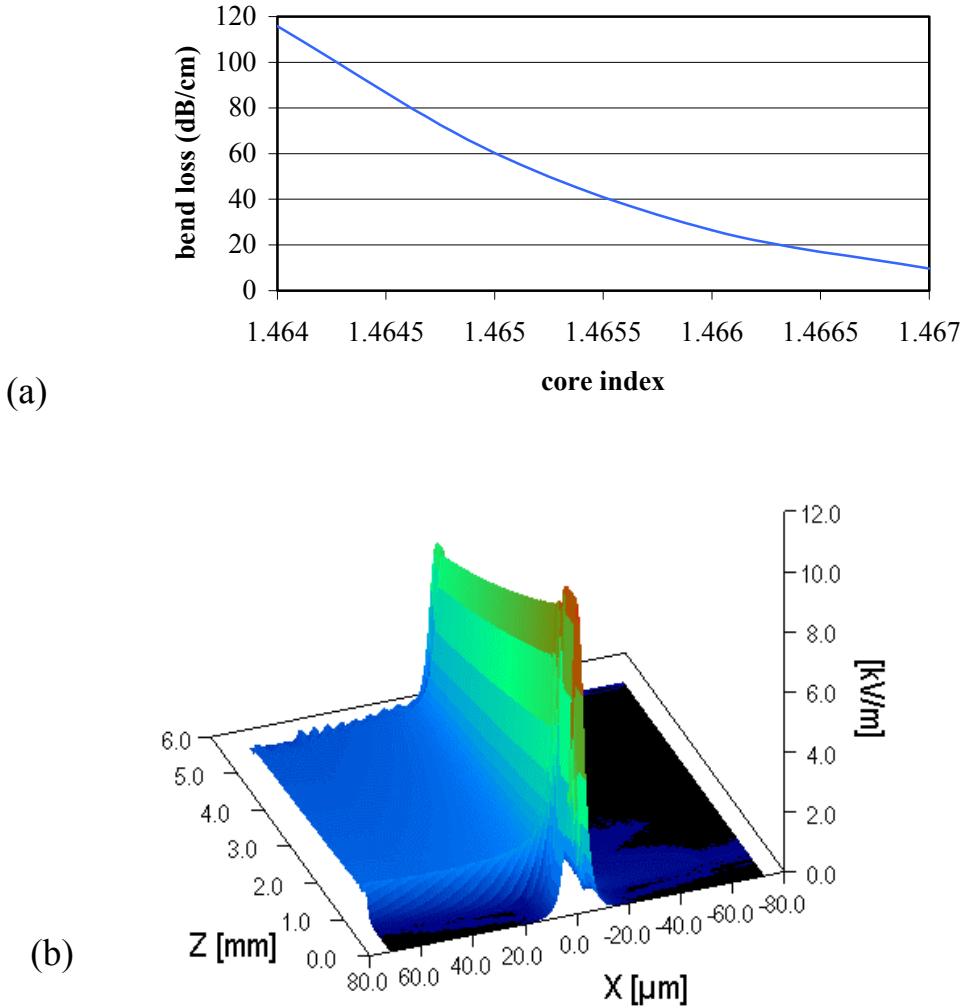


Fig. 8.12 (a) Bend loss of conventional slab waveguide as a function of the core-cladding index difference and (b) the field of the transformed curved waveguide for $\Delta n=0.007$.

Increasing the index difference between the core and the cladding will confine the field more to the core and consequently reduce the bend loss, as already discussed in the previous chapter. At an index difference of 0.007, the pure bend loss is 10dB/cm.

The field of the bent waveguide with that index difference is plotted in Fig. 8.11(b) for the whole structure. Because conformal mapping has been applied, the equivalent structure

appears as a straight waveguide, but it has a graded index profile. It is evident that there is radiation at the beginning of the curved part, which indicates transition loss, and further on there is obvious continuous radiation of mode power-usually called pure bend loss.

Secondly, the bend loss of the one-dimensional single-mode PC slab waveguide is analysed as a function of the index of the layer with higher index value, n_2 (see Fig. 8.10). As the results of the photonic band gap calculation indicate, the curved structure guides well when the PBG is in the high index region when $n_2=1.5$. Increasing the index difference further results in higher losses because the structure can only guide in the lower index region that is less confined to the defect region (see Fig. 8.6). The structure guides again with a further increase of the higher index, for $n_2>2.2$. However the loss is of the same order as for the silica-air structure (0.55dB/cm and 0.4dB/cm). This is a significant loss reduction when compared with the conventional waveguide bend loss.

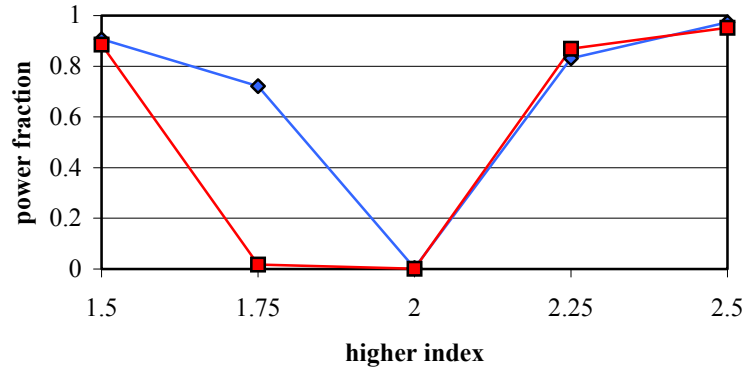


Fig. 8.13 Fraction of power transmitted for straight structure (blue line) and for curved structure (red line) as a function of the higher index n_2 . Lower index is 1.

As mentioned in the previous section, these losses are mainly due to the intrinsic loss, rather than bend loss. The output power for a 5mm long straight structure is plotted as a function of the higher index, n_2 , in Fig. 8.13. There is the same trend, in terms of guidance, for both straight and curved structures. For the silica-air structure ($n_2=1.5$) there is only 2.2 percent difference in transmitted power for the straight and curved structures, and for $n_2=2.5$, the difference is only 1.2 percent. This again shows that bend loss is of importance only when the effective index of the guided mode is low. This occurs for $n_2=1.75$ in the Fig. 8.13. Otherwise, intrinsic loss is the main source of loss in these structures. For the straight air-silica structure, the loss is 0.5 dB/cm. The straight structure with a higher index of 2.5 has 0.35dB/cm loss. Similar loss values have been reported in recent experiments on straight PBG structures [84,85].

The method used for the bend loss calculation is approximate, as already emphasized in chapter 4. Even so, these results are in very good agreement with the results obtained by the transform matrix method for the straight structure in section 8.3.1.

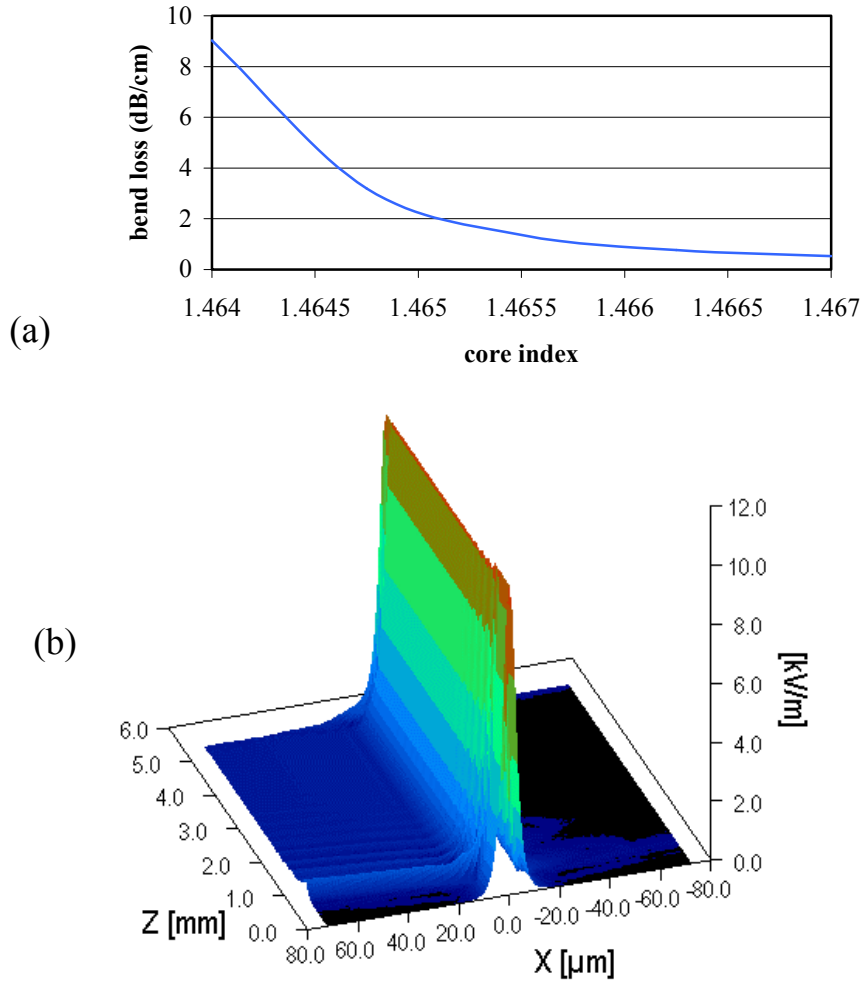


Fig. 8.14 (a) Bend loss for slab waveguide with additional layers in the outer cladding as a function of the core index and (b) the field of the curved waveguide for $\Delta n=0.007$.

Finally, one of the bend loss strategies is applied, with the additional layers being in the outer cladding of a standard waveguide. The cladding and core index, and the core width, have the same values as the conventional waveguide. The cladding-layers index difference is 0.003, so there is no significant coupling between the core and the elevated index region. The width of the layers, $a=12\mu\text{m}$ and $b=8\mu\text{m}$, and their distance from the core, $d=2\mu\text{m}$, are optimized in order to reduce bend loss. In Fig. 8.14, the bend loss is plotted as a function of the core index for the index range 1.464 to 1.467. For the maximum core index value of

1.467, the pure bend loss is 0.4 dB/cm, which indicates a bend loss reduction than that is of the same order as for the periodic structure given above. For the same index value, the field of the curved waveguide is also plotted.

When the fields for the conventional and additional-layer waveguides are compared, it is clear that even the transition loss is smaller for the latter waveguide, even though it would be expected that the additional layers may increase the transition loss. More than 17 percent of power is lost at the beginning of the curved section in the standard waveguide, whereas, in the waveguide with the additional layers, transition loss is reduced to only 2 percent loss of the guided power.

8.4 Conclusions

In this chapter, one-dimensional photonic crystal waveguide structures have been analyzed, with the emphasis being on the bend loss properties of these structures. Additionally, these results have been compared with the bend loss properties of a conventional single-mode slab waveguide and a bend-resistant single-mode slab waveguide. The bend loss calculation results have been supported by band gap calculation results, and agreement was obtained in all cases considered here.

Periodic structures have excellent bend loss reduction characteristics when the light is guided by the band gap effect. With a proper choice of parameters, less than 2 percent of power is lost when the structure is tightly bent ($R=3\text{mm}$) for an arc length of 5mm. However, the intrinsic loss is still present.

Therefore, overall losses (including intrinsic and bend loss) of a bend-loss-resistant waveguide with only two additional layers in the outer cladding are of the same order as for the 1D photonic crystal. The contributions to these losses are different for these two structures. The main source of loss for a standard waveguide is bend loss, whereas for the 1D PC, the main loss comes from intrinsic loss.

The benefit of the band gap effect guidance is that the bend introduces only a small additional loss, compared to the straight guide. Thus very tight bends can be used to connect devices. The defect mode shape may be quite different from that of the input waveguide, so the coupling loss may be relatively high due to this mismatch [89].

The conclusions are drawn for slab waveguides. The picture may be different for two- and three-dimensional waveguides which can have PBGs in two or three dimension.

APPENDIX A

Beam Propagation Method

The beam propagation method (BPM) is a widely used propagation technique for modelling waveguides, fibres and devices with an arbitrary refractive index profile. Essentially, the BPM is a numerical method for approximating the exact wave equation for monochromatic waves and solving the resulting equations numerically. There are many variations of the BPM, the most common are the Fast Fourier transform (FFT) and the finite-difference (FD). In this thesis the FD BPM has been used [3]. In the following section this method is described in more detail firstly for the scalar, paraxial FD BPM and later on it will be explained how this method can be extended for including polarization (vectorial BPM) and how paraxiality and one-way propagation can be overcome. Further details about the BPM can be found in listed references.

A.1 Scalar, paraxial, one-way propagation BPM

The scalar field assumption means that the polarization effects are neglected and paraxiality means that the propagation is restricted to a narrow range of angles relative to the waveguide axis. We start with the scalar wave equation:

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} + k_0^2 n^2(x, y, z) \right] \phi(x, y, z) = 0, \quad (\text{A.1})$$

where $k_0 = \frac{2\pi}{\lambda}$ is the free space wavenumber and the scalar electric field is written as $E(x, y, z, t) = \phi(x, y, z)e^{-i\omega t}$, and $n(x, y, z)$ is the refractive index distribution.

Making the assumption that the most rapid variation in the field is the phase variation due to propagation along the guiding axis and taking the z-axis for the propagation axis the field can be represented as:

$$\phi(x, y, z) = \psi(x, y, z)e^{ik_0 n_0 z} \quad (\text{A.2})$$

where $\psi(x, y, z)$ is a slowly varying field and the rapid variation is factored out with the exponential term in which n_0 is the reference refractive index. This factorisation allows the slowly varying field to be represented numerically on a longitudinal grid.

Substituting the field $\phi(x, y, z)$, the scalar wave equation becomes:

$$\left[\frac{\partial^2}{\partial z^2} + 2ik_0 n_0 \frac{\partial}{\partial z} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k_0^2 (n^2 - n_0^2) \right] \psi = 0 . \quad (\text{A.3})$$

The second derivate term in z can be neglected because the variation of the field $\psi(x, y, z)$ is assumed to be slow. The scalar wave equation (A.3) reduces to:

$$2ik_0 n_0 \frac{\partial \psi}{\partial z} = \left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k_0^2 (n^2 - n_0^2) \right] \psi . \quad (\text{A.4})$$

Equation (A.4) is the basic three-dimensional BPM equation which can be reduced to a two-dimensional equation by omitting dependence on y . With the input field at $z=0$, the evolution of the field in the z -direction can be obtained by solving (A.4). This can be done using a number of standard numerical technique. Here, the finite difference method based on the Crank-Nicholson scheme is used [30].

The field in the transverse plane is represented at discrete points on a grid, and at discrete planes along the propagation direction. The aim is to use the given discretized field at one z -plane to determine the field at the next plane. The equation (A.4), simplifies to a two-dimensional field (slab model) and is represented at the plane between the unknown plane $n+1$ and the known plane n , with the grid points equally spaced:

$$\frac{\psi_i^{n+1} - \psi_i^n}{\Delta z} = \frac{i}{2k_0 n_0} \left[\frac{\delta^2}{\Delta x^2} + k_0^2 \left(n^2 \left(x_i, z_{n+1/2} \right) - n_0^2 \right) \right] \frac{\psi_i^{n+1} + \psi_i^n}{2} , \quad (\text{A.5})$$

where $\delta^2 = \psi_{i+1} + \psi_{i-1} - 2\psi_i$, and $z_{\frac{n+1}{2}} = z_n + \frac{\Delta z}{2}$.

The equation (A.5) can be rearranged into the form of a standard matrix equation [25]. The grid sizes (Δx and Δy) and step size (Δz) directly affect accuracy. Smaller grid sizes and smaller step sizes improve the accuracy of the computations. More information about benchmarking and the accuracy of the BPM can be found in the Appendix of the User Manual [91] and in chapter 1 of the Tutorial in [92].

In this thesis, the accuracy of the calculations depends on the particular problem. Propagation constants are generally accurate to several significant figures. The BPM results are usually less accurate for problems which are more complex or which involve long

propagation distances. In chapters 4, 5 and 8, at least two different methods have been used to analyze the problem at hand. In these cases, the analytical and numerical calculations are in good agreement, generally within a few percent. This gives us confidence in using BPM methods, even for the problems with complicated refractive index structures.

A computational domain is finite and therefore the boundary condition has to be set. Here the transparent boundary condition is used [42] as it avoids the artificial reflection of field incident on the boundary.

With the paraxial approximation the second order boundary problem is reduced to a first order initial value problem. However, there are restrictions on the index constant and an arc used in bend calculations when applying the scalar, paraxial, one-way BPM. These problems can be overcome with the extension to the vectorial, wide-angle, bi-directional BPM, that is more suitable for the this thesis purposes.

A.2 Vectorial, wide-angle, bi-directional BPM

Vectorial beam propagation method can account for the polarization effects and high index difference [41]. We use an approach in which the equations are formulated in terms of the transverse component of the field and result in a set of coupled equations for the slowly varying fields:

$$\begin{aligned}\frac{\partial \psi_x}{\partial z} &= A_{xx} \psi_x + A_{xy} \psi_y \\ \frac{\partial \psi_y}{\partial z} &= A_{yx} \psi_x + A_{yy} \psi_y\end{aligned}\quad . \quad (A.6)$$

The expression for the complex differential operators A_{ij} can be found in [41]. The semi-vectorial approach is obtained when $A_{xy}=A_{yx}=0$, resulting in decoupling of the transverse field components. The effect of off-diagonal terms is usually weak and consequently the semi-vectorial approximation is a good choice.

Including higher order Padé approximations the paraxiality restriction on the standard BPM can be excluded [90]. Accordingly, the BPM can be used for high index contrast and propagation in curved waveguides.

We start with the scalar wave equation (A.3) before making paraxial approximation. This equation can be viewed as quadratic equation to be solved for the differential operator $D = \frac{\partial}{\partial z}$:

$$\frac{\partial \psi}{\partial z} = ik_0 n_0 \left(\sqrt{1 + P} - 1 \right) \psi \quad , \quad (A.7)$$

where:

$$P \equiv \frac{1}{(k_0 n_0)^2} \left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k_0^2 (n^2 - n_0^2) \right]. \quad (\text{A.8})$$

In order to solve (A.7) the differential operator P must be calculated first. It can be expanded via Padé approximation. Including higher order terms the accuracy of the BPM can be increased. In all cases considered here the second order Padé approximation (1,1) has been used.

Finally, restriction to only forward propagation can be overcome by including the transform matrix method at the interfaces between regions with different refractive index in the propagation direction [43]. The transfer matrix is composed of successive applications of propagation (describing the uniform regions) and interface matrices (describing the interfaces with forward and backwards propagating field).

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