Coupling Analysis of GaAs-Based Microdisk Lasers With Different External Claddings

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Abstract—In this paper, we analyze the coupling of light from a GaAs microdisk laser into a waveguide. Starting from an air cladding, we examine several configurations to couple light into the waveguide with different cladding structures aimed to foster light coupling into the waveguide: photonic crystal and metallic (plasmonic cladding). In these coupling schemes, we tried to optimize the coupling of the emitted light into the waveguide, while maintaining a reasonable quality factor to allow the lasing operation of the device. We show that a plasmonic layer, introduced beside the waveguide can lead to a significant improvement in the coupling efficiency, reaching an efficiency close to 80%.

Index Terms—Microdisk lasers, photonic crystals, plasmonics, whispering-gallery modes.

I. INTRODUCTION

ELECTRONIC technology has been revolutionized by integrated circuits. The advent of integrated circuits has led to cheaper, more reliable, and more compact electronic devices and systems. Moreover, it has also allowed the insertion of many new functions in these systems. A typical device that strongly relies on electronic integration is the mobile telephone handset, which only became available with the advent of electronic integrated circuits.

Now, if optical circuits want to play a more important role in future, optical devices and systems need to achieve a much higher degree of integration. However, if we wish to produce optical devices that are very small and compact, it is necessary to confine light in small regions. There are three basic physical mechanisms to confine light in small spaces: the photonic bandgap effect [1]–[4], total internal reflection [5]–[20], and plasmonic propagation [21]–[24].

Among these techniques, total internal reflection-based devices are very popular due to their high performance and not so demanding fabrication. These devices generally employ polygonal resonators such as squares, triangles, and microdisks. Although triangular resonators have fewer modes than microdisk

lasers, they generally have lower quality factors (Q). The presence of high Q resonances might be the main reason for microdisk resonators to be so popular.

The study of light coupling from polygonal resonators into waveguides has a long history. In general, light coming from (or sometimes entering into) a given polygon (e.g., square and corner-cut square [25], microdisk and microring [26], elliptical [27], racetrack [28] resonators) is evanescently coupled into a waveguide. This waveguide can be either positioned in the same plane of the core layer of the resonator [27] or in a different plane [16], [17]. Also, the waveguide can be a straight waveguide or wrapped around the cavities to improve the coupling efficiency [18], [19], [29].

In this article, we examine different ways to couple light from a microdisk laser into a waveguide. The main focus of this article is to compare different coupling schemes that could maximize the coupling of light into the waveguide. These coupling schemes are based on the introduction of different cladding structures to the laser and waveguide structures: low refractive index cladding (air), periodic cladding operating in its bandgap region [photonic crystal (PhC)], and metallic (plasmonic) cladding. The basic idea is to increase the coupling rate into the waveguide when compared with other loss rates (e.g., radiation losses), so that it would be easier for light to be coupled into the waveguide, producing an overall increase in the coupling efficiency (into the waveguide).

However, there is a detrimental effect when the coupling rate into the waveguide is increased. Starting from an isolated microdisk, it is possible to find modes with very high-quality factors (Q_i). However, the introduction of a coupled waveguide leads to an increase of the overall losses in the cavity (more light is being (lost) coupled into the waveguide). The net effect is the reduction of this quality factor of the system to a new value ($Q_1 < Q_i$), when the microdisk is loaded with a waveguide. If this loaded quality factor Q_1 falls below a certain value (e.g., $Q_1 < 600$), the threshold pump optical power would be so high that lasing would be virtually impossible. Hence, we need to make sure that not only the coupling of light into the waveguide is efficient but also that the quality factor of the resonant mode does not fall below a minimum value beyond where lasing would be impossible.

II. GENERAL DESCRIPTION OF THE DEVICES AND ANALYSIS OF STRUCTURES BASED UPON TOTAL INTERNAL REFLECTION

The epitaxially layered structure that will be used to fabricate the laser devices is shown in Fig. 1. The core layer incorporates three 7.4-nm-thick $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ quantum wells (QWs),

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Fig. 1. Epitaxially layered structure of the optically pumped devices.

separated by 6 nm GaAs confinement barriers. The total thickness of this layer is 140 nm. These QWs provide a maximum gain at $\lambda = 980$ nm (λ is the free-space wavelength) with a linewidth of about 40 nm. In order to provide a good vertical confinement of light in the core region, a high aluminum content $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer is grown below the core region. This layer will be wet oxidized later. The thickness of the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layer is about 450 nm (before oxidation takes place). Both of these two layers are grown on a GaAs substrate by using metal-organic chemical vapor deposition system. This epitaxially layered structure is grown to fabricate devices that will work under optical pumping. This epitaxially layered structure is mainly designed to fabricate devices that operate under TE modes (main magnetic field in the y -direction) as shown in Fig. 1.

In order to analyze the performance of these devices, commercial 3-D FDTD software is used. A Gaussian source with spot size diameter of 300 nm is placed close to the edge of the microdisk structure. Power/magnetic field monitors are placed in the middle of the waveguide. The computation region is terminated by perfectly matched layers. The grid sizes in both x and z directions are 40 nm and 20 nm in the y direction. The time step is 6.67×10^{-17} s.

Before considering different schemes of coupling the emitted light into the waveguide, let us first consider the microdisk alone. This is a well-known structure in which the confinement of light in the microcavity is achieved by total internal reflection. Total internal reflection occurs at the boundary between the high refractive index material (in our case GaAs) and the low refractive index material (air). This structure supports high-quality factor (Q) whispering gallery resonant modes. The resonant frequencies of these TE-like WGMs $\text{TE}_{m,l}$ (m and l are angular and radial mode numbers) can be determined by solving the following eigenvalue equation [20]:

$$J_m(n_{\text{eff}}kR)H_m^{(2)}(KR) = \eta J_m'(n_{\text{eff}}kR)H_m^{(2)}(KR) \quad (1)$$

where J_m and $H_m^{(2)}$ are the Bessel and second-kind Hankel functions of order m , k is the free-space wave number, n_{eff} is the effective index of the TE mode, and η equals to $1/n_{\text{eff}}$ for the TE-like WGMs [20]. By solving this equation, we find out that the main resonant mode (with the highest quality factor in the gain linewidth) is the $\text{TE}_{18,2}$.

The first case to be considered here is a microdisk coupled to a “wrapped” waveguide [Fig. 2(a)]. This is a reference structure

that will be used to compare the performance of different laser structures. The width of the waveguide is chosen as 500 nm and is a little bit larger than a single-mode waveguide, which should have a width of less than 350 nm. In fact, this waveguide can support two transversal modes, but the higher order mode has much higher radiation losses than the dominant mode since its effective index is close to the refractive index of the oxide region. The air gap between the wrapped waveguide and the microdisk resonator has a width of 150 nm. Although a stronger coupling would result with smaller gap widths, this value was chosen to facilitate the fabrication of future devices: gap widths larger than 100 nm could be easily fabricated with electron beam lithography/reactive ion etching systems and even with focused ion beam milling system.

In order to identify different resonant modes and assess their quality factors in the absence of a gain medium (Q), we place a magnetic field monitor (field component H_y , which is the strongest magnetic field component for TE modes) at the center of the waveguide. We then place a Gaussian source in the microdisk that has a finite duration in time (a pulse that decays quickly in time with a broadband spectrum) and detect the response of the system to this excitation. After processing this response, we obtain its frequency response by using fast Fourier transform algorithms. The magnetic field spectrum (H_y) allows us to determine the wavelength and quality factors of the resonant modes. Once we identify the desirable resonant peak (generally the peak with the highest Q in the gain linewidth of the QWs, which is the first resonant mode to lase), we launch a continuous sinusoidal wave at this chosen wavelength. From laser theory [30], [31], all the power that is generated from a laser resonator must exit through the cavity “losses” to avoid accumulation of energy in the cavity. Based on this premise, we can place power detectors around the cavity to determine how much of the generated power is coupled into the waveguide, assessing the coupling efficiency (into the waveguide).

The magnetic field spectrum (H_y) for the structure in Fig. 2(a) obtained at the center of the waveguide is shown in Fig. 2(b). The main peak appears at $\lambda = 972$ nm with $Q = 6500$. Its field distribution is shown in Fig. 2(c). A power budget analysis indicates that 61% of the power is coupled into the waveguide (there is more power being coupled into the upper waveguide because the source is generating a clockwise propagating wave). About 10% of the input power is lost downward in the oxide region, while 3% escapes through the air region. All the remaining power escapes in the lateral direction.

The coupling efficiency could be increased by reducing the air gap width to zero. This merged structure is similar to that presented in [19], but the waveguide is not placed at one of the edges of the microdisk laser. One immediate effect is a small shift in the resonant peak of the main mode to $\lambda = 971$ nm. There is also a reduction of the quality factor of this peak to 4000, which can be easily explained by an improved coupling of light from the microdisk structure into the merged waveguide. This reduction is not very drastic and still allows the device to lase (Q must be higher than 600 to allow lasing with our setup).

A power budget analysis at $\lambda = 971$ nm indicates that about 70% of the input power is now being coupled into the waveguide, an increase of 10% in the coupling efficiency with a

Fig. 2. (a) Top view of the microdisk laser coupled into a wrapped waveguide. (b) Magnetic field (H_y) spectrum at the center of the waveguide. (c) Magnetic field distribution (H_y) at the resonant wavelength of 972 nm.

reduction of Q of 40%. It looks apparent that we could have removed the wrapped waveguide and substituted this complex waveguide by straight waveguides at the edge of the microdisk resonator, as was done in [9], [20]. This procedure does not work well because of the symmetry of the whispering gallery mode, leading to lower coupling efficiencies (lower than 50%).

III. COUPLING OF LIGHT ASSISTED BY A PhC CLADDING

Lateral radiation losses limit the coupling of light into the waveguide. In order to further increase the power coupling efficiency, we can use a PhC cladding as shown in Fig. 3. This PhC consists of a triangular lattice of air holes with lattice constant of 277 nm and radius of 100 nm. The bandgap region of this

Fig. 3. Microdisk laser with PhC cladding. In this case, we introduced a small air gap (width of 150 nm) between the microdisk laser and the waveguide.

PhC (in all directions in the plane x - z) is between 922 nm and 1061 nm. In this bandgap region, light cannot propagate through the PhC region and is forced to funnel through the waveguide region or escape in the vertical direction.

The main magnetic field spectrum (H_y) is shown in Fig. 4(a) with the magnetic field monitor placed at the center of the upper portion of the waveguide. A bad collateral effect of the introduction of the PhC cladding is the appearance of many additional resonant modes due to the tighter lateral confinement (in case of an air cladding, low-quality factor modes suffered higher radiation losses). Moreover, we can no longer claim that the main peak in the region where the QWs have high gain is $\text{TE}_{18,2}$. The main peak (the resonant mode with largest quality factor in the gain region of the QWs) appears at $\lambda = 976$ nm and is no longer a whispering gallery mode. The reduction in the lateral losses is strongly reflected at the Q of this resonant mode, which increases to 11 200. A power budget analysis indicates that 86% is now coupled into the waveguide, the only losses being accounted for those losses in the vertical direction. This can be observed in Fig. 4(b) where we can observe that the PhC is operating in the bandgap region and there are virtually no lateral losses.

We also analyze the reduction of the air gap between the waveguide and the microdisk to a zero width. The magnetic field (H_y) spectrum is shown in Fig. 5, which is very similar to that in Fig. 4(a). The main peak appears at $\lambda = 976$ nm with quality factor of 6100. This Q is higher than in the case of the structure shown in Fig. 6(b) but is considerably lower than that in the Fig. 4(a). This can be explained by an improved coupling of light into the waveguide. A power budget analysis indicates that 87% of the input power is now coupled into the waveguide. The magnetic field distribution (H_y) of this resonant peak is shown in Fig. 7. The merging of the waveguide and the microdisk laser does not result in a major improvement of the overall coupling efficiency because the loss limitation is now due to the vertical losses, since light is very tightly confined laterally.

A further improvement of coupling efficiency implies the reduction of the vertical losses. One way to reduce the vertical

Fig. 4. (a) Magnetic field spectrum (H_y) of the microdisk coupled to a waveguide and surrounded by PhC cladding. (b) Magnetic field distribution at $\lambda = 976$ nm.

Fig. 5. Magnetic field spectrum of the microdisk overlapping with a waveguide and surrounded by PhCs.

losses is to substitute the oxide region by a Bragg stack operating in its bandgap region. Although it would be harder for light to escape through the highly reflecting bottom Bragg stack, light could still escape through the air region (besides the obvious

Fig. 6. (a) Magnetic field spectrum (H_y) of the merged microdisk laser and wrapped waveguide. (b) Magnetic field distribution (H_y) at $\lambda = 971$ nm.

Fig. 7. Magnetic field distribution of the microdisk overlapping with a wrapped waveguide and surrounded by PhCs at the main peak.

route through the waveguide). In all our calculations, the power escaping through the air layer was below 5%; hence, we could expect that more than 95% of the generated light could be funneled into the waveguide.

Although this solution may lead to nearly 100% coupling of light into the waveguide, it results in the generation of rather strong additional resonant peaks. This can lead to a stronger mode competition in the laser device, where the pump power

Fig. 8. Microdisk laser coupled to a waveguide with a plasmonic cladding.

will be distributed among different modes in a tentative to reach lasing. The overall consequence is an increase of the threshold power of the structure, an undesired effect.

IV. COUPLING OF LIGHT ASSISTED BY A PLASMONIC CLADDING

Recently, it has been shown that light could be transmitted through very tiny holes, in defiance to diffraction [21]. This physical phenomenon was called “extraordinary” transmission of light. It is argued that the excitation of surface plasmons can funnel light into these subwavelength apertures, what is not normally possible with dielectric structures. This phenomenon appears very promising to the development of very compact structures such as filters, waveguides, and sensors.

The discovery of the extraordinary transmission of light has opened up the possibility of confining light in very small spaces, even further than with low refractive indexes (with total internal reflection) and with PhC claddings. However, one major obstacle to fully using plasmonic cladding is the metal losses. Another special feature of plasmonic devices is the generation of high intense electric fields, which can be used in biological and chemical sensing applications [23], [24].

In order to assess the efficiency of a plasmonic cladding, we substitute the classical air cladding by a plasmonic cladding. This plasmonic cladding consists of lateral layers of gold as shown in Fig. 8 (black regions in this figure). There are not as many peaks as in Fig. 2(b), as can be observed in the H_y spectrum in this figure. However, the main peak appears at $\lambda = 984.35$ nm with $Q = 1500$ [see Fig. 9(a)]. This quality factor is considerably lower than in the previous cases, an indication that the metal losses play a major role in the performance of the device.

The field distribution at $\lambda = 984.35$ nm is shown in Fig. 9(b). However, a power budget analysis indicates that only 40% of the generated power is coupled into the waveguide, 13% is lost in the vertical direction while 47% is lost laterally and is quickly dissipated in the metallic region.

In the previous approach, we tried to introduce the plasmonic regions as reflectors around the waveguide and microdisk res-

Fig. 9. Microdisk laser coupled to a waveguide with a plasmonic cladding. (a) Magnetic field (H_y) spectrum at the center of the waveguide and (b) field distribution at $\lambda = 978$ nm.

Fig. 10. Microdisk laser coupled to a waveguide with a plasmonic cladding beside the waveguide.

onator. This approach proved inefficient because of the metal losses and poor shielding provided by the plasmonic layers. However, a better approach is obtained by placing a plasmonic layer beside the waveguide, as shown in Fig. 10.

We changed the thickness of the metallic layer (dark region) and assessed the quality factor of the main mode (peak with the highest quality factor in the gain region of the QW) as a function of the thickness of the cladding layer. The results are shown in Fig. 11. The increase of the gold layer leads to an increase in the absorption of light in the metallic regions but can also lead

Fig. 11. Microdisk laser coupled to a waveguide with a plasmonic cladding beside the waveguide. Quality factor as a function of the gold thickness.

Fig. 12. Microdisk laser coupled to a waveguide with a plasmonic cladding beside the waveguide. Coupling efficiency as a function of the gold thickness.

to a reduction in the radiation losses of the structure. This may explain a small oscillation at a thickness of 800 nm. However, the general trend is that an increase in the thickness of the gold layer leads to a reduction of the quality factor of the main mode that appears at $\lambda = 972.62$ nm and closely resembles the mode $TE_{18,2}$. Moreover, the H_y spectrum is similar to the one presented in Fig. 2(b), with no additional peaks but lower quality factors.

A much more interesting result is obtained when we examine the effect of this one-sided plasmonic layer on the coupling efficiency as a function of the thickness of the gold layer. The results are shown in Fig. 12. Several physical mechanisms interplay in this case: absorption of light in the gold layer, reflection of light by the plasmonic layer that is funneled into the waveguide, and reflection of light by the plasmonic layer that is radiated elsewhere. The first and last physical mechanisms tend to reduce the light coupling into the waveguide, but the second physical mechanism increases the light coupling into the waveguide. This can be clearly observed for thicknesses of 200 nm and 800 nm, where we can couple more light in the waveguide than in the case where the plasmonic layer was absent. In fact, the introduction of a gold layer of thickness of 200 nm leads to a coupling efficiency of 76%, which is nearly 16% better than in the case of Fig. 2(a) (in the absence of the plasmonic layer).

The field distribution for the plasmonic-assisted coupling is shown in Fig. 13. We can see that a significant portion of the input power is indeed coupled into the waveguide. However, there is still some portion of the generated power that is radiated away from the waveguide because of the bends. The asymmetric

Fig. 13. Electromagnetic field distribution for a microdisk laser coupled to a waveguide with a plasmonic cladding beside the waveguide.

Fig. 14. Electromagnetic field distribution for a microdisk laser coupled to a 300 nm wide single-mode waveguide with a plasmonic cladding beside the waveguide.

coupling of light is an artifact of our simulation: the source is generating light that propagates clockwise with the result of “artificially” coupling more light in the $z > 0$ direction).

It seems that the optimized value of the thickness of the gold layer is 200 nm: the quality factor is not so low ($Q = 5600$, since there is not much absorption by the plasmonic mirror) and the plasmonic layer helps to funnel light into the waveguide. In fact, a closer look at the interface between the metallic and waveguide region shows the generation of high intense local electric fields, showing the excitation of plasmonic waves. With further improvement in the confinement in the vertical direction (e.g., introduction of a bottom Bragg stack), it would be possible to reach even higher values of coupling efficiency. In the absence of vertical losses, the coupling efficiency could reach values close to 90%.

Now, if we reduce the width of the waveguide to 300 nm (truly single-mode as seen in Fig. 14), the coupling efficiency is reduced to about 71%. In the absence of vertical losses, the coupling efficiency would reach values of about 81%. The increase of the waveguide width to 500 nm leads to more light being coupled into the waveguide, but at the expense of exciting higher order modes.

V. STEADY-STATE LASER ANALYSIS OF A FEW SELECTED CASES

Equations (2) and (3) [11], [32] represent the rate equations for carrier and photon densities. These devices are going to be pumped optically in the vertical direction by an external optical pumping laser with a spot diameter of 6 μm . These equations are able to provide an estimate for the laser performance of these combined microdisk and waveguide structures.

$$\frac{dN}{dt} = \eta \frac{P_{\text{in}} \lambda_p}{h c_0 V_a} - (AN + BN^2 + CN^3) - \Gamma G(N)S \quad (2)$$

$$\frac{dS}{dt} = \Gamma G(N)S + \beta BN^2 - \frac{S}{\tau_p} \quad (3)$$

where N and S are the carrier and photon densities, respectively, P_{in} is the optical pump power, c_0 is the free-space velocity of light, η is the absorption ratio of the pump in the QW region, λ_p is the pump wavelength, A , B , and C are recombination coefficients, Γ is the confinement factor, $G(N)$ the gain of the QWs, β is the spontaneous emission factor, τ_p is the photon lifetime, and V_a is the active pump volume. The active pump volume V_a is given by

$$V_a = h_a \pi \frac{\phi_s^2}{4} \quad (4)$$

where h_a is the thickness of the active region and ϕ_s is the spot diameter of the external pump laser.

The time constant τ_p is given by [32]

$$\tau_p = \frac{Q \lambda_e}{2\pi c_0} \quad (5)$$

where λ_e the emitting wavelength and Q is the quality factor of the resonant mode.

The gain $G(N)$ of the QWs can be expressed as [32]

$$G(N) = v_g G_o \ln \left(\frac{N}{N_{\text{tr}}} \right) \quad (6)$$

where v_g is the group velocity of the mode, G_o is the gain coefficient (typical value of $1.5 \times 10^5 \text{ m}^{-1}$), and N_{tr} is the transparency carrier density with a typical value of $1.5 \times 10^{24} \text{ m}^{-3}$.

In the steady-state regime, the two derivatives in (2) and (3) are equal to zero, allowing us to determine the steady-state photon and carrier densities. Once we determine the steady-state photon density S , we can find the output power by using (7) [32]

$$P_{\text{out}} = \eta_a \frac{h c_0}{\lambda_e} S \frac{V_{\text{mode}}}{\tau_{\text{mirror}}} \quad (7)$$

where η_a is the coupling efficiency of the waveguide, τ_{mirror} is the mirror lifetime, which is assumed to have the same value as τ_p [32], and V_{mode} is the optical mode volume which expressed as

$$V_{\text{mode}} = h_p \pi r^2 \quad (8)$$

TABLE I
TYPICAL LASER PARAMETERS

Symbol	Quantity	Typical value
η	Absorption ratio of pump in QW region	0.26
λ_p	Pump wavelength	637 nm
h	Planck's constant	$6.626 \times 10^{-34} \text{ kg/s}$
c_0	Free-space velocity of light	299792458 m/s
η_a	Coupling efficiency to the waveguide	0.7
A	Linear recombination coefficient	$2.5 \times 10^8 \text{ s}^{-1}$
B	Bimolecular recombination coefficient	$1.6 \times 10^{-16} \text{ m/s}$
C	Auger non-radiative recombination rate	$5 \times 10^{-41} \text{ m}^6/\text{s}$
Γ	Confinement factor	0.22
β	Spontaneous emission factor	10^{-41}

Fig. 15. Steady-state response for the microdisk coupling in five different cases: dotted line with no markers for the PhC cladding, solid line with circular markers for the one-sided plasmonic cladding beside the waveguide, solid line with no markers for the merged waveguide-microdisk structure, solid line with triangular markers for the microdisk with a wrapped waveguide separated by an air gap and dotted curve with square markers for a double plasmonic cladding.

where h_p is the thickness of the active layer and r is the radius of the microdisk resonator. Typical values of the remaining parameters are summarized in Table I.

This laser structure can lase at distinct resonant wavelengths. However, the mode with highest Q will be the first mode to lase and we will present some steady-state laser responses for this main mode. We will analyze the amount of power coupled into the waveguide (P_{wg}). The cases under consideration are shown in Fig. 15: (a) microdisk with a wrapped waveguide and an air gap (solid curve with triangular markers), (b) microdisk with overlapping wrapped waveguide (solid curve), (c) microdisk with double plasmonic cladding (dotted curve with square markers), and (d) microdisk with a single plasmonic cladding beside the waveguide (solid curve with circular markers). For sake of comparison only, we add an additional case (case (e), dotted curve) in which we add the PhC cladding (with the warning that the “generation” of many additional modes may lead to strong mode competition and lead to a much higher threshold level than the one presented in the plot). It is clear

from these curves that the plasmonic-assisted coupling (a single metallic layer beside the waveguide) has improved the coupling of light into the waveguide without an acute reduction of the quality factor of the combined structure (which would lead to a much higher threshold pump power) and this curve approaches the curve in which there would not be any lateral losses (dotted curve).

VI. CONCLUSION

We analyzed the coupling efficiency of a microdisk laser and a single-mode waveguide with three different claddings: air, PhC, and plasmonic claddings. The photonic crystal cladding provides the best coupling efficiency into the waveguide but at the expense of generating many additional resonant peaks, which may lead to strong mode competition in the laser device. The introduction of a single metallic layer funneled light into the waveguide leading to a significant improvement in the coupling efficiency without the generation of many additional modes and seems to be the best coupling scheme studied in this article.

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