Hybrid Waveguide from As_2S_3 and Er Doped TeO_2 for Lossless Nonlinear Optics

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The fabrication and characterization of loss compensated dispersion engineered nonlinear As_2S_3 on $Er:TeO_2$ waveguides is reported for the first time. The hybrid waveguide is a strip loaded structure made from an Er doped TeO_2 slab and an etched As_2S_3 strip. Almost complete loss compensation is demonstrated with 1480nm pumping and a fully lossless waveguide with high nonlinear coefficient can be achieved with higher 1480nm pump power.

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Highly nonlinear Chalcogenide optical waveguides have been successfully employed in a number of important breakthrough experiments in nonlinear optics and telecommunications [1, 2]. As_2S_3 rib waveguides in particular have been extensively used and have attained propagation losses as low as 0.05dB/cm for a 4x2.6µm waveguide [3]. However, to increase the nonlinear coefficient for low power signal processing and to obtain zero/anomalous dispersion as required to enable efficient nonlinear processing, smaller dimensions are required [4]. This has led to an increase in loss to typically 0.3dB/cm [5].

Propagation loss is well known to severely impact the efficiency of nonlinear optical processes in waveguides. To cite four wave mixing as an important example, then in the low power/low dispersion regime at optimal length for a given loss, the mixing efficiency is proportional to the inverse square of the propagation loss [6]. There is then significant scope for improving the efficiency of nonlinear processes by achieving much lower losses. Despite extensive process research in Chalcogenides, this goal remains to be attained, and so it is worthwhile to investigate alternative approaches. One such method is to compensate the waveguide loss by introducing rare earth doping to add offsetting gain. Given the small amount of compensation required, the lack of progress to date in rare earth doped Chalcogenide amplification, and the desire to not degrade the nonlinear characteristics of the waveguide, the most straightforward means of accomplishing this is to use a rare earth doped undercladding.

For cladding based gain, there are a number of criteria which become more important than in standard amplification applications. Firstly, as the interaction with the gain medium is via the evanescent field, the gain medium needs to have a high enough refractive index to enable sufficient evanescent field penetration to obtain the desired gain. Secondly, the gain medium needs to have high gain as the overlap is much smaller than for core based gain (ie high gain cross sections and high doping are required). Lastly, 1480nm pumping is preferred as this keeps the pump wavelength well away from the band edge and Urbach tail absorptions in Chalcogenide glasses. Tellurium dioxide Erbium doped waveguide amplifiers (EDWAs) have recently demonstrated perhaps the highest gain per unit length for 1480nm pumped EDWAs [7] and have high enough refractive indices to enable enough field overlap for the loss compensation. Tellurite hosts in general also offer larger emission bandwidths, low ion to ion cross relaxation, relative independence of the 1550nm Erbium lifetime on concentration, and high Erbium solubility as has been demonstrated in Tellurite glasses and fiber amplifiers [8-11]. It is clear that Tellurite based devices have the potential to deliver higher ultimate gain per unit length and bandwidth than previous demonstrations in other materials [11].

This work attempts to combine the two materials into a zero loss anomalous dispersion waveguide for non-linear optical signal processing. The Er doped TeO_2 layer provides gain to compensate for the propagation loss of the As_2S_3 above. The As_2S_3 layer provides the high nonlinearity. One key issue is how to obtain zero/anomalous dispersion whilst providing sufficient overlap with the $Er:TeO_2$ to obtain loss compensation (the high index of the TeO_2 tends to lessen the compensation of the As_2S_3 material dispersion). A design study was performed, and a regime identified for the As_2S_3 and $Er:TeO_2$ thicknesses where suitable performance could be obtained, see Fig. 1. The range of film thicknesses where dispersion engineering and suitable overlap were possible was however relatively small before modal degeneracies set in potentially causing serious mode coupling effects. The Er doped TeO_2 thin film was fabricated by reactive co-sputtering of pure Te and Er targets into an $Ar+O_2$ plasma as previously described [7]. The Er concentration was ~1% or 2.2×10^{20}ions/cm^3. The lifetime of the 1.55µm decay was 1.6ms, which is better than previously reported in Ref [7] due to lower OH contamination in the sputtering chamber. The layer had a thickness of 387nm with refractive index at 1550nm of 2.081. The As_2S_3 layer was deposited by thermal evaporation to a thickness of 350nm as previously described [4].

The As_2S_3 waveguides were fabricated using standard lithography and plasma etch methods with CHF_3 [3, 4]. Waveguides with nominal widths of 2.0µm provided a mode area of 1µm^2 and an overlap of 30% and 35% to the Er:TeO_2 layer for TE_0 and TM_0 modes respectively. The mode overlap loss to the coupling tapered fibres were 3.0dB (TE_0) and 2.4dB (TM_0) per end. These dimensions also provide anomalous dispersion for the TM_0 mode at 1550nm as shown in Fig. 1b. The dispersion coefficient at 1550nm for this structure is ~150ps/km/nm. The nonlinear coefficient, γ was calculated to be 13.5$W^{-1}m^{-1}$ which is higher than that of a typical dispersion engineered As_2S_3 waveguide (9-10$W^{-1}m^{-1}$ [12]). A chip with length of 70mm was achieved after manual cleaving with a diamond tip scriber, and this was then cleaved into 65mm and 5mm long segments to enable cutback measurements.

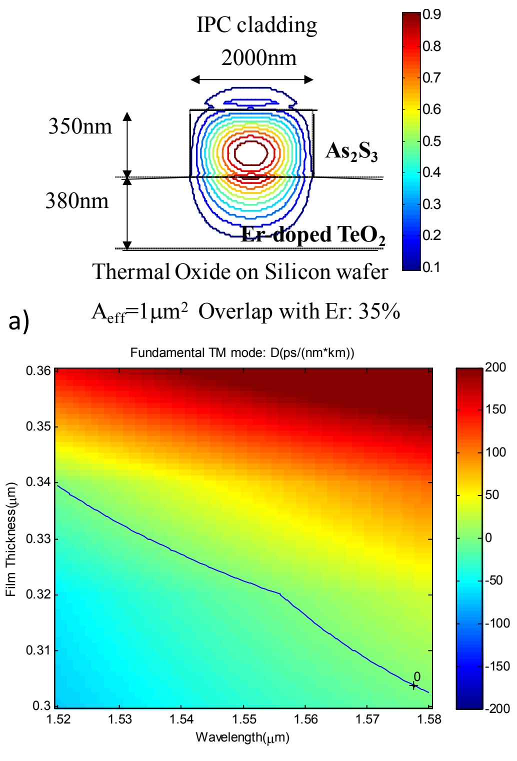

Fig. 1. a) The hybrid structure and TM0 mode profile of the waveguide; b) and the dispersion parameter map again the wavelenth and thickness of the As_2S_3 layer.

Fig. 2 shows the results of the cutback loss spectrum obtained using an OSA and supercontinuum source. To estimate the actual propagation loss at 1550nm, the measured spectrum was deconvolved to its constituent parts using the measured absorptions of Erbium in TeO_2, SU-8 (the protective layer on top the As_2S_3) and an inorganic polymer glass IPG™ (top cladding) with calculations of their overlaps to the modes and fitting to the overall trend for the $1/\lambda^2$ sidewall scattering loss. The red dashed line in Fig 2. shows the result of the spectrum fitting compared to the measurement, good agreement being achieved. The resulting estimated propagation loss at 1550nm was 0.6dB/cm. The loss spectrum shows that there was significant Er absorption as expected at 980nm and between 1400nm and 1600nm. The peak absorption is more than 14dB at 1532nm. The shallow absorption bands at 1150nm and 1420nm were due to the cladding layers, which are SU8 photoresist and IPG™.

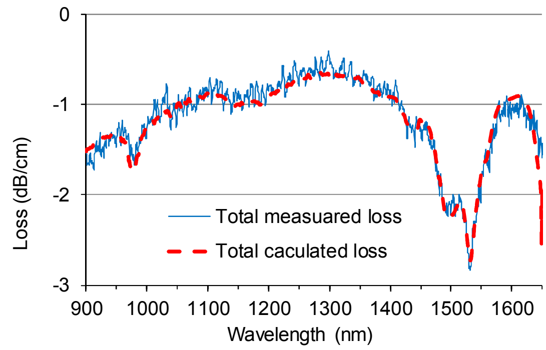

Fig. 2. Propagation loss spectrum of the As_2S_3 on Er doped TeO_2 waveguide. The scattering loss fits to the measured data. The total calculated loss sum the scattering loss, Er absorption and absorption of the cladding polymer. OSA bandwidth setting was 2nm.

The performance of the 65mm chip was characterized using the set up shown in Fig. 3. Two AR coated tapered fiber lenses were used to deliver the pump power to both facets of the chip. Each pump at 1479nm had a maximum power output of up to 300mW at the diode. Broadband pump WDMs were used to combine the pump with a signal from a supercontinuum source. The supercontinuum signal power at the WDM input was attenuated to -30dBm/nm to reduce the pumping effect of the signal. The output of the set up was characterized with an OSA. Normalisation of the measured response was performed with the unpumped 5mm long waveguide loss spectrum to yield propagation losses for a 6cm long segment. The internal gain available for loss compensation was defined here as the signal enhancement (power at output with pumps on minus power at output with pumps off) minus the Erbium absorption loss. The measured results are shown in Fig. 4. The waveguide could handle up to 97mW of pump power incident at each end before catastrophic waveguide damage occurred. This damage likely originated from the uncoated facets of the waveguide as coated facet devices have been tested with up to 700mW of incident 1550nm radiation with no damage evident.

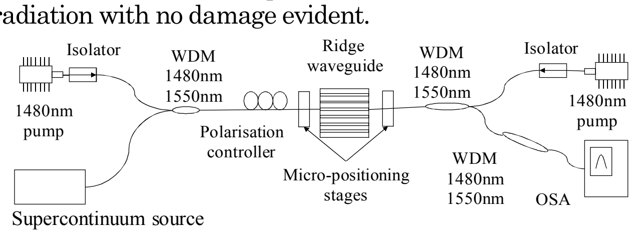

Fig. 3. Experimental set for gain measurement

Loss compensation was possible between 1520nm and 1620nm at 97mW of incident pump power (Fig. 4). The internal gain spectrum in the 1520-1620nm region is positive with pump power above 23mW. The maximum gain is between 4-5dB in the 1550nm region. The flat gain spectrum from 1530 to 1570nm indicated that the population inversion is around 60-65% compared to the maximum possible value of 75% when pumped at 1480nm [13]. Therefore, there is room to increase the gain further once the pump power damage threshold is increased. There is significant noise on the spectrum originating from the supecontinuum source, which has random polarization post the ~25m delivery fiber which interacts with the polarization dependent loss of the waveguide (measured at 4dB over the 6.5cm chip) generating to random ripples in the transmission spectra.

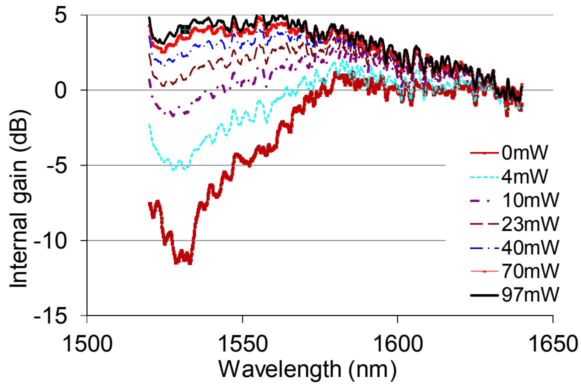

Fig. 4. Internal gain spectrum at various total pump powers. OSA bandwidth setting was 2nm.

Further analysis of the gain and loss between 1520nm and 1640nm was performed. Fig. 5 shows curves of the total loss per unit length with no pump and pump on at maximum allowable pumping. Essentially complete compensation occurred around the main 1530nm Erbium gain peak and at the secondary gain peak at 1550nm.

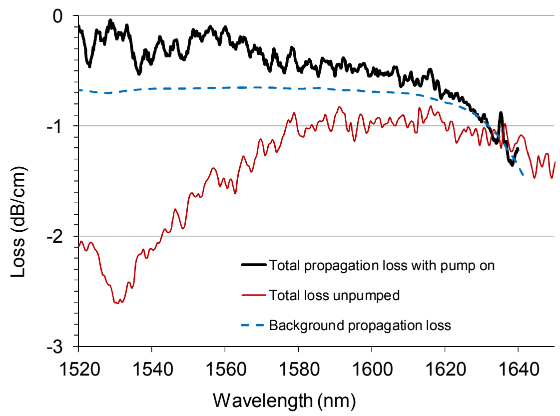

Fig. 5. Loss and gain analysis showing the near zero loss of the waveguide when pumped at 97mW of 1480nm at each end.

Since, there is only ~35% mode field overlap with the Erbium layer, the absorption of the Er doped layer at the peak is ~45dB. The ideal gain of the Er layer is expected to be ~22dB or ~3.4dB/cm. Taking into account the 35% overlap factor, the gain of the whole structure can be estimated to be ~1.2dB/cm, which is higher than the propagation loss of 0.6dB/cm at 1500nm. The absorption component due to the cladding can easily be removed by using alternative cladding materials such as SiO_2. Calculation using the model for fitting of the total loss showed that propagation loss will be fully compensated with a SiO_2 cladding, and a higher damage threshold (enabling higher pump power) will result in net on-chip gain.

In conclusion, anomalous dispersion As_2S_3 on Er doped TeO_2 hybrid waveguides with near zero propagation loss have been successfully fabricated. The next step is to improve background loss of the waveguide and improve the pump power handling of the waveguide to achieve wideband lossless performance.

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