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Erbium-doped polymer waveguide amplifiers for PCB-integrated optical links

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ABSTRACT

Optical technologies are increasingly considered for use inside high-performance electronic systems to overcome the performance bottleneck of electrical interconnects when operating at high frequencies and provide high-speed communication between electronic chips and modules. Polymer waveguides are a leading candidate to implement board-level optical interconnections as they exhibit favourable mechanical, thermal and optical properties for direct integration onto conventional printed circuit boards (PCBs). Numerous system demonstrators have been reported in recent years featuring different types of polymer materials and opto-electronic (OE) PCB designs. However, all demonstrated polymer-based interconnection technologies are currently passive, which limits the length of the on-board links and the number of components that can be connected in optical bus architectures. In this paper therefore, we present work towards the formation of low-cost optical waveguide amplifiers that can be readily integrated onto standard PCBs by combining two promising optical technologies: siloxane-based polymer waveguides and ultra-fast laser plasma implantation (ULPI). Siloxane-based waveguides exhibit high-temperature resistance in excess of 300°C and low loss at different wavelength ranges, while ULPI has been demonstrated to produce very high dopant concentrations in thin films with values of 1.63×10^{21} cm^{-3} recently reported in Er-doped silica layers. Here we present detailed simulation studies that demonstrate the potential to achieve a net gain of up to 8 dB/cm from such structures and report on initial experimental work on Er-doped polymer films and waveguides demonstrating photoluminescence and good lifetimes.

Keywords: EDWA, polymer, plasma implantation, optical interconnects, erbium

1. INTRODUCTION

Optical interconnect technologies have recently gained a lot of interest for use in short-reach communication links inside high-performance systems such as data centres and supercomputers. The main arguments supporting the use of optics in such environments are related to the performance advantages they offer over conventional electrical solutions. Key benefits of optical links include lower power consumption, higher bandwidth and increased density [1]. One of the leading candidates for the implementation of board-level optical interconnects are polymer waveguides. A new class of polymer materials which exhibit favourable mechanical, thermal and optical properties for direct integration onto printed circuit boards (PCBs) have been developed in recent years enabling the formation of low-cost high-speed optical backplanes [2, 3]. A number of successful system demonstrators based on various types of such polymer materials and implementing different optical bus architectures have been reported [4, 5, 6]. Siloxanes are one of the leading types of polymer materials as they exhibit all the necessary properties to withstand the manufacturing processes of PCBs (solder reflow), good environmental stability, long lifetimes and low absorption at the datacommunications' wavelength of 850 nm (~ 0.04 dB/cm) [7]. High-speed data transmission over polymer multimode waveguides has been achieved using 850 nm low-cost vertical-cavity surface-emitting lasers (VCSELs), with record values of 40 Gb/s and 56 Gb/s demonstrated over 1 m long polymer multimode waveguide using non-return-to-zero (NRZ) and 4-level pulse amplitude modulation (PAM-4) respectively [8]. There is currently a great interest in migrating this technology to longer telecommunications' wavelengths (1310 nm and 1550 nm) and single mode waveguides in order to enable the direct interface of board-level polymer waveguides with the emerging high-performance Si photonics chips and photonic integrated circuits (PICs) based on III-V materials. This has led to advancements in polymer structures engineered specifically for telecommunications C-band (1550 nm) with the material loss of less than 0.25 dB/cm in thin films [9] and under 0.8 dB/cm in single mode waveguides [9].

However, all polymer-based optical backplanes that have been implemented so far have been purely passive, which imposes a limit not only on the length of the on-board links but also on the number of components that can be connected. As a result, there is great interest in developing optical amplifiers suitable for integration onto PCBs. Whilst erbium-doped fibre amplifiers (EDFAs) have been greatly successful in long-haul optical links [10], no practical equivalent erbium-doped waveguide amplifier (EDWA) for use in board-level optical interconnects has been demonstrated. Although various materials and doping approaches have been studied and some encouraging results have been reported in recent years [11, 12, 13], high-gain, power-efficient and PCB-compatible EDWAs are still to be demonstrated. It has been identified however, that for such devices much higher ion concentrations are needed due their desired much shorter lengths than EDFAs, on the order of a few centimetres for practical applications [14]. As a result, in order to reach the required erbium concentrations with minimal ion clustering and gain quenching a number of fabrication techniques have been employed, such as atomic layer deposition [15], liquid phase epitaxy [16] or RF-sputtering [17] with some good results. Out of these, ultra-fast laser plasma implantation (ULPI) appears to be most promising [18]. Using this method erbium-doped tellurite-modified silica (EDTS) thin films with extremely high rare-earth ion content of 1.63×10^{21} cm^{-3} have been demonstrated, while maintaining a long erbium lifetime of 9.1 ms, which is essential for efficient optical amplification [19].

In this work, we present a hybrid approach to form EDWAs suitable for board-level optical interconnects by combining an EDTS layer fabricated using ULPI with polymer materials. The performance of the EDWA is studied for two different device configurations (channel and strip-loaded waveguides) using suitable models and its optimum design in terms of optical gain is explored in each case. Additionally, co-doping the EDTS with ytterbium is investigated in order to further improve the performance of the proposed EDWA and identify optimum Er-Yb ratio for different waveguide geometries.

The rest of the article is organised as follows. In section 2, the siloxane polymer waveguide technology and ultra-fast laser plasma implantation (ULPI) process used in this work are described. Experimental studies on the optical properties of Er-doped thin films and parameter extraction for amplifier modelling are reported in section 3. In section 4, amplifier studies for two device configurations are presented together with the results of the device optimisation. Finally, section 5 provides the conclusions.

2. TECHNOLOGIES

2.1 Ultra-fast laser plasma implantation

Femtosecond lasers can be reliably used for material processing, micromachining and surface ablation [20]. The erbium-doped thin film described in this work has been fabricated using the ULPI process [19] (Figure 1). The tellurite glass targets is prepared using standard glass melting and quenching processes [21], which provides good control of the molar concentration and ratio of erbium and ytterbium ions in the final deposited layer. The addition of the Yb-ions has been proven to improve the pump power absorption as well as limit photoluminescence quenching of the material [22]. The high-energy femtosecond laser pulses are then used to ablate the prepared tellurite glass target. The absorbed laser beam generates highly energetic plasma that expends towards a heated-up substrate surface in low-pressure deposition chamber environment. The thermally-assisted diffusion results in a homogenous Er-doped thin film layer that can be used in integrated optics systems [23]. Although the ULPI process has been mainly used for rare-earth ion implantation into silica glass [24], attempts have been made using other substrates, including polymer substrates [25].

The sample characterised in this paper was prepared using a target glass with the following composition $85TeO_2$-$5.5ZnO$-$7.15Na_2O_3$-$1.3Yb_2O_3$-$0.65Er_2O_3$. The deposition process was carried out under a 65 mTorr O_2 atmosphere and lasted 4 hours resulting in 2.54-μm-thick EDTS layer.

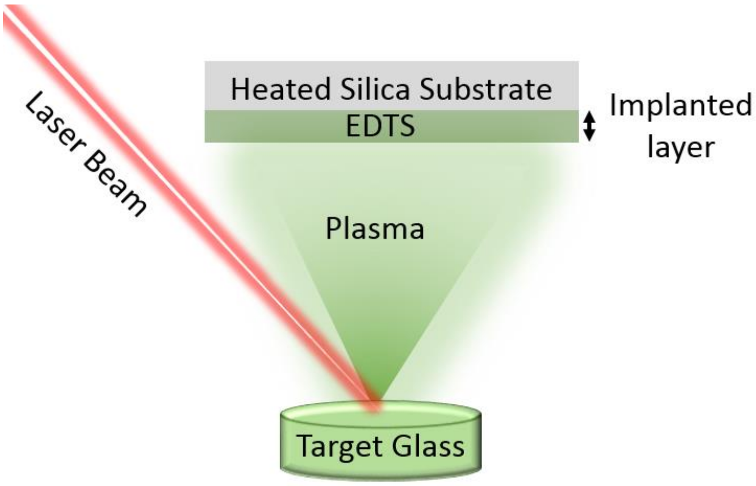


Figure 1. ULPI schematic showing formation of the EDTS glass layer.

2.2 Siloxane polymers

The polymer waveguides described in this work (Figure 2) are made using siloxane materials prepared by Dow Corning: Dow Corning® WG-2020 Optical Elastomer (core) and Dow Corning® WG-2021 Optical Elastomer (cladding). These materials possess the necessary mechanical and optical properties for PCB integration: they can be easily prepared and patterned; they can withstand the high-temperature (> 300°C) required for solder reflow and lamination processes; they exhibit long environmental stability and appropriate lifetimes in typical opto-electronic systems [26]. The polymers can be used to create a wide range of waveguides and waveguide components with a variety of fabrication methods. They can be deposited by a range of methods (spin-coating, doctor-blading or drop casting) on various substrates (glass, silicon, FR4) and then patterned with UV photolithography, embossing or direct laser writing [28, 29]. The nominal refractive index (RI) difference Δn between the core and cladding materials is 0.007 at 1550 nm allowing the formation of single mode waveguides with relatively large dimensions (up to 7.5 μm).

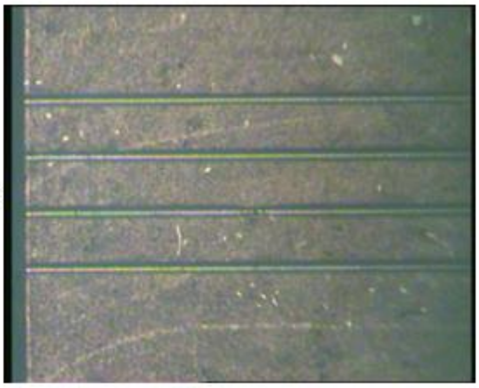
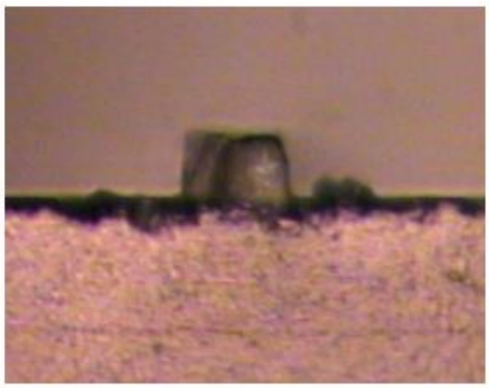
(a)  (b) 

Figure 2. Images of polymer waveguides deposited on EDTS glass layer (a) top view. (b) side view.

3. OPTICAL CHARACTERISATION

Optical characterisation of the erbium-doped sample is performed in order to extract the key parameters required for the amplifier simulation studies. The photoluminescence (PL) emission spectrum and lifetime of the EDTS layer are measured at a room temperature using the FS920 spectrometer (Edinburgh Instruments,UK) under an 980 nm laser-diode excitation. The pump light is prevented from reaching the spectrometer by using a long-pass filter with a cut-off wavelength of 1100 nm. The PL emission spectrum of the thin film was recorded around erbium $I_{13/2}$ to $I_{15/2}$ transmission band.

Figure 3(a) shows the obtained normalised PL emission spectrum in the 1450 nm to 1650 nm range. The spectrum demonstrates a strong peak at 1534.4 nm and a full-width at half-maximum (FWHM) range of 24.2 nm. Even though the exact spectral shape of the emission depends on the host material, comparable performance has been observed from similar types of materials [29]. Figure 3(b) presents the decay of the normalised spontaneous emission intensity light at 1534 nm with time. The lifetime of the Er ions in the material is calculated by finding amount of time it takes for signal to exponentially drop to the 1/e level. In this case, it is estimated to be 12.07 ms. The existence of a long metastable time that the erbium ion remains in the $I_{13/2}$ energy level is a key parameter for the implementation of efficient optical amplifiers. The long lifetime observed for the EDTS layer confirms the great potential of the ULPI fabrication process for forming high-gain waveguide amplifiers.

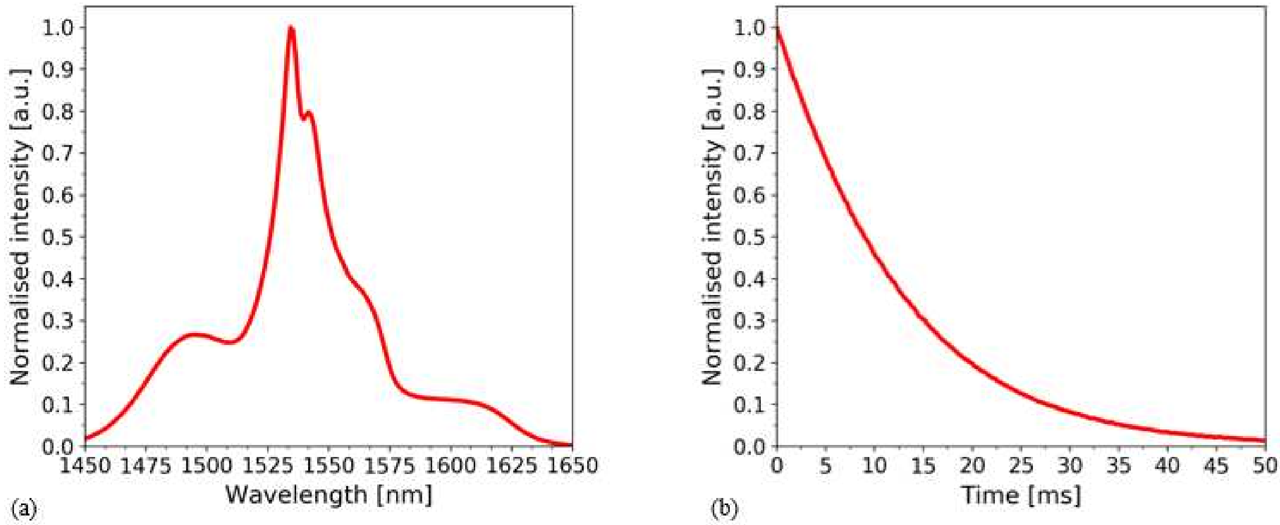


Figure 3. Optical characterisation results for an Er-doped thin film. (a) PL intensity profile. (b) Metastable lifetime

The measurement of the erbium lifetime and the refractive index of the doped layer (1.63 at 1550 nm) allow the estimation of the effective emission cross section σ_e between the excited ($I_{13/2}$) and ground ($I_{15/2}$) levels using the shape of the photoluminescence spectrum as shown by the Füchtbauer-Ladenburg equation [30]:

$$\sigma_e(\lambda) = \frac{\lambda^4_{e,peak} I_e(\lambda)}{8\pi c n^2 \tau \int I_e(\lambda) d\lambda} \tag{1}$$

Here, $\lambda_{e,peak}$ is the wavelength at the emission peak, τ is the lifetime of the metastable level, n is the refractive index of the glass, c is the velocity of light and $I_e(\lambda)$ the fluorescence spectrum. Eq. (1) is used to calculate the emission cross section for the EDTS layer used here and is shown in Figure 4. In order to implement a full EDWA model the corresponding absorption spectrum is calculated based on McCumber theory [31] using the emission cross section extracted above. According to the procedure proposed by Miniscalo and Quimby [32], and confirmed for a range of various materials, these two quantities are related with the equation below:

$$\sigma_a(\nu) = \sigma_e(\nu) e^{{h\nu - \varepsilon}/{kT}} = \sigma_e(\nu) e^{{h(\nu - \nu_0)}/{kT}} \tag{2}$$

where σ_a and σ_e are absorption and emission cross-sections respectively, h and k are Planck and Boltzmann constants, T is the temperature, ε is the net free energy required to excite one Er ion from $I_{15/2}$ to $I_{13/2}$ and ν corresponds to the wave frequency. Eq (2) is used to calculate the corresponding absorption cross-section of the fabricated EDTS layer and is plotted in Figure 4.

The obtained results show that the fabricated sample exhibits absorption and emission peaks of very similar magnitude of 4.7×10^{-21} cm^2, which agrees quite well with previous reports on a similar Er-doped tellurite-based glass thin film [33].

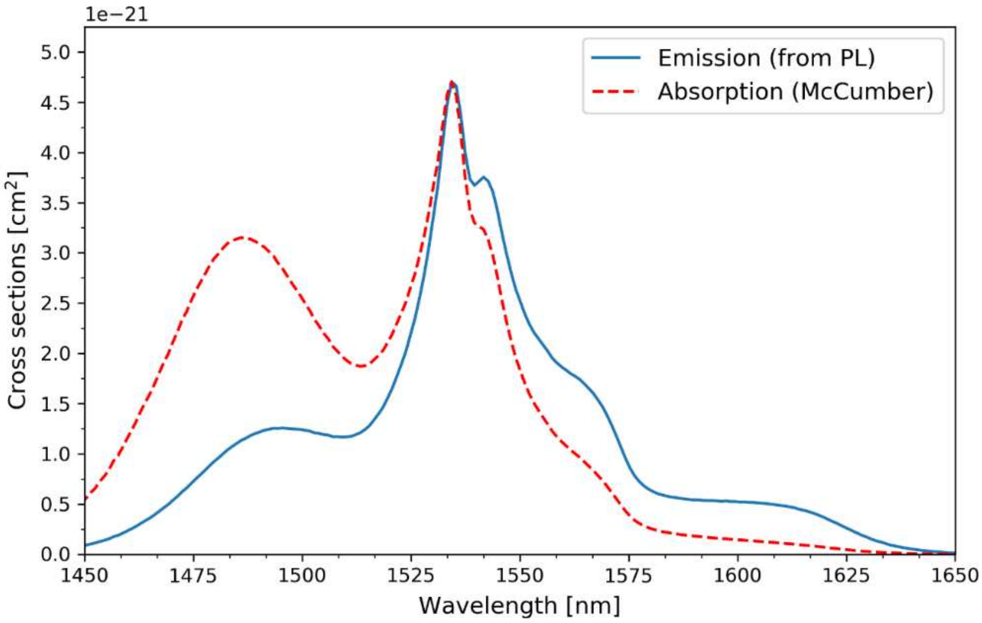


Figure 4. Emission and absorption cross-sections of the EDTS layer

4. WAVEGUIDE AMPLIFIER STUDIES

4.1 Waveguide configurations

In this work we study two simple waveguide designs that can be easily implemented using the Er-doped layer presented above: (i) channel and (ii) strip loaded waveguide (Figure 5). The channel Er-doped waveguide can be fabricated by common lithography and etching processes, while the strip-loaded waveguide requires only the formation of a polymer waveguide on top of the Er-doped layer. In both cases the dimensions of the waveguide that ensure single mode operation can be obtained and depend on the refractive indices of the glass layer, the polymer materials and the operation wavelength.

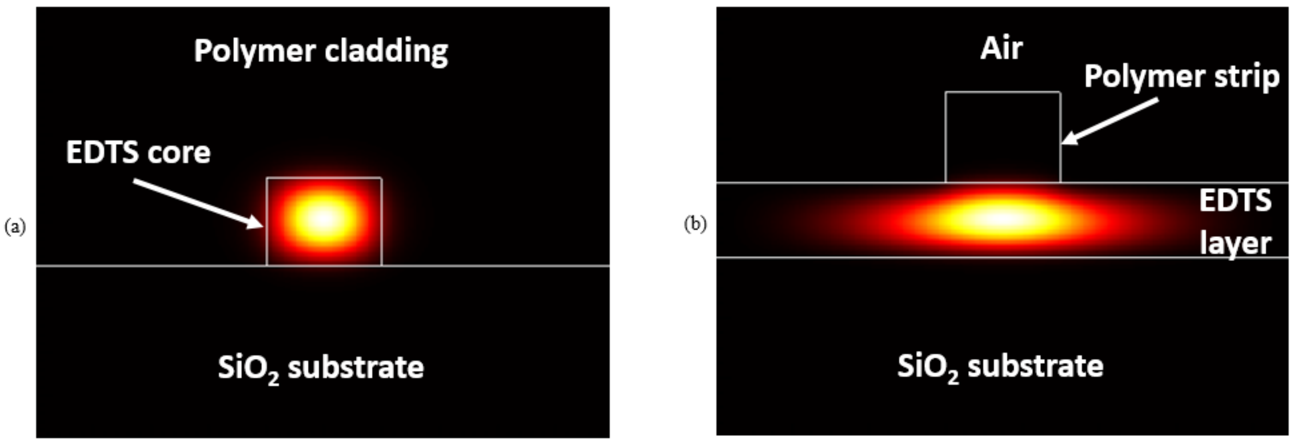


Figure 5. Investigated waveguide geometries: (a) channel, (b) strip-loaded with fundamental mode shown (λ = 1550 nm).

Both of the above structures are simulated using Fimmwave® simulation package in order to check the viability of the designs for the formation of a high-gain EDWA and determine their optimum parameters. The key parameters for the EDWA simulations are listed in Table 1 below for both configurations.

Table 1. Key waveguide simulation parameters extracted.

Parameter	Channel	Strip-loaded
Overlap factor at signal wavelength (1550 nm)	0.87	0.98
Overlap factor at signal wavelength (980 nm)	0.97	0.99
Effective Er overlap area [μm^2]	4	16.2

Both of the above geometries show high overlap factors with the Er-doped area, which indicates efficient pumping of the dopant ions. The main difference between the two configurations can be noted when comparing their effective overlap areas. The strip-loaded waveguide exhibits ×4 larger effective Er overlap area which indicates its stronger potential for forming higher gain amplifier. However, both configurations are studied in the next sections, as the channel waveguide is a typical configuration and provides a reference performance for the strip-loaded EDWA.

4.2 Channel amplifier

The gain performance of a 1-cm-long device is obtained using multi-level rate equations implemented using the VPI Photonics® software. The model parameters are chosen to match the parameters experimentally obtained or derived for the Er-doped layer. The values of unknown parameters such as the ytterbium lifetime (1.5 ms), its absorption cross-section (1.4×10^{-20} cm^2) and up-conversion coefficient (0.8×10^{-23} m^{3}s^{-1}) are obtained from the literature on similar glass systems [35, 36, 37].

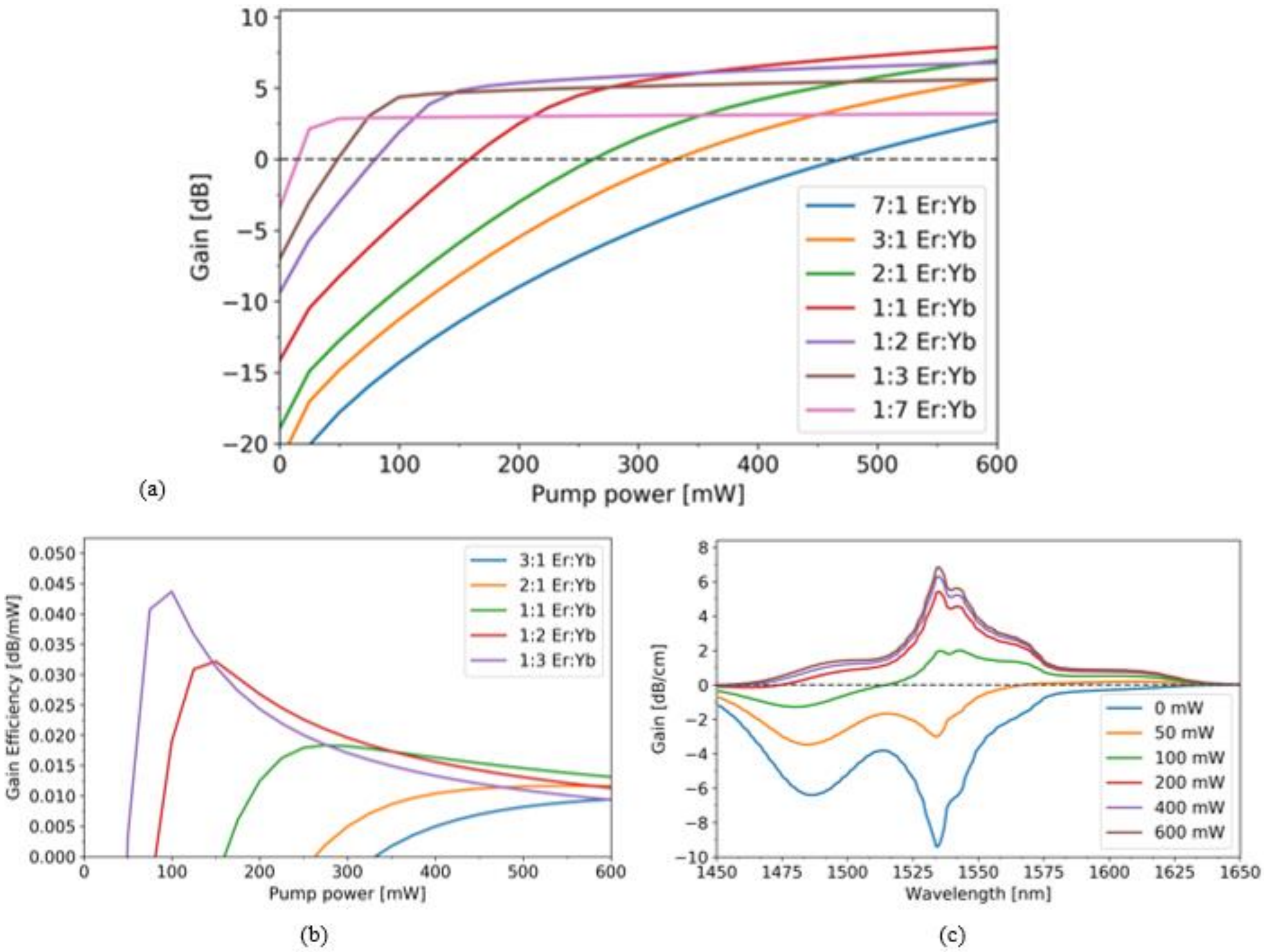


Figure 6. Channel waveguide EDWA results showing Er:Yb ratio impact on (a) achievable gain, (b) amplifier efficiency and (c) gain spectrum for various pump powers at ratio fixed at 1:2.

Figure 6 and Figure 7 present simulation results for both waveguide configurations focusing on the important performance metrics of the EDWA devices. Firstly, the achievable amplifier internal gain at the peak emission wavelength of 1534 nm is plotted against the pump power for a range of Er:Yb ratios (Figure 6(a) and Figure 7(a)). Additionally, the efficiency of the system in terms of gain per 1mW of pump power is analysed to find the optimal operating conditions (Figure 6(b) and Figure 7(b)). Finally, after an optimal Er:Yb ratio is found for a given waveguide configuration, full spectral response is obtained to assess the performance not only at the peak wavelength but across the entire telecommunications C-band (Figure 6(c) and Figure 7(c)).

The results presented in Figure 6(a) show that the optical gain can potentially reach 8 dB/cm for a channel structure when the waveguide is pumped at a high power of 600 mW. However, it is difficult to envisage a real-world system where that would be feasible, due to the high pump power required and the related effect on the lifetime of such device. Therefore, it is important to consider both the achievable gain, but also device efficiency as shown in Figure 6(b). On both graphs a range of Er:Yb ratios with a constant total dopant concentration of 1.63 $\times$ 10^{21} cm^{-3} have been simulated looking for a system capable of providing high gain while efficiently using the pump power. When a more reasonable pump power of 200 mW is chosen, it can be noticed that maximum gain of 5.4 dB is possible when the ratio of 1:2 is selected. This also is the most efficient combination in terms of gain per pump power. Further analysis of this amplifier is presented in Figure 6(c) showing the gain spectrum at various pump powers. It can be seen that increasing the pump input beyond the 200 mW does not result in a significant increase of the optical gain. The peak gain occurs, as expected from the emission spectrum measurements, at 1534 nm with a gain FWHM of 37 nm, which covers almost the entire telecommunications C-band. What is more, the internal gain threshold at the peak wavelength occurs at approximately 75 mW of pump power because of the large concentration of Er ions in the waveguide.

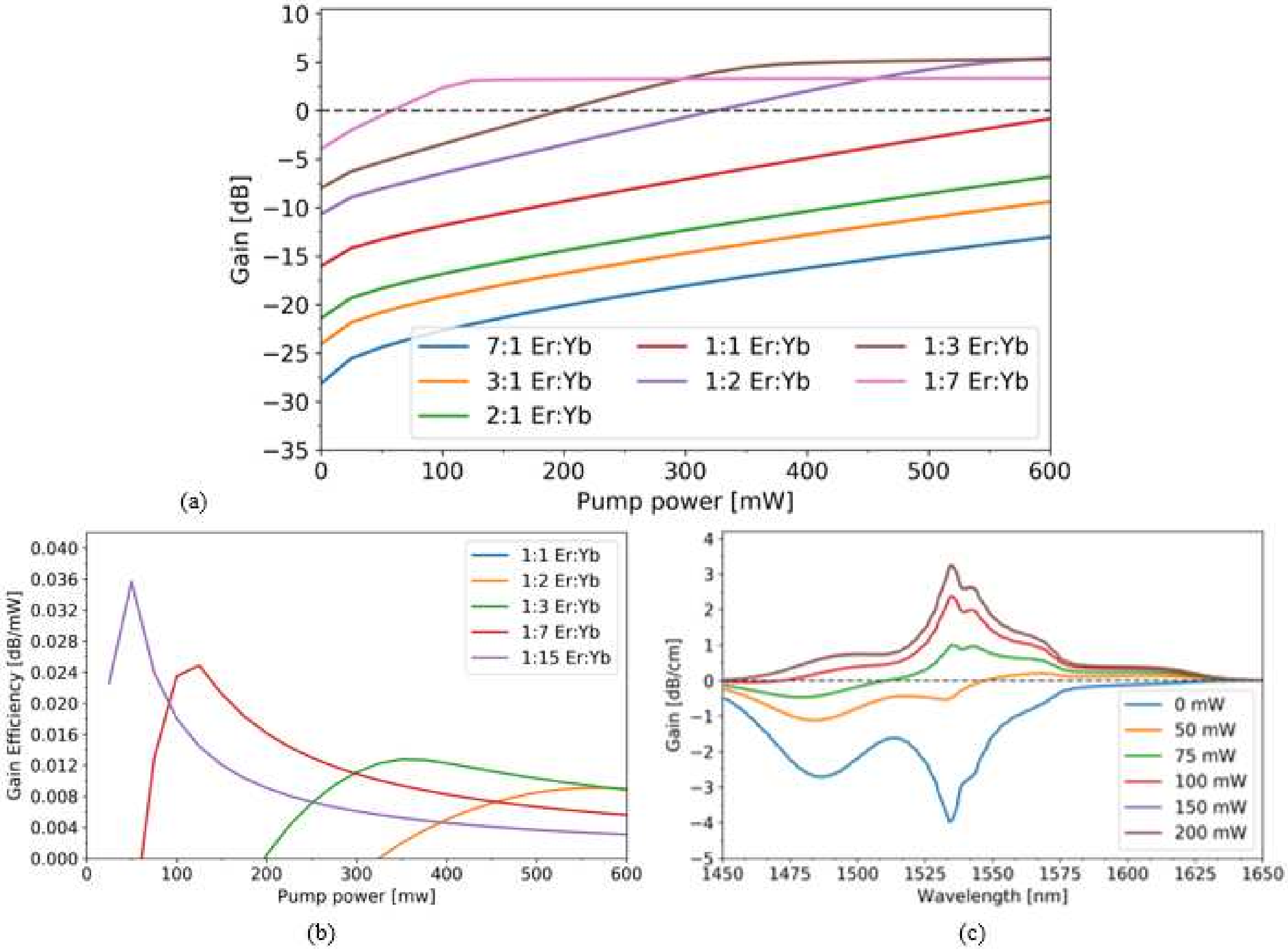


Figure 7. Strip-loaded waveguide EDWA results showing Er:Yb ratio impact on (a) achievable gain, (b) amplifier efficiency and (c) gain spectrum for various pump powers at ratio fixed at 1:7.

4.3 Strip-loaded amplifier

The same analysis is performed on the second waveguide geometry and the respective results are shown in Figure 7. The first key observation is that despite the presence of more erbium ions in the amplifier, due to the larger overlap area, the achievable gain (5.5 dB) is lower than that achieved from the channel structure. This is due to the fact that the highest considered pump power of 600 mW is inadequate to achieve complete erbium population inversion in the system.

In terms of the amplifier efficiency, Figure 7(b) indicates that, based on a practical 200 mW pump power optimal Er:Yb ratio is found to be 1:7. It is worth noticing that while the efficiency is lower than in case of a channel waveguide, a reasonable gain of 3.2 dB is achievable at 1534 nm peak. It can also be noticed from Figure 7(c) that there is virtually no benefit in increasing the pump power from 150 to 200 mW. This result confirms that when erbium concentration is relatively low, much less 976 nm light is needed to fully invert the ion population or to reach internal gain threshold (62.5 mW).

When the two systems are compared, it can be clearly noticed that a channel structure is more efficient due to its compact size. This is confirmed by both the calculated gain efficiency and the required pump power for gain saturation at a given Er:Yb ratio. In order to optimise the gain per 1-cm-long waveguide different Er:Yb ratios of 1:2 and 1:7 are chosen leading to gains of 5.4 dB and 3.2 dB at 1534 nm when pumped with 200 mW for the channel and strip-loaded EDWAs respectively.

5. CONCLUSIONS

The combination of the ULPI fabrication method and cost-effective siloxane materials can provide high-gain PCB-compatible optical amplifiers. The characterisation of the Er-doped glass thin film fabricated with the ULPI process shows excellent optical properties and therefore great potential for the formation of EDWAs. In this article, we investigate the performance of such erbium-doped waveguide amplifiers via simulation studies based on the parameters of the fabricated Er-doped glass layers and studying two common waveguide configurations: channel and strip-loaded geometry. It is shown that a 1-cm-long channel-based EDWA with a Er:Yb ratio of 1:2 can achieve an optical gain of 5.4 dB at 1534 nm when pumped with 200 mW at 976 nm. The strip-loaded geometry yields slightly worse performance with a peak gain of 3.2 dB at the same pump power for an optimised Er:Yb ratio of 1:7.

6. ACKNOWLEDGEMENTS

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