Erbium-doped polymer waveguide amplifiers for board-level optical interconnects

M. Ziarko[1], N. Bamiedakis[1], E. Kumi-Barimah[2], G. Jose[2], R. V. Penty[1], and I. H. White[1]

[1]*Centre for Photonic Systems, Department of Engineering, University of Cambridge, UK*

[2]*Institute for Materials Research, School of Chemical and Process Engineering, University of Leeds, UK*

ABSTRACT

Optical interconnects have an important role to play in next-generation high-performance electronic systems by enabling power-efficient high-speed board-level communication links. Polymer-based optical waveguides is a leading technology for integrating optical links onto standard printed circuit boards as it is sufficiently low cost and enables cost-effective manufacturing and assembly. Various polymer-based optical backplanes have been reported in recent years enabling different on-board interconnection architectures. However, all currently demonstrated systems are purely passive, which limits therefore the reach, complexity and functionality of these on-board systems. Here, we present recent simulation and experimental studies towards the development of Er-doped polymer-based waveguide amplifiers. Two different approaches to integrate Er-doped materials in siloxane polymer are investigated: (i) ultrafast laser plasma implantation of Er-doped glasses and (ii) solution-based dispersion of Er-doped nanoparticles. Experimental and simulation results on the achievable performance from such waveguide amplifiers are presented focusing on impact of the waveguide loss and upconversion on the gain figure.

Keywords: EDWA, polymer, erbium, optical interconnect, upconversion

1. INTRODUCTION

Optical interconnects have gained a lot of interest for use in board-level communication links inside high-performance electronic systems such as data centres and supercomputers. The vital arguments supporting the use of photonics in such applications are linked to the performance advantages they provide over currently employed electrical solutions, such as lower power consumption, higher bandwidth and increased channel density [1]. One of the leading candidates for the implementation of such systems are polymer waveguides, in particular a recently developed new class of polymer materials which exhibit favourable mechanical, thermal and optical properties for direct integration onto printed circuit boards (PCBs) [2], [3]. Siloxanes are one of the most promising types of such polymer materials: they can withstand the manufacturing processes of PCBs (solder reflow and board lamination), they exhibit good environmental stability and long lifetimes, they are sufficiently low cost and exhibit low loss at the wavelength of interest (~ 0.04 dB/cm at 850 nm) [4]. Initial work has been focused on multimode waveguides (~ 50×50 μm^2) as these provide relaxed alignment tolerances in the system assembly and are an ideal match for low-cost vertical-cavity surface-emitting lasers (VCSELs) and multimode fibres (MMFs) which are widely used in short-reach links in datacentre environments. High-speed transmission using VCSELs over multimode polymer waveguides has been achieved, with record values of 40 Gb/s and 56 Gb/s demonstrated over a 1-m-long waveguide using non-return-to-zero (NRZ) and 4-level pulse amplitude modulation (PAM-4) respectively [5], [6]. Additionally, a number of successful system demonstrators implementing different optical on-board interconnection architectures have been recently reported [7]–[9]. Migration of this polymer-based technology to longer telecommunications' wavelengths (1310 nm and 1550 nm) and single mode waveguides has gained a lot of interest in order to enable the direct interface of board-level polymer waveguides with the emerging high-performance photonic integrated circuits (PICs) and Si photonics (SiPh) [10], [11]. Recent advances in polymer structures engineered specifically for C-band (1550 nm) have demonstrated reduced material loss of less than 0.5 dB/cm in single mode waveguides [12].

However, so far, only purely passive polymer-based optical backplanes and on-board links have been implemented. This imposes a limit on both the length of the on-board links and the number of passive optical components (such as crossings, splitters) that can be used due to additional loss that they introduce. Whilst erbium-doped fibre amplifiers (EDFAs) have dominated long-haul optical links [13], no practical equivalent erbium-doped waveguide amplifier (EDWA) has been demonstrated for PCB-based optical interconnects. Various host materials and doping approaches have been studied and some encouraging results have been reported in recent years [14]–[16], but a PCB-compatible EDWA with high-gain and power-efficiency is still to be demonstrated. In order to reach the required erbium concentrations for few-centimetre-long devices with minimal ion clustering and gain quenching, different fabrication techniques have been investigated, such as atomic layer deposition [17] and liquid phase epitaxy [18] with some encouraging results. Out of these, ultra-fast laser plasma implantation (ULPI) and nanoparticle (NP) dispersion seem to be very promising. The first method has demonstrated erbium-doped thin films with extremely high rare-earth ion content of 1.63×10^{21} cm^{-3} [19], while the latter has already been shown to generate relatively high internal gain of 6.6 dB/cm [20]. Here, we

therefore present recent work towards the formation of EDWAs suitable for board-level interconnects using these two methods. Er-doped polymer thin films are fabricated using both ULPI and NP dispersion and their basic optical properties are compared in terms of their emission spectra and metastable lifetimes. Signal propagation in waveguides fabricated using the latter approach are then characterised across the erbium emission spectrum. Additionally, the potential to achieve high-gain amplification using hybrid channel waveguide EDWA is also demonstrated using multi-level rate equations model and its optimum design in terms of highest achievable optical gain is explored based on known physical properties of the material. Additionally, effect of co-doping the device with ytterbium, varying background loss and upconversion coefficient are investigated in order to improve the performance of the proposed EDWA and identify optimum Er-Yb ratios for different operating conditions.

The rest of the article is organised as follows. In section 2, the fabrication processes used in this work are introduced and experimental studies on the optical properties of Er-doped polymer thin films are reported. Waveguide measurements of the optical properties of NP-doped waveguides are shown in section 3. In section 4, amplifier modelling studies for a hybrid polymer-glass EDWA are presented with particular focus on device optimisation based on losses and upconversion in the system. Finally, section 5 provides the conclusions.

2. ERBIUM-DOPED THIN FILM FABRICATION AND CHARACTERISATION

The two approaches used in this work to integrate erbium ions into polymer thin films are briefly described and the spectral properties of the thin films produced are compared.

2.1 Polymer and Er-doped glass technology and fabrication

The polymer materials used in this work are siloxane-type WG-2020 (core) and WG-2021 (cladding) Optical Elastomers developed by Dow Corning. These materials have been engineered to exhibit all the necessary mechanical and optical properties for PCB integration [21]. Additionally, these materials 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 [22]. The refractive index difference Δn between undoped core and cladding materials is 0.0065 at 1550 nm allowing the formation of single mode waveguides with relatively large dimensions (up to 7.5 μm).

The first type of erbium-doped thin films described in this work has been fabricated using the ULPI process [23]. The Er-doped tellurite glass target is prepared using glass melting and quenching processes [24], which provide good control of the molar concentration of erbium ions in the deposited layer. High-power femtosecond laser pulses are then used to ablate the Er-doped tellurite glass target and generate a highly energetic plasma that then expands towards a heated-up substrate surface in low-pressure deposition chamber environment. The thermally-assisted diffusion leads to formation of a homogenous Er-doped thin film layer as shown for hosts such as silica glass [25]. The ULPI technique has been appropriately modified to enable implantation of Er-doped glass into polymer thin film and has been reported in detail in [26].

The second type of erbium-doped thin films has been prepared by directly dissolving Er-doped nanoparticles into a siloxane polymer solution. The erbium-gadolinium-cerium (EGC) nanoparticles are synthesised through the Leeds alginate process [27] with an estimated size of approximately 10 nm. The NPs are dispersed in a polymer and toluene solution using magnetic stirring and the resulting composite solution is deposited on a silica glass using a 200 nm syringe membrane filters to form a 10-μm-thick polymer film. Various samples with different NP doping concentrations are produced and characterised.

2.2 Thin Film Characterisation

Optical characterisation of the erbium-doped thin films is performed to compare the properties of the films prepared using the different methods and extract the key parameters required for amplifier simulation studies. The photoluminescence (PL) spectrum and lifetime are measured at a room temperature using the FS920 spectrometer (Edinburgh Instruments,UK) under an 980 nm laser-diode excitation. The pump light is blocked 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 is recorded around 1550 nm which corresponds to the erbium $^4I_{13/2}$ to $^4I_{15/2}$ transition. A broad emission spectrum and a long lifetime (long metastable time that the erbium ion remains in the $^4I_{13/2}$ energy level) are important parameters for the implementation of efficient optical amplifiers.

Fig. 1 shows the normalised photoluminescence spectrum obtained from the two Er-doped polymer thin films produced via the ULPI and NP dispersion methods described in the previous section. Although both spectra show the same emission intensity peak at ~ 1533 nm, some differences can be observed in terms of their shape. For the film fabricated using the ULPI method, the emission spectrum full-width at half-maximum (FWHM) is 38.7 nm, while the NP-doped film exhibits a slightly reduced FWHM of 31.5 nm.

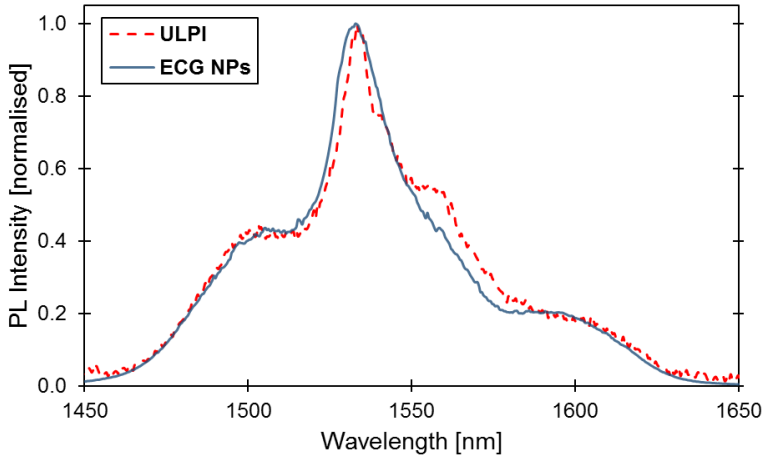

Figure 1. PL comparison of Er-doped polymer thin films obtained through ULPI and NP dispersion.

The lifetime of the Er ions in the NP-doped polymer film is measured and shown in Fig. 2 for the different concentrations of Er dopants as well as for the Er-doped polymer film fabricated by ULPI. The erbium lifetime is estimated to be 3.52 ms and 5.67 ms for the implanted and dissolved NPs respectively by fitting the decay with single exponentials. In case of the ECG particles some variation in the lifetime was observed depending on the weight percentage of the dopant as shown in Fig. 2. This measurement confirms the potential of the polymer material for forming high-gain waveguide amplifiers using both methods. It has to be noted though that a longer lifetime of 12.07 ms has been reported using ULPI in silica substrates [28].

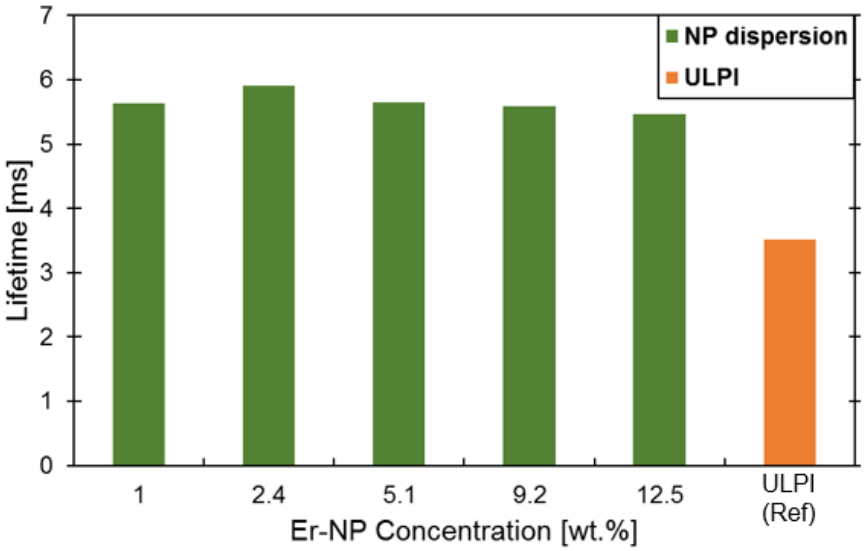

Figure 2. Erbium lifetime variation with concentration of dispersed NPs. ULPI polymer film used as a reference.

3. NP-DOPED WAVEGUIDE MEASUREMENTS

Polymer waveguide samples have been prepared using the NP-doped core solution with the NP concentration of 5.1 wt.% and their loss performance in the 1475-1575 nm wavelength range was measured using a tuneable laser (HP 8168E) and optical spectrum analyser (Yokogawa AQ6370D).

Fig. 3 presents the obtained insertion loss of a 1.4 cm long NP-doped polymer waveguide across the erbium emission region. The total insertion loss is > 20 dB in the wavelength range of interest which is too high for the formation of efficient waveguide amplifiers. As a result the underlying loss components are identified and their magnitude is estimated in order to better understand the limitations in the observed device performance. Three main loss components can be identified: propagation and coupling loss due light propagation in the polymer waveguide (polymer-only), scattering (Rayleigh) loss due to the presence of the NPs, and erbium absorption loss due to the presence of Er ions. The polymer-only loss is estimated using a non-doped polymer waveguide of the same dimensions and length, while the scattering loss is calculated using a Rayleigh model [29] and the fact that very low Er-induced absorption losses are expected at the longer wavelength of 1575 nm [30]. The analysis reveals a scattering loss in the range of 11 to 14 dB for wavelength range studied. The remaining loss is assigned to erbium absorption.

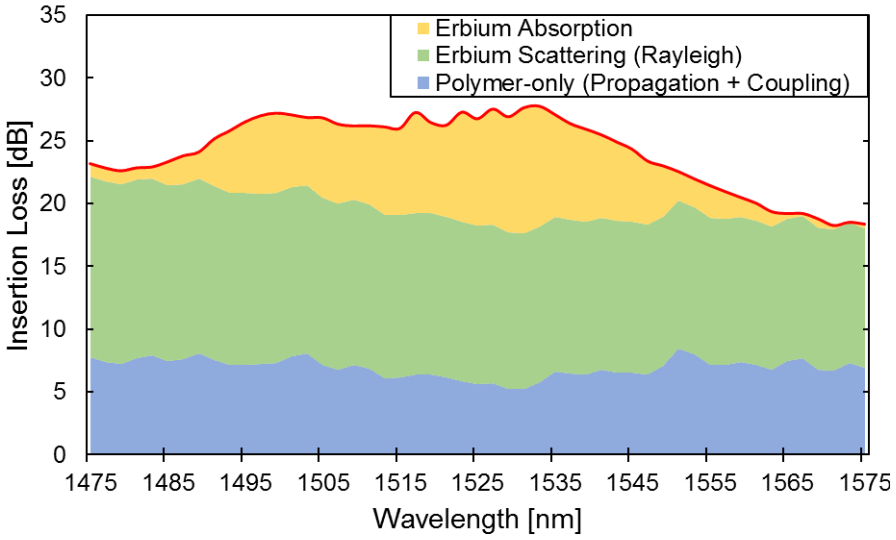

Figure 3. Insertion loss (red line) of a 1.4-cm-long NP-doped waveguide and estimated loss components.

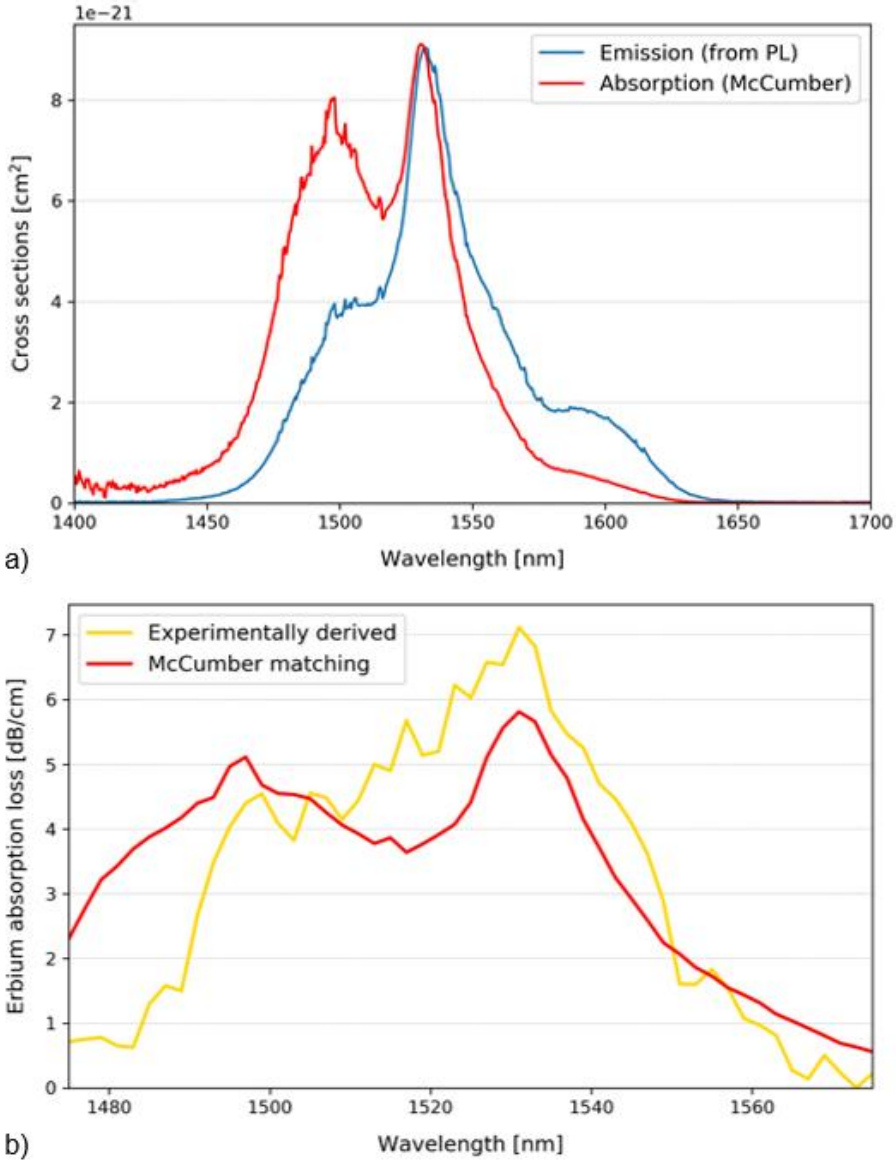

Figure 4. Er-absorption analysis: a) expected absorption cross-section based on McCumber theorem and b) matching with measured absorption.

In order to validate the loss analysis, the McCumber theorem [31] is employed to derive the Er absorption cross section (Fig. 4a) and estimate the erbium absorption spectrum. This spectrum is then compared with that obtained through the above analysis of the experimental results (Fig. 4b). The absorption cross-section is obtained using the Fuchbauer-Ladenburg method [32] based on the measured PL emission spectrum shown in Fig. 1. Fig. 4b compares the predicted Er absorption loss through the McCumber theorem (red line) and the loss analysis (yellow line) on the experimental results. Relatively good agreement is obtained between the two methods validating the loss analysis presented above. As a result, we conclude that the fabricated NP-doped polymer waveguides suffer from large scattering losses due to NP clustering in the polymer matrix. The estimated Er concentration in the waveguide is in the range of 1.47-1.8 × 10^{20} cm^{-3} which is calculated to be adequate for achieving internal gain (1.1 dB/cm without further doping optimisation) in such structures, provided that the scattering loss is significantly reduced to 0.3 dB/cm. As a result, work towards improving the dispersion of the NPs in the polymer matrix is currently underway and we hope to the present these at the conference.

4. HYBRID EDWA STUDIES

An alternative approach to produce polymer-compatible EDWAs consists of using hybrid glass-polymer waveguide structures [28]. The hybrid channel waveguide studied here comprises an Er-doped glass core (EDTS) fabricated using the ULPI method and a polymer cladding. Using a waveguide amplifier model we demonstrate the potential to achieve a high-gain amplifier using this type of structures. The results presented below are based on a 1-cm-long 2x2 μm^2 hybrid ETDS-polymer channel waveguide (Fig. 5).

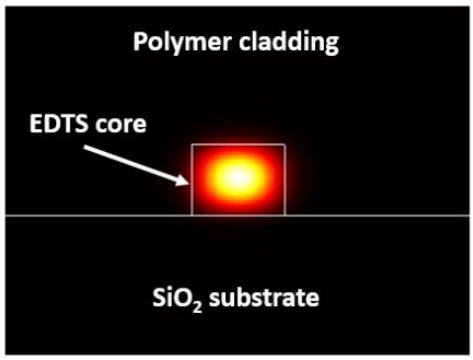

Figure 5. Channel waveguide cross-section based on a hybrid glass-polymer structure

The key parameters used in the EDWA simulations are listed in Table 1 and are based on values either extracted from fabricated glass samples using the UPLI method [28] or reported in literature on similar Er-doped glass systems [33]–[35]. The main unknown parameters for the hybrid structures are the upconversion factor and the background waveguide propagation loss. As a result, the rest of the parameters (total ion concentration, lifetime and cross-sections) are kept constant, while these two are varied to assess their impact on the amplifier's performance and optimum design. Three values are used for the background loss: 0.3, 1 and 3 dB/cm, as 0.3 dB/cm represents a very good quality waveguide, 1 dB/cm represents an average quality waveguide and 3 dB/cm a worst-case scenario. In terms of upconversion factor, a similar approach is undertaken with three values chosen based on values reported in other Er-doped glass systems: 0.8, 5 and 10 × 10^{-23} m^3s^{-1}.

Table 1. Main simulation parameters

Parameter	Value	Reference
Dopant concentration	1.63 × 10^{21} cm^{-3}	[28]
Lifetime [Er $I_{13/2}$ / Yb $F_{5/2}$]	12 / 1.5 ms	[28], [33]
Erbium emission cross-section [1534 nm]	4.7 × 10^{-21} cm^2	[28]
Erbium absorption cross-section [1534 nm]	4.7 × 10^{-21} cm^2	[28]
Erbium absorption cross-section [980 nm]	2.5 × 10^{-21} cm^2	[28]
Ytterbium absorption cross-section [980 nm]	1.4 × 10^{-20} cm^2	[33]
Upconversion rate	0.8,5,10 × 10^{-23} m^3s^{-1}	[33],[36]
Er-Yb cross-relaxation	2.3 × 10^{-22} m^3s^{-1}	[33],[35]
Background loss	0.3, 1 or 3 dB/cm	-

A multi-level rate equations model implemented using the VPI Photonics software is employed to obtain the gain of the amplifier by taking into account both upconversion and Er-Yb ion interactions. Ytterbium co-doping is used with erbium ions in order to take advantage of its very high absorption cross-section and efficient energy transfer mechanism to the neighbouring Er ions [34]. In order to find an optimum performance of the EDWA for a given set of background loss and upconversion factor, the ratio of erbium and ytterbium has been varied while maintaining the total ion concentration of 1.63 × 10^{21} cm^{-3} constant. Fig. 6 shows optimised internal gain that

could be achieved from a 1-cm-long device as a function of the pump power (from 0 to 600 mW) and Er:Yb ratio (from 1:99 to 99:1). Fig 6. (a-c) show how the background loss affects the device performance. Comparison of the three graphs indicates that the background loss reduces the achievable gain of the device for a given pump power. Although the highest gain can be achieved by using a 600 mW pump power, this power is too high for practical applications and as a result, a more realistic pump power of 200 mW is used for comparing the different plots (red dashed line in plots).

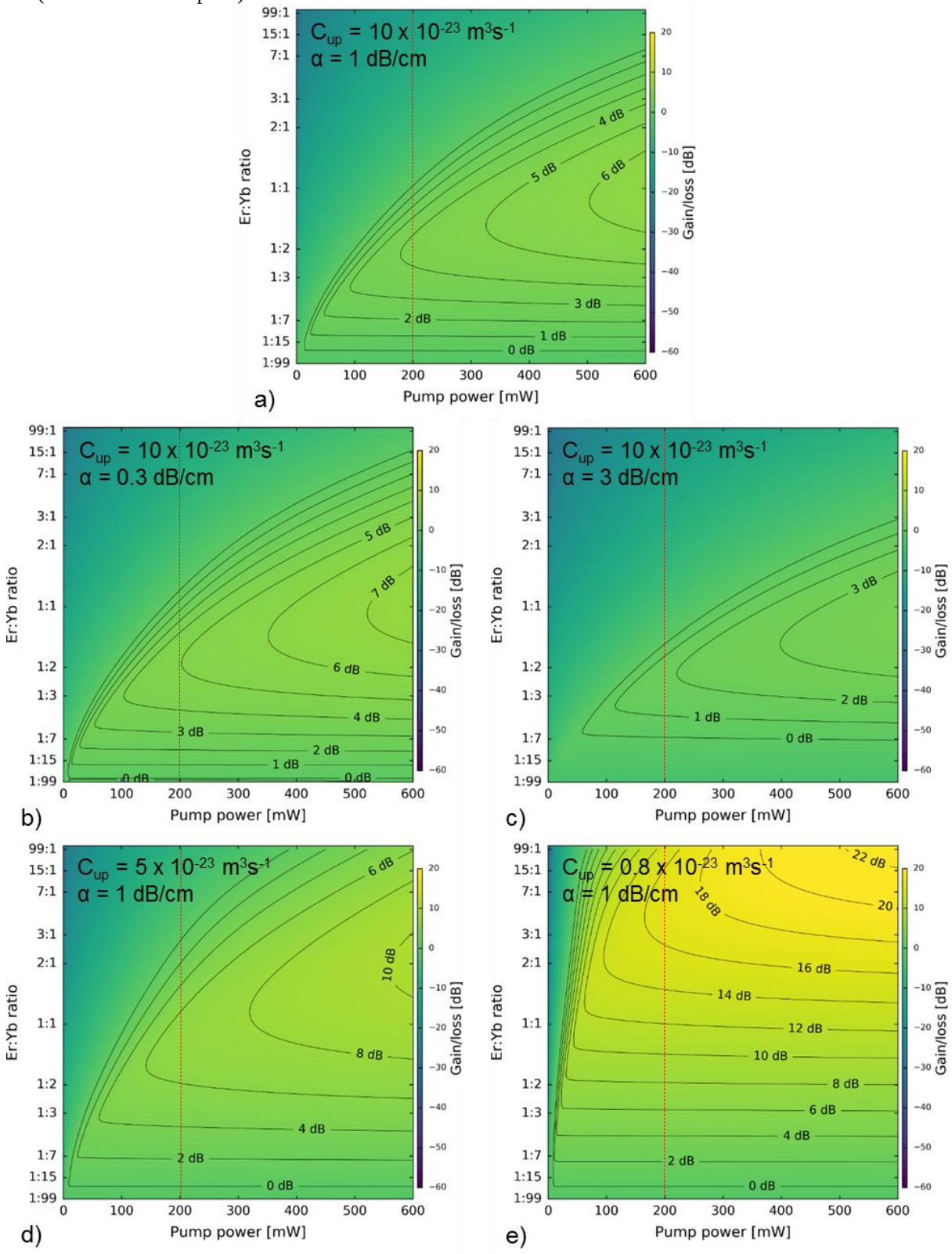

Figure 6. Gain and Er:Yb ratio optimisation for a 1-cm-long EDWA with varied upconversion and background losses (a-e).

A summary of the simulation results for the optimised hybrid EDWA is shown in Table 2. For an EDWA with a 1 dB/cm loss (Fig. 6a), a maximum gain of 4.2 dB can be achieved with an Er:Yb ratio slightly below 1:2. When the loss in the waveguide is changed to 0.3 dB or 3 dB, the maximum gain changes to 5 dB and 1.9 dB respectively, as shown in Fig. 6(b) and (c). The 2 dB loss increase results in a 2.3 dB gain drop, while the 0.7 dB loss reduction yields a 0.8 dB gain increase. Changing the background loss affects the intensity of the pump signal along the device length and therefore the population inversion along the device and the obtained gain itself. However, the variation of the waveguide loss does not significantly affect the optimum Er:Yb ratio for a particular device which is found to be ~ 1:2.

With respect to the upconversion factor, a more pronounced effect on the optimum device structure is observed. In the initial scenario [Fig. 6(a)], a strong upconversion effect due to very high erbium concentration is assumed. However, introduction of ytterbium as a co-dopant not only acts as a sensitizer for the pump signal, but it has also been shown to reduce the effect of upconversion due to adding an additional energy transition in the system [37]. Therefore, Fig. 6(d) and (e) present simulation results where the upconversion factor is reduced from 10×10^{-23} m^3s^{-1} to 5 and 0.8×10^{-23} m^3s^{-1} respectively. For a design with the pump power limited to 200 mW, the reduction in the upconversion coefficient results in a significant increase in the maximum achievable internal gain: from 4.2 dB to 6.8 dB and 16.8 dB for the two values studied. A reduction in the upconversion coefficient by a factor of 2 and 5 increased the internal gain by 2.6 and 12.6 dB respectively. Additionally, the change in the value of the upconversion coefficient significantly affects the optimum Er:Yb ratio for the amplifier, changing it from ~ 1:2 to ~ 1:1 and ~ 7:1 for the upconversion coefficients of 5 and 0.8×10^{-23} m^3s^{-1} respectively. These results highlight the importance of the upconversion factor for optimising the amplifier design and achieving high-gain in this material system.

Table 2. Summary of the simulation results for an optimised EDWA

Operating Conditions		Optimisation Results	
Upconversion coefficient [$\times 10^{-23}$ m^3s^{-1}]	Background loss [dB/cm]	Maximum internal gain [dB/cm]	Optimum Er:Yb ratio
Varying background loss			
10	0.3	1.9	1:2
	1.0	4.2	1:2
	3.0	5.0	1:2
Varying upconversion coefficient			
0.8	1.0	16.8	7:1
5		6.8	1:1
10		4.2	1:2

5. CONCLUSIONS

Two approaches of doping polymers with erbium, namely ultrafast laser plasma implantation and nanoparticles dispersion in a polymer matrix are studied for PCB-compatible optical amplifiers. The comparison of the PL spectrum of fabricated Er-doped polymer thin films using these two methods has shown similar spectral characteristics. ULPI implanted film has a wider FWHM of 38.7 nm while the NP-dissolved approach yields to a longer Er lifetime of 5.67 ms. Early work on NP-doped waveguides indicate that scattering loss due to NP clustering is the major limiting factor in demonstrating gain from such structures. As a result, methods to achieve improved dispersion of the NP in the polymer matrix are currently under investigation. The initial results suggest indicate that gain of 1.1 dB/cm at the estimated Er concentration of 1.5×10^{20} cm^{-3} could be achieved if the scattering losses were reduced to 0.3 dB/cm. This could be then improved through increasing erbium content and adding ytterbium to the mix.

Hybrid glass-polymer waveguide structures are an alternative approach to achieve high gain EDWAs. Simulation results on a 1-cm-long channel EDWA provide optimisation guidelines for the co-doping of Yb as a function of the background waveguide loss and upconversion coefficient. The result indicate that a gain of 4.2 dB can be achieved for the reasonable values of 1 dB/cm background loss and a upconversion coefficient of 10 × 10-23 m^3s^{-1}. It is further shown that the variation of the upconversion coefficient has a greater impact of the optimum design of such an EDWA that a change in background loss. Experimental studies are underway to determine these and allow the formation of high gain hybrid EDWA structures.

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