Investigation of the Spectral Advantages of Sol-Gel Layered Erbium Doped Waveguide Amplifiers

Athanasios Laliotis and Eric M. Yeatman

Department of Electrical & Electronic Engineering
Imperial College London
Exhibition Rd, SW7 2BT, U.K.

Abstract: High levels of net gain have recently been reported in sol-gel phosphorous-aluminium co-doped silica waveguides. However, compositions providing both high net gain and large spectral width have not yet been achieved. In this paper we propose the use of laminated cores of multiple compositions to achieve improved spectral performance in erbium-doped waveguide amplifiers. We demonstrate the potential advantages of this technique by simulations of cores laminated from previously demonstrated individual glasses.

1. INTRODUCTION

Erbium doped waveguide amplifiers (EDWAs) have been widely investigated due to their advantages in size and cost over their fiber counterparts. However, the low solubility of erbium in a glass host can lead to ion clustering and reduce gain at high doping levels. To date, the highest net gain has been demonstrated for phosphate glass ion exchanged waveguides [1], since phosphorous co-doping can increase the Er solubility. However, phosphorous co-doping also narrows the emission spectrum, making such amplifiers less attractive for optical WDM networks. Net gain has been demonstrated in alumino-silicate glass hosts as well with better spectral performance [2]; however, it has been impossible so far to achieve similar levels of inversion as in phosphate glass hosts. A variety of glass networks, such as soda-lime glass, and co-dopants, such as aluminium, germanium [3] and titanium, have been proposed with relative success, but there has not been one solution that deals satisfactorily with the problems described above.

Although a more complex composition suggests itself as a route to obtaining the benefits of several co-dopants, there are many practical limitations to what can be achieved in the composition of a glass host. In this paper we investigate the possibility of creating waveguide amplifiers consisting of laminated layers with different spectral characteristics. We demonstrate that by this technique, one can combine features and advantages of different glass hosts without the need to combine them in a single glass. Moreover we show that advantage can be taken in this technique of the pump mode profile in the core design.

2. LAYERED AMPLIFIERS

The sol-gel technique has been extensively studied as an alternative glass deposition method for photonics, but it had not been until recently that net gain had been demonstrated [4]. Typically, in this method, metalorganic precursors such as tetra-ethyl-ortho-silicate (TEOS) in an alcohol solution are mixed with catalysed water, and undergo hydrolysis and condensation reactions. The resulting solution can be spun onto a silicon substrate followed
by rapid heat treatment, thicker layers being achieved by iterating this procedure. Since the thickness of each layer can be controlled within certain limits, and given the flexibility of the method in the co-dopants one can introduce in the silica network, sol-gel is ideal for fabrication of layered waveguide structures. In the simplest case of such devices, two different compositions are deposited alternately to make the amplifier's core. Similar structures could be fabricated with three or more different compositions.

The increase in power for a single frequency $v$ in a small step $dz$ in the direction of propagation is described in the simple 1D case by:

$$\frac{dP_v}{dz} = \int \sigma_s(x) \left[ N_2(x) - \frac{g_2}{g_1} N_1(x) \right] f(x) dx$$

where $\sigma_s$ is the emission cross-section, $I$ the intensity, $N_2$ and $N_1$ the erbium ion populations in the ground and meta-stable level respectively, $g_1$ and $g_2$ correspond to the degeneracy of the levels, and $P_v$ is the power density. This equation depends on the solution of the complete rate equations describing the amplifier and on the pump profile. However, in the simple case where the amplifier is fully inverted and the width of each layer is small compared to the total width, it can be shown that the output will be approximately equal to the output of a homogeneous amplifier with a cross section equal to the average of the different cross-sections of the individual layers, the average being weighted by the erbium doping levels and the layer widths. For the complete solution, numerical models are required, since the outcome depends heavily on other parameters, such as ion-ion interactions and pump power distribution along the waveguide.

In Fig.1 we show different emission spectra as have been fabricated by various deposition methods with different glass compositions, from Refs. [1-4]. Although net gain for sol-gel has been demonstrated for only one composition of phosphorous-aluminium co-doping, there is evidence for the meta-stability of the material which suggests that similar compositions to those of Fig. 1 can be fabricated by the sol-gel method as well.

Fig. 1 Different emission cross-sections of homogeneous cores. From Refs. [1-4].

Fig. 2 Emission spectra of phosphate (Comp. I), alumino-silicate (Comp. II) and lamination of the compositions.
3. SIMULATION RESULTS

To investigate the output of layered amplifiers we have used the Method of Lines. This numerical scheme was first applied to waveguide amplifiers in [5]. The method consists of the following steps: a) the lateral direction (x-axis) of the amplifier is discretised in lines of uniform refractive index; b) the amplifier is excited with both signal and pump fields at its input end; c) at each line we solve the rate equations and calculate the profile of the complex refractive index.

We have investigated heavily phosphorous and aluminium doped glass, since those are the most prominent in the field of EDWAs, and it is possible to find published experimental results on the ion interaction coefficients [1,6]. The parameters used for the simulations are shown in Table 1. We refer to the phosphorous co-doped composition as Composition I and alumino-silicate as Composition II.

<table>
<thead>
<tr>
<th>TABLE I PARAMETERS USED FOR THE NUMERICAL MODELING</th>
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<tr>
<td>Composition I</td>
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<tr>
<td>$\tau_1 = 5,\text{msec}$</td>
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<tr>
<td>$C_\text{ph} = 0.2\times10^7,\text{m}^2/\text{sec}$</td>
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<tr>
<td>$K_2 = K_3 = 0.2\times10^4,\text{m}^2/\text{sec}$</td>
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<tr>
<td>$\sigma_\text{P(Er)} = 5.0,\text{m}^2$</td>
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<tr>
<td>$\alpha_{\text{signal}} = 0.2,\text{dB/cm}$</td>
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In order to show that one can combine the different spectral characteristics by layering the two compositions, we calculate the spectral output of a 5 μm width waveguide doped with 0.35% Erbium. The amplifier consists of alternating layers of phosphate and alumino-silicate glass types, of 0.5 μm each. The total length is 1 cm, and the pump power 100 mW. We also calculate the output of the two homogeneous amplifiers respectively for the same parameters. In Fig. 2 one can see the results; it is clear that the outcome of the layered amplifier is approximately the average of the other two.

While the spectral averaging effect gives some benefit, we can also take advantage of the fact that the pumping mode profile is not uniform and so achieve better and more practical results, even if the available compositions are limited. As an example we have investigated a structure whose core is 0.5% erbium, phosphorous co-doped glass, and whose edges are alumino-silicate glass 1% erbium doped. The total width of the amplifier is 6μm and it is divided in three parts of 2 μm each. Since the edges of the waveguide are under-pumped, the levels of inversion are lower. This is the phenomenon of L-Band amplification that is widely used for EDFA’s. The center, however, is fully pumped and gives gain in the C-Band. The output of the two cases separately is shown in Fig 3 for a 1 cm waveguide. We can see that the two spectra are complementary. Finally in Fig.4 we plot the outcome of a 4 cm long waveguide for different pump powers. We can see that the resulting spectrum extends from 1.53-1.6 μm and is much flatter than those for homogeneous cores.
4. CONCLUSIONS

We have proposed the use of laminated waveguide cores to broaden and flatten the spectra of EDWAs, and carried out simulations showing the benefits this technique can provide, particularly when the laminated structure is designed with the shape of the pump mode in mind.

Fig. 3 Absorption (dashed line) and emission (solid line) spectra of L-Band and C-Band.

Fig. 4 Emission spectrum of layered amplifier for different pump powers.

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REFERENCES