Planar Waveguide Amplifiers

S. Berneschi*, G. Nunzi Conti*,, and G. C. Righini*,***

*MDF-Lab, "Nello Carrara" Institute of Applied Physics, IFAC-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy

**Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Piazzale del Viminale 2, 00184 Roma, Italy

***CNR, Department of Materials and Devices, Piazzale Aldo Moro 7, 00185 Roma, Italy

E-mail: g.c.righini@ifac.cnr.it

Abstract: Over the past few years, due to the great development of optical communications, an increasing R&D activity has been focused on the design and manufacture of the integrated optic amplifiers, with particular reference to their application in wavelength-division-multiplexing (WDM) systems. In this technological context, rare-earth-doped oxide glasses, which had been widely used for solid state lasers, gained much attention as highly performing materials in the third telecom window, around 1.5 micron. The aim of the present paper is to provide a brief overview of the progress made, with particular reference to the authors' work in this area, and to shortly discuss its perspectives.

1. INTRODUCTION

Optical technologies have become more and more important in the present information era as they provide adequate answers to the ever increasing demand for high speed internet access and broadband communication services, necessary for both long distance communications and Metropolitan or Local Area Networks. One of the crucial steps that mainly contributed to the development of optical communication systems was the advent, during the 80s, of the Erbium Doped Fiber Amplifier (EDFA)[1,2]. In fact an EDFA is able to optically regenerate a signal around 1.55 μm by a stimulated emission process involving a transition between 4f states in erbium ions. The use of this all-optical process avoids the double opto-electronic conversion that represented the bottleneck for the performance of the network. The success of the EDFA combined with the continuous improvement of glass integrated optics (IO) technologies[3] gave a strong impulse towards the development of planar Erbium-Doped Waveguide Amplifiers (EDWAs)[1]. This 'gain element' can be integrated anywhere on the optical chip allowing true lossless circuit as in electronics[4,5]. In order for an EDWA to achieve high gain values in a few centimeters (as compared to the EDFAs which are meters long) it is necessary to increase the Er^{3+} ions concentration inside the host material (typically, two or three order of magnitude higher than that of EDFAs). However this solution presents some inconveniences related to the fact that, at such high erbium doping levels, parasitic effects -such as concentration quenching or co-operative up-conversion - can occur and affect the optical pump efficiency and the gain characteristic of the amplifier[6-8]. For this reason a major research challenge in this field has been the study and development of glass materials where these phenomena have a reduced effect even at high doping levels. Moreover in some cases also the fabrication process may affect the spectroscopic properties of the material used and consequently the final performance of the amplifier[9]. Ultimately, depending also on the specific application, the goal is the selection of the most appropriate combination of material and fabrication process in order to obtain the targeted performances for the amplifier at the lowest possible cost. If this research approach is still necessary for implementing low noise narrowband waveguide lasers, more recently an alternative route is being developed for waveguide amplifiers. In fact recent achievements in reducing waveguide propagation losses as well as in allowing very small bending radius (by increasing the mode confinement) made possible the fabrication of high performance, low erbium concentration, long (tens of centimeters), spiral wave-

guide amplifiers on an extremely small area (tens of square millimeters). In this way it is possible to combine the advantages of low doping levels and high pump efficiency (like in fiber amplifiers) with that of a small footprint. This solution, already proposed years ago by some researchers[10-12], seems to be that finally adopted by some companies (www.teemphotonics.com, www.inplane.com).

The aim of this article is double. In section 2 we present our recent works in the area of Rare-Earth doped glass materials and channel waveguide fabrication for optical amplification, while in Section 3 we overview the state of the art in planar waveguide amplifiers. An outlook section (Section 4) concludes this review paper.

2. Materials: Special Classes of Optical Glasses for EDWAs

Bulk or thin film oxide glasses are well-known as convenient hosts for Rare-Earth (RE) ions in order to fabricate planar optical waveguide amplifiers and lasers[6-7,13-14] and the choice of the glass matrix is a crucial step for the performance of these devices.

If silicate glasses remain very attractive materials for the development of IO devices, due to their chemical durability and adaptability to different waveguide fabrication processes, the realization of optical amplifiers in these glasses may be limited by the reduced solubility of rare-earth ions and the relative narrower fluorescence bandwidth as compared to other oxide glass hosts, like phosphate glasses. In fact, due to their internal chemical structure, phosphate glasses offer the possibility of higher RE doping levels and wider emission bandwidths[6,15]. Nevertheless, because of their lower chemical durability, all those techniques that involve chemical reaction processes during the fabrication procedures (like wet etching during standard photolithography) become more critical for these latter glasses. In order to improve the stability of phosphate glasses and improve their chemical robustness a proposed solution has been the addition of Al_2O_3 in the glass matrix[6,16].

Among the many glass hosts studied for erbium doping, we initially selected soda-lime silicate glasses because they offer some important advantages: i) easy adaptability to different fabrication processes; ii) relatively high erbium doping levels are allowed without significant reduction in the metastable state ($^4I_{13/2}$) lifetime[17]. On the contrary a major disadvantage of these glasses is related to the rather narrow fluorescence bandwidth around 1.55 μm. In order to overcome this latter limitation we then developed a set of alumino-silicate ion-exchangeable glasses and we studied the effect of Al_2O_3 addition on the absorption/emission bandwidth.

More recently we have investigated novel chemical compositions: multifunctional rf-sputtered erbium doped silica-germania thin films and erbium doped tellurite glasses.

The main experimental results we obtained in glass fabrication, spectroscopic characterization and waveguide fabrication are summarized and commented in what follows.

2.1 Glass fabrication

Soda-lime-silicate glasses (M and MY glasses): A set of soda lime silicate glasses were prepared at the 'Stazione Sperimentale del Vetro' in Murano using a platinum crucible and the melting/cooling process described in ref.[18]. All the samples presented the same basic mol% composition (73% SiO_2 – 14% Na_2O – 11% CaO – 1% Al_2O_3 – 0.4% P_2O_5 – 0.6% K_2O) and were doped with different percentages of Er_2O_3 (0.32 and 0.48%, labelled as M2 glass and M3 glass, respectively). Two samples were also codoped with Yb_2O_3 (0.63 and 0.78%, MY2 glass and MY3 glass, respectively). Ytterbium co-doping allows to strongly enhance the pump efficiency at 980 nm and, at the same, time may reduce the unwanted Er^{3+}-Er^{3+} ions interactions by increasing the mean inter-atomic distances.

Soda-Lime-Alumino-Silicate glasses (AL glasses): In order to investigate the effect of aluminum oxide content on the optical and spectroscopic properties of soda-lime-silicate glasses (with particular reference to the emission bandwidth around 1.55 μm) the type of composition reported above was maintained with the sole exception of the alumina concentration. This latter, in these new glasses, was varied from 1 mol% (AL01 sample) up to about 20 mol% (AL25 sample)[19,20]. Table 1 lists the nominal compositions of the set of six-soda-lime alumino silicate glasses including

Table1. Nominal Composition of the Six Soda-lime Alumino Silicate Glasses.

Sample	Chemical Composition [mol%]						
	SiO_2	Na_2O	CaO	Al_2O_3	P_2O_5	K_2O	Er_2O_3
AL01	72.64	13.94	10.96	0.99	0.4	0.6	0.47
AL05	69.84	13.40	10.54	4.81	0.38	0.58	0.45
AL10	66.64	12.79	10.05	9.17	0.37	0.55	0.43
AL15	63.71	12.23	9.61	13.16	0.35	0.53	0.41
AL20	61.14	11.73	9.23	16.67	0.33	0.51	0.39
AL25	58.70	11.26	8.86	20	0.32	0.49	0.39

the Er_2O_3 mol%.

From Table1 we observe that the composition of AL01 samples is very close to that of M3 samples. These six new AL glasses were fabricated at the Material Engineering Lab of the University of Modena using the following heating cycle: from 20 to 1000℃ at 10 ℃/min, with a 24 h soaking time at 1000℃, from 1000 to 1550℃ at 20 ℃/min and finally 1 h of soaking time at the maximum temperature of 1550 ℃. Eventually, the melt was quenched in a graphite mould to obtain small pieces of glass having a bar form; each bar was then cut to 1 mm thickness and optically polished on both faces.

SiO_2-GeO_2 thin film: In the last years, much attention has been paid to the study of permanent photorefractive effects in transparent optical materials in order to fabricate integrated guiding structures and diffractive elements by simple exposure to a light source. The advantages of these fabrication procedures, especially from the technological point of view, are evident, since they avoid costly and slow fabrication steps such as lithographic patterning and subsequent etching. Among these materials, silica-germania thin films are known to offer excellent UV photo-refractive properties. So it appears clear that the addition of rare-earth elements to photorefractive films may provide an effective route to the simple fabrication of integrated optical amplifiers.

In our experiments, thin films with $75SiO_2$-$25GeO_2$ (molar %) composition, doped with 0.27 mol% each of Er_2O_3 and Yb_2O_3, were deposited onto vitreous silica substrates by Radio Frequency Magnetron Sputtering (RFMS) technique[21,22]. The films were fabricated at the Institute of Photonics and Nanotechnologies (IFN-CNR) in Trento. In order to improve the adhesion of the active films, the substrates were cleaned inside the RF sputtering deposition chamber by removing some atomic layers just before starting the deposition procedure. We used a sputtering process that does not require a target sintered on purpose, as we simply placed pieces of GeO_2, metallic ytterbium and metallic erbium onto a 4" silica target. The residual pressure, before deposition, was about $2x10^{-5}$ Pa. During the deposition process the substrates were not heated. The sputtering was carried out with Ar gas at a pressure of 0.7 Pa and an applied RF power of 150 W. The deposition time was 4 h 15 min, producing a film with a thickness of about 3.35 μm.

Tellurite Glasses (WNT glasses): Among the various materials currently being investigated for further development of EDWAs, tellurite glasses have gained a growing attention because of their broad emission band around 1.55 μm and low phonon energy (largest phonon energy is around 800 cm^{-1}). Modelling has shown that tellurite-glass hosts can offer the additional advantage of reducing the deleterious gain peak effect making easier the way to gain-flattened optical amplifiers[23].

In our experiment we studied two families of tellurite glasses, one including zinc and the other one including tungsten[24]. In particular the tungsten-tellurite glasses (labelled as WNT) were fabricated at the Scientific and Technological Department of the University of Verona and their basic composition in mol% was the following: 60% TeO_2 – 15% Na_2O – 25% WO_3, with a different percentages of Er_2O_3 oxide: 0.05 mol% (WNT005 sample), 0.5 mol% (WNT05 sample), 1 mol% (WNT10 sample), 1.5 mol% (WNT15 sample) and 2 mol% (WNT20 sample). They were prepared by melting batches composed of analytical grade of the constituents in a platinum crucible for 2h at 750℃. The same glasses were then quenched in air on a stainless steel plate, and finally annealed for 2h at 360℃.

2.2 Main spectroscopic parameters

In Table 2 we report the main fluorescence spectroscopic parameters measured in some of our samples and relative to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} ions. The effective emission cross section bandwidth is defined as $\Delta\lambda^{eff} = \int \sigma_e(\lambda) d\lambda / \sigma_{e,max}$, where λ_p is the peak emission wavelength and τ_{meas} is the measured lifetime.

Table 2. FWHM and Effective Fluorescence Bandwidths for the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ Er^{3+} Transition, Peak Emission Wavelength and Measured Lifetime for Some Different Glass Formulations.

Sample	$\Delta\lambda^{FWHM}_{fl}$ (±1 nm)	$\Delta\lambda^{eff}_{fl.}$ (±1 nm)	λ_p (±1 nm)	τ_{meas} (ms)
M3	18	34	1535	8.0 (± 0.5)
AL25	33	51	1533	5.1 (± 0.2)
SiO_2-GeO_2	40	-	1533	8.7 (± 0.2)
WNT	-	63	1531	3.3 (± 0.2)

By comparing the data obtained for M3 and AL25 samples we observe that the effective bandwidth almost doubles its value when alumina content rises from 1 mol% (in the case of M3 sample, that has a composition close to that of AL01 sample) to 20 mol% (in the case of AL25 sample). The bandwidth broadening versus the alumina content is shown in Fig.1 where we can also notice that the curve slope has a maximum between 9 mol% and 13 mol%.

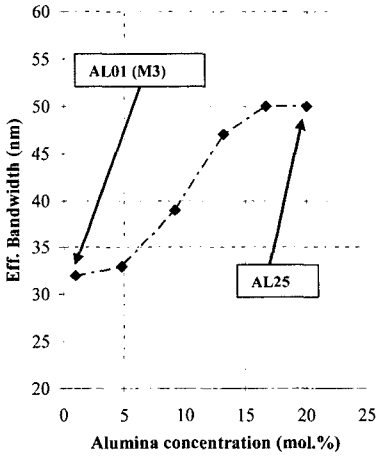

Fig. 1. Absorption effective bandwidth of AL samples as a function of Al_2O_3. The dot line are traced only as an help to eyes.

These results suggest that the behaviour of this class of glasses has a drastic change when the concentration of aluminum ions becomes larger than that of sodium ions[19]. A possible explanation refers to the different effect that the aluminum oxide has on the silica network when acting as glass modifier or as glass former. In particular, in the former case (sample AL01 or M3, AL05, and AL10), the aluminum ions contribute to disrupting the silica structure and producing non bridging Al-O groups which can coordinate the Er^{3+} ions, so reducing the Er^{3+}-Er^{3+} ions interaction and increasing the lifetime of the metastable $^4I_{13/2}$ level. A further increase of aluminum oxide, on the contrary, reduces the non-bridging oxygen ions to form the Al-O-Si bridging oxygen (the alumina acts as glass former), thus reducing the value of the lifetime (see the value of the AL25 sample). For all samples, the quantum efficiency defined as the ratio between the measured lifetime and the calculated radiative lifetime, is larger than 55% with a maximum of 75% for the AL20 sample[20]. This glass, therefore, can have high potentials for the development of broadband EDWA.

As to the sputtered SiO_2-GeO_2 thin films, they also exhibit quite good spectroscopic properties. Their bandwidth is rather large (FWHM = 40 nm), in fact much larger than in most multi-component silicate glasses, and the measured lifetime exceeds 8 ms[22].

Finally, for what concern the tungsten-tellurite glasses, Fig. 2 shows the absorption cross sections (measured) and emission cross sections (calculated using the McCumber theory[25]).

These data specifically refer to one sample (WNT10), but the absorption cross sections were practically the same for all the samples[26,27]. The emission cross section σ_e of Er^{3+} ions in tellurite glasses are high since the refractive index n of the glass is high (around 2.04 at 635 nm) and the cross section values increase with the refractive index of the host as $(n^2 + 2)^2 / n$. Also the effective emission cross section bandwidth $\Delta\lambda^{eff}$ is very large in tellurite glasses, as compared to silicate

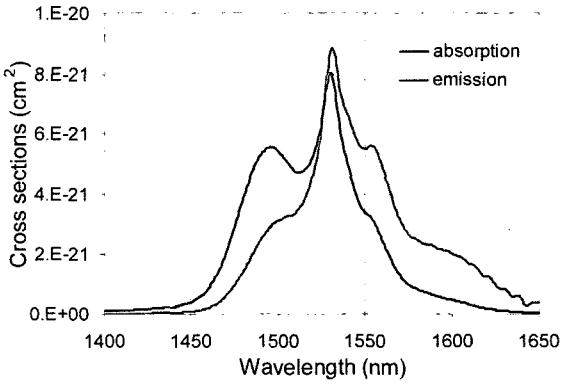

Fig. 2. Absorption and emission cross sections of WNT10 glass.

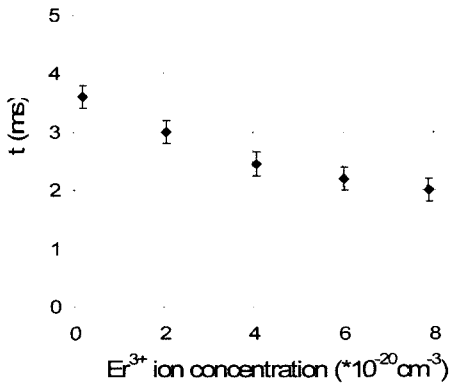

Fig. 3. Measure lifetime of the $^4I_{13/2}$ level as a function of Er^{3+} concentration for the WNT glass.

and phosphate glasses[28], with a value of 62 nm as reported in Table 2.

The measured lifetime of the $^4I_{13/2}$ level is shown in Fig.3 as a function of Er^{3+} ions concentration in these glasses.

As expected, a reduction in lifetime occurs for increasing Er^{3+} concentrations, because of concentration quenching, mainly due to a higher probability of non-radiative relaxation due to energy transfer processes. The $^4I_{13/2}$ level decay curves presented a single exponential decay with values ranging from 3.6 ms to 2 ms and a maximum quantum efficiency of 94% (WNT005 glass). These measured parameters in tungsten-tellurite glasses indicate that they are also promising materials for the development of broadband integrated waveguide amplifiers.

2.3 Waveguide fabrication

Various fabrication techniques are commonly used to realize 2D guiding structures but we can divide the major manufacturing routes for integrated optic devices in two main categories:

a) processes were the circuit pattern is first written on a mask and then duplicated (or imprinted) on the glass substrate by photolithography. These processes include thin film deposition techniques (such as RFMS, Sol-Gel, Chemical Vapour Deposition (CVD), Flame Hydrolysis Deposition (FHD)) followed by Reactive Ion Etching, Ion Exchange technique, and UV or ion beam imprinting[5,10,12,17,29-37];

b) processes were the pattern is directly written on the substrate (bulk glass or glass layer) using a focused laser beam (femtosecond laser or UV laser) or an ion beam[38-40].

Obviously all of these fabrication processes present some advantages and disadvantages, and in general the choice of the fabrication process also depends on the material used. In our case, for the two classes of silicate glass, because of their excellent chemical durability, we decided to use molten salt $Ag^+ \leftrightarrow Na^+$ ion exchange technique in order to fabricate channel waveguides. We obtained the best results in term of net gain by using MY3 glass. In a 4 μm wide and 3.5 cm long waveguide, after an ion exchange time of 7 minutes in a diluted solution of $AgNO_3$: $NaNO_3$ (0.5 mol% : 99.5 mol.%) at 325° C followed by an annealing post-process of 25 minutes at the same temperature, we measured a maximum net gain of 5 dB at 1536 nm with a pump power of 250 mW (see also Table 3). The propagation losses, measured at 1300 nm, were lower than 0.6 dB/cm.

In order to fabricate channel waveguides in the SiO_2-GeO_2 thin films we simply performed a single step UV exposure of the film through an amplitude mask[22]. As light source we used a KrF excimer laser operating at 248 nm. This technique is successful because in our sputtered films, the value of the UV induced positive refractive index change is high enough (up to $4 \cdot 10^{-3}$ with cumulative exposure dose of 20 kJ/cm^2) to allow a good lateral confinement of the radiation. The SiO_2-GeO_2 film UV-light absorption, which induces the refractive index change, has been recognized to be produced by the presence of germanium-oxygen-deficient-centers (GODC's) that are formed, depending on the sintering conditions, during the glass matrix growth. It appears that, due to the reduced pressure and pure oxygen-free argon atmosphere, the sputtering technique we used favors the generation of the oxygen vacancies, thus increasing the photosensitive proprieties of the film.

This fabrication approach, as stated above, is simpler and potentially cheaper than conventional methods since it avoids time consuming and expensive fabrication steps such as conventional lithography followed by chemical or physical etching. Moreover in comparison with direct UV writing, this 'imprinting' method does not require any moving part in the exposure system.

The near field intensity distribution at 1.55 μm of

a single mode, 7 μm wide channel waveguide is shown in Fig. 4. The field is strongly asymmetric because the difference between the substrate and the film refractive indices (in the vertical direction) is about one order of magnitude higher than that induced by the UV exposure (in the transversal direction). Because of the rather low erbium concentration we could not measure net gain but we found out that the UV imprinting did not increase the low propagation losses of the Er^{3+}/Yb^{3+} doped slab waveguides (< 0.3 dB/cm) so that development of active devices at 1.55 μm appears as a well feasible target.

In tellurite glasses slab (1D) optical waveguides were successfully obtained[26, 27], but the realization of channel (2D) waveguides, which are the building block of any integrated device, still appears a challenge mainly because of the low chemical durability of these glasses. We indeed tried to produce channel waveguides by common fabrication processes, namely ion-exchange and femtosecond laser writing, but without any success. In the former case surface damages occurred during the photolithography process, while in the latter one the induced refractive index change was negative.

Later on, our successful approach has been the use of ion beam irradiation, which is a technique extensively used to modify physical and optical properties of a wide range of materials[41]. Also in this case we used an 'imprinting' technique by placing a silicon mask with openings of about 25 μm in front of the glass substrate in order to define channel waveguides. The irradiations were carried out with a 1.5 MeV N^+ collimated beam from a 5 MeV Van de Graaff accelerator with normal incidence on the sample. The lateral homogeneity of the irradiation was ensured by defocusing the ion beam with a magnetic quadrupole. The best guiding channels were obtained with a dose of 1.0×10^{16} ions/cm^2 and Fig. 5 shows the near field image of a corresponding waveguide at 633 nm. Because of the large mask openings the propagation is multimode but the light is indeed confined both in vertical and in lateral direction around the implanted region. This fact implies that there is an increase of the effective refractive index ($\Delta n>0$) of the Er^{3+}-doped glass due to the N^+ irradiation. A 2D guiding effect is also confirmed observing the green up-conversion emission along the waveguide obtained pumping the Er^{3+} ions at

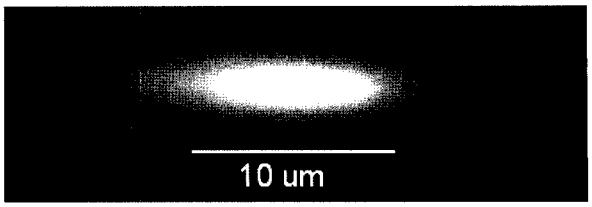

Fig. 4. Measured Near Field Intensity Distribution at 1550 nm of a Channel Waveguide Obtained by UV-imprinting Through a 7 μm Wide Opening.

980 nm, as shown in Fig. 6[24]. The upconversion emission, which tracks the pump propagation, is in fact well confined into the waveguide. Unfortunately because of the short length of the waveguide (only 7 mm) with its multimode propagation we could not perform reliable measurements of parameters such as propagation losses and optical gain.

3. EDWAs: A Brief Overview of the State of the Art

The fabrication of EDWAs proceeds through the patterning of channel waveguides in active glasses. Microphotolithographic techniques are generally used, but sometimes the chemical and/or physical etching processes are not very effective, due to specific glass characteristics. As already mentioned, novel approaches have been therefore developed, e.g. using ion beam[12, 24, 38], UV[22], or femtosecond laser[39, 40] direct writing.

The characteristics of several EDWA devices fabricated in different laboratories worldwide are summarized in Table 3 For commercial applications two main specifications should be considered, namely the net gain per length unit G_L (dB/cm) and the net gain per pump power unit G_P (dB/mW). Other specs would also be important for system management, such as the noise figure, but only few papers give such a value, which seems to be in the range 3 to 4 dB[31].

The comparison of performance of the various devices is not always straightforward, also because it is not clear if measurement methods and units are used everywhere in a consistent way. In the literature sometimes the doubt occurs if authors refer to signal enhancement (namely, the increase of transmitted signal due to stimulated emission, without considering propagation and absorption losses) rather than to true net gain. In some papers,

moreover, the level of pump power is given as the optical power actually injected into the waveguide (which implies measuring, or at least estimating coupling loss), while in other papers only the power available at the end of the input fiber is given, or, even worse, no clear indication is provided. Despite these issues, however, it emerges that several devices with high performance have been demonstrated and that EDWAs can be efficiently integrated with passive components, like 1×N splitters and WDM components. At this regard, it can also be underlined that integrated optical devices also have a better form factor than the corresponding fused-fiber devices: a typical 1×8 fiber power splitter has a footprint of about $10 \times 8 \times 1$ cm^3, whereas the IO device can

Table 3. Comparison of Measured Performances of Waveguide Amplifiers. NOTEs: (*) if not Explicitly Indicated, Pump Wavelength is Around 980 nm; (**) if not Otherwise Indicated, the "Loss" Value Refers to the Propagation Losses for Unit Length Measured Far from the Er^{3+} Absorption Wavelength Around 1.5 μm; (♦) Flame Hydrolisis Deposition; (♥) Plasma-Enhanced Chemical Vapor Deposition; (*) Femtosecond Laser Writing; N.A. = Not Available

Technology	Host Material	RE doping level (Er^{3+}/Yb^{3+})		Max. Net Gain (dB/cm)	Pump (*) Power (mW)	Length (cm)	Loss (**) (dB/cm)	Ref.
Sputtering	Aluminosilicate	N.A.		0.8	140 (@1480 nm)	14.0	0.15	[29]
	Phosphate	5.3×10^{20} ion/cm^3	-	4.1	21	1.0	< 0.90	[30]
	Silicate	3.3 wt%(Er_2O_3)	-	4.2	80	1.7	0.4	[17]
	Soda-Lime	4.1×10^{20} ion/cm^3	-	4.2	300	4.5	N. A.	[31]
Ion Exchange	Phosphate	7.5×10^{20} ion/cm^3	11×10^{20} ion/cm^3	4.1	150	0.3	0.50	[32]
	Phosphate	2 wt%(Er_2O_3)	2 wt%(Yb_2O_3)	3.3	120	1.0	0.80	[33]
	Silicate	3 wt%(Er_2O_3)	5 wt%(Yb_2O_3)	2.3	130	3.9	3.6 dB (insertion)	[5]
	Soda-Lime	2.3×10^{20} ion/cm^3	3.8×10^{20} ion/cm^3	1.5	250	3.4	< 0.60	[34], [35]
FHD (♦)	P_2O_5:SiO_2	0.64×10^{20} ion/cm^3	-	~ 0.7	210	23.0	0.15	[10]
PECVD (♥)	P_2O_5:SiO_2	0.64×10^{20} ion/cm^3	-	~ 0.7	120	3.7	0.17	[36]
Sol-Gel	Al_2O_3: P_2O_5:SiO_2	0.25 mol%	0.25 mol%	1.1	175	5.0	0.10	[37]
Ion Implantation	Al_2O_3	2.7×10^{20} ion/cm^3	-	0.6	9	4.0	0.35	[12]
Proton Ion Beam	Phosphate	2.16 wt%(Er_2O_3)	4.7 wt%(Yb_2O_3)	1.57	100	1.0	~ 0.80	[38]
FLW*	Phosphate	2.0 wt%(Er_2O_3)	4.0 wt%(Yb_2O_3)	1.97	460 (bidirectional pumping)	3.7	0.40	[39]
	Oxyfluoride Silicate	1.0 wt%(Er_2O_3)	2.0 wt%(Yb_2O_3)	0.72	555(@1480 nm + 980 nm)	1.0	0.34	[40]

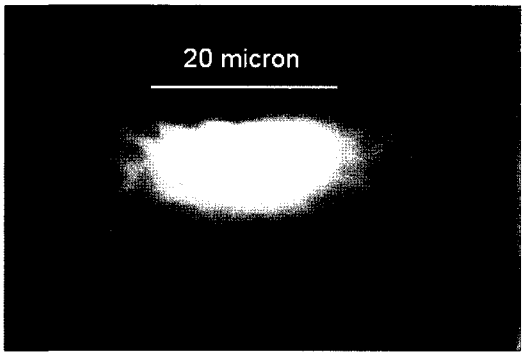

Fig. 5. Measured near field intensity distribution at 633 nm of a channel waveguide obtained by N^+ ions irradiation through a 25 μm wide opening. The 2D confinement of the light demonstrates that there is an increase of the refractive index in the exposed region.

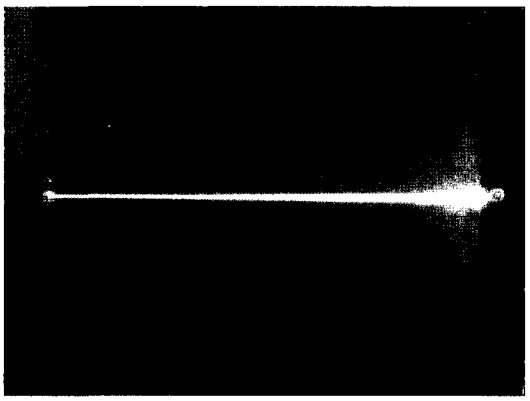

Fig. 6. Confined green up-conversion of Er^{3+} ions along the waveguide of Fig. 5 after 980 nm pumping. The end-fire coupled input fiber is visible on the right side.

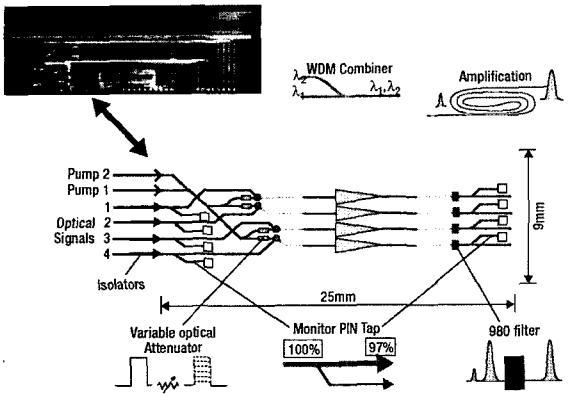

Fig. 7. Schematic presentation of a four EDWA array on an integrated platform fabricated by Inplane Photonics Inc[42].

be of the size of 67×7.5×6.5 mm^3 [43].

Few more words may be spent as a comment to the results presented in Table 3 From a quick look, it appears clear how the performance and the available net gain for each EDWA are strongly material and fabrication process dependent. In particular, with the only exception of Ref.[32], the rf −magnetron sputtering technique, followed by other fabrication processes (i.e.: standard lithography or reactive ion etching) in order to perform ridge or strip waveguide structures, seems to give the best results in terms of gain for unit length in comparison with other techniques, either for phosphate or silicate glasses. The reason of this result may be due to: i) the possibility to obtain a higher index contrast with a better confinement for both signal and pump modes[8]; ii) the high quality and homogeneity of the multi-component glassy thin films deposed, if compared to that of the fused glasses, which reduces the possibility of RE ions interactions and improves the spectroscopic properties of the material[8]. Moreover, the very promising results reported in[17,30,32] demonstrate that it is possible to reach high gain with low pump power even in short and highly doped waveguide amplifiers.

FHD and PECVD techniques, on the contrary, present a different characteristic: a high value for the optical gain can be obtained, at lower erbium/ytterbium doping concentration, by increasing the length of the device and contemporary decreasing the losses along the waveguide[10,36]. At the state of the art, this solution is the one adopted by one of the main manufacturers, namely *Inplane*, which offers on the market different and very compact amplifier families (see Fig. 7) having a net gain, across the C-band, larger than 30 dB in few square centimetres of the device surface[42].

In this consolidated background, the main strain of the research consists in the study of new materials and fabrication processes suitable for a broadband amplification. An example of innovative processes is constituted by femtosecond laser writing[39,40]. In these recent papers, however, a high value of the pump power is reported; this is obtained by a bidirectional pumping system used to obtain the population inversion. For instance, in[40] the gain performance of the waveguide was investigated by a bidirectional pumping scheme with up to 342 mW at 980 nm and 213 mW at 1480 nm, while in[39] it involves two pumps at 975 nm having a power of 260 mW and 200 mW, respectively.

4. Conclusions and Perspective

In this paper an overview on the state of the art of EDWAs has been presented with a particular reference to glass materials for their capability to host high RE ions concentrations. While compact devices formed by a cascade of long amplifier arrays, with low erbium/ytterbium doping level and high performance, are definitively imposing on the market, the future of the research will still be focused on the optimization of materials composition and fabrication processes, in order to get at the same time high gain, broadband and flat amplification characteristics, and rapid and cheap manufacturing. In this sense the possibility, recently demonstrated by our research group, to fabricate i) channel waveguides with low propagation losses (< 0.3 dB/cm) in activated SiO_2-GeO_2 thin films by an UV photoimprinting technique[22] and ii) channel waveguides in Er^{3+}-doped tellurite glasses by ion beam irradiation of N^+ ions[24], can be considered as a good starting point for the realization of a new broadband and L-band amplifier, respectively.

Our ongoing work is also aiming at improving the performance of different glasses: the soda-lime-alumino-silicate (ALxx) glasses, for instance, with an increase up to 60% on the effective emission bandwidth (around 50 nm) if compared with that of a common soda-lime silicate glass, respond to this novel techno-

logical challenge. A detailed analysis of the effects of the matrix composition and of the Yb^{3+}/Er^{3+} ratio on the photoluminescence of a zinc-soda-silicate glass has also been performed in order to achieve high intensity and broadband Erbium emission[44].

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