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# ERBIUM-ACTIVATED SILICATE WAVEGUIDES AND AMPLIFIERS

Giancarlo C. Righini, Stefano Pelli, Maurizio Ferrari *, Massimo Brenci

Optoelectronics & Photonics Dept., IROE CNR "Nello Carrara"
Via Panciatichi 64, 50127 Firenze, Italy
Phone: +39055 4235239 – Fax: +39055 412878 – *righini@iroe.fi.cnr.it*
* CeFSA CNR, via Sommarive 14, 38050 Povo (Trento) Italy
Phone: +390461 881684 - Fax: +390461 881680 - *mferrari@science.unitn.it*

## INTRODUCTION

The development of $Er^{3+}$-doped fiber amplifiers (EDFAs) has had a profound impact on the evolution of optical communication systems. Ten years after the first demonstration of a practical EDFA in 1987 [1], this device had become an almost ideal critically important component for long-haul communications[2], and its inclusion in these systems had already resulted in a capacity (intended as bit rate-distance product) increase of more than two orders of magnitude, from ~ $10^3$ up to $10^5$ Gbit/s·Km [3]. However, the use of optical amplifiers shows a great potential also in local area networks and in access networks, where they can compensate for signal attenuation resulting from distribution or from component-insertion losses. In these cases, $Er^{3+}$-doped waveguide amplifiers (EDWAs) – which are also sometimes referred to as planar optical waveguide amplifiers (POWAs) – promise additional advantages over EDFAs, including integration of passive components on the same chip. It is clear, however, that fiber amplifiers will not be replaced by integrated optical amplifiers, only complemented.

The main difficulty of EDWAs, as compared to EDFAs, is that a sufficiently large gain must be obtained in a device with a much shorter length. This implies using about two order of magnitude higher concentration of $Er^{3+}$ ions, with correspondingly higher risk of cluster formation and stronger ion-ion interactions. Crucial issues are therefore the optimization of glass material composition (which often implies co-doping with $Yb^{3+}$ ions [4]) and of waveguide fabrication processes.

A large number of studies have therefore been performed during recent years on optical glasses activated by Rare Earths. Phosphate and silicate glasses have been the most widely studied materials, the latter ones being attractive due to their superior chemical resistance and compatibility to optical fibers. As to waveguide manufacturing technologies, RF-sputtering, flame-hydrolysis deposition, PECVD, as well as ion implantation, have all been successfully employed.

Aim of this paper is to provide a brief overview of the progress on the development of integrated optical waveguides and amplifiers based on $Er^{3+}$ doped silicate glasses, with special focus on ion-exchanged graded-index guiding structures.

## PLANAR ERBIUM-DOPED WAVEGUIDES

All of the conventional fabrication techniques adopted for integrated optical circuits have been used for $Er^{3+}$-activated waveguides as well. These technologies include: ion-exchange [5-8], RF magnetron sputtering [9], sol-gel [10-13], electron-beam vapor deposition [14].

Some approaches involved the combination of two different technologies, such as ion-exchange to fabricate waveguide and ion implantation to dope the glass with erbium [15], or flame hydrolysis deposition and aerosol doping [16]. Thus, ion exchange and sol-gel techniques have been combined in order to produce channel waveguides [13.b]. Less conventional waveguide configurations have also been suggested, such as a composite guiding structure consisting of an ion-exchanged waveguide in a soda-lime glass and an overlapped Er-doped-glass [17].

Table I summarizes the main characteristics of some typical waveguides, taken as examples among the many more which have been fabricated in laboratories worldwide.

**Table I**

| Glass material | dopant | fabrication technology | loss @633 nm | fluorescence lifetime | ref. |
|---|---|---|---|---|---|
| Na-modified BK7 | 2 wt% $Er_2O_3$ | $K^+$-ion exchange | 0.8 dB/cm | NA | [5] |
| Soda-lime glass | 0.3 mol% $Er_2O_3$ | diluted $Ag^+$ ion exchange | NA | $\tau$=10.5 ms | [6] |
| Soda-lime glass | 3 wt% $Er_2O_3$ | diluted $Ag^+$ ion exchange | 0.7 dB/cm | $\tau$=6 ms | [7] |
| Soda-lime glass | 0.42 atl% Er + 0.54 at% Yb | diluted $Ag^+$ ion exchange | 0.4 dB/cm | $\tau$=6 ms | [8] |
| Soda-lime glass | 0.2 atl% Er * | $K^+$-ion exchange | ~ 1 dB/cm | $\tau$=7.2 ms | [16] |
| Na-Ca-silicate | 1 at% Er | RF-magnetron sputtering | 1 dB/cm | $\tau$=7-10 ms | [9] |
| Aluminosilicate | 8535 ppm Er | sol-gel | NA | NA | [10] |
| Aluminosilicate | 0.5 at% Er | sol-gel | 0.5 dB/cm | $\tau$=3.5 ms | [11] |
| Silica-titania | 1 at% Er | sol-gel | NA | $\tau$=1.8 ms | [12] |
| Germania-silica | 0.2 mol% Er | sol-gel | 2-3 dB/cm | $\tau$=3-6 ms | [13] |
| Germania-silica | 600 ppm Er | electron-beam vapour dep. | 0.11 dB/cm ** | NA | [14] |
| P-doped silica | 0.5 wt% Er | FHD + aerosol doping | ~0.5 dB/cm | $\tau$=3.5 ms | [15] |

Notes: NA= not available; *doping is obtained by 3- and 5-MeV ion implantation; ** loss measured at $\lambda$=1.30 µm.

## ERBIUM-DOPED WAVEGUIDE AMPLIFIERS

The most critical issue to step from an $Er^{3+}$-activated waveguide to an integrated optical amplifier, exhibiting net gain, is concerned on one side with the reduction of propagation losses and on the other side with the proper concentration of erbium ions. Generally, at low $Er^{3+}$concentration, the lifetime of the metastable level is longer and quantum efficiency is higher, but obviously the total intensity of stimulated emission is lower; at higher concentrations, fluorescence quenching may occur, due to ion clustering or ion-to-ion interaction. Another important parameter to judge about the quality of an EDWA is the pump power necessary to reach the maximum gain (before going into gain saturation); alternatively one can consider the pump threshold, i.e. the power at which the material becomes transparent (signal amplification being able to compensate for propagation and absorption losses, or, in other words, for insertion losses minus input-output coupling losses).

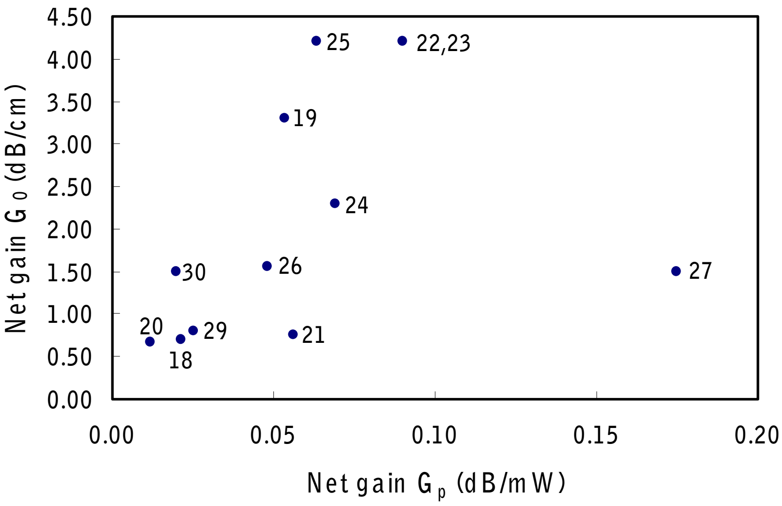


Fig. 1. Optical gain merit factors of several fabricated EDWAs based on erbium doped silicate glasses. Labels of data points correspond to references.

Here we considered two factors of merit for an EDWA: the net gain per length unit $G_0$ (dB/cm) and the net gain per pump power unit $G_p$ (dB/mW). Figure 1 shows these two factors for many, but definitely not all, results published on EDWAs in silicate or silica-based glasses; Table II reports the additional information available. We apologize with colleagues for any involuntary omission.

It has to be underlined that comparison of the reported results should be considered only qualitative, because one of the problems often encountered when checking literature is that it is not clear if measurement methods and units are used everywhere in a consistent way. As an example, not always it is certain if authors refer to signal enhancement (namely, increase of transmitted signal due to stimulated emission, without considering propagation and absorption losses) or to net gain; in some cases, 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 cases only the power available at the end of the input fiber is given, and in some other cases there is not a clear indication. However, even if not fully quantitative, the results reported in Fig.1 and Table II clearly indicate that there have been rapid progresses and that efficient amplifiers can be integrated with other passive components, like 1 x N splitters and WDM components.

**Table II**

| **Glass material** | **Fabrication technology** | **Dopant** Er | Yb | **MAX Net Gain (dB)** | **Length (mm)** | **Pump power (mW)** | **Ref.** |
|---|---|---|---|---|---|---|---|
| P-doped silica | FHD | 0.55 wt% | | 13.7 | 19.4 | 640 | *[18]* |
| Soda-lime silicate | RFS | 14600 ppm | | 15.0 | 45.0 | 280 | *[19]* |
| Phosphosilicate | PECVD | 0.48 wt% | | 5.0 | 75.0 | 420 | *[20]* |
| Soda-lime silicate | RFS | 0.7 $10^{20}$ at/cm$^3$ | | 4.5 | 59.0 | 80 | *[21]* |
| Silicate | RFS | 3.3 wt% $Er_2O_3$ | | 7.2 | 17.0 | 80 | *[22.23]* |
| Borosilicate | IE | 3 wt% $Er_2O_3$ | 5 wt% $Yb_2O_3$ | 9.0 | 39.0 | 130 | *[24]* |
| Soda-lime | RFS | 4.1 $10^{20}$ at/cm$^3$ | | 19.0 | 45.0 | 300 | *[25]* |
| Soda-lime | IE | 2 wt% $Er_2O_3$ | 5 wt% $Yb_2O_3$ | 4.3 | 28.0 | 90 | *[26]* |
| Aluminosilicate | RFS | NA | | 21.0 | 140.0 | 120 | *[27]* |
| Er-Yb BK7 IE | IE | 1 wt% $Er_2O_3$ | 5 wt% $Yb_2O_3$ | 2.2 | 2.2 | 110 | *[28]* |
| Silicate RFS | RFS | 0.77 wt% | | 5.0 | 56.0 | 200 | *[29]* |
| Soda-lime IE | IE | 2.3 $10^{20}$ at/cm$^3$ | 3.8 $10^{20}$ at/cm$^3$ | 5.0 | 34.0 | 250 | *[30]* |

Notes: FHD=Flame Hydrolysis Deposition; RFS= Radio Frequency Sputtering; PECVD=Plasma-Enhanced Vapor Deposition; IE= ion exchange

Just to complete the scenario, it may be useful to mention that similar, or better, results have been obtained in phosphate-based glasses too. For instance, 4.1 dB/cm net gain at a very low pump power of 21 mW was reported for an RF-sputter deposited phosphate film [31]; a record net gain of 7.3 dB in a 6 mm waveguide (i.e. 12.2 dB/cm) with 50 mW pump power was claimed for an ion-exchanged Er-Yb doped phosphate glass [32].

## CONCLUSIONS

The development of integrated optical amplifiers based on $Er^{3+}$-$Yb^{3+}$ co-doped glasses is proceeding at a fast rate. Quite good results, such as net gains higher than 4 dB/cm and 0.15 dB/mW have been already demonstrated in different oxide glasses. Even if erbium-doped phosphate glasses so far seem to offer slightly better performance [33], $Er^{3+}$-$Yb^{3+}$-activated silicate waveguides continue to attract great attention, and the search for more and more efficient compositions and guiding structures is still going on.

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