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# Rare earth-doped confined structures for amplifiers and lasers

B. Jacquier*, E. Lebrasseur[1], S. Guy, A. Belarouci, F. Menchini[2]

*Laboratoire de Physico-Chimie des Matériaux Luminescents (L.P.C.M.L.), UMR No. 5620 CNRS-Université Claude Bernard Lyon 1, Bât. 205, 69622 Villeurbanne Cedex, France*

**Abstract**

Here, we present an overview of the specific spectroscopic properties of fluoride planar waveguides which emphasize the difference between rare earth-doped waveguide and bulk and demonstrate their potentiality to be used as lasers and amplifiers. We illustrate this with recent results obtained at strategic wavelengths for telecommunications. Furthermore, we are dealing with even more confined structures such as optical microcavities that are resonators in which at least one of the dimensions is of the order of the optical wavelength. These structures enable to control the spontaneous emission properties of rare-earth doped materials placed inside them. 

*Keywords:* Fluoride planar waveguides; Lasers; Amplifiers

## 1. Introduction

Rare-earth doped insulating materials exhibit varieties of luminescent behavior with applications in solid-state physics, high-energy physics, medical physics and telecommunications as well as for fundamentals research. Recently the incorporation of trivalent rare earths into waveguides has created an upsurge of interest in the field of signal processing for telecommunication systems based on the success of the very efficient erbium-doped fiber amplifier (EDFA) for long-haul transmission links [1], promptly followed by the praseodymium-doped fluoride fiber amplifier working at 1.3 μm [2].

More recently, much effort has been dedicated to the development of doped planar waveguides, either crystalline [3,4] or glassy [5] oxide materials for which laser action and amplification have been already reported. The elaboration of erbium-doped high optical quality thin films structured in stripes by photolithography for waveguiding applications techniques has permitted to demonstrate small signal amplification in the third telecommunication window at 1.5 μm as well as division multiplexing. Net gains up to 3.3 dB/cm have been achieved in silica-based materials [6] or in phosphate glasses [7]. However, short devices of few centimeters long, are required for integrated optics which limit the gain performance. This is particularly critical for silica-based glasses where well-known concentration-quenching effects occur even at low concentration because of the low solubility of rare earth ions in the silica net and inhomogeneous doping distribution. As a consequence, phosphate glasses were successfully proposed to circumvent this concentration quenching effect, the phosphate group acting to limit the coupling interaction between rare earth ions, though a higher phonon energy slightly affects the radiative properties. These are the reasons for which heavy metal fluoride glasses (HMFG) are good candidates to fulfill high rare earth concentration conditions, low phonon energy and excellent radiative probabilities [8]. As a consequence, fluoride, either bulk or fiber, materials have extended the range of wavelengths to the visible and near UV [9]. More recently, the elaboration of rare earth-doped planar and channel waveguides using different techniques has been reported [10,11]. At present, the main reports demonstrate the potentiality of the HMFG channel waveguides with emphasis on the determination of spectroscopic parameters and some amplification measurements [12].

In the first part of this paper, we review the main examples of the literature and bring some new amplification measurements obtained on rare earth-doped waveguides made by the physical vapor deposition technique in Le Mans. In waveguide amplifiers, advantage is taken of

*Corresponding author. Tel.: +33-4-7244-8336; fax: +33-4-7243-1130.

*E-mail address:* jacquier@pcml.univ-lyon1.fr (B. Jacquier)

[1]Present address: LIMMS/CNRS-IIS University of Tokyo, Minato-ku, Tokyo 106-8558, Japan.

[2]Permanent address: ENEA, Dip. Innovazione, C.R. Frascati C.P. 65, 00044 Frascati, Italy.

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the propagation of light combined with spontaneous and stimulated emissions of atoms in free space modes. In the second part of the paper, we detail our recent spectroscopic results on praseodymium-doped tantalum oxide film in a stack of multi-dielectric layers [13,14]. Due to the advent of high quality optical thin films with thicknesses of a fraction of a wavelength and multi-deposition techniques, Fabry Perot resonators are available to control the spontaneous emission properties of luminescent centers embedded in so-called microcavity [15].

## 2. Rare earth-doped fluoride waveguides

### *2.1. Characterization of waveguides*

High optical quality glass films are now available with many chemical compositions, such as low and high index of refraction oxides or more recently with heavy metal fluoride glasses. Much effort has been made to introduce active ions such as rare earth in the glass net to induce efficient luminescent properties. For fluoride waveguides, two types of techniques have been used.

- Fluorine→chlorine anionic exchange was achieved at the surface of rare earth-doped ZBLA ($ZrF_4$, $BaF_2$, $LaF_3$, $AlF_3$) glass substrate following a diffusion process. Strip waveguides were prepared by carrying out photolithography to create masked regions of silica on glass surface. The anionic exchange was then followed by a reactive ion etching (RIE) technique to remove the $SiO_2$ mask. Optical characterization was performed by m-line technique or near field to reveal the index of refraction change and mode profiles resulting in a single mode propagation in the near infrared at 830 and 1.015 nm for an undoped 3-μm wide waveguide [16]. Rather high losses have been measured in the rare earth-doped structures.
- Physical vapor deposition technique was used to produce planar or channel rare earth-doped waveguides with glass composition including lead, zinc, gallium fluorides (PZG), due to similar vapor pressure of the constituents. Because of higher vapor pressures of rare earth chlorides with respect to fluorides, it was recently proposed to evaporate simultaneously PZG glass composition together with rare earth chloride as dopant [17]. This procedure was applied after a photolithography process used to create strips. The doped glass composition was deposited on a $CaF_2$ plate, resulting in a number of channel waveguides with multimode propagation because of the high index of refraction differences between the film and the substrate. Low loss waveguides have been obtained in the near infrared range.

The luminescent properties of the rare earth-doped channel waveguides were spectroscopically analysed using end-pump configuration as described in an earlier report [12]. Since our attention was focused on erbium-doped HMFG channel waveguides, laser diodes around 1.5 μm were required both to pump at 1.485 μm (up to 100 mW) and to stimulate the emission across its broad spectral range with a tunable laser diode (from 1.48 to 1.58 μm). Indeed, for low phonon energy material such as HMFG, it is necessary to pump directly the laser transition on its high energy side (quasi four-level system), as shown in Fig. 1 where the absorption and emission spectra are reported together with the pump wavelength and the tunable signal wavelength. The various cross-sections were measured from the bulk (Table 1) while the lifetimes were

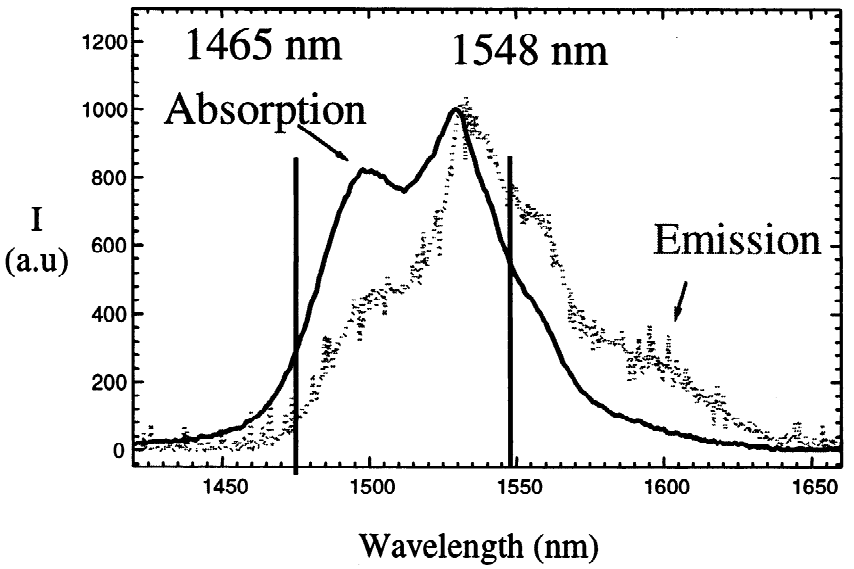


Fig. 1. Absorption and excitation spectra of a 0.5 erbium-doped ZBLA bulk.

Table 1
Absorption ($\sigma_a$) and emission ($\sigma_e$) cross-sections for the various samples

| Sample | $\sigma_a$ ($cm^2$) at 1485 nm | $\sigma_e$($cm^2$) at 1548 nm |
|---|---|---|
| ZBLA bulk | $2.9\times10^{-21}$ | $3.4\times10^{-21}$ |
| ZBLA/$CL^-$ | | $3.8\times10^{-21}$ |
| PZG bulk | $3.0\times10^{-21}$ | $4.5\times10^{-21}$ |

determined with the end-pump configuration since its value is highly sensitive to the method of preparation.

In most of the cases, the lifetimes are affected by the presence of residual $OH^-$ groups always present in the elaboration process and at high rare earth concentration. This is shown in Figs. 2 and 3 [18,19].

From these figures, we observe a shortening of the decay which is due to either concentration quenching by energy transfer processes or vibrational relaxation in presence of high energy phonons. However, we note that for passivated (anionic $Cl^-/F^-$ process) waveguides, the long decay time

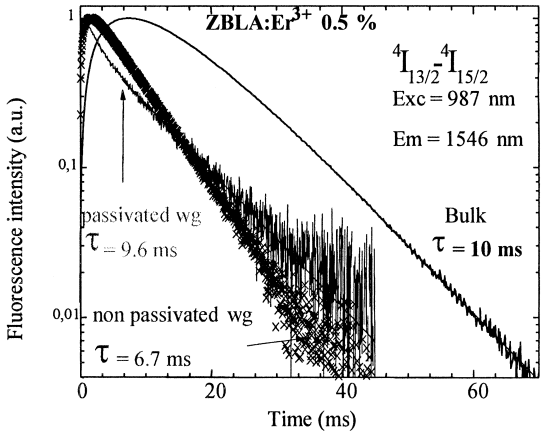


Fig. 2. Fluorescence decay of erbium-doped ZBLA channel waveguides: comparison with bulk.

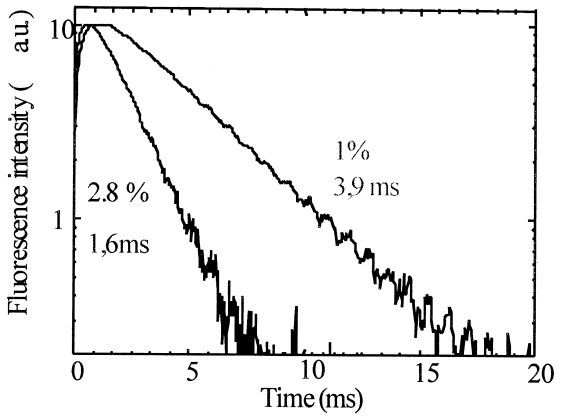


Fig. 3. Fluorescence decay of erbium-doped PZG glass channel waveguides for two concentrations.

reaches that of the bulk, although the short time behavior is not yet well explained. Similarly, the 3.9-ms value determined in the 1.0% erbium-doped waveguides is slightly shorter than the 5.9 ms measured in the 0.1% doped bulk [20].

### 2.2. Amplification

Pump beam at 1465 nm and tunable signal beam around 1530 nm were colinearly superimposed through a glass plate and then shone on the input end-fire of the channel waveguides. At the output, the signal is discriminated from the pump by filtering and modulation to measure gross (or internal) gain by comparing the intensity on the detector with and without the pump beam. Finally, losses (absorption and propagation) must be subtracted to reach the net gain.

As an example, we report in Fig. 4 the internal gain as a function of the wavelength of the signal in a 5-μm wide, 1.34-cm long erbium-doped PZG channel waveguide [19].

A maximum gain of 1.6 dB/cm was achieved at 1530 nm with only 3 mW of absorbed pumped power. Knowing that losses including absorption and propagation should be of the same order of magnitude as the gain in the infrared region, we are expecting to achieve net gain shortly.

## 3. Optical microcavities

### 3.1. Resonators

In this study, micro-resonators are composed of a multi-dielectric thin ($\lambda/4$) film stack of alternating layers of $SiO_2$ ($n=1.47$) and $Ta_2O_5$ ($n=2.27$ at 633 nm) in which the central layer ($\lambda/2$) is a rare earth ion-implanted $Ta_2O_5$ film. A full theoretical treatment of the coupled electromagnetic field of the atom and of the cavity, either classically [21] or quantum mechanically [22], shows that the position of the atom in the central layer can greatly enhance (or inhibit) the radiative emission if it stands at an antinode (or node) of the field amplitude. Consequently, it is possible to point out the effects of the cavity on the radiative properties such as radiation pattern, wavelength filtering and angular dependence, as well as fluorescence dynamics [23]. All the layers studied here were prepared by plasma-assisted deposition technique (ion plating) on silica substrate. Three types of samples have been considered in this work: (a) a single layer with $6\lambda/4$, (b) a halfmicrocavity with a mirror $Ta_2O_5/M8/SiO_2$ (M8 is eight alternate layers of $Ta_2O_5/SiO_2$, (c) a microcavity, Fabry-Perot structure (half cavity closed by a mirror M8), as shown in Fig. 5.

Praseodymium ions have been implanted at room temperature with doses ranging from $2.5\times10^{13}$ to $2.5\times10^{15}$ ions $cm^{-2}$ at an energy of 300 keV. Then, the praseodymium ions are lying in a layer of approximately

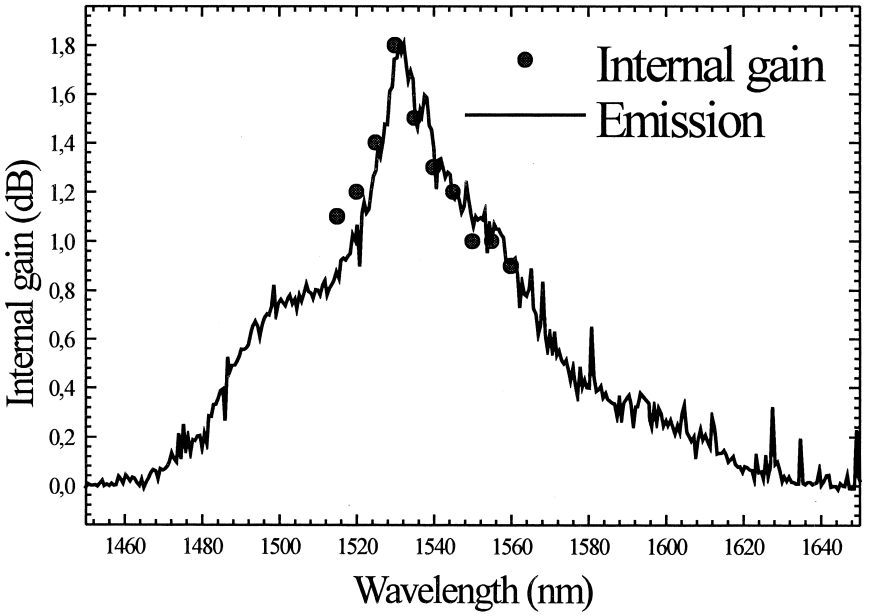


Fig. 4. Internal gain versus wavelength.

50 nm thick at the surface, with concentrations of $10^{18}$ to $10^{20}$ ions/cm$^3$. Finally, the samples were annealed in air at 400°C for 10 h.

### *3.2. Spectroscopy of the praseodymium-doped microcavity*

Spectroscopic measurements were performed either with a CW or a pulsed laser tuned to the blue or red absorption of praseodymium ions. The most original part of the experiment is the angular conditions of excitation and detection with respect to the excitation and emission wavelengths; this has been already reported elsewhere [24,25].

To illustrate the angular dependence of the emission, the Fig. 6a,b shows the change in the radiation pattern of the blue $^3P_0$ emission of praseodymium at 490 nm between halfcavity and microcavity. A subsequent strong enhance-

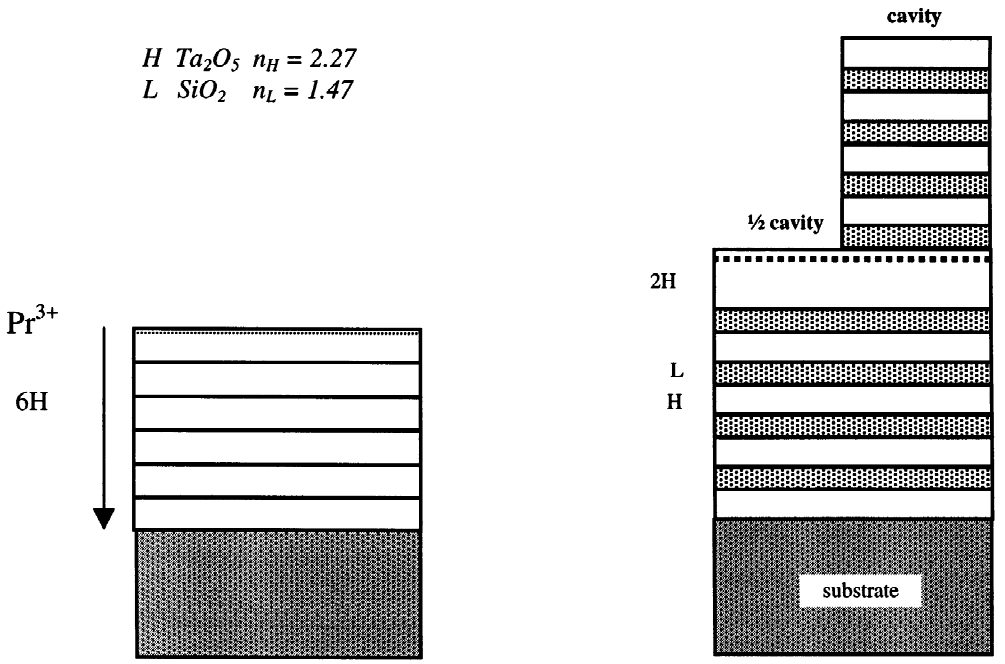


Fig. 5. Praseodymium-doped single layer, halfcavity and microcavity.

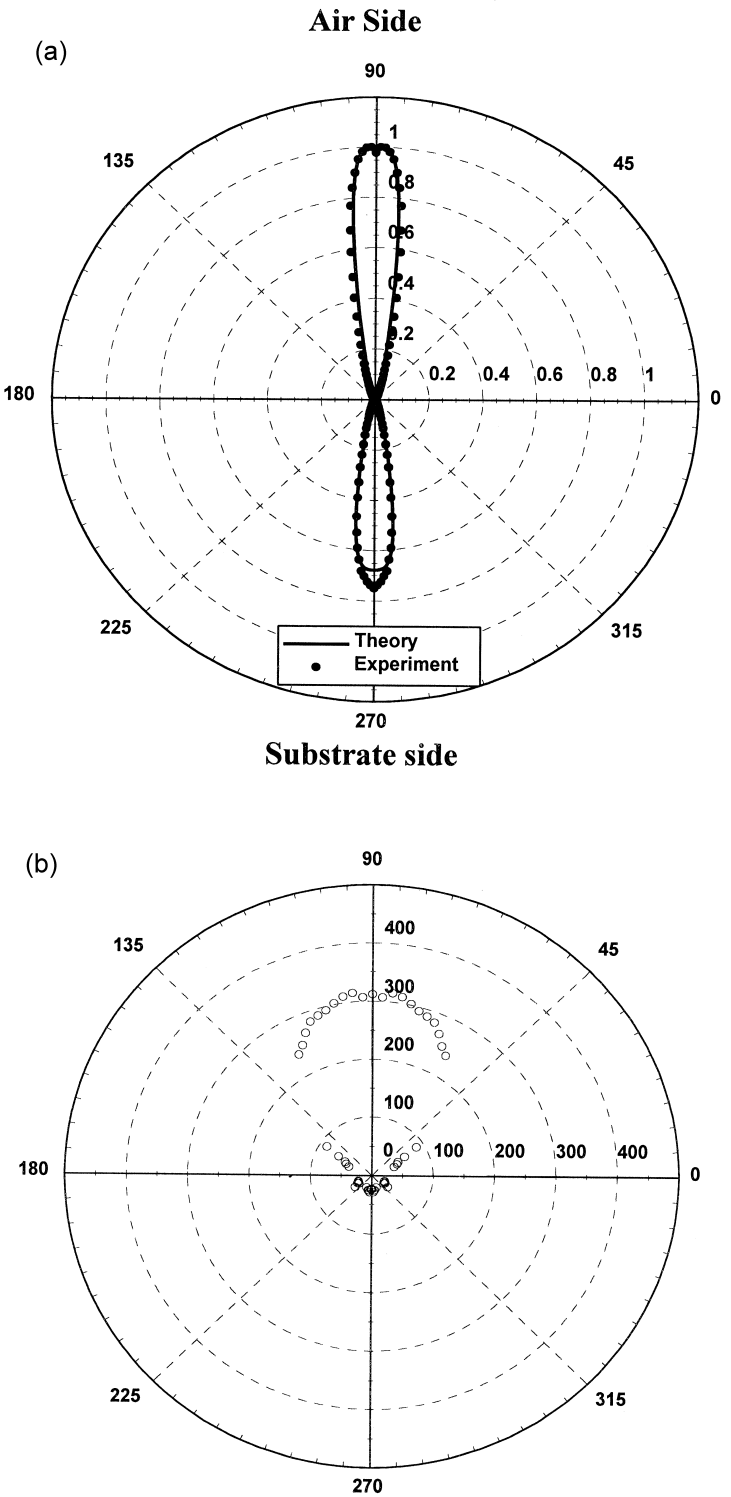


Fig. 6. (a) Experimental and theoretical radiation patterns for a blue microcavity at 490 nm. (b) Experimental radiation pattern for a blue halfcavity at 490 nm.

ment of the emission is measured, typically a factor of 40 (not on scale in the figures). As the wavelength is tuned either toward higher or lower wavelength, the maximum of the intensity deviates from the normal direction by an angle related to the wavelength shift [13].

The last observation is the modification of the radiative probability measured by the change in the fluorescence decay, as shown in Fig. 7.

The observed change of the decay is somewhat larger than expected from the theory (30%). However, for the

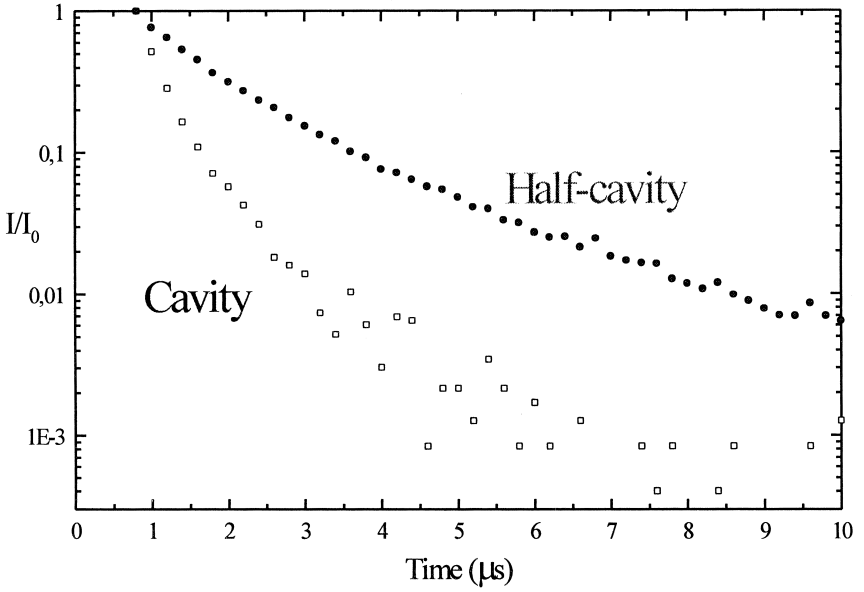


Fig. 7. Fluorescence decay recorded at 495 nm for the halfcavity and microcavity.

same measurement in the red cavity [14], the agreement is much better, but the difference here is presently not well understood.

## 4. Conclusion

We have reviewed the highest performances obtained in the determination of signal gain amplification in erbium-doped heavy metal fluoride glass channel waveguides. We are expecting in the very near future to demonstrate net gain, as for silica or phosphate channel waveguides but with a much broader spectral range useful for wavelength division multiplexing devices. As we confine more light into Fabry-Perot structure, we have shown the modification of the spontaneous emission rate in dielectric media which can be applied for the realization of a laser without threshold.

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