Microsphere laser in Er$^{3+}$ doped oxyde glasses

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ABSTRACT

We have succeeded in continuous-wave laser oscillation on $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of Er$^{3+}$ ions around 1550 nm in microspheres fabricated with Erbium doped phosphate “Schott” and silica “Baccarat” glasses. The microsphere lasers have been studied under pumping at 1480 nm. Whispering Gallery Mode laser spectra were analyzed for different sphere diameters. Wavelength Red-shift effect of both fluorescence and laser spectra was experimentally observed in Er$^{3+}$ doped phosphate glass when the pump power was increased, originating from thermal effects.

Keywords: Whispering Gallery Modes, Erbium, microlaser, microspherical resonator

1. INTRODUCTION

In dielectric spheres light can be guided through high-Q whispering-gallery-modes (WGMs). A unique combination of strong temporal and spatial confinement of light can be achieved in microspheres which makes these systems of interest for a large number of applications such as quantum optics$^1,2$ or optical communications.$^3$ Since the pioneering works of Garret et al.$^4$ on Sm$^{2+}: \text{CaF}_2$ spheres and works on Morphology-Dependent Resonances (MDR) and lasing effects in droplets during the 80’s,$^5$ rare earth-doped glass microspherical lasers became subject to numerous studies and significant progress has been achieved in the past decade, as described in a recent review.$^6$ Many papers have been published on such type of lasers and most of them merely focus on the laser performances such as the threshold of oscillation, the slope efficiency as well as coupling designs. However, few studies describing the role of spectroscopic and thermal properties of the active medium on the laser behavior have been published. In this paper, we will essentially focus our attention on them. The idea is that a very small amount of glass is necessary to fabricate a microspherical laser. If one knows how to relate the laser properties to the glass properties, it will be easier to optimize the composition of the glass before making large quantities for use in larger systems, such as amplifiers or optical fiber lasers.

In this paper, after a brief introduction to WGMs we describe experimental results on laser oscillations obtained using a tapered fiber for efficient coupling. Our experiments have been focused on the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition at 1550 nm of Erbium ions in phosphate glass spheres. Both fluorescence and laser spectra have been experimentally observed when the pump power was increased, giving rise to thermal effects. We also report the preliminary results of our investigation on the effects that the sphere shaping by fusion in microwave plasma torch has on spectroscopic properties of Baccarat glasses.

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2. GENERAL PROPERTIES OF WHISPERING GALLERY MODES

In the optical domain, whispering-gallery modes can be viewed as high angular momentum electromagnetic modes in which light propagates by repeated total internal reflection (TIR) surface at grazing incidence with the proper phase condition after circling along the sphere surface. By going through the standard Mie scattering formalism,\(^8\) the resonance condition can be written as:

\[
P N(x) = N(x)
\]

where \( P = N \) for TE polarization (\( P = N^{-1} \) for TM) and \( \nu = \ell + 1/2 \) comes about in translating the spherical Bessel and Neumann functions to their cylindrical counterparts. The quantities in Eq.1 can be expressed as asymptotic series\(^9\) in powers of \( \nu^{-1/3} \). This leads to the first terms of the resonances expressed in size parameter:

\[
N x_n, \ell = \ell + 1/2 - \left( \frac{\ell + 1/2}{2} \right)^{1/3} \alpha_n = \frac{P}{\sqrt{N^2 - 1}} + \ldots
\]

where \( \alpha_n \) are zeros of Airy function \( A_1(–z) \). This equation allows to precise the main characteristics of WGM spectrum. WGM resonances are described by a polarization (TE or TM) and three quantum numbers \((n, \ell, m)\) which represent the radial, angular and azimuthal mode numbers, respectively. First, (for one \( n \) value) the spectrum is quasi-periodic versus \( \ell \), this corresponds to a pseudo-Free Spectral Range (FSR) \( \Delta_\nu = c/2\pi Na. \) Second, the spacing between modes having same quantum numbers but different polarizations is \( x_{n, \ell}^{TE} - x_{n, \ell}^{TM} = \sqrt{N^2 - 1}/N^2 \). The greatest change of frequency is produced by variation of \( n \) (as example with \( \ell = 250 \) the mode separation \( \sim 10\Delta_\nu \)) it decreases when \( n \) values grow up. Small ellipticities lead to a quasi-equidistant mode family characterized by \( \Delta \nu/\Delta|m| = e \Delta_\nu. \)

2.1. Experimental Setup

To excite High-Q WGMs (lowest \( n \)), light has to be launched from a phase-matched evanescent wave in an adjacent waveguide or a prism under total internal reflection. For microspherical lasers, most of couplings have been realized by free beams,\(^10\) prisms,\(^11, 12\) tapers\(^13\) and half tapers.\(^14\) Among the different pumping wavelengths which can be used with Erbium doped glasses\(^15\) (810 nm, 975 nm and 1480 nm) we chose 1480 nm to obtain a good overlap between the pump and laser mode volumes in the micro-sphere and to optimize the lasing process in our system. Another advantage of using one single half-taper is that the pump wavelength is close enough to that of the laser field, so both pump and laser fields can be coupled in and out the microsphere. The fiber coupling experiments were performed with half-tapered fiber, that we obtained by heating and stretching.
standard telecommunication fiber (single mode at 1.55 μm) until breaking, using a fusion splicer. The drawn length was typically 850 μm, and the taper end reduced to 1.5 μm in diameter. The experimental Setup (see Fig.1) was realized with standard fiber-optic components spliced or connected with APC connectors. Mounting Erbium doped spheres on micro-translations brought the equator region in contact with the evanescent field surrounding the taper. The pump device was based on a multimode-fiber laser diode operating at 1.48 μm, an isolator that prevent feedback into the laser diode, and an multiplexer/demultiplexer (X-coupler) at 1.48-1.55 μm. The X-coupler allowed us to use the same fiber to pump and to collect the fluorescence or the laser signal. The X-coupler enabled us to have a pump reference separated from the sphere signal, which was analyzed with a 70 pm resolution optical spectrum analyzer (OSA). The sphere fabrication by fusion in a microwave plasma torch was described in previous work.12

3. RESULTS

3.1. Phosphate glass spectroscopy

The phosphate glass used, was an Er3+/Yb3+ co-doped phosphate glass (Schott IOG-2) doped with 2% weight of Er2O3 and co-doped with 3% weight Yb2O3. Absorption spectra were recorded on a Cary 9000 spectrometer with a resolution better than 0.1 nm. Figure 2.a presents sections for the 4I_{13/2} —> 4I_{15/2} transition. The emission cross section spectra were derived using the reciprocity relation of McCumber’s theory16 where absorption (σ_a(λ)) and emission (σ_e(λ)) cross sections are related by

$$\sigma_e(\lambda) = \sigma_a(\lambda) \cdot \frac{Z_L}{Z_U} \exp\left[\frac{hc}{k_BT} \left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)\right] $$

where $Z_L, Z_U$ are the partition functions of the upper and lower levels, $\lambda_0$ the wavelength corresponding to the two lowest Stark levels of the $4I_{13/2}$ and $4I_{15/2}$ levels. $h$ is the Planck's constant, $c$ the light velocity, $k_B$ the Boltzmann’s constant and $T$ the temperature in Kelvin. Computation of $Z_L, Z_U$ needs the spectroscopic values of both levels of Erbium ion, i.e. their degeneracies and Stark-level energies (see Eq.2 in Ref. 16). In general, such Stark components of Er3+ doped glasses can be deduced from the low temperature absorption-emission spectra.17 Based on these absolute cross section spectra, the net gain spectra $G(λ,p)$ (Fig.2.b) can be computed in terms of the pumping level18 as the following:

$$G(λ,p) = n_{Er} \cdot [p\sigma_e(λ) - (1-p)\sigma_a(λ)]$$

where $p$ is the fractional factor of the excited Erbium ions in the metastable level $4I_{13/2}$. It is important to note that $p$ is an excitation parameter averaged over temperature due to Stark effects of both the upper and
lower levels. \( G(\lambda, p) \) represents the gain spectra at room temperature which is applicable to the lasing threshold condition where there is no significantly increase of temperature. We can note a laser domain extending in the L band for low pumping level.

### 3.2. Laser effects in phosphate glass

For any sphere diameter, the optical spectrum of the output signal from the sphere below the laser threshold shows an enhancement of the fluorescence intensity and a higher peak density (Fig.3.a) than those obtained with a prism as demonstrated in a previous paper. Nevertheless we can use an analysis similar to that used for excitation by a prism for the fluorescence spectra on the basis of asymptotic expressions for WGM size parameters. This standard analysis shows that these series of peaks can be assigned to several families of modes, each of them having the same radial order \( n \) but different polarizations and angular momenta \( \ell \). When increasing the pump intensity we obtained laser oscillation. By varying the gap \( e \) and the position \( d \) between the tip of the half taper and the sphere (see Fig.1) the emission domain can be selected. For a large gap value and a low pumping ratio we have obtained a laser emission around 1601 nm (Fig.3.b). For a lower gap value associated to higher pumping ratio we have obtained single mode or multimode laser effects for lower wavelengths.

Red shift effect on the wavelength of WGMs is experimentally observed when the pump power is increased. This effect was previously observed and explained by a simple model in Er\(^{3+}/\)Yb\(^{3+} \) phosphate microchip laser and Er-ZBLAN microspherical laser. Typical results are illustrated in figure 4, the two lasing peaks at 1567.1 nm and 1569.4 nm when the probe intensity is 0.5, shift further to 1567.6 nm and 1569.9 nm, respectively, under 3.5 excitation (Fig.4.a). Similar red-shift behaviours have also been observed for other lasing or non-lasing WGMs (Fig.4.b) as the pump intensities is increased and this happens for every sphere diameter. It should be noted that all WGMs shift by almost 0.5 nm towards longer wavelength under the probe power domain extending from 0.5 to 3.5. A spectroscopic technique based on the green upconversion fluorescence could be used to compute a loading effective temperature in the Er\(^{3+}/\)Yb\(^{3+} \) phosphate microsphere and this further should allow us to calibrate the properties of the microsphere laser in terms of the thermal expansion as well as the variation of the refractive index.

### 3.3. Baccarat glasses spectroscopy

In this section we report the preliminary result on the spectroscopic properties of silica microspheres doped with different Erbium content, and on their comparison with the corresponding bulk glasses. The microspheres were prepared starting from modified-silica bulk samples doped with 0.2, 0.5 and 1.5 mol % of Erbium, respectively. We focalise our attention on the sample doped with 1.5 mol % of Erbium; similar result are obtained for the other glasses. Photoluminescence spectroscopy, in the region of the \( ^{4}I_{13/2} \rightarrow ^{4}I_{15/2} \) transition of Er\(^{3+} \) ion was performed using the 980.8 nm line of a Ti:Sapphire laser as excitation source. The luminescence was
dispersed by a 320 mm single-grating monochromator with a resolution of 2 nm. The light was detected using a Si/InGaAs two-colors photodiode and standard lock-in technique. Decay curves were obtained recording the signal by a digital oscilloscope. For both the precursor bulk samples and the microspheres the standard bulk measurement configuration has been used. In figure 5.a the photoluminescence spectra of the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of Er$^{3+}$ ion are reported for the bulk and the corresponding microsphere. Figure 5.b shows the related luminescence decay curves obtained after pumping at 980.8 nm with an excitation power of 450 mW. The luminescence spectrum and lifetime measurements made for bulk and microsphere are different; as to the former measurement, the main difference is the spectral broadening. The bandwidth is larger for erbium-activated microsphere when compared with the precursor glass. It is evident that the site-to-site inhomogeneities are effective in the microspheres and this is probably due to the fabrication process. However, because of the restricted number of samples, so far it is impossible to determine the specific reason of the induced inhomogeneity. In fact it would be necessary to have several concentrations, spanning on a larger scale, and also to check the effect of different fabrication temperatures. Lifetimes measurements give further information about the site-to-site inhomogeneities. In fact, the decay curve of the Erbium in microspheres shows a faster relaxation indicating that energy transfer mechanism among active ions is effective. The conclusion of this preliminary study is that the transformation into microsphere could actually change the environment of Erbium ion in a same glass matrix. Recently, using the same half taper coupling scheme, continuous-wave laser oscillation around 1570 nm was obtained in 0.5 mol % Er$^{3+}$ doped spheres (inset Fig.5.a).

4. CONCLUSION

WGMs lasing action was obtained in Er$^{3+}$/Yb$^{3+}$ doped phosphate glass with high Erbium concentration. This indicates that good coupling of the pump wavelength from a fiber half-taper into a low n-order WGMs was achieved. Red-Shift of the lasing wavelength with increasing pump power was also observed and explained as a consequence of thermal effects.

Luminescence spectra and lifetimes of the $^4I_{13/2}$ level of Er$^{3+}$ ions in silica Baccarat glass both in bulk and microspheres configurations were measured and compared. The bandwidth extension and the lifetime reduction in the microsphere were related to the changes induced by the fabrication process.

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Figure 5. Room temperature measurements in 1.5 mol % Erbium doped glass (a) photoluminescence spectra of the \( ^4I_{13/2} \rightarrow ^4I_{15/2} \) transition of Er\(^{3+}\) ion for the bulk sample (full line) and the microsphere (dotted line)- inset - Laser action in 0.5 mol %-Er\(^{3+}\) doped sphere. (b) luminescence decay curve from the \( ^4I_{13/2} \) state

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