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Photoluminescence and lasing in whispering gallery mode glass microspherical resonators

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ABSTRACT

We report experimental results regarding the development of Er^{3+}-doped glass microspherical cavities for the fabrication of compact sources at 1.55 μm. We investigate several different approaches in order to fabricate the microspheres including direct melting of Er^{3+}-doped glass powders, synthesis of Er^{3+}-doped monolithic microspheres by drawing Er^{3+}-doped glass, and coating of silica microspheres with an Er^{3+}-doped sol–gel layer. Details of the different fabrication processes are presented together with the photoluminescence characterization in free space configuration of the microspheres and of the glass precursor. We have analyzed the photoluminescence spectra of the whispering gallery modes of the microspheres excited using evanescent coupling and we demonstrate tunable laser action in a wide range of wavelengths around 1.55 μm. As much as 90 μW of laser output power was measured in Er^{3+}-doped glass microspheres.

1. Introduction

Optical resonators play a ubiquitous role in modern optics. A particular class of optical resonators is constituted by spherical dielectric structures, where optical rays are totally internally reflected. Due to minimal reflection losses and potentially very low material absorption, these guided modes, known as whispering gallery modes, 10^{-4} can confer the resonator an exceptionally high quality factor Q, leading to high energy density, narrow resonant-wavelength lines and a lengthy cavity ringdown. These attractive characteristics make these miniaturized optical resonators especially suited for the investigation of fundamental processes in quantum or non-linear optics [1–4] as well as for applications in photonics [5,6] but also as very sensitive sensors [7,8].

WGM microspherical resonators play an important role in the pursuit of compact and efficient laser sources because of their intrinsic potential for low lasing threshold and narrow spectral characteristics [9–12]. Since the pioneering works of Garret et al. [13] on Sm^{2+}:CaF_2 spheres and works on Morphology-Dependent Resonances (MDRs) and laser effects in droplets during the 80's [4] rare earth-doped glass microspherical lasers became subject of numerous studies, significant progress was achieved in the past decade as described in recent reviews [14,15]. Up to now, WGM microspherical lasers have been obtained by melting rare-earth doped optical fiber tips using fusion techniques [11,16–18], by microwave plasma torch fusion of grounded powers [19,9] or by electric tube furnace [20] by sol–gel [21–23] or glass [24] coating of silica microspheres and by rare-earth ion implantation [25]. The literature about WGM microresonators (WGMR) laser is vast and deep; there are many papers based on WGMR with different geometrical shapes (microspheres, microdisks, toroids, etc.), made of various glasses (silica, telluride, phosphate, ZBLAN, etc.) and various dopants (Er, Er:Yb, Nd, Tm, Er:Yb:Tm, etc.), which cannot be all cited here but have been described in several reviews [14,26] and specially in [15].

In this paper we will present the results obtained in our laboratories studying up to three different types of Er^{3+}-doped glass microspherical cavities for the implementation of compact

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and low threshold laser sources at 1.55 μm. For light coupling into the WGMs we used tapered silica fibers.

We first report experimental results on the characterization of microspherical cavities obtained by melting powders of Er^{3+}-doped glasses. After a brief description of the fabrication process and characterization setup, we investigate the effects that our glass fusion process has on the spectroscopic properties of different Er^{3+}-doped commercial oxide glasses, i.e. two phosphate glasses and one silicate glass from Schott. This study is important especially considering the idea that in principle, as a very small amount of glass is necessary to fabricate a microspherical laser, by studying its properties, it will be easier to optimize the glass composition before making larger quantities for systems such as fiber or integrated lasers and amplifiers. Our experiments have been focused on the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} ions. We also measured the shift of the laser line by UV irradiation of microspheres fabricated in photorefractive glass.

A similar characterization was performed on monolithic microspheres obtained by drawing one type of commercial Er^{3+}-doped phosphate glass (IOG1).

We then present a simple method based on the sol–gel technology that has been developed to coat passive microspheres with an Er^{3+}-doped layer. This technique is quite flexible as the sol–gel process permits a precise control of the dopant concentration and of the thickness and index of the active medium. This technique offers the possibility to prepare tailored materials with an attractive improvement in their physical and chemical properties [27,28], such as selecting the radial order *n* of the 'active' WGM [29]. The microspheres were prepared by fusion of a standard telecom fiber and they were then dipped in a silica–hafnia sol activated with Er^{3+} ions. We first report on the luminescence properties of this latter coating that was selected because of the high quantum efficiency previously measured in Er^{3+}-doped silica–hafnia waveguides [30]. Then WGMs spectra were analyzed for different sphere diameters, coating thicknesses and Er^{3+} concentrations.

In all types of glasses we demonstrate whispering gallery mode laser action at various wavelengths around 1550 nm by using a 1480 nm pump laser in order to avoid the strong thermal effects typical of 980 nm pumping mechanism [31].

2. Microspheres fabrication

2.1. Microspheres from bulk glass

Microspheres were produced from different type of glasses: three commercial glasses: two phosphate glasses, i.e. a sodium–alumino–phosphate glass (Schott IOG1) which contains 1.5 wt% of Er_2O_3 and 3 wt% of Yb_2O_3 and a potassium–barium–alumino phosphate glass (Schott IOG2) which contains 2 wt% of Er_2O_3 and 3 wt% of Yb_2O_3; and one silicate glass (Schott IOG10), which contains 1 wt% of Er_2O_3 and 8 wt% of Yb_2O_3.

In a first approach pieces of each bulk glass were ground first, and microspheres were then fabricated using a plasma torch. The plasma is generated using a microwave supply with a nominal oscillator frequency of 2.4 GHz and a maximum power of 2 kW. Argon is used as plasma gas and oxygen or nitrogen as sheath gas. The glass powders are axially injected and melt when passing through the plasma flame while the surface tension forces give them their spherical shape. Free quenched spheres are collected a few ten centimeters lower. No additional annealing was performed on them. The diameter of the spheres depends mainly on the powder size and may vary from 10 to 200 μm. Microspheres with diameters in the range between 50 μm and 100 μm were selected and then glued to the tip of a taper optical fiber with diameter below 20 μm for ease of handling (Fig. 1a).

In the second approach, 5 cm long rods of 1.5 mm square cross section were cut from the commercial IOG1 wafers. The rods are then drawn in a home–made drawing device in a controlled environment; the obtained glass thread is then introduced for a certain length in a glass capillary in order to confer mechanical stability to the whole structure and an easy handling. The drawn glass threads have a nominal diameter of 10 μm and a length of 2 cm. The entire microsphere fabrication system was encased in a glass enclosure with an N_2 saturated atmosphere. An oxygen-butane torch was carefully aligned and slowly approached to the tip of the thread till the glass started to melt, and the microsphere was formed because of surface tension, remaining attached to the fiber stem (that is why we would refer to them as monolithic microspheres). The exposition time lasted less than 2 s, and the whole process was monitored with a CCD camera. After retracting the torch, the microspheres were stored under vacuum conditions. We obtained microspheres with diameters in the range between 60 and 120 μm, depending on the glass thread diameter and the exposition time. Over-heating would collapse the structure while under-heating would not form a microsphere. It is worth noticing that by using this approach, useful post-processing steps like, for instance, thermal annealing or ion-exchange, could be implemented (as no polymer glue is used in this case [9]) Fig. 1b shows the optical image of a monolithic microsphere of 105 μm of diameter.

2.2. Sol–gel coated microspheres

Silica microspheres were made by melting the end of a stripped standard telecommunication fiber (SMF 28) using both a fiber

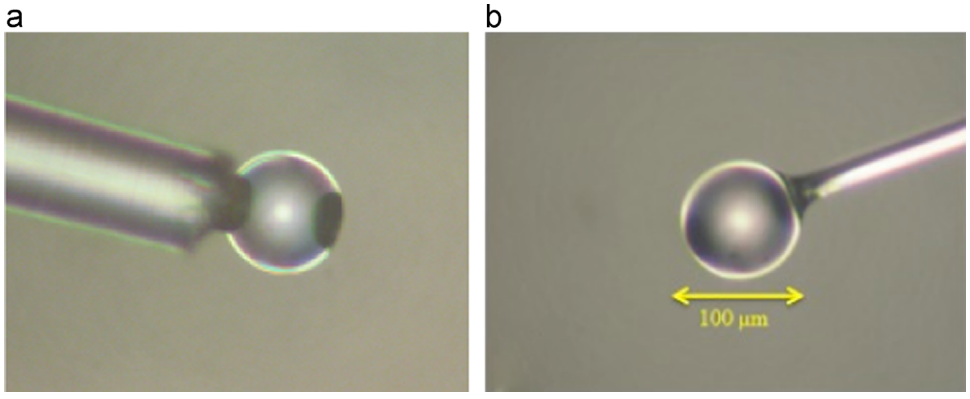

Fig. 1. Optical image of: (a) a microsphere of about 80 μm fabricated by direct melting of glass powder and glued to the tip of a fiber; (b) a 'monolithic' microsphere fabricated directly from the tip of an Er^{3+} doped phosphate glass thread.