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Materials Science and Engineering B 131 (2006) 27–31

MATERIALS SCIENCE & ENGINEERING B

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High-power microcavity lasers based on highly erbium-doped sol–gel aluminosilicate glasses

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Received 12 August 2005; received in revised form 7 December 2005; accepted 7 December 2005

Abstract

High-power whispering-gallery-mode (WGM) lasing from highly erbium-doped sol–gel aluminosilicate microsphere cavity coupled to a half-tapered optical fiber is presented. The lasing output power as high as 0.45 mW (−3.5 dBm) was obtained from sol–gel glass microsphere cavity with diameters in the range of 40–150 μm. The sol–gel method for making highly concentration Er-doped aluminosilicate glasses with Er-ion concentrations from 0.125 to 0.65 mol% of Er^{3+} is described. Controlling collected lasing wavelength at each WGM is possible by adjusting the distance between the half-taper fiber and the microcavity and by diameter of the waist of half-taper fiber. Using the analytic formulas we calculated the TE and TM lasing modes and it is shown that the experimental results are in good agreement with the calculation prediction.

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Keywords: Erbium-doped glasses; Sol–gel; Microcavity lasers

1. Introduction

In a dielectric microspherical resonator light can be guided though whispering-gallery-mode (WGM) which is propagating around the equator, spatially confined to a narrow beam near the microsphere's surface by total reflection [1]. The WGMs can exhibit high quality factor (up to 10^{10}), and are of interest for fundamental research in cavity quantum electrodynamics (QED), non-linear optics, photonics and sensing [2–6]. Many experiments have been performed on microdroplets and solid spheres or spheriods showing various cavity-enhanced effects and laser action [7–9]. In recent years, multi-component glasses have attracted great interest as hosts for rare-earth ions since they can accommodate larger impurity concentrations than silica, and rare-earth doped microcavity lasers have been successfully shown for practical applications. Sanghdar et al. demonstrated a very low-threshold Nd-doped microsphere laser, Cai et al. showed highly doped Er:Yb phosphate/silica glass microsphere lasers and Yand and Vahala presented the gain functionalization of silica microspheres by use of Er-doped sol–gel films in C-band [10–12], Peng et al. demonstrated the Er-doped tellurite glass microsphere lasers for L-band [13]. Experiments show that the highly concentrated Er-doped aluminosilicate glasses (SiO_2–Al_2O_3) made by sol–gel method with optimum Al/Er mole ratio (for example, Al/Er mole ratio is of 10–11 by Refs. [14,15]) have strongest emission with broadened band (full-width at half-maximum (FWHM) is up to 60 nm) [16]. The relatively wide FWHM implied that the microsphere lasers based on highly Er-doped aluminosilicate glasses can cover a wider wavelength range at 1550 nm: at standard wavelength for telecommunications since it coincides with the low-loss window of standard silica-based optical fibers.

In this paper, we used the sol–gel method for preparing Er-doped aluminosilicate glasses with high dopant concentrations (from 0.125 to 0.65 mol% of Er^{3+}), making microsphere cavity lasers based on these materials and study in detail lasing characteristics when these devices are coupled to a half-taper optical fiber with different waist diameters and with various distance between the half-taper fiber and the microcavity. In addition, experimental results are correlated with calculated results to understand the basic lasing mechanism such as emission of TE

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0921-5107/$ – see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.mseb.2005.12.033

and TM modes of Er-doped sol–gel aluminosilicate glass microsphere lasers.

2. Fabrication of Er-doped sol–gel aluminosilicate glasses and microsphere cavity lasers

Highly Er-doped materials are good candidate for integrated optoelectronic technology due to their Er-ion emission at wavelength range of 1550 nm for telecommunication. However, due to the small cross section for Er excitation ($\sim 10^{-21}$ cm^2), high density of Er-ions is required to get reasonable gain value in the small volume. This means that the distance between Er-ions is small enough to allow dipole–dipole interactions (ion-pairs) which can reduce the gain performance by quenching effect [17]. The sol–gel preparation process allows for precise control of dopant concentration, making possible a low-cost study of a wide range of inversion concentration and component of the glasses. The highly Er-doped sol–gel aluminosilicate glasses have been demonstrated as large emission spectra materials at 1550 nm-wavelength range. The broadening of emission spectra suggests a wider distribution of Er-ions and also the fact that the co-dopant Al_2O_3 has effectively dispersed Er-ions in the glass matrix [18] avoiding quenching due to Er-ion pairs or clusters. In this work we study the optimal proportion of Al_2O_3 and SiO_2 for the Er-ion emission in the glasses doped in range from 0.125 to 0.65 mol% of Er_2O_3 (it is equivalent to 0.25–1.3 mol% of Er^{3+}-ion in glass matrix), which is the optimal concentration in pure SiO_2 sol–gel glass [19]. Y_2O_3 is added to the glass to form the multi-composition of $(1-x)$ SiO_2–xAl_2O_3–yY_2O_3:zEr_2O_3 (x and y; z in mol%). In the preparation procedure of Er-doped silica and/or aluminosilicate glasses the solutions TEOS [Si $(OC_2H_5)_4$], Al $(C_4H_9O)_3$, YCl_3 and $ErCl_3$ were used as precursors of SiO_2, Al_2O_3, Y_2O_3 and Er_2O_3, respectively. The composition TEOS:H_2O:isopropyl alcohol (*i*-PrOH):HCl as 1:4:2:0.0027 was used for SiO_2 gels. Hydrochloric acid was included as the catalyst for hydrolysis process. The $ErCl_3$ and co-activated YCl_3 were dissolved in water and *i*-PrOH and then added into the SiO_2 colloidal. Samples were prepared with Er_2O_3 concentration ranging from 0.125 to 0.65 mol% of Er_2O_3 and with Y_2O_3 concentration from 2 to 4 mol%. In separated bottle the required amount of Al $(C_4H_9O)_3$ was first dissolved in (*i*-PrOH) and then slowly added in to the sol. In this process, the pH condition must be kept in constant. Xero-gel samples were dried in air in the range of 60 °C for 2 days. After drying process, samples were heated in 950 °C for 5 h. Dense, clear samples of SiO_2:Er_2O_3 or SiO_2–Al_2O_3:Y_2O_3:Er_2O_3 are obtained only when the heating goes up to 950–1000° C, which leads to be amorphous phase (characterized by X-ray diffraction measurement). The optimum molar composition, as would be justified in experiments, for SiO_2–Al_2O_3:Y_2O_3:Er_2O_3-bulk was 90 SiO_2–6Al_2O_3:4Y_2O_3:0.25 Er_2O_3.

We formed two kinds of Er-doped aluminosilicate glass microspheres by molten method using electrical are: one used the homogeneous sol–gel Er-doped glass bulk and other was ready-made undoped silica sphere covered with Er-doped sol–gel films with thickness about 1.5–2 μm. The Er-doped silica–alumina thin films with thickness of about 0.15 μm were made by a dip-coating method starting from solutions of Si $(OC_2H_5)_4$, Al $(C_4H_9O)_3$, YCl_3 and $ErCl_3$ in air. The glass thin film was annealed in air at temperatures 70°, 300°, 1050 °C for 1 h and melted under electrical are or CO_2-laser beam. The coated layer consists of 10–12 dip-coating thin films. The thin film gain layer may have an important effect on laser dynamics and light confinement. Both kinds of Er-doped aluminosilicate microspheres ranged in diameter from 40 to 150 μm. Efficient optical coupling to the spherical microcavity both for pumping and for laser output extraction was performed with half-taper optical fiber with waist diameter of 1–4 μm. Lasing wavelength and optical power at each WGM can be controlled by waist diameter of the half-taper fiber and/or by distance between taper fiber and microcavity.

3. Experiments

3.1. Excitation and extraction of WGMs

Our study is focused on the high-output lasing power from Er-doped sol–gel aluminosilicate glass microspheres. We choose 976 nm laser diode with output power up to 170 mW in single-mode emission (SDLO-2564-170) for excitation of Erbium ions. The pump laser beam and the laser WGMs are coupled to two different half-taper optical fibers. The taper fibers were fabricated by chemical etching a standard single-mode fiber. The waist diameters of half-taper fiber were from 1 to 4 μm, which may be optimized to phase matching and coupling to the fundamental WGMs ($n = 1$, $m = l$). The non-absorbed pump beam and the fluorescence or laser emission corresponding to the WGMs of the microsphere are separated with a demultiplexing coupler 980 nm/1550 nm. Thus we can analyze simultaneously the pump and the laser signals. The collected laser output fiber can be forward or backward with respect to the pumping direction. The distance between taper fibers and microcavity can be adjusted by micro-positioner with accuracy of 0.2 μm. The spectral characteristics of the emission around 1550 nm were analyzed with a 0.08 nm resolution optical spectrum analyzer (OSA: HP-70952B) directly after the demultiplexing coupler.

3.2. Spectral properties of high-concentration Er-doped silica glass microsphere lasers

Fig. 1 shows WGMs spectra of an Er-doped aluminosilicate glass coated microsphere with a full diameter of 110 μm and coated thickness of 2 μm measured by the fiber taper coupling configuration when the optical pump power was below the laser threshold ($P_{pump} = 1.5$ mW at 976 nm). We can observe the laser oscillation modes (WGMs) of the microspherical cavity in the large wavelength range from 1510 to 1610 nm, which is in the both C-band and L-band for telecom. Here, the Er-ion concentration was ranging 0.45–0.5 mol% of Er_2^{3+}.

In our experiment, for any sphere diameters we obtained an enhancement of the laser intensity when increasing the Er-concentration up to 0.25 mol% of Er_2O_3 in the aluminosilicate glass matrix. The laser signal has been obtained by forward and backward coupling configuration. Fig. 2a shows the spectra of

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