Whispering-gallery modes in glass microspheres: optimization of pumping in a modified confocal microscope

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Whispering-gallery modes (WGMs) on Nd^{3+}-doped glass microspheres with a radius of $\sim 15\,\mu m$ were measured in a modified confocal microscope, where a dual spatial resolution in both excitation and detection zones was possible. As an alternative to the standard excitation mechanism by an evanescent wave, we used an efficient pumping/detecting scheme, focusing a laser in the microsphere and exciting the Nd^{3+} ions, whose fluorescent emission produces the WGMs. We have also measured the generated WGMs by changing the detection zone, where higher amplitude resonances were found when exciting in the center and detecting at the edge of the microsphere. © 2011 Optical Society of America

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Whispering-gallery modes (WGMs) resonances in dielectric microspheres are receiving considerable attention in both fundamental and applied studies [1–5]. Light is trapped internally by continuous reflections at the glass surface, which makes the microsphere a high-Q resonator system. Many applications, such as optical switching and bistability [6], quantification of small displacements [7], quantum nondemolition experiments [8], spectral hole burning memory [9], ultrafine environmental sensing using phase or reflection response [10], and laser frequency locking and stabilization [10], have been suggested or demonstrated. For these applications, light must be coupled into the sphere. The use of prisms [6,7,11,12], half-block couplers [13], tapered fiber [14], angle-polished fiber couplers [15], the dual tapered fiber method [16,17], and other waveguides [4] have been validated as efficient coupling techniques. In all of these configurations, light is coupled from the coupler to the glass microspheres through an evanescent field. The microsphere is separated from the coupler by a distance of only a few wavelengths because the evanescent field extends over a very short range. The resonances are experimentally observed by measuring the light transmitted through the coupler in a way that it gets resonantly attenuated when the input light frequency matches that of a supported WGM of the spheres.

In this Letter, WGMs, in active glass microspheres, were excited with a relatively new, efficient pumping scheme, employing a similar technique to the one used by Garrett *et al.* [18]. The pumping and detection conditions were analyzed using a modified confocal microscope where the detection zone could be shifted away from the excitation zone so the confocal condition could be achieved completely (when both zones coincide) or could vanish if the detection zone is shifted more than an Airy unit. In our case, the fluorescence emission from excited Nd^{3+} ions was coupled to the supported WGM of the cavity.

Microspheres can be made by different methods, including: polishing, chemical etching, and rapid quenching of liquid droplets [3,11]. In this Letter, the microspheres were fabricated by the method exposed by Elliot *et al.* [3] from borate glass doped with Nd^{3+} ions. With this technique, it is easy to obtain spheres with diameters ranging from 5 to 100 μm. In the present work, we have produced microspheres with diameters of about 30 μm (see Fig. 1). Excitation of the WGMs within active glass microspheres has been performed with a confocal microscope, described in several publications from our research group

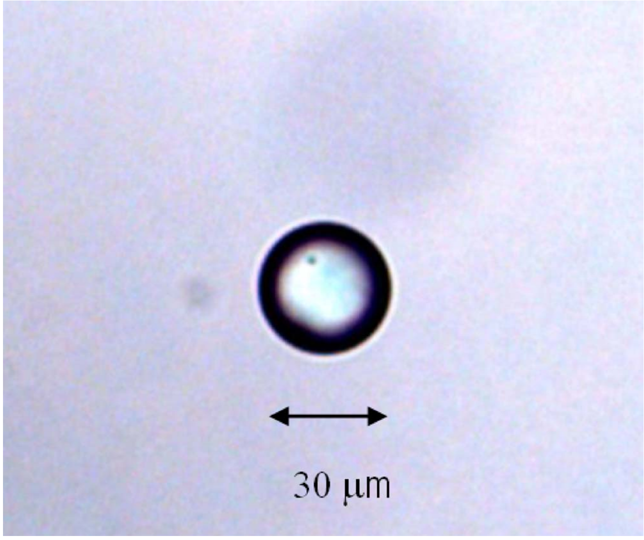

Fig. 1. (Color online) Optical image of one microsphere.

[19]. The scheme of the confocal setup used is shown in Fig. 2. The sample is located on a motorized translation stage at the focal plane of a 20× microscope objective (Mitutoyo, M-Plan NIR, NA $= 0.4$). The Nd^{3+}: $^4I_{9/2} \rightarrow {}^4G_{7/2}$ absorption transition is excited by using the 532 nm line of a doubled cw Nd:YAG laser. The luminescent emission associated to the Nd^{3+}: $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition (which provides a broad emission band centered at ~890 nm that can couple to the WGM), is detected using a CCD spectrograph. A dichroic mirror is used to reflect the laser light while letting the emitted light pass through it. In this modified confocal microscope, the detection pinhole is placed in a XYZ translation stage, where the point of analysis can be displaced around a limited region with respect to the point of the excitation. As a consequence, the analysis region can differ from the excitation area.

In the first part of the experiment, the WGMs are obtained by exciting tangentially to the sphere and detecting at the opposite side of the sphere equator (see Fig. 3). When the excitation point is moved from the edge to the middle of the microsphere while keeping the detection position fixed, stronger amplitude resonances are found (see Fig. 3). The final pumping configuration provides the highest resonance amplitude, which implies a more efficient optical power transfer to the WGM. One attempt of explanation is that when the incident light is tangential to the sphere, only the pumping beam that propagates inside the sphere can excite Nd^{3+} ions and thus generate a WGM [2,5]. A small region of the sphere is excited and there are also reflection losses on the surface. By shifting the incident position of the beam inside the sphere, a greater volume is excited. The top surface reflection losses are reduced due to the normal incidence on the surface. These advantages result in higher amplitude resonances.

In the second experiment, the excitation is fixed to the center of the microsphere and the detection region is displaced along the same plane from the center to the edge of the sphere as it is shown in the inset of Fig. 4(b). In the first detection point, at the center of the sphere (D3), it is not possible to observe any WGMs. A similar result is obtained when the detection region is moved to an intermediate point between the edge and the middle of the microsphere (D2). In D2 and D3 detection points, the spectra obtained are slightly different than the spectrum of the Nd^{3+}-doped glass precursor of the microspheres [see Figs. 4(a) and 4(b)]. In fact, in the bulk doped glass case, the radiative recombination probabilities between levels of the Nd^{3+} ions are influenced by the glass matrix properties. On the contrary, inside a microcavity, the photonic density of states differs from the bulk case and may produce a modulation to the Nd^{3+} emission probabilities. Finally, as it is expected, when the detection point is situated at the edge of the sphere (D1), resonances associated to WGMs are clearly observed.

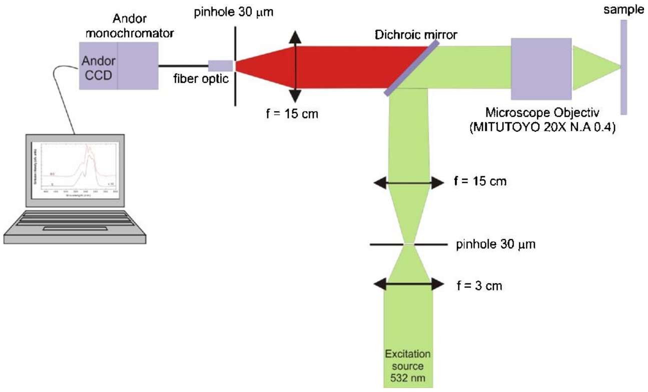

Fig. 2. (Color online) Confocal microluminescence setup used.

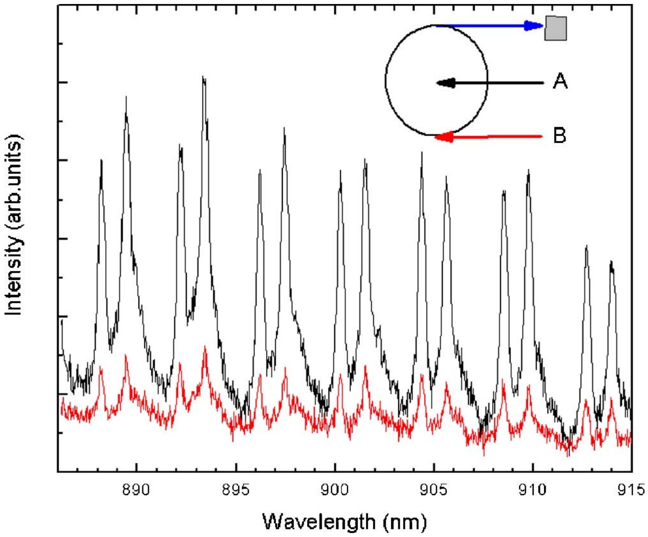

Fig. 3. (Color online) Resonance spectra of the microsphere. The red lower curve corresponds to a configuration in which the pump is at the border of the sphere, while the black upper curve corresponds to one in which it is at the center of the sphere. The inset shows the different pumping schemes.

The optimum configuration found, i.e., pumping at the center and detecting at the border of the microsphere, gives rise to a Q factor [3,4] higher than 10^3 (limited by the detection equipment), with a free spectral range

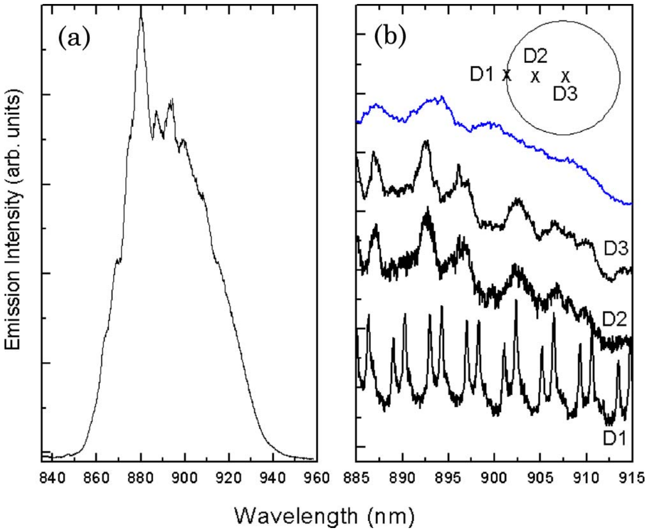

Fig. 4. (Color online) Emission spectra of the precursor glass. (a) Emission spectra obtained by pumping at the center and different detection positions; (b) according to the inset figure (curves D1, D2, and D3) and photoluminescence emission spectrum of the Nd^{3+}-doped glass in this wavelength range (blue topmost curve). The inset shows the different detection schemes.

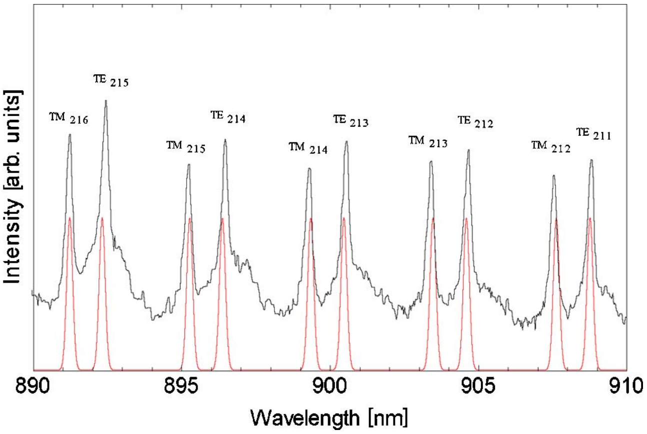

Fig. 5. (Color online) Emission spectra at the optimum configuration (black upper curve) and simulated spectra (red lower curve). Peaks are indexed as TE_l and TM_l (with $n = 1$ and $m = l$).

[4] of 4.12 ± 0.1 nm at the central wavelength, and a contrast or visibility [20] of 0.6. The resonances can be fitted to the characteristic equation resulting from matching the electric and magnetic fields of the tangential components at the sphere boundary [4], where the TE (TE_{nlm}) and TM (TM_{nlm}) modes are assigned. In Fig. 5, the experimental and simulated spectra are shown with the assigned mode numbers, TE_l and TM_l (with $n = 1$ and $m = l$).

To summarize, we have fabricated and analyzed Nd^{3+}-doped active glass microspheres with a radius of $\sim 15\,\mu$m. This analysis has been carried out under two different configurations due to the versatility of the modified confocal microscope. First, we have excited WGMs indirectly, by laser pumping the Nd^{3+} ions inside the microsphere. Second, under this pumping condition, the detection region has been displaced from the middle to the edge of the microsphere and the different spectra have been studied. The highest resonance amplitudes were obtained by pumping at the center and detecting from the edge of the microsphere with a measured Q factor higher than 10^3 (limited by the detection equipment).

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