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Lead silicate glass microsphere resonators with absorption-limited Q

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We report the fabrication and characterization of a lead-silicate glass microsphere resonator. We show that at the wavelengths near 1555 nm high Q modes can be efficiently excited from a 109 μm diameter lead-silicate glass microsphere via evanescent coupling using a tapered silica fiber with a waist diameter of 2 μm. Resonances with Q-factors as high as 0.9×10^7 were observed. This is very close to the theoretical material-limited Q-factor and is the highest Q-factor reported so far from a nonlinear glass microsphere. © *2011 American Institute of Physics*. [doi:10.1063/1.3586771]

Over the last few decades whispering gallery mode (WGM) microsphere resonators have increasingly attracted interest because of their very high quality factors (Q-factors),[1,2] the ease with which they can be manufactured and their versatility in terms of materials and dopants for a variety of passive and active devices. Furthermore, microsphere resonators have the potential to add significant functionality to planar lightwave circuits providing wavelength filtering, delay and low-power switching, and laser functions to waveguides.[3] The design of such photonic circuits requires precise coupling between spheres and waveguides to allow for the control of the Q-factor and hence of the stored energy and resonator bandwidth.[3–6] To date, most studies on microsphere resonators have utilized silica microspheres fabricated by melting the tip of an optical fiber with the resulting stem used as a tool to position the sphere while it is being characterized.[1]

Lead-silicate (SiO_2-PbO) glass, especially the ones with a high content of lead-oxide, has the nonlinear refractive index n_2 that can be as high as 20 times that of silica.[7] Glasses with high nonlinearity are of immense importance for devices performing optical switching and frequency comb generation.[8,9] Thus a lead silicate glass based microsphere resonator with high Q-factor is promising for realizing such nonlinear processes with very low-threshold power. In this letter we report the fabrication of high Q lead-silicate glass microspheres using resistive heating method and the excitation of WGMs with Q factors up to 0.9×10^7. This is the highest Q factor for a microsphere resonator based on nonlinear glass material reported to date.[10–12]

A single-mode high-index lead-silicate fiber was fabricated in house. Two commercial Schott glasses (Mainz, Germany), SF57 and SF6, with the refractive index n of 1.80 and 1.76 at 1550 nm respectively, were used as the core and the cladding of the fiber. The outer diameter (OD) and the core diameter of the fiber were measured to be 175 μm and 2.4 μm, respectively. The nonlinear refractive index n_2 of the core and the cladding glasses are 41×10^{-20} m^2/W and 22×10^{-20} m^2/W at 1.55 μm, respectively.[13] The effective nonlinearity γ $(=2\pi n_2/(\lambda A_{eff})$ at 1.55 μm of the fiber was therefore estimated to be 225 W^{-1} km^{-1}, which is 225 times higher than that of the conventional silica fiber (SMF28). The propagation loss in the fiber core was measured to be 5 dB/m at 1550 nm using cutback method. And the propagation of the cladding was thus estimated to be 3 dB/m at the same wavelength, due to the shorter thermal history of the cladding than the core in the fabrication process.

To fabricate a microsphere with the diameter further smaller than the fiber OD, the lead-silicate glass fiber was first elongated. As shown in Fig. 1(b), a small region of the fiber is heated by a resistive microheater with a "Ω" shape at a temperature of circa 500 °C. The microheater was scanned along the fiber and the fiber was simultaneously pulled by two computer-controlled translation stages each with submicron precision. Tapers with an extremely uniform waist diameter ($d<10$ μm) and taper transitions of well defined length and shape were then made.[14] After the tapering, the uniform waist region (~4 mm long) was then cut in the center, as shown in Fig. 1(c). The tip of the taper was then heated to about 900 °C, which is significantly higher than the softening point (540 °C) of the cladding (SF6) glass,[15] and the surface tension of the softened lead-silicate glass molds the tip into a spherical shape. Note that during this process, the tapered fiber needs to be rotated slowly to ensure that the tip of the taper can be heated uniformly and the stem does not bend.

Figure 2 shows the experimental apparatus used to observe the WGM resonances. A tapered silica fiber with a

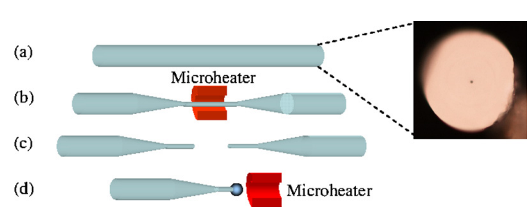

FIG. 1. (Color online) Schematic diagram illustrating the fabrication of microspheres from lead-silicate fiber. (a) A lead-silicate glass fiber with a microscope image of its cross section (NA ~ 0.365, V ~ 1.78, core diameter: 2.4 μm, cladding OD: 175 μm); (b) the lead-silicate fiber is tapered to a waist diameter $d<10$ μm over a length of ~4 mm by using a microheater at a temperature of ~500 °C; (c) the tapered lead-silicate fiber is cut in the middle; (d) a microsphere is formed at the taper tip when the tip approaches the microheater maintained at about 900 °C, which is significantly higher than the softening point of SF6 lead-silicate glass (approximately 540 °C).

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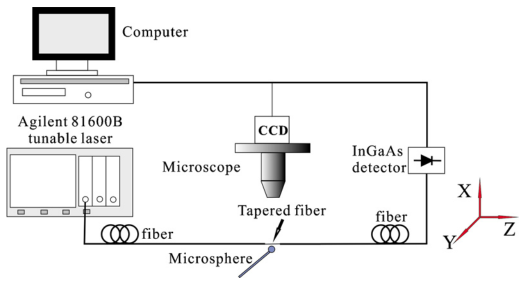

FIG. 2. (Color online) Experimental apparatus used for microsphere resonance characterization. Light from a narrow-line tunable laser source (Agilent 81600B, Agilent, Santa Clara, CA, USA) emitting 1 mW over the wavelength range 1554–1556 nm was launched into a tapered fiber and coupled to the microsphere. The throughput signal was collected using an InGaAs detector. The separation between the microsphere and the tapered fiber was controlled with a precision nanotranslation stage equipped with piezoelectric actuators and stepper motors and monitored using a microscope equipped with a CCD camera.

waist diameter d of $\sim 2\ \mu$m (fabricated as described above) was used to couple light into the microsphere using the well-established evanescent field coupling technique.[16] The tapered fiber was placed in close proximity to the lead-silicate microsphere and their relative positions were observed from the top using a microscope equipped with a charge-coupled device (CCD) camera. The separation between the microsphere and the coupling tapered fiber and the microsphere position along the fiber taper were controlled by precision nanotranslation stages equipped with piezoelectric actuators. A narrow-line tunable laser source (Agilent, Santa Clara, CA, USA) delivering 1 mW light over the wavelength range from 1554 to 1555.9 nm with a tuning resolution of 0.1 pm. was used to launch light into the tapered silica fiber. The power transmitted through the tapered optical fiber was measured using an InGaAs detector as shown in Fig. 2. The tapered fiber stem supporting the microsphere ensured that the microsphere orientation remained fixed with respect to the tapered silica coupling fiber as it was translated across and away from it.

Figures 3(a) and 3(b) show the top view of the lead-silicate glass microsphere resonators with diameters of 103 and 109 μm, in close proximity to tapered silica fibers with

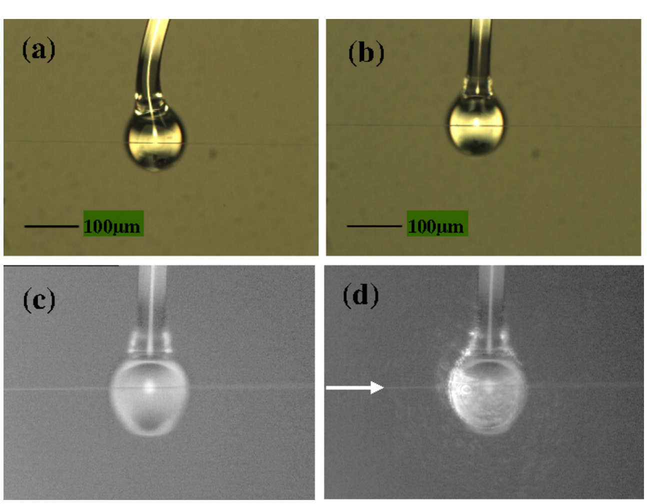

FIG. 3. (Color online) Microscope images of lead-silicate microspheres with diameters (a) 103 μm and (b) 109 μm showing their fiber stems and the tapered coupling fibers. (c) and (d) show the infrared images of the microsphere when the input laser light is turned off and on, respectively.

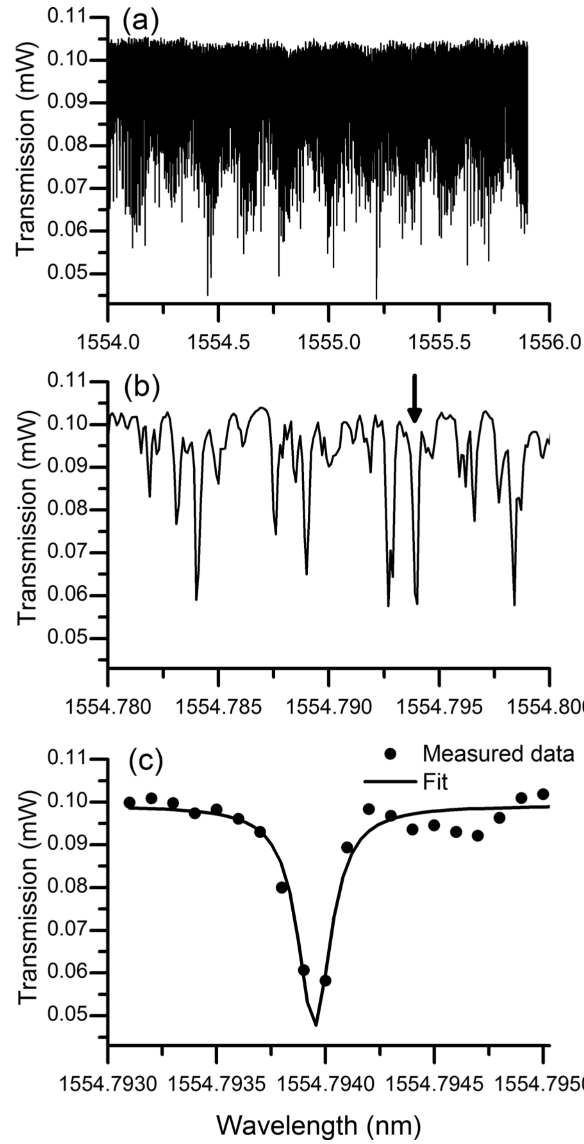

FIG. 4. (a) Experimental resonance spectra for wavelengths between 1554 and 1555 nm for the microsphere with diameter 109 μm (b) Close-up spectrum in the region 1554.78–1554.80 nm clearly showing the high-Q resonances and (c) a Lorentzian fit to one of the measured tuning-resolution limited resonance dips used to accurately determine the bandwidth.

waist diameters d of approximately 2 μm. Figures 3(c) and 3(d) show the CCD images when the input light is off and on, respectively. The CCD camera is sensitive to the 1550 nm radiation and Fig. 3(d) clearly shows scattered light from an excited WGM emanating from the left side of the microsphere. There is also some evidence of leakage into the stem, possibly due to the wide-spread higher-order angular modes associated to the ellipticity observed in the microspheres.

Dips in power transmission through the tapered coupling fiber are observed on the InGaAs detector as a function of wavelength when good coupling to the microsphere is achieved. This is because of strong wavelength-dependent coupling into WGMs, which are inherently lossy due to microsphere curvature. Figure 4 shows resonance spectra of the microsphere with a diameter of 109 μm, over wavelength ranges of (a) 1 nm (b) 20 pm and (c) 2 pm. It is evident from the figure that the tapered fiber excitation produces dense spectral features as experienced in other high index glass microspheres.[10] This is due to the excitation of many higher-order radial modes by the low effective index fiber taper and many non-degenerate higher-order angular modes associated with microsphere ellipticity. The effective indices of the first 6 radial modes ($n=1-6$) for a lead-silicate microsphere of about 100 μm diameter at a wavelength of 1550 nm were calculated to vary from 1.69 to 1.51.[17] The effective index of the fundamental mode in a 2 μm tapered fiber at the same wavelength was approximately 1.35. In this study, we used silica tapered fiber instead of a phase-matched tapered high index fiber to excite WGMs, so that any nonlinear effects from the delivery fiber would be minimized. The planned construction of a nonlinear device will require the nonlinear interactions to be localized within resonators and not to be found in the signal delivery fiber.

The Q of a microsphere resonator can be easily estimated from its WGM spectrum through the relation, $Q=\lambda/\Delta\lambda$, where $\Delta\lambda$ is the full width at half maximum (FWHM) and λ is the resonance central wavelength. Figure 4(b) shows the spectrum over a short wavelength range, showing the high Q nature of the observed resonance dips. One of the dips is fitted to a Lorentzian function [Fig. 4(c)] and a FWHM of 0.18 pm (22 MHz) was found, corresponding to a Q factor of 0.86×10^7, which we believe to be the highest Q achieved in a non-silica glass microsphere resonator reported in the literature. This value for Q is very close to the theoretical limit (1.0×10^7) predicted using the equations reported in Ref. 1 for the transmission loss measured in the fiber. Indeed, this value is also close to the value for pure SF6 lead silicate glass using an optical attenuation of 4×10^{-3} cm^{-1} (1.74 dB/m) and a refractive index of $n_{1550}=1.764$ which yields a calculated $Q\sim1.78\times10^7$ at a wavelength of $\lambda\sim1.55$ μm.[15]

In conclusion, the fabrication of lead-silicate glass microspheres has been demonstrated. WGM resonances have been observed and a Q factor close to 10^7 was observed at $\lambda\sim1.55$ μm. We believe that this microsphere will provide an ideal building-block for several applications including highly integrated optical switches, modulators, ultrasmall optical filters, microlasers, and optical biosensors. Investigation of the nonlinear optical properties of these lead-silicate microspheres is underway.

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