Eroded monomode optical fiber for whispering-gallery mode excitation in fused-silica microspheres

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We demonstrate the efficient excitation of high-Q whispering-gallery modes in near-spherical fused-silica microparticles in the size range 60–450 μm by the use of an eroded monomode optical fiber. When the sphere is placed in the evanescent field of the guided fiber mode, light is resonantly coupled from the fiber into the microparticle. We report a broadening of resonance modes and a shift of the resonance central frequency as the coupling strength is increased by reduction of the gap between the sphere and the fiber.

High-Q electromagnetic whispering-gallery modes in near-spherical dielectric microparticles (hereafter referred to as microspheres) have several potential applications in pure and applied science. Whispering-gallery modes (sometimes called morphology-dependent resonances) are high-angular-momentum electromagnetic modes that correspond to photons' being strongly confined within the microsphere by repeated total internal reflection from the surface at grazing incidence, satisfying a phase condition after circling around the particle perimeter.[1] They can result in long photon lifetimes within the microsphere and can cause strong resonant fields near the sphere surface. The theoretical diffraction-limited Q value ($Q = \tau_c \omega$, where τ_c is the cavity lifetime and ω is the frequency of the light) in dielectric microspheres of size $D > 10$ μm can be extremely large at optical frequencies: in practice the highest observable Q is limited either by material absorption or by scattering as a result of surface roughness or material inhomogeneity. $Q > 10^9$ has been observed by several research groups[2,3] at near-infrared and red wavelengths in fused-silica microparticles. Such high Q values, coupled with the very small resonant mode volume, make the system attractive for the pursuit of cavity quantum electrodynamic and quantum nondemolition experiments at optical frequencies.[4,5] Similarly the use of whispering-gallery mode cavities as monolithic resonators for laser frequency stabilization[6] and as low-threshold microlasers[7] has been suggested for optoelectronic and integrated-optics applications. There is thus a substantial interest in simple and efficient excitation of these cavity modes.

To excite high-Q whispering-gallery modes (WGM's) one needs to couple light into the microsphere beyond the critical angle, which cannot be done efficiently by illumination of the sphere from the outside with a plane wave. Researchers previously demonstrated efficient excitation of WGM by placing the microsphere in the evanescent field produced by the total internal reflection of a focused laser beam from a high-index prism and using resonant frustrated total internal reflection.[2,3] In this Letter we describe the realization of a novel excitation method for a fused-silica microsphere: the use of an eroded monomode optical fiber. The transverse dimension of the guided mode in a monomode fiber is typically 3–5 μm for visible or near-infrared wavelengths, close to the transverse confinement of the WGM that we are trying to excite. By erosion of the cladding of a length of such fiber to approach the fiber core the evanescent field of the propagating mode in the core is exposed and can be used for WGM excitation in the same way as is done with total internal reflection from a high-index prism. This simplifies the excitation procedure and is more appropriate than the use of a prism for potential optoelectronics and integrated-optics applications. We fabricated the optical fiber couplers used in our experiments by mounting a length of monomode optical fiber (Photonetics FS-SN-4221, core diameter 5.5 μm, N.A. 0.12) in a groove in a curved piece of alumina (see Fig. 1) with a radius of curvature of 8 cm. We then eroded the fiber mechanically to form an elliptical polished plane in the curved fiber, approaching the fiber core. While the polishing proceeded, the transmission of the fiber was monitored; by polishing near the core with a 0.1-μm diamond suspension we achieved a high-quality surface, resulting in a low level of losses from the eroded region. After polishing, the coupling surface was carefully cleaned by ultrasonic agitation and repeated wiping with a lens tissue. We shall refer to the polished fiber mounted upon a substrate as a fiber half-coupler, as two of these placed face to face were previously used as bidirectional fiber couplers.[8]

In our experiments silica microparticles are formed by heat fusion of the tip of a length of fine silica fiber: the molten silica on the fiber tip is pulled into a nearly spherical shape by surface tension. In this way spheres with sizes in the range 60–450 μm are easily produced and readily manipulated by the silica stem. We have used spheres made of pure silica as well as of doped silica from the optical fiber used in the fabrication of the half-coupler. By thus matching the refractive indices of the sphere and the fiber, we maximize the launch angle for light coupled into the sphere. In doing so we optimize the coup-

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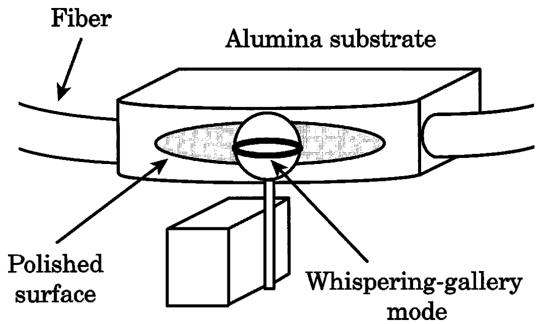

Fig. 1. Schematic diagram of the eroded fiber coupler, showing the relative orientation of the microsphere and of the coupling surface (not drawn to scale). The fiber coupler and the microsphere are independently mounted upon microtravel plates with piezoelectric fine control. The brass block on which the microsphere is mounted is temperature stabilized.

ling to low radial mode number modes, which have the largest launch angle,[6] the highest angular momentum inside the sphere, and the smallest mode volume. The last-named property results in the maximum field/photon for these modes, which is desirable for several applications.[4,5] The sphere is mounted in front of the eroded optical fiber, with its equatorial plane parallel to the fiber axis (Fig. 1). In this way the WGM's in the equatorial plane of the sphere are preferentially excited. (We anticipate that the modes near the equatorial plane in our microparticles, where the departure from sphericity is smallest, will most closely retain the diffraction-limited Q value and the mode volume of a perfect sphere.) The fiber coupler is held horizontally with its eroded plane parallel to the vertical axis of the sphere's stem. The sphere/fiber gap, and the relative heights of the sphere and the fiber, are controlled accurately by piezoelectric transducers and are monitored with a microscope and a CCD camera. We have used a semiconductor diode laser emitting at 790 nm as a light source, at which wavelength the fiber used is monomode. If the diode laser is placed in an external cavity with grating feedback it can be continuously scanned over several gigahertz. When the laser frequency passes a resonance of the microsphere, light is coupled out of the fiber into the microsphere: a corresponding decrease appears in the light transmitted by the fiber. This decrease is due to the light that is coupled into the sphere but is not coupled back into the fiber because of absorption or scattering in the sphere. As is shown in Fig. 2, our detection is performed in one of two ways: by monitoring the loss from the fiber as the laser frequency is scanned across a resonance or by directly measuring the light scattered out of the sphere on resonance. For the first of these a dither is introduced into the laser frequency, which serves as an oscillator for lock-in detection; for the second the sphere is simply imaged onto a photodetector. To reduce reflection from the fiber tip, which causes Fabry–Perot fringes to appear in the transmitted power as the laser is scanned and interferes with the lock-in detection, we terminate the fiber in index-matched liquid. By avoiding sharp bends in the fiber we maintain the polarization of the propagating mode well over the 0.5-m length of fiber used in the experiment, permitting independent excitation of the transverse electric and transverse magnetic modes of the microsphere.[1] However, aside from their different polarizations, no significant differences were noted between the two.

The maximum coupling that we have achieved is 10% (corresponding in our case to as much as 250 μW of power coupled into the mode), which we observe for sphere/fiber gaps up to 100 nm. This efficiency may be limited by the roughness of the polished fiber surface or by an imperfect discontinuity in the core/cladding index in the fiber being used, or more fundamentally by the geometrical overlap of the modal patterns in the sphere and the fiber. This figure of 10% is attained with a loss level of the order of 0.05 dB from the eroded fiber. Using the liquid drop method,[9] we estimate that less than 1 μm of cladding remains in the eroded zone. Continuing to polish the fiber closer to the core leads to higher levels of loss with little increase in the coupling efficiency.

When the gap is increased into the undercoupled regime the strength of the coupling falls off exponentially, corresponding to the decay of the evanescent field of the guided wave away from the fiber core. Similarly, in the overcoupled regime the nearby presence of the fiber perturbs the sphere mode, causing some additional broadening and a shift of the resonance frequency. The shift and the broadening of the mode are both expected to exhibit the same exponential behavior as a function of the gap. An example of the observed resonance frequency and linewidth dependence on the sphere/fiber gap distance is shown in Fig. 3. In plotting this figure we have assumed a definition for the shift $S = \nu_\infty - \nu_g$, where ν_g is the observed frequency corresponding to a gap g and ν_∞ is the frequency observed for a large gap. We can divide the observed behavior as a function of the gap into three regions. For very small gaps (<20 nm in Fig. 3) we do not have reliable information on the sphere/fiber gap variation with applied piezo voltage because in this regime van der Waals and electrostatic forces can act upon the sphere, pulling it toward the fiber by bending the stem to which it is attached. At some point in this interval the sphere was brought into contact with the

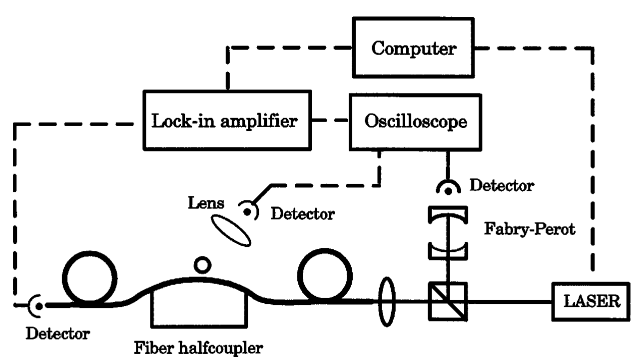

Fig. 2. Layout used for exciting and detecting WGM's in microspheres by use of the eroded fiber half-coupler. The scanning of the laser and the recording of the lock-in signal are controlled by computer.

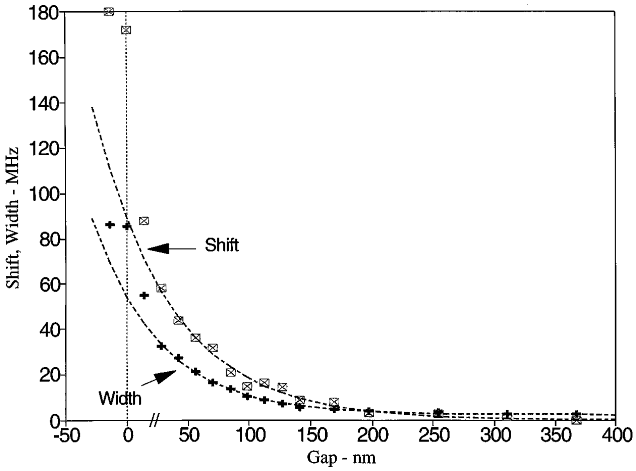

Fig. 3. Observed linewidth and shift of a WGM resonance as functions of the coupler/sphere gap. The experimental data are represented as symbols: the curves are best-fit exponentials, with an offset for the width to account for its limiting value. The data were recorded from a TE mode in a sphere of radius 215 μm made of the same material as the fiber coupler.

polished fiber surface. For very large gaps the shift approaches zero (by definition), while the observed linewidth approaches the limit imposed by the laser linewidth or, ultimately, by absorption or scattering in the sphere. In the intermediate regime we observe an exponential decrease for the shift and the width with increasing gap, reflecting the decrease in the intensity of the field. This decrease is in good agreement with the expected evanescent field behavior for glancing-incidence total internal reflection and is the same for two curves to within experimental error [observed exponential decay constants $2\kappa = 0.0159$/nm (shift), $2\kappa = 0.0183$/nm (width); expected value for glancing incidence $2\kappa = 0.0169$/nm (Ref. 10)]. The noise on the shift data is due to the temperature dependence of the refractive index of the microsphere, which shifts the mode by approximately 2 MHz/mK. The systematic uncertainty in the calibration of the sphere-fiber gap (calibrated interferometrically) over this range is estimated at 10%. The shift/width ratio shown in Fig. 3 is ~2 in the overcoupled case: for different modes (corresponding to different angles inside the sphere) different values of this ratio have been observed. We expect the direction of the shift and the shift/width ratio to depend both on the refractive indices of the two materials and on the angle of incidence inside the resonator (which varies with the particular mode being studied) as well as on the polarization of the mode (TE or TM). Because we do not identify the mode numbers of the specific modes being excited it is impossible to isolate experimentally the dependence of the shift on these different parameters. This shift was not reported in our previous experiments that used total internal reflection from a high-index prism to excite WGM's because in that case the shift was much smaller than the coupling-limited linewidth. The features of the gap-dependent resonance shift and broadening that we observed are in qualitative agreement with a model for evanescent-wave excitation of WGM's in microspheres. A similar shift in resonance frequency (although in the opposite sense) was previously observed in a nonspherical fused-silica monolithic resonator of millimeter proportions.[11] In both cases it corresponds to a gap-dependent phase shift on total internal reflection inside the resonator, altering the phase condition for resonance.

The narrowest linewidth that we have observed is $\Delta\nu < 3$ MHz, corresponding to a cavity $Q > 10^8$. This is limited by the acoustic linewidth of our diode laser. We confidently expect to be able to observe cavity Q of the order of 10^9, as was done with high-index prism excitation, when the experiment is repeated under conditions similar to those used there. On the other hand, the Q remains as high as 10^7 even in contact: such high Q in a mechanically stable configuration is promising for technological applications of WGM microresonators.

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