Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper

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We show that high-Q whispering-gallery modes in fused-silica microspheres can be efficiently excited by an optical fiber taper. By adjusting the taper diameter to match the propagation constant of the mode in the taper with that of the resonant mode of interest, one can couple more than 90% of the light into the sphere. This represents a significant improvement in excitation efficiency compared with other methods and is, we believe, the most efficient excitation of a high-Q microcavity resonance by a monomode optical fiber yet demonstrated. © 1997 Optical Society of America

Whispering-gallery-mode (WGM) resonances are electromagnetic resonances that occur in circularly symmetric dielectric particles.[1] They correspond to light trapped in circling orbits just within the surface of the particle, being continuously totally internally reflected from the surface. Under these circumstances the leakage of light from the particle can be extremely low. The high-Q values and small mode volumes of these WGM resonances in fused-silica microspheres make this system of interest for a number of fundamental and applied studies.[1–3] A crucial point of these studies is that one needs to be able to couple light into and out of the cavity. Braginsky *et al.* used prism coupling to excite the modes.[2] Using total internal reflection, one produces an evanescent field at the surface of a high-index prism, with the angle of incidence upon the internal surface of the prism chosen to match the propagation constant with that required for excitation of the mode of interest. Hence one is coupling a large number of free-space modes into the resonant mode of interest. This method is flexible and can be made efficient, but it is bulky and awkward. Other workers have used a side-polished optical fiber as an excitation source.[4,5] This method has the advantage that the excitation source is an optical fiber and is thus convenient to use. Furthermore, the propagation constant in the core of a silica-based optical fiber will always be closest to that of the lowest radial mode number WGM,[1] which (as described below) is the mode with the most desirable properties. However, this matching is perfect only in the limit of large sphere size, limiting the attainable coupling efficiency to ~20% for very large spheres, of diameter 1 mm, and to much less for smaller spheres.[4] In this Letter we report that, by replacing the side-polished fiber with an adiabatically tapered fiber, we can maintain several of the advantages of the side-polished fiber source while coupling light with high efficiency to any particular mode of interest, in spheres with a wide range of sizes.

We refer to a homogeneous fiber taper of radius ρ and a sphere of size parameter $x = 2\pi a/\lambda$ (where a is the sphere radius and λ is the wavelength of the light in free space). To determine the size of fiber taper required for efficient excitation of the chosen WGM we need to match the propagation constant of the WGM at the surface of the sphere to the propagation constant of the appropriate mode in the tapered fiber. The WGM is characterized by the mode numbers n, l, and m, the radial, angular, and azimuthal mode numbers, respectively.[1] To maximize the advantage of a microcavity resonance we are interested in exciting modes with low n and with $m \cong l$. These are the modes with the smallest mode volume, as they are most closely confined to the surface of the sphere (lowest radial mode number n) and to the sphere equator ($|m| = l$). In this case we can approximate the propagation constant β by $\beta = kl/x_{nlm}$, where x_{nlm} is the size parameter that corresponds to the n, l, and m resonance and k is the free-space propagation constant. This formula gives the correct value because $2l$ is the number of maxima in the angular variation of the resonant field around the microsphere equator. For large spheres and for the lowest radial mode number β approaches the propagation constant in pure silica, but for smaller spheres it quickly becomes significantly smaller. Here we calculate the values of l that correspond to the various values of n for a sphere of a given size a and refractive index N in the wavelength region of interest, using the approximate expressions described by Schiller.[6]

We form a fiber taper by heating and stretching a section of optical fiber to form a narrow thread, or waist, which is joined to the untreated ends of the fiber by a gradual taper transition.[7] In the waist region the fiber core is no longer significant, and the light travels in the fundamental mode along the waveguide formed by the silica waist surrounded by air. The taper waist can be as little as a micrometer in diameter. On reaching the other end of the waist, the light remaining in the waist is returned to the guided mode in the fiber core. If the waist is small, the fundamental mode will have an evanescent tail extending significantly out into the free space surrounding the taper, and the propagation constant of the mode will be a function of the waist radius. For the radii of interest here this dependence can be expressed as

$$\beta^2 = k^2N^2 - (2.405)^2/\rho^2\,, \qquad (1)$$

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where k is the free-space propagation constant of the light. For the taper diameters used in our experiments (with 1.4 μm $< \rho <$ 3 μm) this approximation is in error by less than 1% compared with the exact values.[8]

Some results of the phase-matching calculations are shown in Fig. 1. The solid curve represents the propagation constant β of the fundamental taper mode [Eq. (1)] as a function of the radius (top axis). The points are plotted on the lower axis and show the propagation constants of the lowest few radial mode numbers for several different sphere diameters (differing l) in the wavelength range of interest. The top and bottom scales in the plot have been chosen to match approximately the β for a given taper size (on the top scale) with that of the lowest radial mode number mode in a particular size of sphere (on the bottom scale). A relatively small range of taper sizes is seen to match the propagation constants over a wide range of sphere sizes. Because the interaction length is limited by the curvature of the microsphere surface, the overall coupling is not expected to be sensitive to small variations in the taper diameter or sphere size. Coupling to higher-n modes in a sphere of a given size would require smaller taper diameters.

The tapered fibers used in our experiments were formed from lengths of standard telecommunications fiber (which guides a single mode at the wavelengths near 1550 nm used in these experiments). The polymer coating was stripped from a short length of the fiber. The fiber was then heated with a traveling flame while being drawn gradually to be stretched to the desired size. By monitoring the light through the fiber while the drawing proceeded we were able to ensure that the overall losses from the taper were kept at the level of 0.1 dB. The heated length of fiber and the draw extension are controlled by a computer and are chosen to result in a taper waist of the required diameter. The accuracy of the resulting waist diameter is of the order of 5%. After fabricating the taper we mounted it horizontally by suspending it at both ends so that it could be drawn taught. We formed a fused-silica microsphere by flame fusing the end of a fine silica wire. The wire remained attached to the sphere, and resonances were excited in the equatorial plane perpendicular to the wire axis. The sphere was mounted upon $x-y-z$ microcontrols to bring the sphere equator region into contact with the tapered fiber. A tunable single-mode diode laser (with $\lambda \approx 1550$ nm and $\Delta\nu \cong 3$ MHz) was coupled into one end of the tapered fiber while the fiber throughput was monitored with a photodiode (PD) at the far end. The experiment is shown schematically in Fig. 2(a).

When the laser wavelength was scanned past a microsphere resonance, a dip appeared in the transmitted light. Examples of such resonances are shown in Fig. 2(b). The main trace shows a sphere of size $a \cong$ 85 μm ($x \cong 350$) excited with a taper of $\rho \cong 1.7$ μm. More than 72% of the light in the fiber is coupled out on resonance, and the cavity Q value is $Q = 2 \times 10^6$. Off resonance, only a negligible fraction of the light in the fiber ($\ll$1%) is coupled out by the presence of the sphere. The oscillations on the off-resonant transmission signal are caused by the reflections from the fiber ends and are not related to the presence of the microsphere; the slope on the curve is due to the variation of the power in the fiber while the wavelength is scanned. The amplitude of the dip depends on the alignment of the fiber and the sphere as well as on the particular mode being excited: we observed a dip of more than 90% of the off-resonance transmission when we used a somewhat larger sphere, of radius 210 μm, with $Q \cong 1.5 \times 10^6$. The inset shows a mode in this larger sphere excited by a taper of $\rho \cong 2.25$ μm. The measured linewidth corresponds to a Q of $\sim 5 \times 10^7$ and is due entirely to the acoustic linewidth of our laser source. In principle there is no reason why Q factors as high as 10^{11} could not be observed like this,

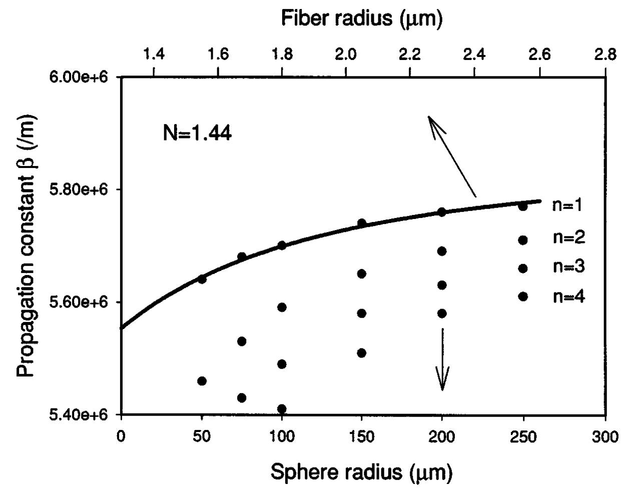

Fig. 1. Calculated values of the propagation constants for a fiber taper (solid curve) as a function of the radius (plotted on the top axis) and for the first few radial mode numbers of WGM resonance for spheres of different sizes, plotted on the lower axis.

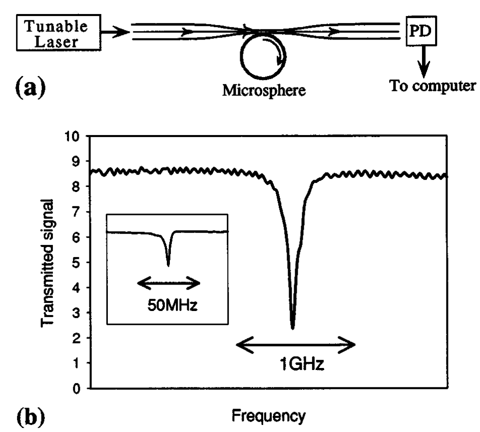

Fig. 2(a) Schematic representation of the experiment. The microsphere is mounted upon $x-y-z$ micropositioners to allow it to be manipulated with respect to the tapered fiber. (b) Example of a resonance dip appearing on the transmission signal. In this case 72% of the light is coupled into the resonance, which has a Q of 2×10^6. The sphere size is $a \cong 85$ μm, and the taper size is $\rho \cong 1.7$ μm. The inset shows a narrower mode in a larger sphere with a larger taper radius ($a \cong 210$ μm, $\rho \cong 2.25$ μm, $Q = 5 \times 10^7$, excitation efficiency 37%).

provided that proper precautions were taken.[9] Although the presence of the tapered fiber in the mode volume couples light out of the microcavity resonance, causing it to be broadened, and although it is not possible to control accurately the gap between the fiber and the microsphere, it is nonetheless possible to control the spacing between the fiber and the mode volume, which occupies only a spatially localized region on the microsphere surface.[10]

When the sphere is in the overcoupled regime (when losses that are due to the presence of the fiber dominate the resonance linewidth) one might expect to see a substantial decrease in the dip on the transmission signal as the light coupled out of the sphere is returned to the fiber guided mode.[11] Although we do indeed see such a decrease, it varies from a few to perhaps a few tens of percent and is not nearly so substantial as expected. This finding indicates that the light coupled out of the sphere is not all reentering the fundamental fiber mode, which is surprising given the efficient coupling into the sphere and may indicate that we are exciting $l \neq |m|$ modes in the sphere at present. This phenomenon will be the subject of further investigation. On the other hand, even at the lowest observed Q when we can couple into the mode efficiently, the light is traveling some tens of centimeters and making several hundred round trips inside the cavity. The ability to couple light in an efficient manner directly from a monomode optical fiber into a high-Q microsphere resonance is essential if microspheres are to be used in optoelectronic devices such as filters and fiber-coupled microlasers.

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