Pigtailing the high-Q microsphere cavity: a simple fiber coupler for optical whispering-gallery modes

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We demonstrate a simple method for efficient coupling of standard single-mode optical fibers to a high-Q optical microsphere cavity. Phase-matched excitation of whispering-gallery modes is provided by an angle-polished fiber tip in which the core-guided wave undergoes total internal reflection. In the experimental setup, which included a microsphere with both an input and an output coupler, the total fiber-to-fiber transmission at resonance reached 23% (total insertion loss, 6.3 dB), with loaded quality factor $Q \geq 3 \times 10^7$ and unloaded $Q \approx 1.2 \times 10^8$ at 1550 nm. A simple pigtailing method for microspheres permits their wider use in fiber optics and photonics devices.

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Optical microsphere cavities,[1] with their unique combination of high quality factor (Q as great as $\sim 10^{10}$ has been demonstrated[2]) and submillimeter dimensions, provide an attractive new building block for fiber optics and photonics applications. Besides their obvious use as ultracompact narrow-band filters and spectrum analyzers, other applications have been proposed, including microlasers,[3] optical locking for laser linewidth narrowing,[4] and replacement of fiber delays in an optoelectronic microwave oscillator.[5] The sensitivity of whispering-gallery (WG) mode frequencies and Q to strain, temperature, and other parameters of the ambient medium can be the basis for ultracompact modulators and sensors.

The prospects for microsphere applications have suffered from the lack of a simple coupler that is compatible with fiber-optic hardware. High-Q WG modes cannot be excited by free beams; instead, light has to be launched from a phase-matched evanescent wave in an adjacent waveguide or a total internal reflection prism.[6] The prism coupler, although it is flexible and versatile, is bulky and requires collimation optics when it is used with fiber.[7] Previous attempts to directly couple a sphere to an optical fiber either had limited efficiency owing to residual phase mismatch (in a side-polished bent fiber coupler[8]) or still had appreciable size, including fragile core-to-cladding transformers (in a tapered fiber coupler[9]). In this Letter we report a simple method for direct fiber coupling to high-Q WG modes in a microsphere—in essence, a hybrid of a waveguide and a prism coupler.

The main idea is illustrated in Fig. 1. The tip of a single-mode fiber (SMF) is angle polished with a steep angle. When it is incident upon the angled surface, the light propagating inside the core undergoes total internal reflection and escapes the fiber. With the sphere positioned in the range of the evanescent field from the core area, an efficient energy exchange occurs at resonance between the waveguide mode of the SMF and the WG mode in the sphere. The angle of the polish is chosen to fulfill the phase-matching requirement $\Phi = \arcsin(n_{\text{sphere}}/n_{\text{fiber}})$. Here n_{sphere} is the effective refractive index for azimuthal propagation of WG modes (as closed waves circulating in the sphere) and n_{fiber} is the effective refractive index for the guided wave in the fiber. Since the linear dimensions of the angle-cut core of the SMF match the scale of the evanescent field overlap area ($\sim 10\ \mu$m for the typical sphere size of few hundred micrometers), the system is equivalent to a prism coupler with the focusing optics eliminated.

The effective index for WG modes TE_{lmq} and TM_{lmq} can be calculated as $n_{\text{sphere}} = cl/a\omega_{lq}$ on the basis of asymptotic expressions[10] for WG mode positions ω_{lq}:

$$\omega_{lq} = \frac{nc}{a}\Bigg[\nu + 2^{-1/3}\alpha_q \nu^{1/3} - \frac{P}{(n^2-1)^{1/2}} + \left(\frac{3}{10}\,2^{-2/3}\right) \times {\alpha_q}^2 \nu^{-1/3} - \frac{2^{-1/3}P(n^2 - 2P^2/3)}{(n^2-1)^{3/2}}\,\alpha_q \nu^{-2/3} + O(\nu^{-1})\Bigg].$$

Here a is the sphere radius; c is the speed of light; n is the refractive index of the sphere material [$n = 1.4440$ (1.4469) for silica at the wavelength $\lambda = 1550$ nm (1300 nm)]; $P = n\ (1/n)$ for TE (TM) modes; $\nu = l + 1/2$; and α_q- is the qth root of the Airy function, $Ai(-z)$, which is equal to 2.338, 4.088, and 5.521 for $q = 1, 2, 3$, respectively. Results of calculation of n_{sphere} (at wavelengths 1550 and 1300 nm) for silica spheres of different radii are given in Fig. 2.

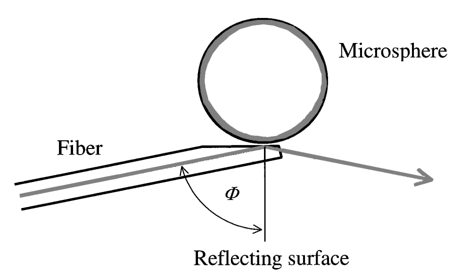

Fig. 1. Angle-polished fiber coupler for WG modes.

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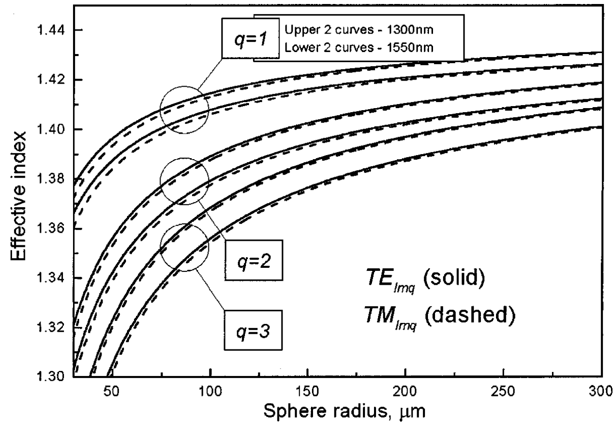

Fig. 2. Effective index for WG mode azimuthal propagation (based on the mode-frequency approximation of Lam *et al.*[10])

Since the guided wave in the core no longer exists after reflection, precise calculation of n_{fiber} is a nontrivial task implying the explicit computation of the evanescent field in the truncation area. As confirmed by the experiments below, a consistent recipe for a functional coupler can be based on a simple approximation in which it is assumed that n_{fiber} is equal to that of a regular fiber. In our experiments we used standard Corning SMF-28 fiber with a core diameter $2b = 8.3\ \mu\mathrm{m}$ and an index difference of 0.36%. The material index was $n_1 = 1.4505$ for the core and $n_2 = 1.4453$ for the cladding at $\lambda = 1550\ \mathrm{nm}$ and $n_1 = 1.4535$ and $n_2 = 1.4483$ at $\lambda = 1300\ \mathrm{nm}$.[11] Using the approximate expression for the mode propagation constant,[12] $\beta \approx kn_2[1 + \Delta(\nu/V)^2]$, where $k = 2\pi/\lambda$ is the free-space wave vector, $\Delta = (n_1 - n_2)/n_2$ is the relative index difference, ν is the normalized transverse decay constant, and $V = kn_2b(2\Delta)^{1/2}$ is the normalized frequency, and the standard solution $\nu(V)$ for the fundamental LP_{01} mode and the parameters of our fiber, we obtain $n_{\mathrm{fiber}} \equiv \beta/k = 1.4476$ at 1550 nm and $n_{\mathrm{fiber}} = 1.4509$ at 1300 nm.

In our first experiment we prepared a SMF-28 fiber tip that was angle polished under the angle $\Phi = 77.5°$, starting with a standard cleave to provide undistorted output of the reflected emission of the core. A close-up view of the coupler with a silica microsphere of radius $a = 235\ \mu\mathrm{m}$ is presented in Fig. 3(a). We adjusted the position of the fiber to maximize the contrast of the characteristic interference response of the WG modes in the far field.[6] We measured the efficiency of the coupler in Fig. 3(a) by sending probe distributed-feedback (DFB) laser light (at 1310 nm) into the fiber and monitoring the overall optical power at the output as function of frequency tuning of the laser. We adjusted the gap between the sphere and the coupler to maximize the contrast of the resonance dips. In Fig. 4 we present an isolated resonance response of a WG mode. The efficiency of the new coupler (greater than 60% power insertion in the mode, or ~2.1-dB single-coupler insertion loss) is comparable with the best reported results for a prism (78%)[6] and for a fiber taper (90%).[9] The 77.5° angle was nearly optimal for excitation of the $q = 2$ WG modes: Exact phase matching can be expected for $n_{\mathrm{sphere}} = 1.4509 \sin 77.5° \approx 1.416$; compare this with $n_{\mathrm{sphere}} = 1.413$ for the TE_{lm2} and TM_{lm2} modes and $2a = 470\ \mu\mathrm{m}$ at 1300 nm (Fig. 2). As mentioned earlier,[9] the efficiency of the coupler may not be critically sensitive to deviation from exact synchronism because of the small (several wavelengths) interaction length, which is limited by the curvature of the microsphere. It is evident, however, that designing an ~100%-efficient coupler will require (1) fine tuning of the angle for the particular sphere dimensions, (2) rigorous analysis of the evanescent field of the coupler, and possibly (3) customization of the core cross section for improved field overlap. The loaded Q factor of the WG mode resonance was 3.2×10^6 (the resonance bandwidth of the Lorentzian fit is 74 MHz in Fig. 4). The linewidth of the DFB laser at our disposal (3–5 MHz, depending on the pump current) was not narrow enough for measurement of the intrinsic Q in the undercoupled regime. Using the ringdown technique (observation of free oscillations in the cavity[2]), we measured the undercoupled energy-decay time

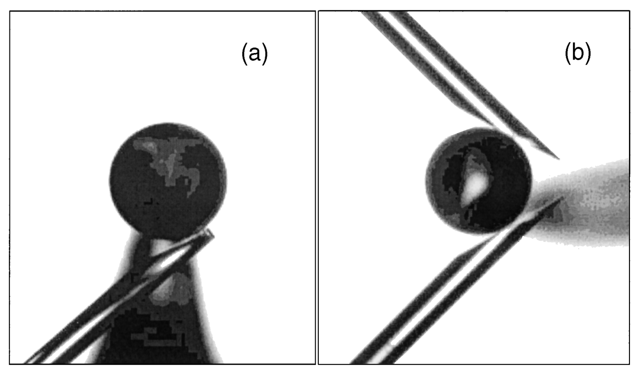

Fig. 3. (a) Microsphere with an angle-polished fiber coupler. The remaining cleave surface facilitates clear output of the reflected core mode. (b) Microsphere with two identical couplers. In both images the dark areas in the background are out-of-focus images of silica rods supporting the microspheres.

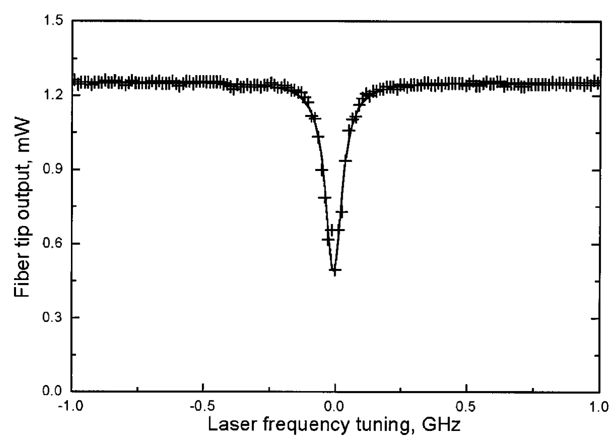

Fig. 4. Characterization of single-coupler efficiency for the assembly in Fig. 3(a). The energy-coupling efficiency at resonance is greater than 60% (single-coupler insertion loss, ~2.1 dB), $Q_{\mathrm{load}} = 3.2 \times 10^6$ at 1310 nm, and the sphere diameter is 470 μm.

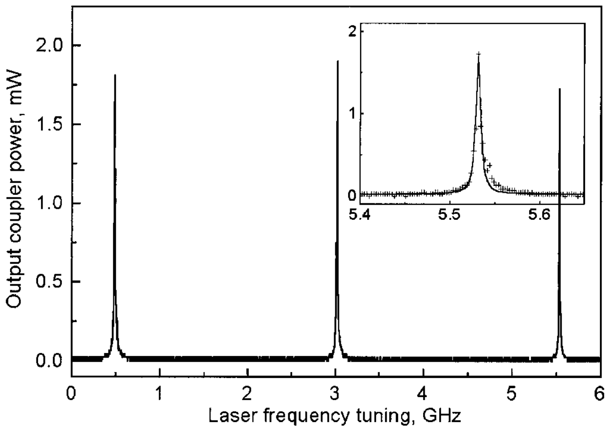

Fig. 5. Transmission of the microsphere + two couplers assembly [Fig. 3(b)]. The input power is 7.5–8.3 mW, the maximum transmission at resonance is ~23.5% (fiber-to-fiber loss, 6.3 dB), $Q_{\rm load} > 3 \times 10^7$ at 1550 nm, and the sphere diameter is 405 μm. Unloaded $Q_0 \approx 1.2 \times 10^8$.

constant $\tau \approx 80$ ns, yielding the unloaded quality factor $Q_0 \approx 1.1 \times 10^8$.

An efficient compact bandpass filter (a microsphere with two fibers) requires that both couplers address the same group of WG modes with equal efficiency. The two couplers have to be geometrically identical and equally aligned. Our original technique for fabricating angle-polished couplers with a partially remaining cleave did not reproduce the angle with precision of better than 2°. A modified technique ensured precision of better than 0.1°, although at this time no flat-cleave surface [Fig. 3(b)] was preserved for easy individual coupler characterization. By adding a two-step alignment procedure, we managed to achieve an overall efficiency of the two-coupler assembly (~6-dB total loss) that was nearly consistent with that of the above single-coupler demonstration. This second experiment was performed at a wavelength of 1550 nm with a similar DFB laser. The essential step in alignment was using an outcoupler prism to optimize the input fiber positioning to excite the TE_{lmq} and the TM_{lmq}, $l \approx m$ modes (tightly localized near the symmetry plane of residual eccentricity).[6] Then we removed the prism and aligned the output coupler to maximize the overall output. The results are presented in Fig. 5 as an overall transmission characteristic of the system. The polishing angle of the two fibers was 75.9°, nearly optimal for excitation of the second-radial-order modes in the sphere. [Exactly matching mode index $n_{\rm sphere} = n_{\rm fiber} \sin \Phi = 1.4476 \sin 75.9° \approx 1.404$; compare this with $n_{\rm sphere} = 1.403$ for $q = 2$; $2a = 405$ μm at 1550 nm (Fig. 2)].

With the input laser power varying from 7.5 to 8.3 mW, maximum fiber-to-fiber transmission at resonance was ~23.5%, corresponding to a total insertion loss of 6.3 dB. In view of the higher loaded Q, we consider this result consistent with the ~2-dB single-coupler demonstration reported above. The observed set of modes with a quasi-free spectral range of $\Delta f = 2.603$ GHz can be interpreted as corresponding to consecutive m numbers and associated with the residual eccentricity $\epsilon^2 = 2l\Delta f/f \approx 3.1 \times 10^{-2}$, $f \approx 1.94 \times 10^{14}$ Hz, $l \approx 1170$, and $2a = 405$ μm at 1550 nm. The loaded Q of the WG modes (see the Lorentzian fit in Fig. 5 with bandwidth of 7.6 MHz), taking into account the DFB laser linewidth of $\delta\nu > 3$ MHz, can be evaluated as $Q_{\rm load} > 3 \times 10^7$. The unloaded Q (as confirmed by a subsequent ringdown measurement at 1550 nm) was $Q_0 \approx 1.2 \times 10^8$. These results correspond to excitation of TE modes; similar coupling efficiency was obtained for orthogonal polarization (TM modes).

In conclusion, we have demonstrated a simple and efficient direct method for coupling very high-Q WG modes in optical microsphere cavities with standard single-mode optical fiber. Simple pigtailing of the microspheres will lead to their wider use in photonics applications. This will permit the realization of a whole class of new devices ranging from ultracompact narrow-band filters and spectrum analyzers and high-sensitivity modulators and sensors to compact laser frequency-stabilization schemes and optoelectronic microwave oscillators.

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