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Polarized transmission spectra of the fiber-microsphere system

G. Guan[a)]
Microparticle Photophysics Laboratory (MP^{3}L), Polytechnic University, Brooklyn, New York 11201

F. Vollmer
Center for Studies in Physics and Biology, Rockefeller University, New York, New York 10021

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The polarized transmission spectra of a fiber-microsphere system was investigated. Light from an optical fiber was side coupled into the dielectric microsphere through optical tunneling. It was found that the polarization of some of the light coupled into the microsphere and back into the fiber changed by 90°. The experiments showed a level of high signal-to-noise ratio peaks at the resonant frequencies in the polarized spectra and the possibility of discriminating between TE and TM modes of the microsphere. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1890465]

The unusually high Q-factor that can be obtained in microsphere resonators has led to the development of several new sensor concepts based on the coupling of microspheres with optical fibers.[1] The microsphere is coupled to the single mode fiber at a location on the fiber where the cladding is removed and the core is tapered by either etching or heating and then stretching the fiber.[1–3] Before and after this tapered region, light propagates only in the fundamental mode of the single mode fiber. In the tapered region, a new fundamental mode is obtained if the fiber is adiabatically tapered.[4,5] If this condition is not met, light propagates in multimodes in the tapered region. The evanescent field of light in the tapered fiber extends several light wavelengths away from the surface. When the microsphere, which has the same refractive index as the fiber, is placed to within the evanescent field, significant exchange of photons takes place between the tapered fiber and the microsphere resonator.

The coupling of light between the fiber and the microsphere resonator is illustrated in Fig. 1. $\mathbf{E}_i$ is the electrical field in fiber before entering the region of coupling, $\mathbf{E}_f$ is the field in fiber after exiting from the coupling region, and $\mathbf{E}_s$ is the field inside the sphere after the coupling region. The electric field in the fiber can be represented in terms of set of the fiber modes denoted as $\{\mathbf{v}_m\}$. Since light travels only in the fundamental mode, the set of fiber modes simplifies to two orthogonal linear polarization modes $\{\mathbf{v}_m, m=1 \text{ and } 2\}$ with polarization axes $\{\hat{e}_1, \hat{e}_2\}$. Assume that the ratio of the transmitted light to that of input light in the fiber mode m is r_m. The electric field in the microsphere can be represented by a set of the microsphere whispering-gallery (WG) modes denoted by $\{\mathbf{u}_n\}$. Here the subscript n represents the group of the electrical mode (TE or TM), the radial quantum number, the angular momentum quantum number, and the azimuth angular momentum quantum number.[6,7] Assume that the single-pass ratio of the fields of the WG mode n after the region of coupling and before the region of coupling is r'_n. The coupling coefficient from the fiber mode $\mathbf{v}_m$ to the microsphere WG mode $\mathbf{u}_n$ is determined by the overlapping on the microsphere of the evanescent field of the fiber mode and the electrical field of the WG mode:[7–9]

$$\kappa_{m,n} = \frac{\omega}{4} \int (\Delta\varepsilon)_s \mathbf{v}_m^* \cdot \mathbf{u}_n da, \tag{1}$$

and the coupling coefficient from the microsphere WG mode $\mathbf{u}_n$ to the fiber mode $\mathbf{v}_m$ is determined by the overlapping on the fiber of the evanescent field of the WG mode and the electrical field of the fiber mode:

$$\kappa'_{n,m} = \frac{\omega}{4} \int (\Delta\varepsilon)_f \mathbf{u}_n^* \cdot \mathbf{v}_m da, \tag{2}$$

where ω is the light frequency. $\int da$ is the double integration over the cross section of the microsphere in Eq. (1) and over the cross section of the fiber in Eq. (2). $(\Delta\varepsilon)_s$ is the dielectric profile difference between having both microsphere and fiber present and having fiber alone. $(\Delta\varepsilon)_f$ is the dielectric profile difference between having both the microsphere and fiber present and having microsphere alone.

The electrical field of a WG mode is approximately uniform in the coupling region since the region is small compared with the microsphere diameter. Assume the polarization of the electrical field of WG mode n at the coupling region is along axis $\hat{e}_n$ with angle θ_{1n} to the axis $\hat{e}_1$ and angle θ_{2n} to the axis $\hat{e}_2$. The addition of the angles θ_{1n} and θ_{2n} is typically larger than 90° since the axis $\hat{e}_n$ is usually not within the plane consisting of $\{\hat{e}_1, \hat{e}_2\}$. The coupling coefficients then become

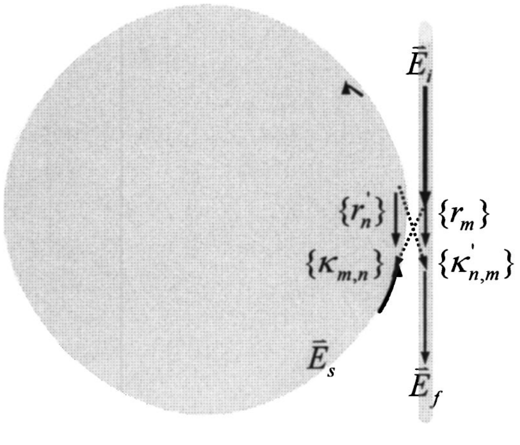

FIG. 1. Coupling between fiber and microsphere resonator.

[a)] Current address: World Precision Instruments Inc., 175 Sarasota Center Blvd., Sarasota, FL 34240; electronic mail: guanguoming@yahoo.com

$$\kappa_{m,n} \approx \cos\theta_{mn}\kappa_n \tag{3}$$

and

$$\kappa'_{n,m} \approx \cos\theta_{mn}\kappa'_n, \tag{4}$$

where κ_n is the coupling coefficient from the fiber mode to the sphere mode n, and κ'_n is the coupling coefficient from the sphere mode n to the fiber mode, as given by Little *et al.*[7] It is noted that in the coupling region all TE modes have similar polarization as do all TM modes.

Light inside the fiber is generally elliptically polarized due to birefringence in the fiber. The electrical field of the input light at the coupling position can be written as:

$$\mathbf{E}_i = E_i(\cos\gamma\hat{e}_1 + \sin\gamma e^{i\delta}\hat{e}_2), \tag{5}$$

where E_i is the complex amplitude of the electrical field of the light incident upon the coupling area, γ is the angle between $\hat{e}_1$ and the axis of the polarization ellipse, and δ is the phase difference between two components along $\hat{e}_2$ and $\hat{e}_1$. Inside the sphere, the electrical field of the WG modes constructively builds up on the coupling light from the fiber. Assume the light in the WG mode n has the phase change φ_n per round and the electrical field of the light has the loss rate α_n per unit distance. The total electrical field in fiber after exiting from the coupling region will be the addition of the field of the transmitted light and the field of light coupled from the sphere:

$$\begin{aligned}\mathbf{E}_f = E_i\Bigg\{&\left[r_1 + \sum_n \frac{\kappa_{1,n}\kappa'_{n,1}\exp(-\alpha_n L_n + i\varphi_n)}{1 - r'_n\exp(-\alpha_n L_n + i\varphi_n)}\right]\cos\gamma \\ &+ e^{i\delta}\sin\gamma\sum_n \frac{\kappa_{2,n}\kappa'_{n,1}\exp(-\alpha_n L_n + i\varphi_n)}{1 - r'_n\exp(-\alpha_n L_n + i\varphi_n)}\Bigg\}\hat{e}_1 \\ &+ E_i\Bigg\{\left[r_2 + \sum_n \frac{\kappa_{2,n}\kappa'_{n,2}\exp(-\alpha_n L_n + i\varphi_n)}{1 - r'_n\exp(-\alpha_n L_n + i\varphi_n)}\right]e^{i\delta}\sin\gamma \\ &+ \cos\gamma\sum_n \frac{\kappa_{1,n}\kappa'_{n,2}\exp(-\alpha_n L_n + i\varphi_n)}{1 - r'_n\exp(-\alpha_n L_n + i\varphi_n)}\Bigg\}\hat{e}_2,\end{aligned} \tag{6}$$

where L_n is the one roundtrip distance of the light in WG mode n. Note the electrical field of the transmitted light in fiber destructively adds the electrical field of the light from the microsphere due to the phase jump after each coupling.

The polarized transmittance is defined as the ratio of the intensity of output light with polarization along one specific axis to the intensity of the input light. Assume that the input light is linearly polarized along $\hat{e}_1$. When the light is in resonance with the microsphere WG mode n, the polarized transmittance along $\hat{e}_1$ is

$$T_1 = \left| r_1 + \frac{\kappa_{1,n}\kappa'_{n,1}\exp(-\alpha_n L_n)}{1 - r'_n\exp(-\alpha_n L_n)}\right|^2, \tag{7}$$

and the polarized transmittance along $\hat{e}_2$ is

$$T_2 = \left|\frac{\kappa_{1,n}\kappa'_{n,2}\exp(-\alpha_n L_n)}{1 - r'_n\exp(-\alpha_n L_n)}\right|^2. \tag{8}$$

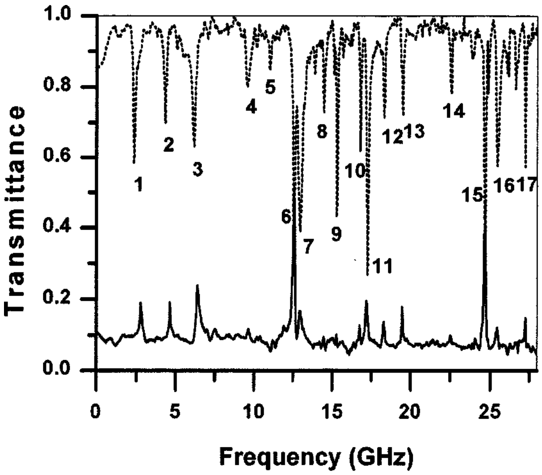

FIG. 2. Polarized T_1 transmission spectrum (dashed line) and polarized T_2 transmission spectrum (solid line).

The T_1 spectrum has dips at the resonant frequencies and the transmittance is near $r_1^2 \approx 1$ without resonance while the T_2 spectrum has peaks at the resonant frequencies and the transmittance is near zero without resonance. The resonant peak in the T_2 spectrum can be optimized or be suppressed by varying the coupling coefficients, for example, changing the angle between the polarizations of the WG mode and the fiber mode. The two transmittances at the same frequency have the following relationship:

$$T_1^{1/2} + \left|\frac{\kappa'_{n,1}}{\kappa'_{n,2}}\right| T_2^{1/2} = r_1. \tag{9}$$

Note all TE modes are grouped into a line in the plot of $T_1^{1/2}$ vs $T_2^{1/2}$ since they have similar polarization. The same is true for the TM modes.

The experiment setup reported in Ref. 1 was modified to measure the polarized transmission spectra. Light from an infrared distributed feedback laser diode (1313 nm nominal wavelength) is optically isolated and coupled into a Corning SMF-28 single mode fiber using a standard fiber coupler. The wavelength of the laser diode is tuned by ramping the operating current (tuning coefficient 0.01 nm/mA, determined by a wavemeter). A length of about 1 cm of the optical fiber is tapered by etching with 25% hydrofluoric acid. An ~400 μm diameter microsphere is evanescently coupled to the tapered fiber. The transmitted light intensity at the other fiber end is detected by an InGaAs photodetector. An IR polarizer mounted in between the fiber end and photodetector selects the polarization of transmitted light. To record the T_1 spectrum, the polarizer was aligned for the maximum transmission of the light when the light frequency is not resonant with any WG mode of the microsphere. To record the T_2 spectrum, the polarizer was aligned for the minimum transmission of the off-resonance light.

Figure 2 shows the recorded T_1 spectrum (dashed line) and the T_2 spectrum (solid line). The transmission at the off-resonance frequency was the level of the background in T_2 spectrum due to the ellipse polarization of the input light. The use of linearly polarized input light can reduce this background and increase the signal-to-noise ratio significantly. This can be achieved by using a linearly polarized light source and short, straight fiber sections to reduce the birefringence effect. Even for long transmitting distances, VanWiggeran *et al.*[10] found that there are two orthogonal orientations in the optical fiber along which light input that is linearly polarized will exit the fiber linearly polarized. By comparing the two spectra, we found that resonance 7, 9, and 11 belong to one electrical mode and resonance 1, 2, 3, 6, and 15 belong to the other electrical mode. The signal-to-noise ratios for resonance 7, 9, and 11 were suppressed in T_2 spectrum compared with those in T_1 spectrum. The reason for this suppression is that the polarizations of these WG modes are near vertical to the axis $\hat{e}_2$.

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