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Spiral morphology-dependent resonances in an optical fiber: effects of fiber tilt and focused Gaussian beam illumination

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Spiral morphology-dependent resonances have been observed in a tilted optical fiber. The polarization-preserving and the cross-polarized elastic-scattering spectra for plane-wave illumination show that the wavelengths of the resonances are blueshifted quadratically as the fiber tilt angle increases. When a focused Gaussian beam illuminates the fiber at its edge, the resonances are blueshifted and broadened as the detector is offset from the scattering plane with the maximum scattering intensity. The blueshift with focused beam illumination is also a consequence of the spiral resonances. © 1998 Optical Society of America

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Morphology-dependent resonances (MDR's) have been observed in various optical cavities such as microdroplets,[1] microdisks,[2] and optical fibers.[3] The resonant internal electric field is greatly enhanced because after each round trip inside the cavity the circulating MDR wave is in phase with the incident wave entering the cavity. One achieves more-efficient coupling of an incident wave to an MDR by focusing a Gaussian beam near the cavity edge. Since a focused Gaussian beam is composed of an angular spectrum of plane waves,[4] we can gain insight into focused Gaussian beam coupling to fiber MDR's by studying the resonances produced by plane-wave illumination of a tilted fiber.

In this Letter we report, for the first time to our knowledge, experimental evidence for the existence of spiral MDR's when the optical fiber is tilted by a small angle θ from the perpendicular to the incident beam propagation direction. In the elastic-scattering spectra the wavelength λ of spiral resonance is predicted to blueshift quadratically as the fiber tilt angle increases.[5,6] We observed the quadratic blueshift of spiral MDR's in all four polarization configurations, TE–TE, TM–TM, TE–TM, and TM–TE, for an unfocused laser beam. We also observed that when the waist of a perpendicularly incident focused laser beam was narrower than the fiber diameter and was focused at the fiber edge, the MDR's were blueshifted and broadened as the detector was offset from the scattering plane with the maximum scattering intensity. The MDR blueshift of a nontilted fiber illuminated by a focused Gaussian beam that is composed of an angular spectrum of plane waves is consistent with the blueshift of a tilted fiber with plane-wave illumination.

Figure 1 shows a tilted fiber in the laboratory reference frame. An incident plane wave propagates along the X_{lab} direction. A ray that is incident upon the tilted fiber at its edge is refracted into the fiber with internal angle α, which is the angle between the spiral and the cross-sectional plane of the fiber. The internal ray has velocity components both parallel and perpendicular to the fiber axis. The ray is confined beneath the fiber surface and spirals along the fiber via successive total internal reflections. An upward-propagating spiral resonance requires that the spiral wave be in phase with the incident wave farther up the tilted fiber. The upper incident wave of the same phase front must travel an extra distance d to reach the tilted fiber. The phase-matching condition between the spiral MDR and the external incident wave

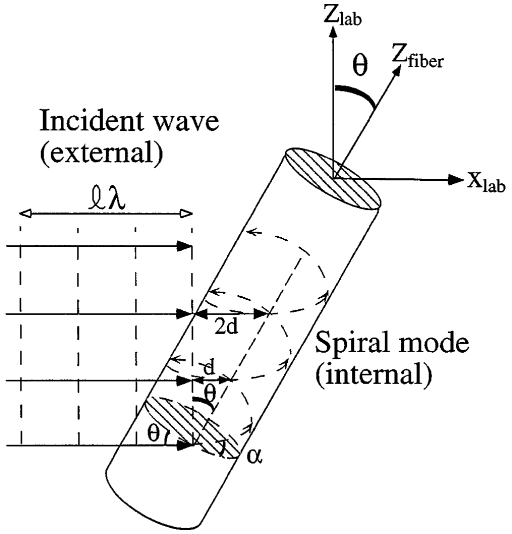

Fig. 1. Internal spiral wave of a tilted optical fiber with respect to the laboratory reference frame. The phase-matching condition between the spiral mode and the external incident wave reduces the effective cavity length for the spiral wave by a distance d/n, where n is the fiber refractive index.

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reduces the effective cavity length for the spiral wave by a distance d/n, where n is the fiber's refractive index. For a small tilt angle, the spiral MDR with a fixed partial wave number l of the MDR (an integer number of wavelength that fits into the cavity length) is blueshifted as follows[5]:

$$\lambda \approx \frac{2\pi a n}{l} - \frac{\pi a}{n l}\,\theta^2, \tag{1}$$

where $2a$ is the fiber diameter.

Experimentally, we employed an optical glass fiber of 125-μm diameter. An external-cavity tunable-diode laser with a wavelength of 664–683 nm, a linewidth of $\approx 10^{-5}$ nm, and a scanning resolution of <0.01 nm was used. Elastic scattering by the fiber was lock-in detected by a photodiode with an acceptance angle $<1°$. The incident and scattered polarizations were set either vertically (TM; the electric field was parallel to Z_{fiber} at $\theta = 0°$) or horizontally (TE; the electric field was perpendicular to Z_{fiber} at $\theta = 0°$) in the laboratory frame. For experiments with a tilted fiber, the fiber was positioned in a goniometer ≈ 1 mm in diameter at the center of the unfocused laser beam and with tilt angle uncertainty of $\approx 0.1°$. When the fiber was tilted in the beam, the physical height of the scattered light shifted. Thus it was necessary to readjust the photodiode height each time the fiber tilt was increased. For experiments with a focused Gaussian beam the fiber was mounted vertically and was transversely displaced from the center of the beam focal waist by ≈ 60 μm.

For the data shown in Fig. 2(a), both the incident and the scattered light were horizontally polarized (TE–TE) and the scattering angle was 90°. A series of MDR's with $Q \approx 10^4$ denoted a, b, and c were observed for normal incidence of the unfocused laser beam. The resonant wavelength of these MDR's blueshifted with increasing θ, and Fig. 2(b) shows a blueshift with θ^2 dependence. The average intercept-to-slope ratio of the θ^2 fits is consistent with the ratio $2n^2$ derived from relation (1) and with $n = 1.456$ for fused silica. However, the values of the intercepts and the θ^2 coefficients are $\approx 30\%$ smaller than those estimated with $l = 600$, that is deduced from matching the measured spectra with Mie calculations. When the fiber was tilted in the TM–TM configuration, both the amplitude and the Q of the TM resonances decreased substantially faster than those of the TE resonances. The TM resonances also blueshifted quadratically with θ, but the θ^2 fits suggest larger coefficients and a systematic intercept shift of ≈ 0.3 nm compared with that of the TE resonances. The polarization dependence of the θ^2 coefficient requires more-sophisticated modeling than the proposed geometric argument.

Cross-polarized scattering with an unfocused laser beam also exhibited MDR peaks, and these peaks blueshifted as the fiber was tilted. At 90° scattering angle and at $\theta = 0°$, the TE–TM and TM–TE spectra consisted of only a broad noise background. As θ was increased, the cross-polarized MDR's appeared and were blueshifted quadratically with θ. The θ^2 fits to the peaks with the TE–TM and the TM–TE configurations are consistent with those of the TM resonances. TE resonances also occurred in the cross-polarized configurations but were substantially weaker than the TM resonances. The presence of both TE and TM resonances in the cross-polarized spectra is due to the slight depolarization of the spiral MDR wave at each total internal reflection.[7] The amplitude difference between the TE and TM resonances in the cross-polarized configurations requires further investigation.

MDR's were also observed by use of focused Gaussian beam illumination at the fiber edge for normal incidence ($\theta = 0°$). The MDR peak-to-background ratio was much improved. The Gaussian beam was focused by a 5-cm $f/7$ lens, and the elastic-scattering spectra were measured at 120° scattering angle, with a detector-acceptance angle of $\approx 0.5°$. Figure 3(a) shows the TM–TM spectra with the three MDR's denoted d, e, and f. The bottom spectrum was measured with the detector at the scattering plane with the maximum scattering intensity. The middle and the top spectra were measured with the detector height offset by 2 and 4 mm, respectively, corresponding to a change in vertical observation angle from 0° to 1° and 2°. A slight blueshift and broadening were noted

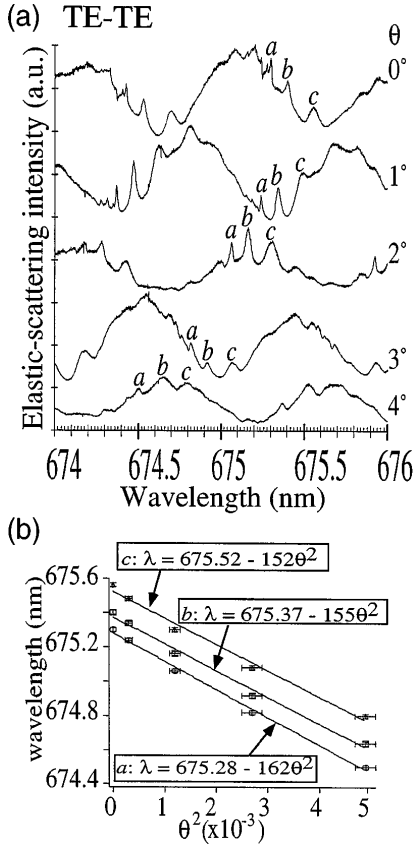

Fig. 2. Elastic-scattering spectra detected at a 90° scattering angle from a tilted fiber that is illuminated by an unfocused beam. The tilt angle is θ. (a) Both the incident and the scattered light were horizontally polarized (TE–TE). (b) Blueshift of the a, b, and c MDR's with θ^2 dependence.

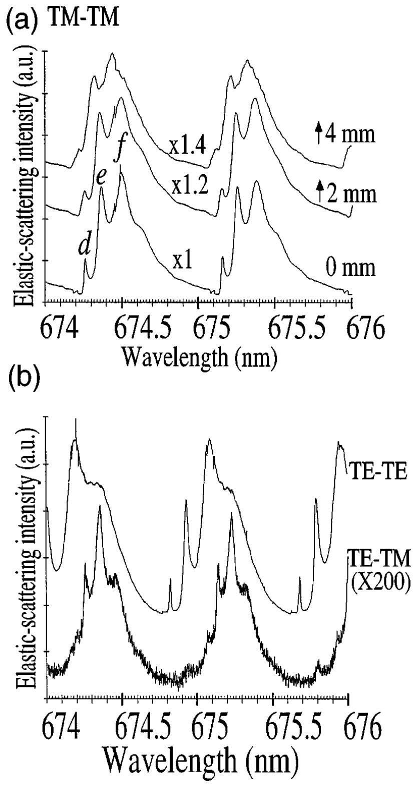

Fig. 3. Elastic-scattering spectra of a perpendicularly incident ($\theta = 0°$) focused Gaussian beam at the fiber edge. (a) TM–TM spectra detected at 120° scattering angle. The three spectra were measured with the detector at the maximum scattering intensity (0 mm) and with the detector height offset by 2 and 4 mm. The f peaks in the three spectra are normalized. The d, e, and f MDR's were broadened and slightly blueshifted as the detector-height offset increased. (b) TE–TE and TE–TM spectra measured at 0-mm height offset. The TE–TM spectrum shows a wavelength shift and is ≈0.5% of the TE–TE intensity.

when the detector-height offset was increased. The slight blueshift is consistent with larger tilt angles in the angular spectrum of plane waves that form the focused Gaussian beam. The TM–TE spectra had similar detector-height dependence. The TM–TE spectrum at the height for maximum scattering intensity resembles the TM–TM spectrum but with only ≈5% of the TM–TM intensity.

A focused Gaussian beam with TE-incident polarization was also studied. Figure 3(b) shows the TE–TE spectrum compared with the TE–TM spectrum measured at 120° scattering angle at the maximum scattering plane. The TE–TM spectrum has a scattering intensity of only ≈0.5% of the TE–TE spectrum and reveals a wavelength shift which suggests that the TE–TM MDR's are the TM resonances. The presence of the TM resonances in the TE–TM configuration with focused Gaussian beam illumination at the fiber edge is consistent with the observation of the TM spiral modes in the TE–TM configuration of a tilted fiber with plane-wave illumination.

In summary, we have observed quantitative evidence of spiral MDR's in a tilted optical fiber. The resonances in each of the four polarization configurations are blueshifted quadratically as the fiber is tilted. The TM spiral modes for cross-polarized scattering appear to have a larger amplitude than the TE spiral modes. Using a Gaussian beam focused at the fiber edge, we find that the resonant wavelength and linewidth are detector-height dependent. Such detector-height dependence is consistent with the angular spectrum of plane waves that form the focused Gaussian beam.

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References

1. R. K. Chang and A. J. Campillo, *Optical Processes in Microcavities* (World Scientific, Singapore, 1996).
2. R. E. Slusher, A. F. J. Levi, U. Mohideen, S. L. McCall, S. J. Pearton, and R. A. Logan, Appl. Phys. Lett. **63,** 1310 (1993).
3. J. F. Owen, R. K. Chang, and P. W. Barber, Opt. Lett. **6,** 540 (1981).
4. J. A. Lock, J. Opt. Soc. Am. A **14,** 640 (1997).
5. J. A. Lock, J. Opt. Soc. Am. A **14,** 653 (1997).
6. L. G. Guimarães and J. P. R. Furtado de Mendonca, Appl. Opt. **36,** 8010 (1997).
7. J. A. Lock and C. L. Adler, J. Opt. Soc. Am. A **14,** 1316 (1997).