

Analysis of forward Brillouin scattering in optical fibers with whispering-gallery modes

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Abstract. A new approach to detect and analyze transverse acoustic mode resonances (TAMRs), responsible for forward Brillouin scattering in optical fibers, is reported using optical whispering gallery modes (WGMs). TAMRs generate perturbations in the geometry and the dielectric permittivity of the fiber that couples the acoustic and optical resonances. This interaction is exploited to probe opto-excited TAMRs exhibiting an optimal efficiency for detecting low-order TAMRs.

1 Introduction

Optical whispering gallery modes (WGMs) are electromagnetic resonances that can exist in circularly symmetric dielectric resonators. These resonant frequencies are highly sensitive to changes in both the geometry of the resonant cavity and the optical properties of the material, making them ideal for WGM-based sensing and characterization applications [1, 2]. Acoustic oscillations inside the resonator can lead to perturbations in the WGM's propagating properties and resonant frequency. Specifically, transverse acoustic mode resonances (TAMRs) in optical fibers, which are responsible for forward Brillouin scattering [3], can generate perturbations of both the dimensions and the dielectric permittivity of the resonator. This mechanism provides a means to detect TAMRs using WGMs.

TAMRs can be generated through electrostriction by an optical pulse traveling in the core of an optical fiber, producing an acoustic wave packet that propagate across the entire cross section of the fiber. In single mode optical fibers, there are two families of TAMRs that can be excited by the fundamental fiber mode: $R_{0,m}$ modes that only have a displacement field in the radial direction and $TR_{2,m}$ modes whose displacement field contains both radial and azimuthal components. While WGMs are sensitive to $R_{0,m}$ modes, they are not sensitive to $TR_{2,m}$ modes since the overlap integral over the azimuthal coordinate of the acoustic and optical fields vanishes, at least for small perturbations.

The geometrical and material perturbations of the resonator (the fiber) induced by the $R_{0,m}$ modes cause the frequency shift of the WGM resonances. Specifically, both contributions are of opposite sign, so they can partially compensate each other. Figure 1(a) depicts the maximum relative wavelength shift of both TM- and TE-polarized WGMs caused by $R_{0,m}$ modes generated by a 700 ps optical pulse with a peak power of 6 kW in a single

mode fiber. It is shown that the wavelength shift depends on the polarization of the WGM.

Excitation of WGMs in the optical fiber can be achieved by using the evanescent field of an auxiliary tapered optical fiber. The amplitudes of the wave inside the resonator and the fiber taper can be calculated by solving a system of coupled differential equations [4]. By introducing a frequency detuning that oscillates with time, as is the case with $R_{0,m}$ modes, the transmitted amplitude through the taper becomes dependent on the frequency of the cavity oscillation. Figure 1(b) presents the calculated frequency response of the transmitted wave for various Q-factors of the WGM. A low-pass filter response is observed, where the cut-off frequency decreases when the Q-factor increases.

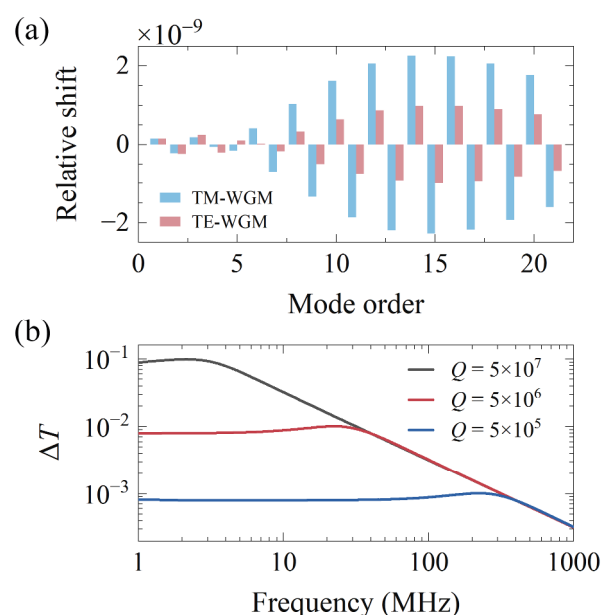


Fig. 1. (a) Calculated relative wavelength shift of the WGM due to $R_{0,m}$ acoustic modes. (b) Frequency response of the transmitted wave in the taper-resonator coupled system.

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2 Experimental results and discussion

TAMRs were generated in a single-mode fiber using a pulsed laser (700 ps, 19 kHz, @1064 nm) while WGMs were excited using a thin tapered fiber ($\sim 3 \mu\text{m}$) perpendicular to the fiber and a tunable narrowband laser. The probe laser was tuned to the slope of a WGM's notch so that variations of the resonant wavelength led to power fluctuations of the transmitted light through the fiber taper. The temporal response of the transmitted light was measured using a fast photodetector and an oscilloscope.

Different WGMs with different Q-factor were employed for the detection of the $R_{0,m}$ modes. Firstly, and according to Fig. 1(b), a relatively low Q-factor was chosen for the detection of the acoustic modes to ensure a broadband response of the WGM. The transmitted signal through the tapered fiber for a WGM resonance with a bandwidth of 2.8 pm and a resonance wavelength of 1535.9 nm (Q-factor $\sim 5.5 \times 10^5$) is shown in Fig. 2(a). The beats separated by ~ 21 ns correspond to the acoustic wave packet of $R_{0,m}$ modes travelling in the radial direction of the resonator at the longitudinal velocity of silica (~ 5960 m/s). The spectrum of the transmitted signal was obtained through Fourier transform of the temporal trace for TM- and TE-polarized WGM, as depicted in Fig. 2(b)-(c). The spectra are significantly different as discussed before, exhibiting a minimum at the $R_{0,4}$ mode for the TM-polarized WGM and at the $R_{0,6}$ mode for the TE-polarized WGM. Such minimum results from the counteracting of the geometrical and material contribution in each case. Low-order modes are accurately observed in both cases, in contrast with previously reported techniques [5].

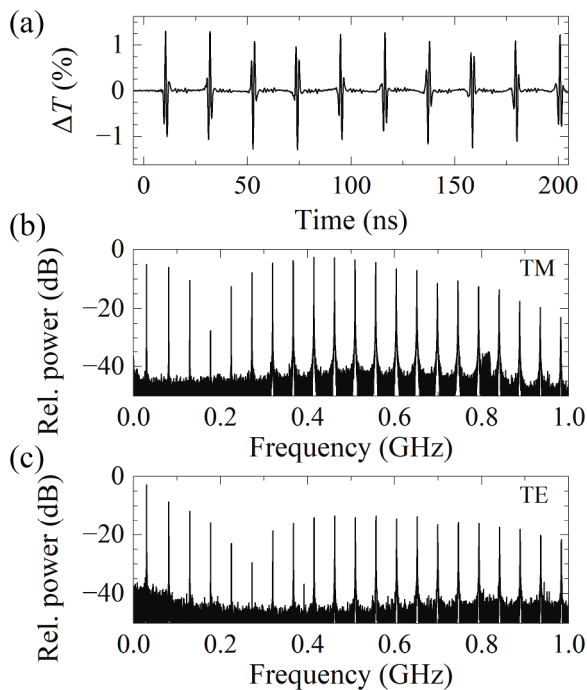


Fig. 2. (a) Temporal response of the probe laser in the presence of $R_{0,m}$ modes for a WGM with a Q-factor of $\sim 5.5 \times 10^5$. (b) Radio-frequency spectrum for a TM-polarized WGM. (c) Radio-frequency spectrum for a TE-polarized WGM.

The response on the transmitted probe wave for WGMs with higher Q-factor was also studied. The results for TM-WGMs with Q-factors of 3.3×10^6 and 1.6×10^7 are depicted in Fig. 3. The results show an agreement with the low-pass filter response discussed before. The contribution of low order $R_{0,m}$ modes is more noticeable when increasing the Q-factor, observing a clear modulation of 30 MHz corresponding to the $R_{0,1}$ mode.

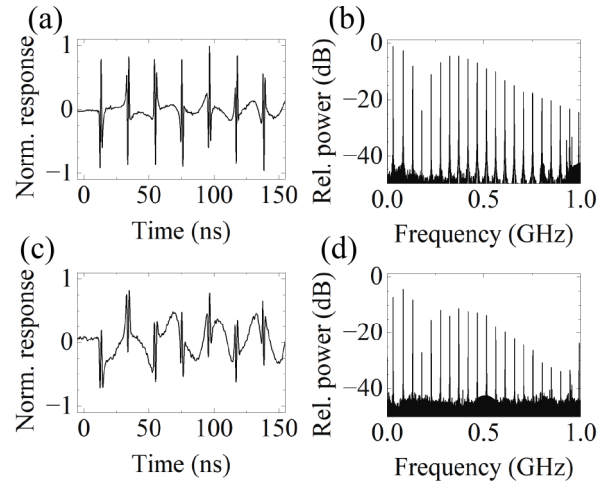


Fig. 3. Temporal traces and radio-frequency spectra for WGMs with Q-factor of (a)-(b) 3.3×10^6 and (c)-(d) 1.6×10^7 .

3 Conclusions

In this work we have studied how the interaction between optical whispering gallery modes and acoustic resonances can be used to investigate transverse acoustic mode resonances in optical fibers. The study shows that TAMRs generate small perturbations in the dielectric permittivity and geometry of the fiber, which affect the fields of WGMs and their resonant frequencies. Low-order $R_{0,m}$ modes can be accurately interrogated using this technique for different Q-factors of the WGMs. The results suggest potential for future developments combining acoustic and optical resonances in a single device.

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References

1. J. Zhu, S. K. Ozdemir, Y. F. Xiao, L. Li, L. He, D. R. Chen, and L. Yang, *Nat. Photonics* **4**, 46 (2009).
2. X. Roselló-Mechó, M. Delgado-Pinar, A. Díez, and M. V. Andrés, *OSA Contin.* **3**, 441 (2020).
3. R. M. Shelby, M. D. Levenson, and P. W. Bayer, *Phys. Rev. B* **31** (1985).
4. M. L. Gorodetsky and V. S. Ilchenko, *J. Opt. Soc. Amer. B* **16** (1999).
5. L. A. Sánchez, A. Díez, J. L. Cruz, and M. V. Andrés, *Opt. Lett.* **45**, 5331 (2020).