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Optical excitation and characterization of gigahertz acoustic resonances in optical fiber tapers

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Transverse acoustic resonances at gigahertz frequencies are excited by electrostriction in the few-micrometer-thick waists of low-loss optical fiber tapers of up to 40 cm long. A pump-probe technique is used in which the resonances are excited by a train of optical pulses and probed in a Sagnac interferometer. Strong radially symmetric acoustic resonances are observed and the dependence of their frequencies on taper thickness is investigated. Such easily reconfigurable acousto-optic interactions may have applications in the high-frequency mode locking of fiber lasers. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2995863]

The interaction of light with acoustic resonances (ARs) in wavelength-scale structures has been the subject of several recent studies. Efficient excitation of ARs at gigahertz frequencies has been demonstrated in small-core photonic crystal fibers (PCFs) with large air-filling fractions[1,2] and micron-scale on-chip spherical resonators.[3] PCFs in particular have attracted much attention due to their long interaction lengths, which have been beneficial in exploring Raman-like forward light scattering by trapped acoustic phonons or "artificial molecules."[1] In this work, the silica core acts as a resonator for acoustic waves traveling in the transverse plane. The acoustic waves are trapped by the large mismatch in acoustic impedance between the core and the surrounding array of air channels, in some cases supplemented by the presence of a phononic band gap in the periodically structured cladding. As a result, both ARs and light can be strongly trapped in the small core (typically $1\sim 2$ μm in diameter), leading to enhanced acousto-optic (AO) interactions compared to conventional optical fibers. Coherent control of ARs in PCFs using a sequence of optical pulses with precisely adjusted temporal spacing has been recently reported, with amplification and cancellation of ARs being demonstrated.[2]

In this paper, we study ARs in the waist of tapered silica optical fibers. The thin silica taper strand, surrounded by air, acts as an acoustic resonator in a similar fashion to the core of a PCF. Taper waists with diameters of a few micrometers have similar acoustic and optical properties to the PCFs previously studied.[1,2] Since both light and sound are confined within the strand, the AO overlap is very high, leading to strong sound-light interactions. Fiber tapers also have some practical advantages. Low insertion loss is easily achieved, enabling stronger excitation of ARs. Moreover, since the AR frequency is solely dependent on taper diameter, the acoustic frequency can be adjusted simply by tapering down to an appropriate thickness.

In the work reported here, ARs are excited in tapered fibers via electrostriction by launching a train of optical pulses.[4–6] It is known that two types of ARs can be excited in this way in isotropic cylindrical rods; these are the axially symmetric R_{0m} radial acoustic mode and the axially asymmetric TR_{2m} mixed torsional-radial acoustic mode.[5,6] Previous work on ARs in PCFs has focused on the TR_{2m} mode.[1,2] However, while the TR_{2m} mode is easier to characterize using a convenient polarization modulation technique,[1,2] the R_{0m} mode is practically more important because it yields stronger and polarization-independent interactions with the fundamental optical mode.[5,6] Since the R_{0m} mode gives rise to only phase modulation in the guided light, interferometric measurement is necessary for its characterization.[7] We propose and utilize a technique based on Sagnac interferometry,[8] which provides passively stabilized characterization of both R_{0m} and TR_{2m} modes. We also investigate the dependence of AR frequencies on the taper thickness, comparing the measurements with theoretical predictions.

Figure 1 shows the schematic diagram of the experimental setup for excitation and characterization of ARs. An optical pulse train with 1543 nm wavelength, 500 kHz repetition rate, 100 ps pulse width, and 40 W peak power is launched into the taper via a 50% directional coupler. The pulse train is synthesized from a continuous-wave (cw) external-cavity diode laser using a $LiNbO_3$ electro-optic in-

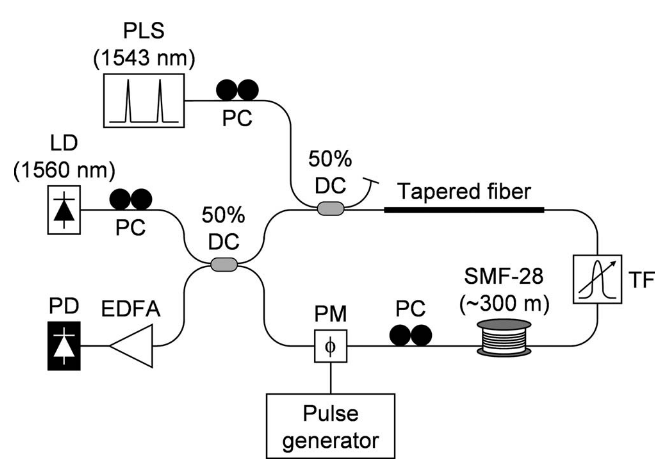

FIG. 1. Schematic diagram of the setup used for excitation and characterization of ARs in the tapered fibers. PLS: pulsed light source. LD: laser diode. PC: polarization controller. DC: directional coupler. TF: tunable filter. PM: phase modulator. EDFA: erbium-doped fiber amplifier. PD: photodetector.

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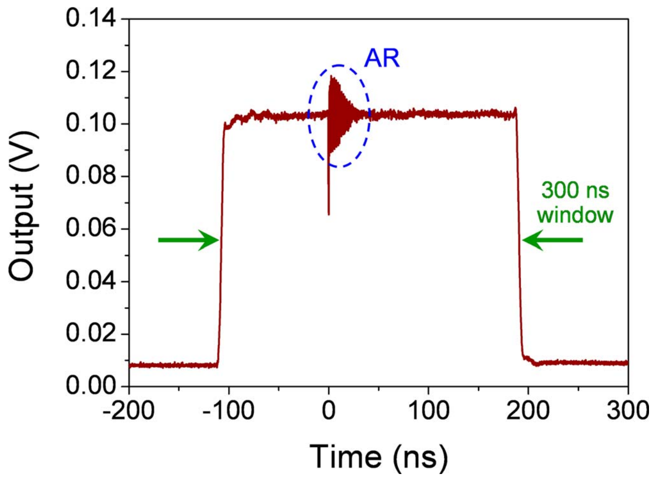

FIG. 2. (Color online) Oscilloscope trace of the output signal of the Sagnac interferometer including the 1.8 μm taper. The excited ARs are detected within the 300 ns time window with the $\pi/2$ phase bias applied. An optical pulse is launched into the taper at $t=0$.

tensity modulator, followed by an erbium-doped fiber amplifier (EDFA).[1] A 1560 nm cw probe beam from another external-cavity diode laser is launched into the Sagnac loop to detect the phase modulation induced by the ARs. A 300-m-long single-mode fiber (Corning SMF-28) delay line is inserted in the Sagnac loop so that only one of the two counterpropagating probe beams experiences the phase modulation. A thin-film tunable filter (TF) is placed close to the taper to prevent the optical pulse train from propagating further and creating ARs in the delay line. We use a $LiNbO_3$ electro-optic phase modulator (PM) in the Sagnac loop. A square-waveform electrical signal with a 300 ns pulse width is applied to the PM so that a $\pi/2$ phase bias is produced between the two counterpropagating probe beams. This phase bias enables efficient and linear conversion from phase modulation to intensity modulation.[8] The square-waveform electrical signal is synchronized to the optical pulse train, the relative time delay being adjusted so that the phase modulation can be observed within the 300 ns time window with the $\pi/2$ phase bias applied. The output signal from the Sagnac interferometer is amplified by another EDFA (preamplifier) to reach an observable intensity level, and then detected by a fast photodetector (PD) (4.5 GHz).

A single-mode fiber (Corning SMF-28) was tapered using a conventional "flame-brushing and pulling" technique with a butane-oxygen flame.[9] Three tapers with waists 40 cm long and diameters of 1.8, 2.8, and 3.8 μm were produced. The insertion loss was measured to be less than 0.2 dB in each case. The thickness and uniformity of each taper were checked with an optical microscope after characterization of the ARs. Uniformity to <0.1 μm was routinely obtained.

Figure 2 shows the oscilloscope trace of the output signal of the Sagnac interferometer for the 1.8 μm taper. The phase modulation induced by the ARs is detected within the 300 ns time window. The sharp notch at the beginning of the AR signal ($t=0$) is due to cross-phase modulation between the optical pulse and the copropagating probe beam. The nonzero output level outside the 300 ns window comes mainly from the amplified spontaneous emission (ASE) in the preamplifier. The damped oscillations of the ARs are clearly visible in Fig. 3(a). Comparison of the peak-to-peak output intensity modulation at $t=0$ ($\sim$30 mV) with the

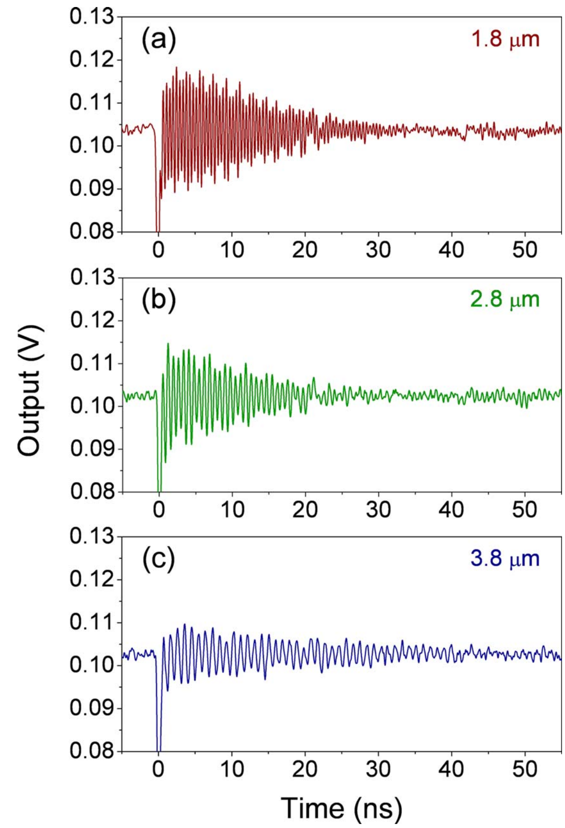

FIG. 3. (Color online) (a) Enlarged view of Fig. 2 around the AR signal. [(b) and (c)] Enlarged output signals of the Sagnac interferometer with a 2.8 μm taper and a 3.8 μm taper, respectively.

background dc level ($\sim$95 mV excluding the ASE level) gives us an estimated index modulation of $\sim 10^{-7}$ distributed along the 40-cm-long waist. This level of index modulation is much larger, by a factor of greater than 100, than any previously reported in PCFs.[1,2] It is attributed to higher pulse intensities, made possible via low insertion loss of the tapers and stronger confinement of ARs with less acoustic leakage.[1] The acoustic lifetime ($1/e$ decaying time) is determined to be $\sim$14 ns. ARs were also excited and characterized in the 2.8 μm taper [Fig. 3(b)] and the 3.8 μm taper [Fig. 3(c)]. As the taper thickness increases, the AR frequency is reduced, leading to an increased acoustic lifetime.[10] The acoustic lifetimes are determined to be $\sim$16 and $\sim$26 ns for the 2.8 and 3.8 μm tapers, respectively.

The AR frequencies were estimated by taking a Fourier transform of the output signals in Fig. 3. Figure 4(a) shows the results for all three tapers. Two spectral peaks, indicating the presence of two different ARs, are seen for each taper. In the case of the 1.8 μm taper, the large peak at 2.2 GHz comes from the R_{01} mode, while the small peak at 1.6 GHz is produced by the TR_{21} mode. The R_{0m} and TR_{2m} modes are experimentally distinguished by examining the dependence of the amplitude of the spectral peaks on the polarization of the optical pulse train exciting the ARs. While the R_{0m} mode is axially symmetric (excitation independent of pulse polarization), the excitation of the TR_{2m} mode is highly dependent on the ellipticity of the pulse polarization.[5] Even though the amplitudes of the spectral peaks for the TR_{21} mode shown in Fig. 4(a) are close to their maxima with adjustment of the pulse polarization, they can be made to almost disappear by control of the pulse polarization. As mentioned above, the

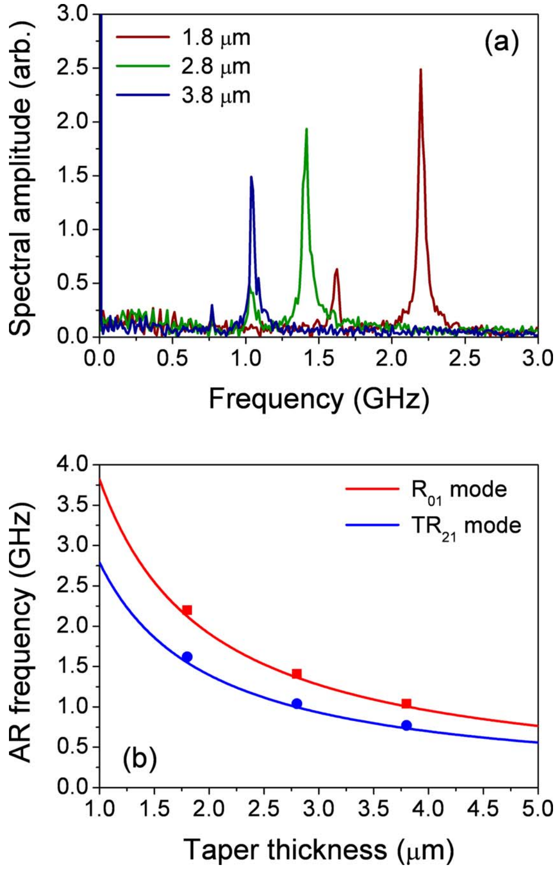

FIG. 4. (Color online) (a) Fourier spectra of the output signals in Fig. 3, showing the AR frequencies. (b) Relationship between the taper thickness and the frequencies of ARs in the R_{01} and TR_{21} modes. Both the measurements (dots) and the theoretical expectations (curves) are shown.

R_{01} mode is excited some five times more efficiently than the TR_{21} mode, when the polarization is adjusted so that the TR_{21} mode is excited most efficiently [as in Fig. 4(a)]. This value is the same as that previously reported for conventional optical fibers.[5] Figure 4(b) shows the measured and theoretically expected frequencies of ARs in the R_{01} and TR_{21} modes with respect to taper diameter. Considering the tapers as isotropic cylindrical rods, one can show that the AR frequency is inversely proportional to the taper thickness as follows:[6,7]

$$f_{\mathrm{AR}} = \frac{q}{d}, \tag{1}$$

where d is the taper thickness and q is a constant depending on the acoustic mode. For the R_{01} and TR_{21} modes, $q_{R01} = 3.82$ GHz μm and $q_{TR21} = 2.79$ GHz μm. In this calculation, the shear and longitudinal sound velocities for bulk silica were used (3740 and 5996 m/s).[7] The theoretical predictions from Eq. (1) show excellent agreement with the measurements [as seen in Fig. 4(b)].

In conclusion, high-quality (<0.2 dB insertion loss) 40-cm-long fiber tapers with uniform few-micrometer-thick waists can be used to study optical excitation of transverse ARs. ARs at frequencies of a few gigahertz can be excited by electrostriction, via a train of optical pulses. A technique based on Sagnac interferometry allows highly effective characterization of the excited ARs. Both R_{01} and TR_{21} modes are identified in the experiments, yielding index modulations of as high as $\sim 10^{-7}$. The measured dependence of the AR frequency on the taper thickness shows excellent agreement with theoretical predictions. The Sagnac characterization technique can thus be used for nondestructive determination of the thickness of a fiber taper. Fiber tapers provide a convenient vehicle for exploring and utilizing strong and nonlinear interactions between light and ultrahigh-frequency ARs. Potential applications include mode locking of fiber lasers at gigahertz repetition rates.

[1] P. Dainese, P. St. J. Russell, G. S. Wiederhecker, N. Joly, H. L. Fragnito, V. Laude, and A. Khelif, Opt. Express **14**, 4141 (2006).
[2] G. S. Wiederhecker, A. Brenn, H. L. Fragnito, and P. St. J. Russell, Phys. Rev. Lett. **100**, 203903 (2008).
[3] T. Carmon and K. J. Vahala, Phys. Rev. Lett. **98**, 123901 (2007).
[4] E. M. Dianov, A. V. Luchnikov, A. N. Pilipetskii, and A. N. Starodumov, Opt. Lett. **15**, 314 (1990).
[5] L. du Mouza, Y. Jaouën, and C. Chabran, IEEE Photon. Technol. Lett. **10**, 1455 (1998).
[6] A. S. Biryukov, M. E. Sukharev, and E. M. Dianov, Quantum Electron. **32**, 765 (2002).
[7] R. M. Shelby, M. D. Levenson, and P. W. Bayer, Phys. Rev. B **31**, 5244 (1985).
[8] K. H. Han, W. J. Lee, and B. Y. Kim, IEEE Photon. Technol. Lett. **13**, 148 (2001).
[9] T. A. Birks and Y. W. Li, J. Lightwave Technol. **10**, 432 (1992).
[10] C. Krischer, J. Acoust. Soc. Am. **48**, 1086 (1970).