Resonance in Fiber-Based Acoustooptic Devices via Acoustic Radiation to Air

S. H. Yun and H. S. Kim

***Abstract*—We describe the experimental observation of acoustic resonance in a packaged all-fiber acoustooptic filter via acoustic radiation from the optical fiber to the air. The phenomenon has resulted in periodic decreases in the efficiency of the device with respect to temperature changes and wavelength tuning and could be eliminated by breaking the cylindrical symmetry of a metal tube package.**

***Index Terms*—Acoustic propagation, acoustic resonators, acoustic waveguides, acoustooptic devices, acoustooptic filters, optical fiber devices, optical fiber filters.**

ALL-FIBER acoustooptic devices have attracted considerable interest due to their extremely low insertion loss (0.1 dB) and have been demonstrated as frequency shifters, tunable wavelength filters, broadband attenuators, and switches [1]–[7]. Efficient acoustooptic interaction has been demonstrated using various fiber-based interaction media such as a single-mode fiber, few-mode fiber, tapered fiber, and fused coupler. Among many schemes, an acoustooptic filter based on a standard telecommunication single-mode fiber and a flexural acoustic wave seems particularly attractive for a practical application to dynamic gain flattening in telecommunication systems [8], since it can benefit from well-established fiber manufacturing without the need for sophisticated fiber tapering or etching process. Due to its strong acoustic absorption, the polymer jacket of the standard fiber needs to be stripped off in the acoustooptic interaction region. The acoustic wave can propagate a bare silica fiber with minimal loss at frequencies up to tens of megahertz due to low intrinsic absorption and scattering in the silica material and excellent structural uniformity of the fiber. Moreover, a large contrast in acoustic impendence by two orders of magnitude between silica and the surrounding air results in minimal radiation loss to the air. In previous acoustics analyses [9]–[11], the surrounding air has often been neglected and replaced by the vacuum because of its small acoustic impedance. However, care must be taken if the small, but nonzero, amount of acoustic wave coupled to the air can be reflected back to the optical fiber and interfere with the main acoustic wave. In this letter, we describe the experimental observation of such acoustic interference in a packaged acoustooptic device. The acoustic wave radiated to the air resonated inside a cylindrical metal tube and caused significant effects to the performance of device, such as periodic variation in optical mode-coupling efficiency with respect to temperature changes and wavelength tuning.

Manuscript received June 16, 2003; revised August 12, 2003.

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Digital Object Identifier 10.1109/LPT.2003.818898

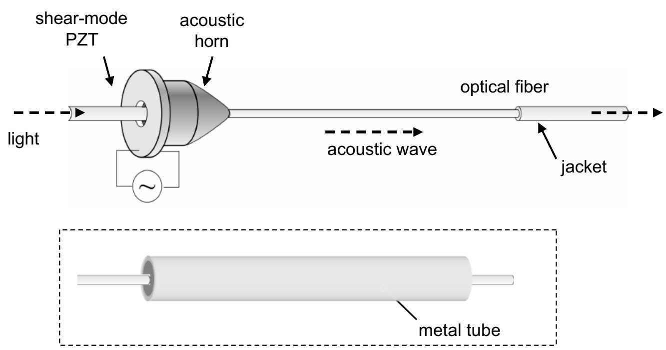

Fig. 1. Schematic of the fiber-based acoustooptic filter. Inset: packaged device with metal tube.

Fig. 1 shows the schematic of our device using a standard silica-based single-mode fiber with 125-μm cladding diameter. The acoustic transducer consisted of a shear-mode piezoelectric transducer (PZT) washer and a coaxial aluminum horn. The optical fiber with a stripped section was threaded into the transducer and bonded with an adhesive. The transverse acoustic wave generated by the PZT is focused onto the horn tip and coupled to the optical fiber. The flexural acoustic wave excited in the optical fiber produces mode coupling between the fundamental core mode (LP01) and the second-order cladding mode (LP12) for an optical wavelength satisfying phase matching. The acoustooptic interaction occurs at the stripped fiber section after which both the acoustic wave and cladding modes are absorbed by an acoustic damper and polymer jacket. The phase-matching acoustic frequency for an optical wavelength between 1.53–1.56 μm was an order of 2 MHz corresponding to an acoustic wavelength of about 0.7 mm. Due to optical modal dispersion and the phase matching condition, the amount of coupling to the cladding mode is a strong function of the optical wavelength, and therefore, the device functions as a spectral notch filter [5], [6]. The full-width at half-maximum notch width of the device was 4 nm for 11-cm-long interaction length. The center wavelength and depth of the notch are determined by the frequency and amplitude of the acoustic wave which are controlled by the frequency and voltage of a radio-frequency (RF) electric signal applied to the acoustic transducer. Fabrication of the device is completed by insertion of the filter assembly to a metal (Invar) tube package and a bonding and sealing process with adhesives (inset of Fig. 1). The Invar tube not only protects the filter assembly and makes handling easier, but also maintains constant tension on the optical fiber attached to the tube

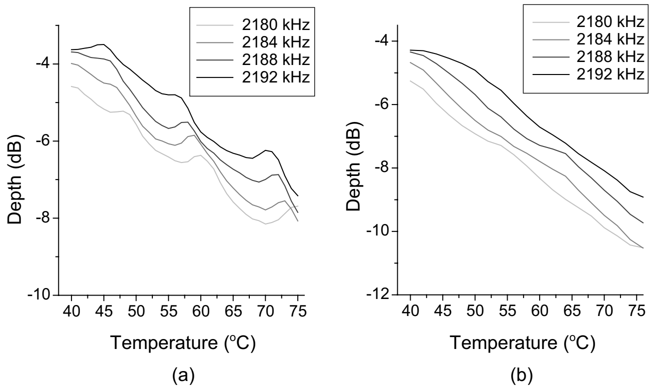

Fig. 2. Notch depths measured as a function of temperature and acoustic frequency (a) with and (b) without the metal tube.

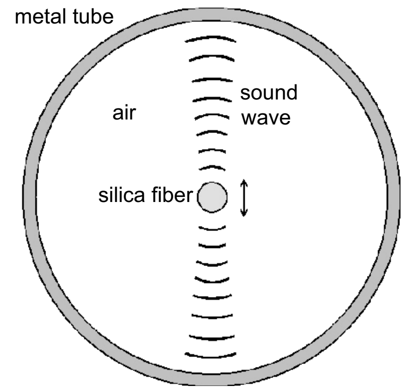

Fig. 3. Resonance of sound wave inside the metal tube.

due to its low thermal expansion coefficient $(1.5 \times 10^{-6}/°\text{C})$ matching that of silica $(0.5 \times 10^{-6}/°\text{C})$. The tension control is critical since the tension affects the coupling efficiency and center wavelength of the notch (~0.04 nm/MPa).

While characterizing the packaged device, we have observed an interesting phenomenon that the efficiency of the device varied periodically with respect to temperature changes and optical wavelength tuning. Fig. 2(a) shows a representative measurement result. For this measurement, the device was placed inside an environmental chamber. At each temperature in the range 40 °C–76 °C, the notch depth was measured at a number of RF frequencies at a constant RF voltage of 20 V (peak-to-peak). The four curves shown in Fig. 2(a) were obtained at 2.180, 2.184, 2.188, and 2.192 MHz, corresponding to notch center wavelengths of 1531.1, 1531.9, 1532.6, and 1533.4 nm, respectively (tuning coefficient: −0.2 nm/kHz). The difference in notch depth at different RF frequencies primarily resulted from the frequency dependence of transducer efficiency arising from acoustic resonance inside the horn [11], [12]. The tendency of increasing efficiency (notch depth) as the temperature increases is attributed to the impedance change of the PZT which consumes more electrical powers at higher temperatures at a given drive voltage. Also, clearly seen is the oscillation of the efficiency (notch depth) as a function of temperature with a period of about 12 °C–14 °C. Note also that the resonant temperatures where the efficiency drops periodically are continuously shifted as the RF frequency is increased, with a rate of −0.3 °C/kHz. This means that the oscillatory variation of efficiency is also present with respect to the acoustic frequency at a constant temperature. The period of the oscillation in frequency was calculated to be about 43 kHz.

The measurement was repeated with the same filter assembly but after the Invar tube was taken out. Fig. 2(b) shows the result which exhibits no periodic oscillation. The slight increase of overall notch depth, compared to Fig. 2(a), is mainly due to a difference in tension on the fiber between the two experiments. We performed the same experiments with a number of other devices of identical design and consistently observed the appearance of the periodic oscillation only when the metal tubes were in place. The results strongly suggest the presence of an acoustic resonator associated with the metal tube.

Fig. 3 illustrates a cross-sectional view of the acoustic resonator where the inner wall of the circular metal tube acts as reflectors and the optical fiber as an acoustic source. The arrow denotes the vibration direction of the optical fiber. The lines drawn in the air represent the resonant acoustic wave which has a sinusoidal angular amplitude distribution since the air propagates only the longitudinal acoustic (sound) wave. If the optical fiber was located exactly at the center of the tube, it would excite only even-order resonance modes having a peak of the standing wave pattern at the center. However, the precision and design of our devices were such that the fiber position was varied from the central axis along the tube by several hundreds of micrometers, more than a few wavelengths of the sound wave. Therefore, both even- and odd-order resonance modes are expected to be excited. In this case, the free spectral range of the resonator is given by $\Delta f = V/(2L)$, where V is the sound velocity in the air and L is the length of the resonator which is equal to the inner diameter of the tube. With $V = 367$ m/s at 60 °C (acoustic wavelength: 167 μm at 2.2 MHz) and $L = 4.1$ mm, the free spectral range is calculated to be 45 kHz in close agreement with the experimental value of 43 kHz within measurement uncertainty. It is well known that the sound velocity varies with the temperature: $V = 344 \cdot \sqrt{T/293}$, where T denotes the temperature in kelvin [13]. The period of resonance with respect to temperature changes is given by $\Delta T = VT/(Lf)$, where f is the acoustic frequency. This predicts $\Delta T = 12.3 - 14.8$ °C between 40 °C–80 °C, in good agreement with the measured values. Owing to an acoustic propagation loss in the air and finite reflectivity of the metal tube, the flexural acoustic wave propagating the optical fiber experiences a maximum loss on each resonance, resulting in periodic decreases of the notch depth as observed in the experiment. The above analysis is based on a simplification of the cylindrical structure into a cascade of independent two-dimensional resonators. Although the approximation gives an accurate estimation of the period of resonance, a rigorous analysis necessitates three-dimensional resonator modeling taking into account the exact profile, phase (traveling), and polarization of the flexural acoustic wave and the diffraction of the sound wave along the tube axis; however, the full analysis is beyond the scope of this letter.

In order to investigate the acoustic resonance further, a packaged acoustooptic filter was completely sealed with silicone except for a small hole which was connected to a vacuum pump.

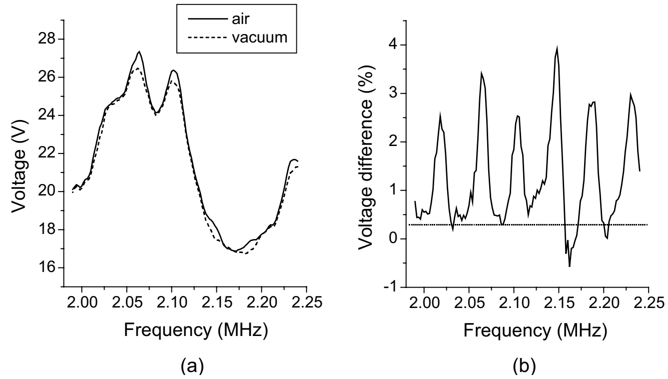

Fig. 4. (a) Voltages for 5-dB notch depth in the air and vacuum. (b) Voltage increase by the air. Dotted line: background voltage increase.

With the vacuum pump switched ON and OFF, the efficiency of device was compared between normal atmosphere and modest vacuum environments. Fig. 4(a) shows the plot of RF voltages for a 5-dB notch depth measured as a function of the acoustic frequencies in the range 1.99–2.24 MHz (1573–1522 nm) with and without the surrounding air at room temperature (20 °C). The relative difference between the two curves is plotted in Fig. 4(b), showing prominent periodic increases in the drive voltage (efficiency drops) arising from the acoustic resonance in the presence of the air. The frequency period was 42 kHz, exactly equal to a theoretical value of 42 kHz at 20 °C. The dotted line indicates the background increase of the voltage, which may represent the intrinsic propagation loss in the silica fiber because of the nonzero acoustic impedance of air. On resonance, the voltage increase reached about 3%, which corresponds to a notch depth decrease by 0.4 dB at 5-dB level and agrees well with the experimental values [Fig. 2(a)].

We have described the acoustic resonance in a fiber-based acoustooptic device employing a metal tube package via acoustic coupling to the air. The resonance caused a significant variation in the efficiency of the device with respect to wavelength tuning and temperature changes. The detrimental effects could be suppressed effectively by breaking the cylindrical symmetry of the package such as using a tube with a nonuniform diameter along the axis. With a proper arrangement, the phenomenon described here may find some applications for excitation or probing of the acoustic wave in an optical fiber through the air.

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