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Low-frequency line shapes in guided acoustic-wave Brillouin scattering

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Guided acoustic-wave Brillouin scattering (GAWBS) measurements were performed on 20-cm lengths of optical fibers with particular attention focused on the lowest lying resonance. In 125-μm-diam silica fibers, this resonance was observed to occur at ~22 MHz and have a line shape which varied erratically from sample to sample. Significant line shape fluctuations were evident even between sequential samples from the same fiber spool. We speculate that the observed effects are attributable to 0.01–0.1 μm distributed geometric deviations from a perfect cylinder. © *1994 American Institute of Physics.*

Since the initial theoretical discussions of Thomas *et al.*[1] followed by the experimental observations of Shelby, Levenson, and Bayer demonstrating light scattering from thermally excited acoustic resonant modes in optical fibers,[2,3] little additional phenomenological work has appeared on the subject. These latter authors introduced the acronym "GAWBS" (guided acoustic-wave Brillouin scattering) and presented a comprehensive theory able to explain in detail many aspects of their experimental data. Specifically, their theory accurately predicted the spectral positions and intensities of the many observed GAWBS lines. Subjects touched upon, although not discussed in as great detail, were line shapes and linewidths.

With the expectation that GAWBS resonances could prove to be a very sensitive measure of the structural properties of optical fibers, we have set out to examine the issues pertinent to this aspect of the technique. In particular, we have taken high-resolution data examining the narrowest of these resonances, and speculate on how variations in the size or shape of fibers could manifest themselves in the GAWBS line shape.

GAWBS spectroscopy was performed as originally described by Shelby *et al.*[2,3] Briefly, we use a heterodyne technique, relying on the acoustically driven index fluctuations at the core to shift (add sidebands to) the fundamental laser frequency. The sidebands are mixed, via the nonlinear response of a photodiode, with the laser fundamental, and the difference frequency detected with a microwave spectrum analyzer. Data were taken in the depolarized configuration primarily for convenience. In this configuration, there is no need for an actively stabilized Mach–Zehnder interferometer containing the fiber sample. Instead, linear polarized light is launched and "beat" with the depolarized component which has been scattered (by the bound acoustic modes we wish to detect) into the orthogonal polarization. However, only those acoustic modes resulting in macroscopic birefringence (i.e., nonrotationally invariant modes) are therefore observable.

We used a cw Ti:sapphire ring laser operating at wavelengths between 850 and 990 nm. The laser (Coherent Model 899) could be operated either in a single longitudinal mode with the aid of intercavity etalons, or multimode, with the etalons removed. When data were taken with the multimode laser output, spurious signals were detected in the frequency region (and overtones thereof) corresponding to the roundtrip frequency (~180 MHz) of the laser cavity. The GAWBS signals themselves were observed to be independent of the longitudinal mode content of the laser. Since we were primarily studying low-frequency resonances well below 180 MHz, multimode laser operation was adequate and somewhat easier to stabilize. Roughly 300 mW of linearly polarized light was launched into a 20-cm-long bare fiber sample. The output from the fiber was collimated and passed through a Babinet–Soleil compensator followed by a Glan–Thompson polarizer. The polarizer-compensator pair was adjusted for minimum transmission, typically less than 0.5 mW, and subsequently opened slightly beyond the null, so that roughly 2 mW was incident upon the photodiode. The output of a 500-MHz-bandwidth InGaAs photodiode was preamplified and analyzed with an HP Model 8568A spectrum analyzer. The band shapes of the signals were verified to be independent of launched laser power between 0.05 and 1 W. Furthermore, line shapes were observed to be insensitive to the polarization orientation of the input laser light.

GAWBS resonances appeared from roughly 22 MHz out to beyond 700 MHz in a manner previously described in detail.[2,3] Specifically, the spectral positions as well as the relative strengths of these lines were in close agreement with those previously reported. In general, the linewidths appeared monotonically related to frequency, with the narrowest linewidth occurring at the lowest frequency. This observation had also been made in the original work of Shelby *et al.* Figure 1 displays a plot of the measured GAWBS linewidth versus frequency. At frequencies less than roughly 300 MHz there appears to be a quadratic dependence of linewidth on frequency: the fitted line in Fig. 1 has slope 2.06. Above 300 MHz, the observed linewidths appear to roll off, and become essentially constant. These data were taken with a sample that gave the narrowest signal at 22 MHz, as will be discussed in detail below.

Several fibers were studied, including many commercial products and some "research" fibers. All samples were required to be single mode at our laser wavelengths, excluding from study, therefore, standard production telecommunication fiber. The fiber type from which most data were collected, including individual samples which gave the narrowest low frequency resonances, was Corning "Flexcore 1060." Two examples of the lowest-frequency resonance taken on different samples from the same 100-m Flexcore

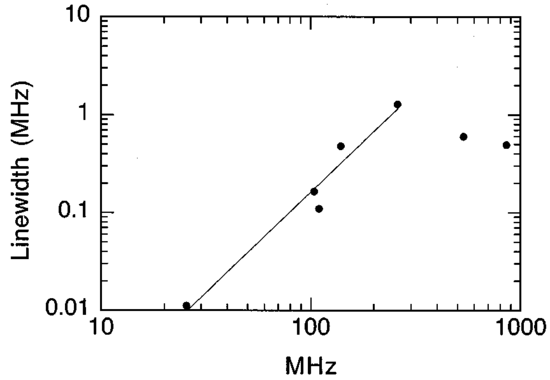

FIG. 1. GAWBS linewidth (FWHM, full width half-maximum) as a function of spectral position. The line is a single exponential fit of slope 2.06 to the first 5 data points. The lowest frequency point at ~22 MHz was taken from a sample displaying the narrowest observed signal.

spool are shown in Fig. 2. The most common spectral shape, one that occurred in approximately 80% of the Flexcore samples, was characterized by a single (or nearly single) peak roughly 25-kHz wide, and a broad sideband or shoulder extending by as much as 80 kHz. This band shape is intermediate between those shown in Fig. 2. Considerably less probable were either a single clean peak with a FWHM as small as 11 kHz, or an overlapping superposition of several spectral features having a composite width in excess of 120 kHz (see Fig. 2). Spectra of a Newport Research Corporation "NRC-820" fiber were taken (not shown) which consistently gave relatively broad (~60 kHz) single-peaked spectral signatures. Additionally, lowest-order GAWBS resonances of "research drawn fibers" were observed to frequently exhibit distinct multiple peaks (similar to the wider trace in Fig. 2) with individual widths on the order of 10–15 kHz.

A discussion of phenomenological linewidths must first establish those factors entering into the homogeneous width. For the current case, we suggest two significant homogeneous broadening mechanisms: material damping and transmission loss at the air-glass boundary. The literature contains several measurements of acoustic loss in silica, the most relevant to our frequency range by Fraser, Krause, and Meitzler.[4] These authors report a value of the absorption coefficient (α) for the transverse acoustic wave at 22 MHz of

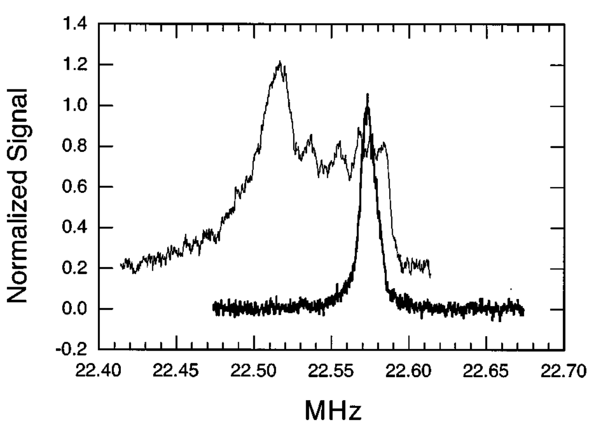

FIG. 2. GAWBS signals from two samples from the same spool of Corning "Flexcore 1060." The narrow resonance has a FWHM of 11 kHz.

2.12×10^{-2} dB/cm. Relating the resonant linewidth (Δ,FWHM) to α (the base-*e* absorption coefficient) as $\Delta=\alpha\nu/\pi$, where ν is the velocity of sound, predicts a homogenous width nearly 20 times narrower than that actually observed.[5] We note that optical fibers are not pure silica rods, but more accurately contain a core of doped silica. For our samples, the cores are roughly 5–8 μm in diameter and consist of germanosilicate glass, doped at not more than 5 mol % germanium. Although we could not find published acoustic loss data on germanosilicate glass, unpublished data for 10 mol % samples indicate these materials to be only a factor of 3 more attenuating at 20 MHz than pure silica.[6] Taken together with the fact that the core constitutes only a few percent of the acoustic path, it seems impossible to attribute the observed 11-kHz width (Fig. 2) to acoustic absorption alone.

Incomplete reflection is another loss mechanism. The core-cladding reflective loss is estimated with the aid of density and velocity data to be miniscule ($R=10^{-6}$).[6] The air-cladding loss, however, appears to be significant ($T=0.2\%,R=99.8\%$). Converting this to an effective α yields a value of 0.16 cm^{-1} (arrived at by assuming a 0.2% loss per traverse across the fiber 125-μm diam, resulting in a 20-kHz component to the linewidth. This appears to indicate that in the narrowest cases, our linewidths are determined by transmission loss at the silica-air boundary. This conjecture could be verified by performing measurements *in vacuo*, where the acoustic reflection at the outer boundary should become unity. We did not attempt this measurement.

The apparent quadratic dependence (Fig. 1) of the linewidth deserves comment as this functional dependence seems to contradict the conclusion that the low-frequency linewidth is due to transmission loss at the outer boundary. Transmission losses are usually considered to be frequency independent, whereas acoustic damping is often observed to have a quadratic frequency dependence.[4,7] While at this point we can only speculate, it seems important to note that the acoustic wavelengths of the bound wave are comparable to the fiber diameter. Although the corresponding wavelengths in air will always be significanly smaller than the fiber dimension, inside the glass, this is not the case. The related subject of plane wave scattering off particles has been discussed extensively in both the acoustics and optics literature, with the most celebrated exposition occurring at the turn of the century with the theory of Mie.[8–10] When the wavelength of radiation becomes comparable to the dimensions of the physical object, a situation somewhere between ordinary reflection and Rayleigh scattering is observed. In the latter case, there exists an ω^4 power law for the scattering efficiency, which turns over to a pseudoquadratic dependence in an intermediate regime, before finally becoming wavelength independent at short wavelengths. The present case is clearly not strictly analogous due to the widely discrepant acoustic wavelengths across the particle boundary, and appears in need of further analysis.

A subject in many ways analogous to the occurrence of bound acoustic waves in highly symmetric objects is the topic of "morphology-dependent (optical) resonances" (MDR). Numerous experimental and theoretical studies of the optical properties of microdroplets[11] and cylinders[12] have led to a sophisticated understanding of the details of this phenomenon, including matters of resonant linewidths.[13] Unfortunately, the experimental optical data pertinent to MDR and the acousto-optic data pertinent to GAWBS occur at very different resonance limits. As discussed by Shelby, the manner in which resonant acoustic waves are detected in fibers restricts the technique to the observation of only those modes which have significant spatial overlap with the fiber core.[3] These acoustic modes are necessarily of low azimuthal and radial order, having relatively smooth spatial profiles. In optical MDR experiments, however, very much the opposite extreme exists. Much larger size parameters (the size of the object compared to the wavelength of radiation), practical limitations on the optical detection of very narrow resonances, and the inhomogeneous damping of the resonances themselves, all result in the technique being preferentially sensitive to high-order modes spatially confined to the perimeter of the microstructure.[13] Nevertheless, it is interesting to contemplate the implications of this analogy, suggesting that a complete theoretical examination would prove instructive.

We now discuss possible causes of broader and more complex line shapes. Fluctuations in fiber diameter, deviations from perfect circularity of the cross section, and compositional variations affecting the velocity of sound could all broaden low-frequency GAWBS resonances. The easiest to appraise of these with respect to effects on the GAWBS linewidth are variations in diameter. Diameter fluxuations would simply shift the resonant peak position by the same fractional extent as the dimensional variation. For instance, a 0.1-μm change in size for a 125.0-μm-diam fiber would shift the GAWBS resonance at 22 MHz by 17.6 kHz (see Fig. 2). Diameter fluctuations distributed along the sample could therefore result in broadened or distorted line shapes, depending in detail on the exact distribution of diameters.

Deviations from perfect circularity of the fiber cross section could also perturb GAWBS resonances. Depolarized GAWBS is produced by vibrational modes depending on azimuthal angle ϕ as either $\cos 2\phi$ or $\sin 2\phi$.[3,14] In a perfect circular fiber the two modes are degenerate. Slight distortions of the cross section from circularity perturb the vibrational modes and, in general, lift the twofold degeneracy of the modes producing depolarized GAWBS light. This problem can, in principle, be solved in perturbation theory by treating the distortion as a small perturbation of the solution for the perfect circular case. We have not carried out such a procedure. However, the simpler problem of the vibrational modes of a nearly circular membrane is discussed by Nayfeh.[15] In that case, a distortion of the circumference of the form $\sin 2m\phi$ or $\cos 2m\phi$ lifts the degeneracy between the $\sin m\phi$ and $\cos m\phi$ modes (i.e., of half the period). Furthermore, if ϵ is the relative amplitude of the distortion of the radius, the two eigenfrequencies are shifted by $\pm\epsilon\omega$, where ω is the eigenfrequency in the absence of distortion. Just as for variations in the size of the fiber, the relative frequency shift is equal to the relative amplitude of the variation. Assuming that a similar result holds for the vibrations in the fiber cross section, a splitting between the depolarized GAWBS modes would arise from perturbations of the form $\cos 4\phi$ and $\sin 4\phi$ in the fiber cross section. These correspond to a slight "squaring" of the circle.

Geometric distortions in optical fibers have been documented and studied by analysis of backscattered light arising from a laser beam that is incident at right angles to the fiber axis.[16,17] These investigations leave little doubt that microscopic geometric deviations can exist in optical fibers.

Work on bulk samples correlating the effects of thermal processing on the acoustic properties of vitreous SiO_2 has been presented.[18,19] In the context of fiber process technology, one might envision pathological cases where nonradially symmetric compositional inhomogeneities could contribute to the inhomogeneous GAWBS linewidth. Lacking any specific data along these lines, we believe that the geometric variations discussed above are the most likely explanation for our current data.

In conclusion, we have investigated in detail the line shape of the lowest GAWBS resonance in nominal 125-μm-diam optical fibers. Spectra typically displayed significant amounts of inhomogeneous broadening. We attribute these effects to distributed variations in the fibers' outer dimensions. For measurements performed in air, we estimate a homogeneous GAWBS linewidth at 22 MHz of ~10 kHz, and ascribe this width to incomplete acoustic reflection at the fiber-air boundary. This technique is therefore expected to be sensitive to radial geometric distortions on the 0.01-μm length scale. Our measurements indicate that 0.01–0.1-μm deviations from perfect cylindrical geometry are statistically very common in commercial optical fibers.

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