Single-Mode Fiber Ultrasonic Sensor

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Abstract—**An acoustooptic ultrasonic sensor using a single-mode fiber is discussed. The sensor is based on acoustically induced modal birefringence which alters the polarization state of the optical beam.**

INTEREST in acoustooptic sensors has continued to increase since the first report on those devices appeared a few years ago [1], [2]. Several types of devices have been proposed based on phase modulation [1], microbending loss [3], [4], polarization rotation [5], and evanescent field coupling [6]; however, with the exception of the work of Kingsley [7] most of the research and development for those devices has been done at sonic or near sonic frequencies, where the acoustic wavelength is much larger than the fiber diameter. The present study examines an acoustooptic sensing technique at ultrasonic frequencies, where the acoustic wavelength is comparable to or smaller than the fiber diameter. This acoustooptic sensor is based on the evolution of a polarization state in a single-mode fiber caused by ultrasonically induced modal birefringence. This theoretical and experimental investigation shows that ultrasonic waves propagating in a fluid and directly incident upon a single-mode fiber induce anisotropic strains in the fiber of sufficient magnitude to be readily detected.

Single-mode fibers are in fact bimodal. They can propagate two nearly degenerate orthogonal polarizations of the HE_{11} mode [8]. The ultrasonic wave breaks the near degeneracy by causing an unequal variation in the phase velocity of each eigenmode (modal birefringence) of the optical beam propagating through the fiber. Detection of the induced birefringence with a circular polariscope [9], [10] can thus form the basis of a sensing system.

We have calculated the modal birefringence induced in a single-mode optical fiber of radius "a" by an ultrasonic wave propagating in a fluid by solving the displacement wave equation [11], [12]

$$\boldsymbol{U} = -\nabla\phi + \nabla \times \boldsymbol{\psi} \tag{1}$$

where $\boldsymbol{U}$ is the displacement vector, ϕ the scalar, and $\boldsymbol{\psi}$ the vector potential. It is necessary to apply four boundary conditions which hold at the surface of the fiber. The displacement and normal stress must be continuous and the tangential stress must be zero at the boundary.

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For ultrasonic waves of normal incidence, with a propagation constant $k = 2\pi/\lambda$, where λ is the acoustic wavelength, the induced principal strains are as follows:

$$\epsilon_1 = \left\{\frac{\epsilon_{rr} + \epsilon_{\theta\theta}}{2} + \frac{1}{2}\left[(\epsilon_{rr} - \epsilon_{\theta\theta})^2 + 4\epsilon_{r\theta}^2\right]\right\} e^{i\omega_0 t} \tag{2a}$$

$$\epsilon_2 = \left\{\frac{\epsilon_{rr} + \epsilon_{\theta\theta}}{2} - \frac{1}{2}\left[(\epsilon_{rr} - \epsilon_{\theta\theta})^2 + 4\epsilon_{r\theta}^2\right]\right\} e^{i\omega_0 t} \tag{2b}$$

where ϵ_{rr}, $\epsilon_{\theta\theta}$, and $\epsilon_{r\theta}$ are the strains in cylindrical coordinates, and ω_o is the frequency of the ultrasonic wave.

The optical phase shift due to the induced anisotropic strains can be written from the concept of index ellipsoid for the polarized modes as [13]

$$\Delta\beta_{\parallel} = -k_o n_o^3\, l(P_{11}\epsilon_1 + P_{12}\epsilon_2)/2 \tag{3a}$$

$$\Delta\beta_{\perp} = -k_o n_o^3\, l(P_{12}\epsilon_1 + P_{11}\epsilon_2)/2. \tag{3b}$$

The induced linear birefringence is given by [13]

$$\Delta\beta = \Delta\beta_{\parallel} - \Delta\beta_{\perp} = -k_o n_o^3\, l P_{44}(\epsilon_1 - \epsilon_2) \tag{4}$$

where $\Delta\beta_{\parallel}$ and $\Delta\beta_{\perp}$ are the induced phase shifts in the parallel and perpendicular directions. The elastooptic coefficients are P_{11}, P_{12}, and $P_{44} = (P_{11} - P_{12})/2$. The principal strains ϵ_1 and ϵ_2 are shown in Fig. 1 as a function of ka, where ka is a nondimensional frequency constant. The free-space optical wavenumber is k_o, the refractive index is n_o, and l is the acoustooptic interaction length. Fig. 2 shows $\Delta\beta_{\parallel}$ and $\Delta\beta_{\perp}$ as functions of ka. At low frequencies, the inducted phase shift is the same for each mode and the value obtained is the same as that calculated by the constrained radial model [14]. The phase shift for the perpendicular polarization $\Delta\beta_{\perp}$ has a peak at the first radial resonance ($ka \sim 6$). Although $\Delta\beta_{\parallel}$ starts at the same point as $\Delta\beta_{\perp}$, the former increases linearly in proportion to ka. It has a zero at $ka \sim 1.5$ and a resonance at $ka \sim 6$.

As can be seen in Fig. 3, the induced modal birefringence is very small for ka less than 0.1, showing that for these ka's, $\epsilon_1 \sim \epsilon_2$. At first, $\Delta\beta$ rises linearly with ka, and then becomes roughly constant up to the first radial resonance of the fiber, where the acoustic wavelength λ is half of the fiber diameter. For a typical single-mode fiber with 80 μm OD, the resonance occurs at a frequency of 35.8 MHz. For such a fiber, $\Delta\beta$ is approximately constant between 10 and 30 MHz.

Measurements of ultrasonically induced birefringence were made on ITT single-mode fibers with 80 μm OD and 4.0 μm core. The schematic of the polariscope arrangement used for the measurement of the induced birefringence is shown in Fig. 4(a). Here, a He–Ne laser generates a linearly polarized optical

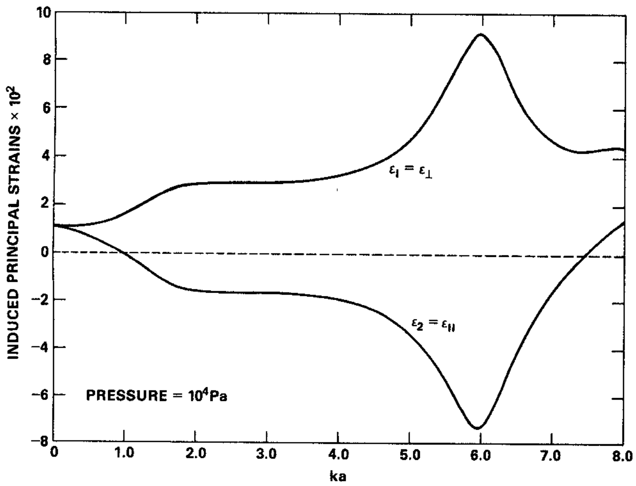

Fig. 1. Ultrasonically induced principal strains.

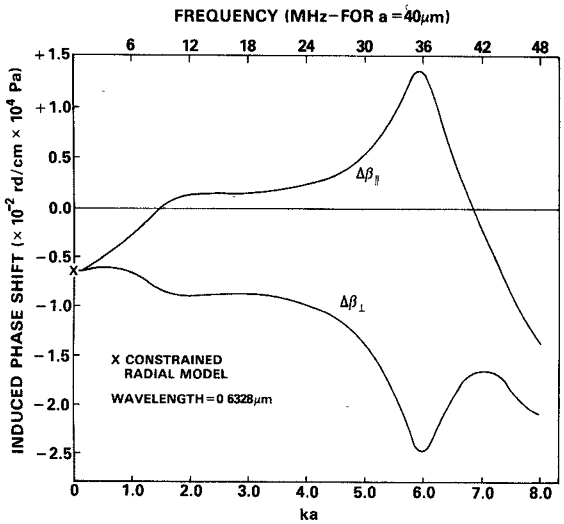

Fig. 2. Induced phase shift for each of the orthogonal polarizations.

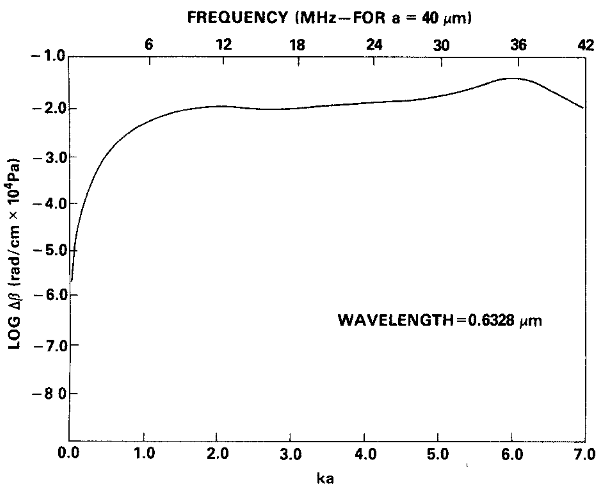

Fig. 3. Ultrasonically induced modal birefringence.

beam with a fixed plane of polarization. This passes through a linear polarization rotator (LP) emerging at any desired polarizing angle. The light then enters a quarter wave plate and the beam is then focused by a microscope objective onto the fiber.

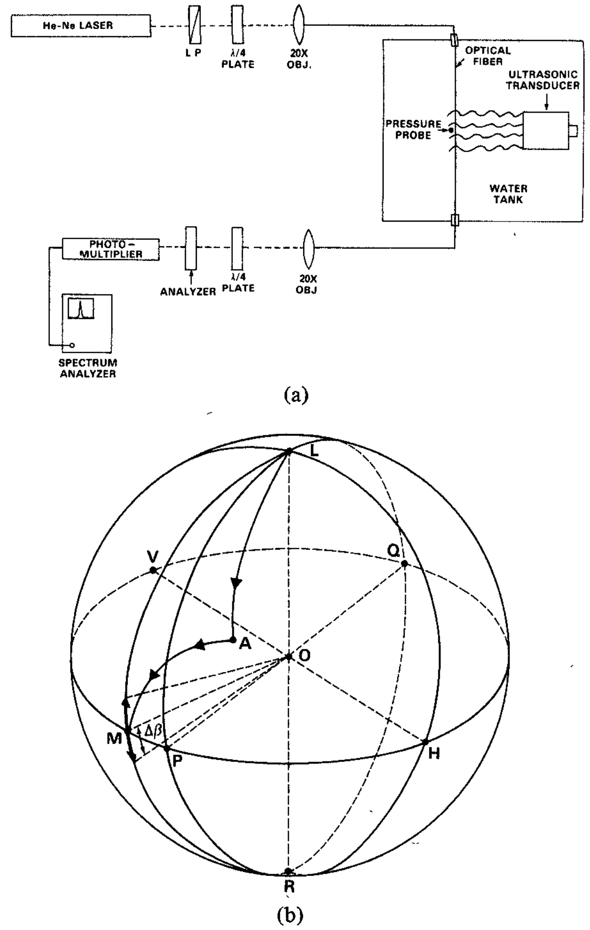

Fig. 4. (a) Experimental setup for measurement of induced birefringence. (b) Poincare Sphere representation of polarization rotation.

A section of the fiber is submerged into a water tank and a small length interacts with the ultrasonic wave. The two eigenmodes are excited equally at the beginning of the region of interaction between the optical beam in the fiber and the acoustic wave. This is accomplished by aligning the input linear polarizer (LP) and quarter wave plate of the polariscope such that circularly polarized light arrives at this point.

Utilizing the Poincare Sphere representation of polarization [15], [16], the circularly polarized light can be represented by point L as shown in Fig. 4(b). The optical beam with an arbitrary but constant azimuth propagates away from the interaction region with a varying ellipticity due to static birefringence in the fiber. The polarization state at the output of the fiber can therefore be represented as point A on the Poincare Sphere of Fig. 4(b). The emerging optical beam is collimated by another microscope objective. The output light passes through a quarter wave plate which is adjusted to rotate the state of polarization from A to M (90° rotation) yielding a linearly polarized light output. The acoustically-induced phase retardation $\Delta\beta$ causes the state of polarization of the output optical beam then to oscillate around M from linear to elliptical and back with frequency ω_o. When the output optical beam is then properly interfered in a selected plane of the analyzer in the polariscope, an amplitude modulation results with a modulation index $\Delta\beta$. The optical beam is detected by

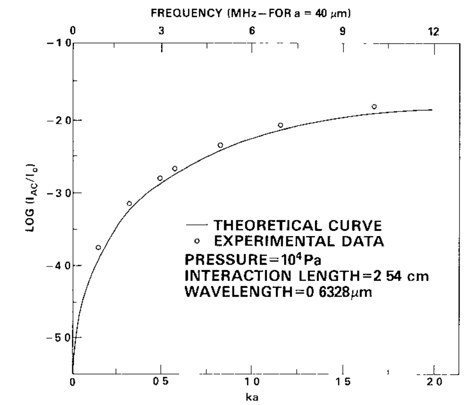

Fig. 5. Intensity modulation from ultrasonically induced birefringence.

a photomultiplier and the resulting intensity is measured with a spectrum analyzer.

With the optical system biased for maximum sensitivity (in quadrature) the output intensity I which consists of a dc term (I_{dc}) plus an ac term (I_{ac}) is

$$I = I_o\left[\tfrac{1}{2} + J_1(\Delta\beta)\sin\omega_o t\right]. \tag{5a}$$

I_o is the incident intensity on the fiber and o is the frequency of the ultrasonic wave. For a small modulation index the expression is simplified to the following:

$$I \approx I_o\left[\frac{1}{2} + \frac{\Delta\beta}{2}\sin\omega_o t\right]. \tag{5b}$$

In Fig. 5 we compare the theoretical curve for log (I_{ac}/I_o) with experimental results up to 10 MHz ($ka \sim 2.0$) As can be seen, there is excellent agreement. Utilizing the current electronic noise limit of the experimental detection system, the minimum detectable pressure is predicted [see Fig. 6] for a 300 Hz bandwidth and 1 mW optical power. This prediction shows that for a typical fiber of 80 μm diameter and for frequencies above 10 MHz a minimum pressure in a unit length of fiber of 5 Pa · cm can be detected. This sensitivity is approximately constant from 10 to 30 MHz, due to the flatness of $\Delta\beta$ in this region. The linear dynamic range of this optical system is estimated to be approximately 80 dB due to a $\Delta\beta$ ranging between 1×10^{-5} and 1×10^{-1}. In comparison, a shot noise limited system with a 1 Hz bandwidth would yield improvements of two orders of magnitude in the dynamic range and minimum detectable pressure.

This work demonstrates that ultrasonic waves incident upon a single-mode fiber induce modal birefringence. As a result, such fibers are seen as useful ultrasonic detectors for frequencies as low as a few hundred kHz and up to several tens of MHz.

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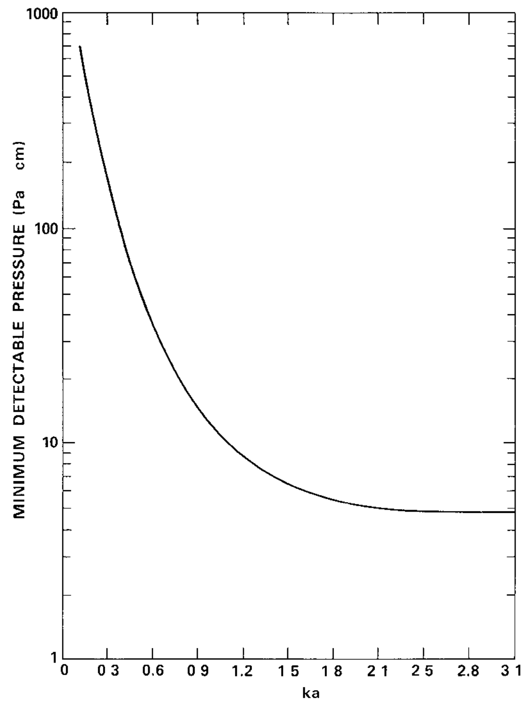

Fig. 6. Minimum detectable pressure.

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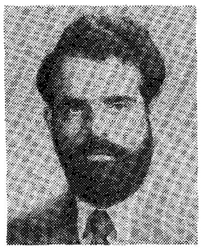

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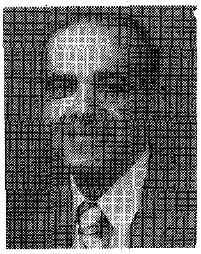

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James H. Cole, for a photograph and biography, see *IEEE J. Quantum Electron.*, p. 665.

Joseph A. Bucaro, for a photograph and biography, see *IEEE J. Quantum Electron.*, p. 665.

Optimizing Fiber Coatings for Interferometric Acoustic Sensors

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Abstract—**The pressure sensitivity of the phase of light propagating in an optical fiber is studied both analytically and experimentally. The analysis, which takes into account the exact composition and geometry of multilayer fibers, is utilized to identify coating properties which optimize the fiber acoustic sensitivity. In order to predict the fiber acoustic sensitivity, the elastic parameters of commonly used coating materials, thermoplastics, and UV curable elastomers have been studied in bulk samples as a function of frequency (10^2-10^4 Hz) and temperature (0-35°C). The analytically predicted frequency dependence of the acoustic sensitivity is found to be in agreement with that obtained experimentally from fibers with coatings of various materials.**

I. Introduction

Acoustically induced phase modulation in single-mode optical fibers has been of growing interest since potential use of fibers as acoustic sensors was established [1], [2]. Studies of the pressure sensitivity of a homogeneous fiber with one jacket [3], [4] and two jackets [5] have already been reported. These studies have demonstrated that the pressure sensitivity of fibers is strongly influenced by the elastic coefficients of the fiber coatings. For most of the commonly used fiber coating materials, however, the elastic moduli required to predict the fiber acoustic sensitivity are not generally known, particularly as a function of frequency and temperature.

In this paper, the acoustic sensitivity of multilayer fibers is studied in detail as a function of the elastic coefficients of the fiber coatings. The analytic results are utilized to identify coating properties which optimize the fiber acoustic sensitivity. The elastic parameters necessary to predict the fiber acoustic sensitivity of various commonly used optical fiber coatings, both thermoplastics and UV curable elastomers, are studied in bulk samples as a function of frequency (10^2-10^4 Hz) and temperature (0-35°C). Utilizing the results of this study, coating properties giving optimum fiber acoustic sensitivity are identified. Finally, these results are compared to those measured experimentally employing a Mach-Zehnder fiber optic interferometer.

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