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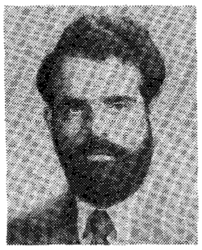

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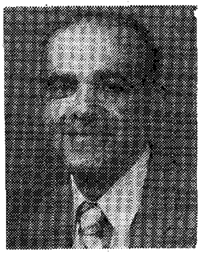

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James H. Cole, for a photograph and biography, see *IEEE J. Quantum Electron.*, p. 665.

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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II. PRESSURE SENSITIVITY PREDICTIONS

The pressure sensitivity of the optical phase in a fiber is defined as $\Delta\phi/\phi\Delta P$, where $\Delta\phi$ is the shift in the phase ϕ due to a pressure change ΔP. If a given pressure change ΔP results in a fiber core axial strain ϵ_z and radial strain ϵ_r, then it can be shown [4] that

$$\frac{\Delta\phi}{\phi} = \epsilon_z - \frac{n^2}{2}\left[(P_{11} + P_{12})\,\epsilon_r + P_{12}\,\epsilon_z\right]. \tag{1}$$

Here P_{11} and P_{12} are the elastooptic coefficients of the core and n is the refractive index of the core. The first term in (1) is the part of $\Delta\phi/\phi\Delta P$ which is due to the fiber length change, while the second and third terms are the parts due to the refractive index modulation of the core, which is related to the photoelastic effect [4].

In order to calculate the sensitivity as given in (1), the strains in the core ϵ_z and ϵ_r must be related to the properties of the fiber layers. The stresses at a point in the fiber can be found from the Lamé solutions as a function of the distance of that point from the center of the fiber in terms of appropriate constants [6]. The strains in a given layer are then related to the stresses through the elastic moduli of that layer [7] while the displacements are expressed in terms of the strains. The constants involved in these calculations are found from the appropriate boundary conditions. In this analysis the axial strains in the various fiber layers are assumed to be equal to each other, ignoring end effects. For long thin cylinders, such as fibers, this plane strain approximation introduces an error of less than 1 percent [4]. The applied pressure is assumed to be hydrostatic [5]. Having calculated the various constants, the strains in the core are determined and the sensitivity is calculated (1) [8].

A typical optical fiber (Fig. 1) consists of a core, a cladding, and a substrate fabricated from glasses having similar properties. Typically, this glass waveguide is coated first with an inner soft elastomer and then with an outer plastic, polymer, or metal jacket to preserve the fiber strength. The composition and the geometry of the fiber is kept constant throughout this paper, with the exception that the outer coating thickness and elastic moduli are allowed to vary. Table I lists the fiber parameters. The waveguide is a typical commercially available (ITT) single-mode fiber composed of a fused silica core with traces of G_eO_2, a cladding of 5 percent B_2O_3–95 percent S_iO_2, and a fused silica substrate in a w shaped index profile. The fiber inner jacket consists of an 83 μm thick layer of silicone. The acoustic response of such a fiber with a polyester (trade name Hytrel) outer coating has already been studied both experimentally and analytically in detail [5], [9], [10].

Fig. 2 shows the calculated fiber pressure sensitivity of such a fiber with various moduli of the outer jacket as a function of coating thickness. Here, the Young's modulus (E) of the coating is varied, while the bulk modulus (k) is fixed at a value of 4×10^{10} dyne/cm^2. As can be seen from this figure, as the coating gets very thick, the fiber sensitivity approaches a limit which is independent of the coating Young's modulus. In the case of a thick coating hydrostatic pressure in the form of an acoustic wave results in isotropic strains in the fiber waveguide whose magnitude depends only upon the coating compressibility (inverse bulk modulus). Thus, for the thick coating case the pressure sensitivity is governed entirely by the fiber coating bulk modulus, independently of the other elastic moduli. An example of a fiber having a thick coating is shown in Fig. 3 where the sensitivity is plotted versus the inverse of the bulk modulus of the fiber coating. In Fig. 3 the fiber OD was taken to be 6 mm and $E = k/2$. As can be seen from this figure, the fiber acoustic sensitivity is proportional to the inverse of the bulk modulus of the fiber coating.

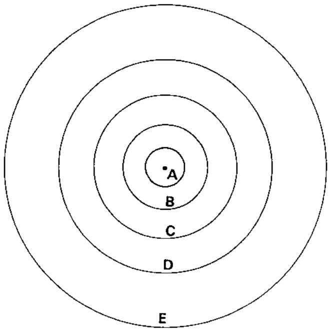

Fig. 1. A typical single-mode ITT fiber: core (A), cladding (B), substrate (C), soft coating (D), and hard coating (E).

TABLE I
STANDARD ITT SINGLE-MODE FIBER (WITHOUT OUTER COATING)

	Core	Clad	Substrate	First Coating (Soft)
Composition	S_1O_2 + traces of G_eO_2 (0.1%)	95% S_1O_2 5% B_2O_3	S_iO_2	Silicone
Diameter (μm)	4	26	84	250
Young's Modulus (10^{10} dyne/cm^2)	72	65	72	0.0035
Poisson's Ratio	0.17	0.149	0.17	0.49947
P_{11}	0.126			
P_{12}	0.27			
n	1.458			

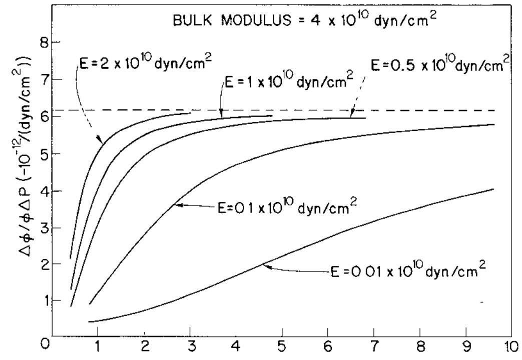

Fig. 2. Calculated pressure sensitivity versus fiber OD for different Young's moduli E, and constant bulk modulus (4×10^{10} dyne/cm^2) of the outer coating. Fiber parameters are given in Table I.

For fibers with more typical coating thicknesses, the sensitivity becomes a more complicated function of the elastic moduli. In this case the waveguide experiences anisotropic

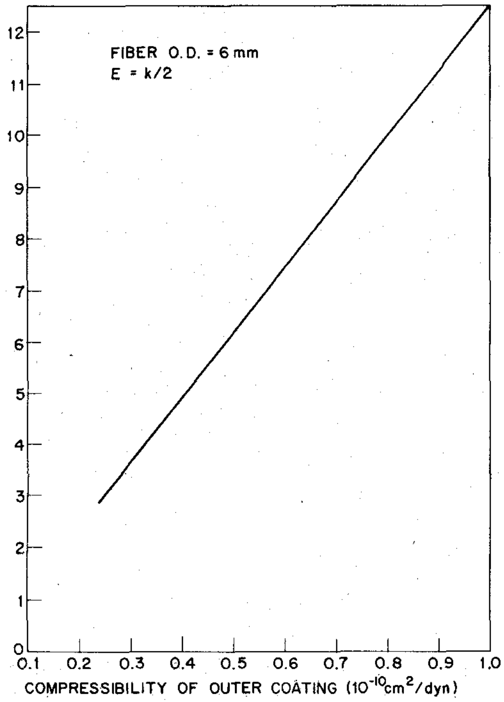

Fig. 3. Calculated pressure sensitivity versus compressibility (inverse of bulk modulus) of the fiber outer coating. Fiber OD is 6 mm and $E = k/2$.

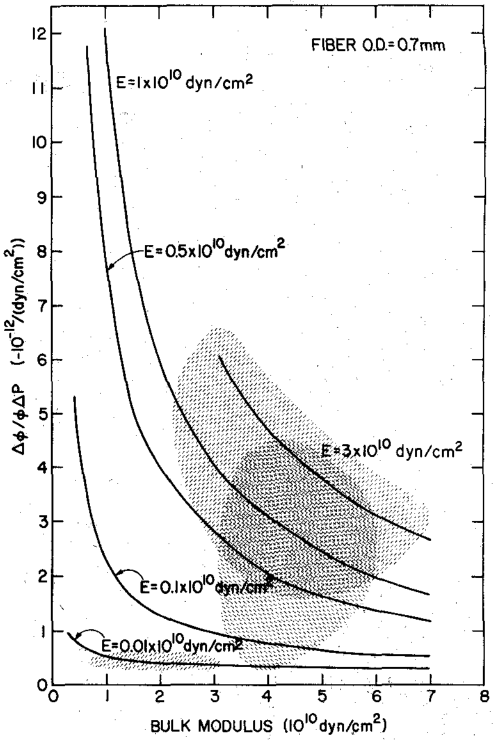

Fig. 4. Calculated pressure sensitivity versus bulk modulus for various Young's moduli of the outer coating of a 0.7 mm OD fiber given in Table I. Shaded areas: plastics (upper), UV curable coatings (middle), rubbers (lower).

strains and knowledge of two independent elastic moduli is required to predict the acoustic sensitivity. Fig. 4 shows the pressure sensitivity of a 0.7 mm OD fiber, whose parameters are given in Table I as a function of bulk modulus for various Young's moduli of the outer coating. As can be seen from this figure, for high Young's moduli the fiber sensitivity is a strong function of the bulk modulus. This function becomes weaker as the Young's modulus decreases. This can be understood in the following way. For a composite fiber geometry, the axial stress carried by a particular layer is governed by the product of the cross-sectional area and the Young's modulus of that layer. Thus, for high Young's modulus materials, very little coating thickness is required to reach the "thick" coating case in which the sensitivity is governed essentially by the bulk modulus of that layer. Accordingly, for typical coating thickness high acoustic sensitivity requires a high Young's modulus-low bulk modulus material.

III. COATINGS

In addition to metals—which are not considered in this paper—the most commonly used coatings are rubbers, thermoplastics, and UV curable elastomers. The coating which is applied directly to the glass waveguide is soft, such as a rubber or a soft UV curable elastomer, introduced for minimizing microbending losses. For typical thicknesses, these soft elastomers having a very small Young's modulus have very little effect on the sensitivity of typical fibers. The outer coating is hard, such as thermoset plastic or a hard UV curable elastomer, introduced for preserving glass strength, protecting fiber from adverse environments and facilitating fiber handling. The elastic moduli required to predict the fiber acoustic sensitivity are not generally known, particularly as a function of frequency and temperature. In this section, the elastic moduli of several commonly used coatings, both thermoplastics and UV curable elastomers, are studied as a function of frequency and temperature. Using these results, the fiber acoustic sensitivity is predicted and coatings optimizing the sensitivity are identified.

A. Elastic Parameters of Coatings

Since the glass parameters are relatively independent of frequency and temperature, the frequency and temperature dependence of the fiber acoustic response is governed by the frequency and temperature dependence of the elastic moduli of the fiber coatings. The frequency and temperature dependence of the Young's modulus was obtained from measurements on bulk samples in the form of rods with diameter 1.5-3.5 cm and length 5-15 cm. The bulk modulus was considered to be frequency independent [11] and was measured at only one convenient frequency.

The elastic moduli of six thermoplastics and two acrylate based UV curable elastomers are reported here. Table II lists the names, trade names, and the manufacturing and extruding companies of the elastomers. The density of the elastomer is also given in Table II since it is used for identification, particularly for elastomers of the same type. Fig. 5 shows the frequency dependence of the Young's modulus of the thermoplastics and one relatively hard, acrylate based UV curable elastomer at 27°C. As can be seen from this figure the Young's modulus of these hard coatings has a similar, relatively small frequency dependence. Thus, it appears that the elastic moduli of hard coatings, both thermoplastics and acrylate based UV curable elastomers, are not strongly frequency

TABLE II
OPTICAL FIBER COATINGS

Coating	Trade name	Manufacturer	Molding or Extruding Co.	Density gm/cm^3
Polyethylene (High Density)	Ultra Ethylux		Westlake Plastics	0.951
Polypropylene	Profax 7823	Hercules Wilmington Delaware	Westlake Plastics	0.900
Polyamide	Nylon 101	DuPont Wilmington, Delaware	Polymer Corp. of Penna.	1.141
Polytetra-fluoroethylene	Teflon TFE Type II	DuPont	Polymer Corp. of Penna.	2.132
Polytetra-fluoroethylene	Teflon TFE Type I	DuPont	Polymer Corp. of Penna.	2.160
Polyester	Hytrel 7246	DuPont	DuPont	1.173
Acrylate based UV curable Coatings:				
Soft		DeSoto	DeSoto	1.168
Hard		DeSoto	DeSoto	1.150

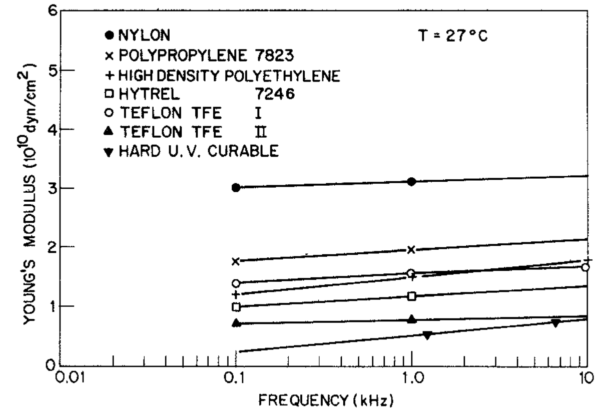

Fig. 5. Frequency dependence of Young's modulus of the hard elastomers at 27°C.

dependent. Such coatings can be utilized in acoustic sensors where frequency independent sensitivity is desired. Fig. 6 shows the temperature dependence of the Young's modulus of the thermoplastics and the hard acrylate based UV curable elastomer. As can be seen from this figure, the temperature dependence of the Young's modulus shows considerable variation for different coatings. Nylon has the weakest relative temperature dependence while polypropylene 7823 and the UV curable elastomer have the strongest.

In addition to the hard coatings, a relatively soft acrylate based UV curable elastomer was also studied. Fig. 7 shows the frequency dependence of the Young's modulus of this elastomer at 0, 27, and 35°C. As can be seen from this figure, the Young's modulus of the soft UV curable elastomer has a strong frequency and temperature dependence, indicating that at these frequencies and temperatures this elastomer is very close to or at its rubber to plastic transition. Such a coating would lead to a strong frequency and temperature dependence of the fiber acoustic sensitivity.

Finally, Fig. 8 shows the bulk modulus of all eight elastomers as a function of temperature. As can be seen from this figure the UV coatings have the strongest temperature dependence and nylon has the least.

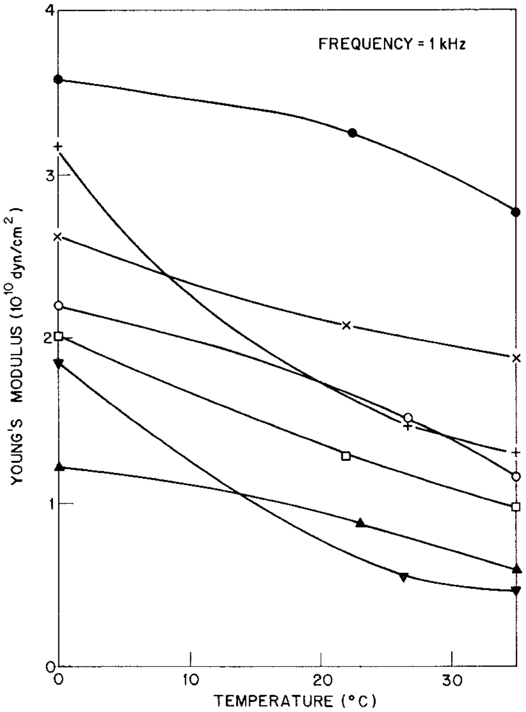

Fig. 6. Temperature dependence of Young's modulus of the hard elastomers at 1 kHz (symbols as in Fig. 5).

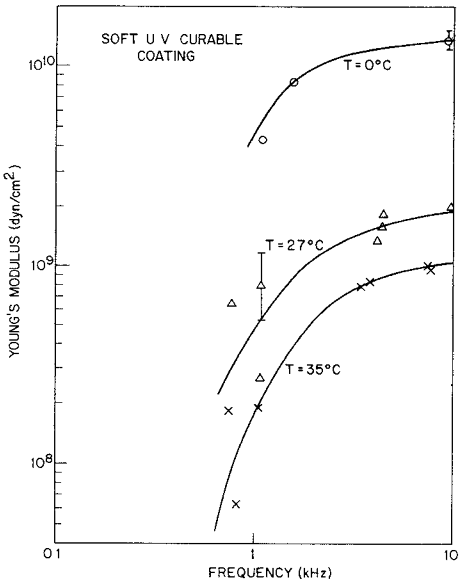

Fig. 7. Frequency dependence of the Young's modulus of the soft UV curable coating at 0°C (○), 27°C (△), and 35°C (×).

B. Acoustic Sensitivity of Coated Fibers

From the bulk modulus (assumed to be independent of frequency) and the Young's modulus (Figs. 5–8) the calculated acoustic sensitivity of fibers coated with these elastomers is obtained. In these calculations, the fiber parameters were taken from Table I and fiber OD was taken to be 0.7 mm, a typical diameter. Fig. 9 shows the frequency response of the acoustic sensitivity of fibers coated with various elastomers in the frequency range of 10^2–10^4 Hz. As can be seen from this figure, the frequency dependence of the sensitivity of fibers with the hard coatings is relatively small, in agree-

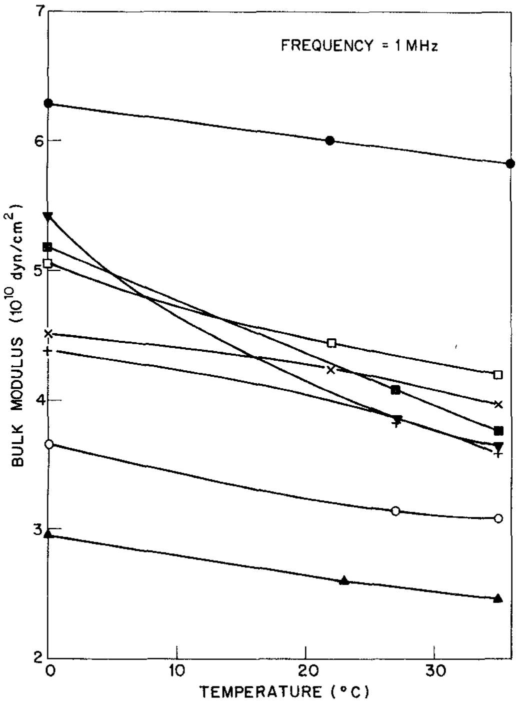

Fig. 8. Temperature dependence of the bulk modulus of the elastomers at 1 MHz (symbols as in Fig. 5). ■ Soft UV acrylate.

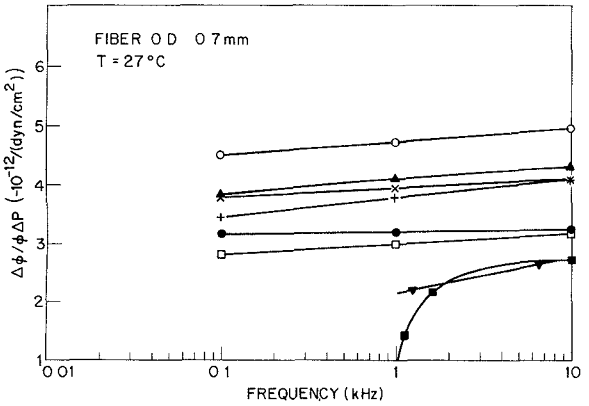

Fig. 9. Calculated frequency dependence of pressure sensitivity of fibers with a 0.7 mm OD coated with various elastomers at 27°C (symbols as in Figs. 5 and 8).

ment with Fig. 5. Nylon gives the weakest frequency dependence, and the soft UV curable elastomer the strongest. The maximum sensitivity is obtained with Teflon TFE type II, while the least is achieved with the soft UV coating. With this coating, the sensitivity decreases rapidly as the frequency lowered below 2 kHz. This and similar coatings would not be compatible with broad-band acoustic performance. However, such a coating can be utilized as low frequency fiber filter allowing the detection of high frequency acoustic signals only.

Fig. 10 shows the temperature dependence of the sensitivity of fibers with OD 0.7 mm at 1 kHz. As can be seen from this figure, nylon coated fibers have the least temperature dependence, while the most temperature dependence is obtained with the soft UV elastomer.

A comparison of Fig. 8 with Fig. 10 shows (in agreement with Fig. 3) that with the exception of Hytrel and the UV curable elastomers, as the bulk modulus of the coating decreases the fiber sensitivity increases. Thus, the least sensitivity is obtained with nylon having the highest bulk modulus, while the maximum sensitivity is achieved with Teflon TFE type II having the lowest bulk modulus. On the other hand, the sensitivity obtained with Hytrel and, in particular, with the UV curable elastomers is low due to their relatively low Young's modulus. With such a small Young's modulus, substantially thicker coatings are required to achieve the sensitivity determined by the bulk modulus (Fig. 2).

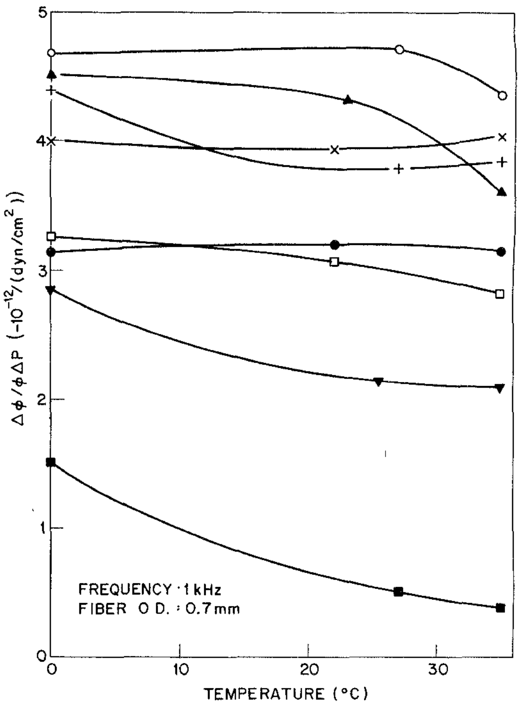

Fig. 10. Calculated temperature dependence of pressure sensitivity of fibers with a 0.7 mm OD coated with various coatings at 1 kHz (symbols as in Figs. 5 and 8).

In Fig. 4 we show by shaded areas the regions encompassing the three basic groups of elastomers, two of which were studied in this work. The upper and middle regions include the polymers and the UV curable acrylate elastomers, respectively, over the 0-35°C and 10^2-10^4 Hz ranges, and the lower region includes rubbers [5], [12]. It is generally expected that most other polymers and rubbers will be placed more or less near the upper and lower regions of Fig. 4, respectively. The UV curable elastomers, however, can vary widely, having a very low or a high Young's modulus [13]. Out of these widely varying elastomers, it is believed that coatings can be found which would further optimize the acoustic sensitivity of fibers.

IV. Experimental Measurements

In order to validate the analytical methods described here, we measured the acoustic sensitivity of available coated fibers. These included three standard ITT single-mode fibers with composition and geometry as given in Table I. The outer coatings of these fibers were Hytrel 7246 with 0.5 mm OD, polypropylene 6523 with 0.62 mm OD, and Teflon FEP 100 with 0.69 mm OD. The only available fiber coated with a hard acrylate based UV curable elastomer was a Corning multimode graded-index fiber, the acoustic sensitivity of which was also measured.

The Mach-Zehnder interferometer arrangement used to measure the acoustic sensitivity of coated fibers was similar to that of [14]. In the interferometer, the sensing fiber, which was the fiber coated with different elastomers, was in a coil form with a 6 cm nominal diameter and 13-16 m length immersed into an acoustic calibrator. The reference fiber was a single-mode ITT fiber (Table I) coated with 0.5 mm OD Hytrel 7246 of 18 m length, partly wrapped on two PZT transducers for phase stabilization [14]. Light from a 100 Tropel laser at 0.6328 μm was collected with 20X microscope objectives after the first beam splitter and directed into the interferometer sensing and reference fibers. Index-matching liquid was used to strip cladding modes in each fiber. The light output from each interferometer arm was separately collimated by 20X microscope objectives and the two beams were superimposed on a beam splitter. The interference pattern established with the superimposed beams was detected by a photomultiplier whose output is proportional to the frequency modulation induced in the sensing coil by the acoustic pressure field. Acoustic signals were generated in an acoustic calibrator consisting of an open-ended column of water excited by an electrodynamic drive. The pressure distribution in such a system is uniform horizontally and has only a small vertical gradient. A standard calibrated hydrophone was inserted at the level of the fiber coil and was used to measure the acoustic pressure levels.

In Fig. 11, the experimentally obtained acoustic sensitivities of the studied fibers at 27°C are compared to those calculated from (1). For the fiber coated with polypropylene 6523, the experimental results are compared to those calculated using the elastic moduli of polypropylene 7823, which are similar to those of 6523 [15], since polypropylene 6523 was not available to us in rod shape. For the multimode fiber (0.2 numerical aperture), the outer coating was taken to be the hard acrylate based UV curable elastomer and the glass waveguide optical and elastic parameters were approximated as those of a 0.15 numerical aperture ITT single-mode fiber reported in [9]. As can be seen from this figure, the experimental results agree well with the analytical results. Maximum sensitivity is obtained with polypropylene and Teflon and minimum with Hytrel and, in particular, the UV curable acrylate, in agreement with the results of Fig. 9.

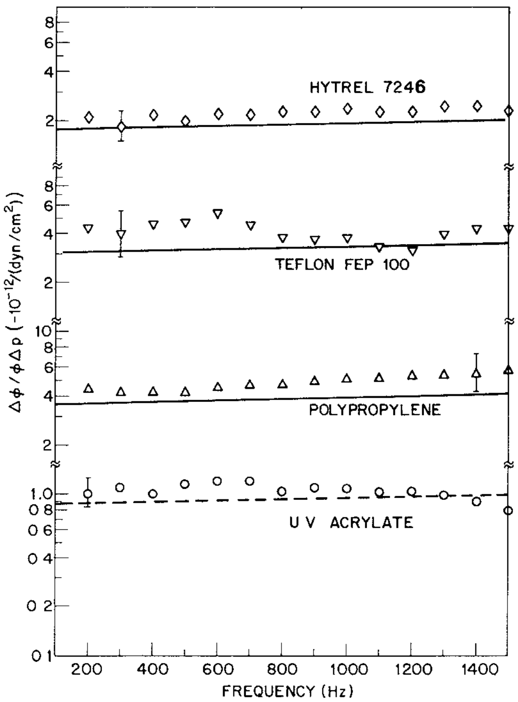

Fig. 11. Pressure sensitivity (points: experimental; lines: analytical) versus frequency of fibers with different OD's and outer coatings at 27°C. Upper 0.5 mm OD Hytrel 7246; second from top: 0.69 mm OD Teflon FEP 100; second from bottom: 0.62 OD polypropylene 6523; bottom: 0.5 mm OD UV acrylate (multimode fiber).

V. Summary

The pressure sensitivity of the phase in optical fibers has been studied both analytically and experimentally. With fibers having thick coatings, the acoustic sensitivity is inversely proportional to the bulk modulus of the coatings. For fibers with typical coating thicknesses, the fiber sensitivity is governed by both the Young's modulus and the bulk modulus of the fiber coatings. High sensitivity with minimum coating thickness is obtained with coatings having low bulk modulus and a high Young's modulus. Among the coatings reported here, which are commonly used as optical fiber coatings, Teflon TFE type II gives the highest sensitivity. All hard elastomers were found to have relatively frequency independent elastic moduli. The soft UV coating, however, results in a strong frequency dependence in the fiber acoustic sensitivity, which is due to its strong Young's modulus frequency dependence. The temperature dependence of the acoustic sensitivity of fibers coated with different elastomers was found to vary considerably. Fibers with nylon coating have the weakest temperature dependent sensitivity, while fibers with the UV curable elastomers have the strongest. The analytically predicted acoustic sensitivity was found to be in agreement with that obtained experimentally from fibers with various coatings.

In this paper only relatively few coating materials have been studied. However, the range of plastics and UV curable elastomers that is possible is considerable and these can have widely different elastic parameters. Out of this wide range of elastomers, it is believed that coatings can be found which would further optimize the acoustic sensitivity of fibers.

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

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