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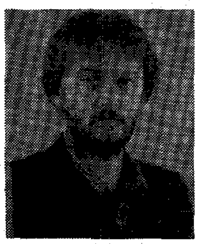

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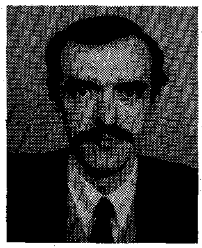
Dr. Puleo is a member of the Italian Electrotechnical and Electronic Association.



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Polarization Holding in Elliptical-Core Birefringent Fibers

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Abstract—**Polarization holding in high-birefringence elliptical-core fibers is evaluated for the fiber birefringence spatial frequency range 1.5 cm^{-1} < β_i < 40 cm^{-1}, corresponding to beat lengths from 1.6 mm to 4.2 cm. This range of spatial frequencies is spanned by making measurements with a broad-band light source on four fibers with different degrees of birefringence. In this way, the strength of the internal birefringence perturbations is mapped to give the first experimental measure of their power spectrum. It is shown that commonly available fiber jackets can significantly degrade the polarization holding. For low spatial frequencies, the strength of the perturbations decreases rapidly with increasing frequency, but this rate decreases by more than half over a one-and-a-half order of magnitude increase in spatial frequency. A possible origin of the perturbations is suggested and it is shown that the strength of these perturbations must be reduced if polarization holding to a very high degree is to be realized in elliptical-core fibers. Presently, internal perturbations limit the polarization holding to ≤14.4 dB over 1 km.**

Manuscript received April 1, 1982; revised June 9, 1982. This work was supported in part by Sachs/Freeman Associates under Contract N00014-82-C-2231.

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I. Introduction

POLARIZATION holding fibers are designed to have a very large intrinsic linear birefrigence β_i so that when light is injected into one of the linearly polarized eigenmodes it will, ideally, propagate without coupling to the orthogonal eigenmode. However, any perturbing birefringence β_p, resulting from either internal defects or externally-applied bends, twists, clamps, etc., whose axes are not aligned with those of β_i will couple the polarization eigenmodes of the fiber and degrade its polarization holding ability. For specific perturbations, for example, core ellipticity, bends, twists, and lateral pressure, for which the strength, location, orientation, and environmental dependences are known, the polarization coupling and the resulting output state of polarization can, in principle, be calculated. This becomes relatively simple if the perturbing birefringences are uniform along the fiber [1], [2]. However, in practical situations, very little is known about the origins, strengths, and distributions of these perturbations β_p along the fiber. Moreover, they will vary with environmental conditions

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and the whole idea of polarization holding fibers is that they should be able to propagate a stable state of polarization along their entire length, regardless of small external perturbations.

In long practical fibers, the perturbations β_p are expected to vary randomly both along the fiber and with environmental conditions [3]. Apart from initial experimental evidence of random polarization-mode coupling in highly birefringent fibers [4], no detailed experimental data on the strength and distribution of β_p are available. Highly birefringent fibers are usually characterized by the strength of their birefringence β_i or, equivalently, their beat length $L_p = 2\pi/\beta_i$. However, in order to optimize the polarization holding ability of birefringent fibers, a knowledge of β_p is essential, particularly if the mechanism which introduces the large β_i also results in large internal defects and hence, increases β_p as well.

In this paper, we present experimental data on the origin, strength, and distribution of the birefringence perturbations β_p in highly birefringent fibers fabricated with an elliptical core. In order to evaluate the fibers over a wide range of birefringence, four different fibers are selected and the strength and frequency dependence of their intrinsic fiber birefringence β_i are discussed in Section II. For the fibers selected, the birefringences correspond to beat lengths of 0.9 mm $< L_p <$ 55 mm. This covers the range of highly birefringent elliptical-core fibers developed to date. Section III reviews the theory of random polarization-mode coupling [3] to show that a measure of the strength of β_p can be obtained from the polarization holding ability of the fibers. This polarization holding ability for the four fibers is discussed in Section IV. It is shown that the strength of the coupling perturbations reduces quickly with reducing L_p, particularly for $L_p > 10$ mm. The contribution of the fiber jackets to these perturbations is discussed and the jackets are removed to leave only those perturbations internal to the fiber. In the elliptical-core fibers examined, these internal perturbations limit the polarization holding (polarization extinction ratio) to $\leqslant$14 dB over 1 km.

II. Fiber Birefringence

A large birefringence can be introduced in a fiber by way of two basic mechanisms which break the circular symmetry in the fiber cross section. The first is the geometrical shape of the core. A noncircular or elliptical core breaks the degeneracy of the two modes polarized along the major and minor axes of the core ellipse. This birefringence β_c can be very large if both the core ellipticity $e = (1 - b/a)$ and the index difference Δn between the core and cladding are large [5]. Here, $2a$ and $2b$ are the major and minor diameters of the core ellipse. The fast axis of this birefringence is directed along the minor core diameter. In the second mechanism, the circular symmetry is broken by a large transverse stress asymmetry in the core region of the fiber [6]. For this material stress birefringence β_s, the light travels fastest when polarized along the direction of maximum compressive stress. Several different approaches have been developed in recent years to maximize either β_s and β_c, with varying amounts of success. However, in all the highly birefringent fibers available to the authors, both β_s and β_c are invariably present, regardless of whether the fibers are fabricated to maximize β_c or β_s [7], [8]. β_s and β_c show different frequency dependences and, in principle, their individual contributions to β_i can be separated by measuring the frequency dependence of β_i [9]. However, in some highly birefringent fibers, the simple theory which applies to fibers with relatively low birefringence [9] is not adequate to describe the stress birefringence β_s [8]. In some fibers, β_c and β_s are found to reinforce each other, in others they partially cancel, and in one particular case β_s changes sign as the V value at which the fiber is operating is changed [7], [8]. Although a knowledge of the individual contributions of β_s and β_c to β_i is important in understanding the various birefringence effects in these fibers and for fabricating the fibers so as to maximize β_i, the relevant information here is a knowledge of the strength of β_i as a function of frequency ν or wavelength $\lambda = 1/\nu$.

Fibers fabricated so as to maximize the stress-induced birefringence β_s are not considered here. Typically, these fibers are fabricated to have a heavily doped elliptical cladding which produces a large transverse stress asymmetry in a nominally circular core [6], [10]. Usually, $\beta_c \ll \beta_s$ in the fibers [7]. The only fibers of this type available to the authors at the time [10] had a limited range of birefringence, corresponding to 6 mm $< L_p <$ 12 mm. Also, an improper choice of the core refractive index resulted in the light tunneling to the higher index substrate tube. Apart from the resulting high loss, this limited the useful, single-moded wavelength range to $\Delta\lambda <$ 200 nm. These problems have now been overcome and the polarization holding characteristics of these fibers will be reported at a later stage. The fibers fabricated with an elliptical core so as to maximize β_c are fabricated differently [10], [11] and transmit over a much wider wavelength range. This, together with the wider range in fiber birefringences, results in fibers with beat lengths ranging from 1–50 mm being available for evaluation.

Although it will be discussed further in Section III, it should be noted here that the measurement of the polarization holding ability of a fiber at one particular frequency ν_o gives a measure of the strength of the perturbing birefringences β_p at the spatial frequency of the fiber birefringence β_i for that frequency ν_o. However, a knowledge of the strength of the perturbations over a wide range of β_i is more useful in determining the character and, perhaps origin, of the perturbations. One possibility is to measure the strength of β_p for a large number of fibers, each fabricated with a different β_i. One problem with this is that the different fabrication procedures needed to produce a wide range of β_i may result in fibers with widely differing perturbations. An alternative is to measure the strength of β_p on a single fiber as a function of wavelength. Fortunately, in highly birefringent fibers, the birefringence β_i varies strongly with wavelength [7] allowing measurement of the strength of β_e over a useful range of β_i. In this measurement, the actual character of the perturbations can be expected to be constant. Of the fibers available to the authors at the time [10], [11], only the elliptical core fibers transmit over a sufficiently wide range of β_i. A combination of both approaches has been adopted here to measure the strength of the perturbing birefringences as a function of β_i for four elliptical-core highly birefringent fibers.

TABLE I
PARAMETERS OF THE FOUR ELLIPTICAL CORE FIBERS FOR WHICH POWER SPECTRUMS OF THE BIREFRINGENCE PERTURBATIONS ARE MAPPED

Fiber	$e = 1 - \frac{b}{a}$	2b (μm)	Δn	L_p (mm) at λ = .83 μm	Jacket	Loss (dB/km) at λ = .83 μm
A (ITT)	~ 0.33	~ 1.12	~ 0.019	27.3	Hytrel + RTV	43
B (ITT)	0.28	~ 1.05	~ 0.027	10.1	Hytrel + RTV	~ 100
C (ITT)	~ 0.52	1.05	~ 0.040	4.7	DeSoto 40	~ 150
D (Andrew Corp)	0.55	1.16	0.064	1.2	Metal	85

The parameters of the four fibers are shown in Table I. Some of the parameters are not known accurately and this uncertainty is indicated in the table. The fibers are selected to have a wide range of beat lengths and jacket materials. As the fibers are fabricated by two different laboratories, each having its own fabricating idiosyncrasies due to, for example, preform collapse procedures, drawing tower resonances, etc., it can be expected that the character of some of the perturbations, particularly those internal to the fiber, will be different for the two laboratories. Nevertheless, the first three fibers, which by themselves have a substantial range of beat lengths, are fabricated in the same laboratory and are expected to exhibit the same fabrication related perturbing birefringences. All the fibers have relatively small core diameters $2b$ and relatively large index differences Δn. None of the fibers have acceptable losses but they are representative of typical elliptical-core birefringent fibers. Recently, attenuations closer to 30 dB/km are typical [11]. Vastly different jacket materials are available, but their effects on the polarization holding ability of the fibers has not previously been considered. Hytrel is a hard, thermally cured plastic jacket which is extruded over a soft RTV silicone primary jacket [10]. Typically, the fiber diameter is ~80 μm and the jacket diameter is ~450 μm. DeSoto 40 is a soft ultraviolet light-cured acrylate jacket which is extruded over the fiber without a primary jacket [10]. The jacket diameter is typically ~250 μm. The metal jacket is a thin, relatively soft indium-based alloy [11]. Typically, it is applied directly over the fiber of ~60 μm diameter and has a diameter ⩽100 μm. As will be shown in Section IV, the choice of the jacket can strongly affect the polarization holding ability of the fiber. Detailed dopant concentrations in the fibers and the fabrication procedures are not known. However, all the fibers are fabricated via the CVD method and, typically, the ITT fibers have germanium doping in the core with boron doping in the cladding [10]. The core of the Andrew Corporation fiber is heavily doped with germanium and the cladding is doped with fluorine [11].

The wavelength dependence of the birefringence β_i of each fiber is measured by placing a short piece of fiber between parallel polarizers, but oriented with its axes at $\pi/4$ to the plane of the polarizers, and counting the interference fringes as the wavelength is scanned [7]. The simple experimental configuration for this measurement is shown in Fig. 1 together with a recording of the wavelength-dependence of the detected intensity for a 120.7 mm length of fiber C. It has been shown previously [7] that this intensity $I(\nu, \delta\nu)$ is given by

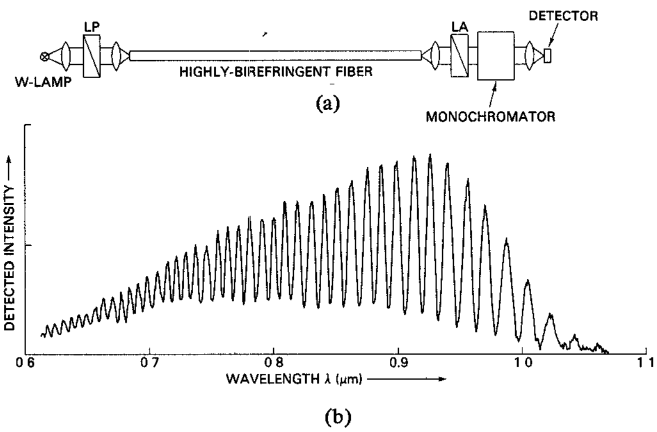


Fig. 1. (a) Experimental configuration for measuring the wavelength dependence of the birefringence and (b) a recording of the detected intensity as the wavelength is scanned.

$$I(\nu, \delta\nu) = p_o \delta\nu [1 + \zeta \cos \beta_{io} L] \tag{1}$$

$$\zeta(\delta\nu) = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{|\sin L \, \delta\nu \, d\beta_{io}/d\nu|}{L \, \delta\nu \, d\beta_{io}/d\nu} \tag{2}$$

where β_{io} is the fiber birefringence at the center frequency ν_o and L is the fiber length. p_o is the spectral power density which is assumed to be constant over the monochromator bandwidth $2\delta\nu$ and $\zeta(\delta\nu)$ is the visibility of the interference fringes. Each interference fringe corresponds to a differential phase change of $\Delta\psi = L \, \Delta\nu_d \, d\beta_i/d\nu = 2\pi$ between the light propagating in the two polarization eigenmodes. $\Delta\nu_d$ is then the distance, in frequency, between adjacent intensity maxima. For the recording shown in Fig. 1, the bandwidth $2\delta\nu$ corresponded to $2\delta\lambda = 4.8$ mm. If the bandwidth $2\delta\nu$ is vanishingly small, (1) reduces to $I(\nu) = I_o \cos^2 \beta_i(\nu)L/2$. As this technique gives only a relative measure of the fiber birefringence, an absolute measure is obtained by accurately measuring the fiber beatlength L_p for, at least, one particular wavelength by means of a Faraday effect modulation applied with a translatable precision electromagnet [1], [7].

The frequency dependence of the fiber birefringence β_i is shown in Fig. 2 for each of the four fibers. The very strong frequency dependence of β_i is evident, particularly for fibers C and D which have the larger birefringences. For these four fibers, the beat lengths range from <0.9 mm to >55 mm which covers the range of highly birefringent fibers fabricated to date. The very rapid falloff in β_i with reducing ν shows that all these fibers have stress birefringence β_s as well as geometrical shape birefringence β_c [7], [13]. If β_s is zero, these curves would exhibit the characteristic humped shape [5], [7]. For the lower birefringence fibers A and B, the doping levels and core ellipticity are not very large and the resulting thermal stresses in the fiber core and near-cladding regions are not yet large. In this case, β_s is still relatively small. For the higher birefringence fibers C and D, the higher doping levels result in a larger stress birefringence contributing to the total fiber birefringence [7], [13]. For these fibers, the simple theory [9] describing the stress birefringence as $\beta_s = C\nu$ where C is an approximately frequency independent constant is no longer valid. The fiber structure and the different stresses in the core and near-core cladding regions must be considered in evaluating the strength of β_s [7]. The individual contributions of β_s and β_c are discussed elsewhere [13].

The measurement shown in Fig. 2 also gives the group delay time different $\Delta\tau = (L/c)(d\beta_i/dk)$ between the two polarization eigenmodes of the fiber [14]. Here $k = 2\pi\nu$ is the free space propagation constant and c is the vacuum velocity of light. The steep slope of the curves in Fig. 2 indicates that the polarization mode dispersion in these fibers is large and does not pass through zero as predicted if no stress birefringence is present [5]. For example, fiber D has $\Delta\tau \sim 3.5$ ns/km at $\lambda = 1.0$ μm. The relevance of this polarization mode dispersion is that if nonmonochromatic light is injected into the fiber so as to excite both eigenmodes, the light will be depolarized after only a short fiber length. Here, we distinguish between a change in the polarization state and depolarization. Initially, for a very short length, the injected light will evolve through a periodic sequence of polarization states due to the difference in phase velocities between the light in the two eigenmodes [1], [2]. However, this light of bandwidth $\Delta\nu$ has a coherence time $T_c \simeq 1/c\Delta\nu$ and, when the group delay time $\Delta\tau$ exceeds T_c, the light becomes depolarized [4], [14]. In the interim, the light is still polarized, although with a reducing *degree* of polarization. The actual *state* of polarization cycles with length with a period equal to L_p. The bandwidth-length dependence of the polarization degree is formally given by (2) with $\Delta\nu$ replacing $2\delta\nu$ and where $I_{\max}$ and $I_{\min}$ now denote the maximum and minimum intensities obtainable with a general polarization analyzer at the fiber output. The length over which this depolarization occurs is $\Delta L_d = \Delta\nu^{-1}(d\beta_i/dk)^{-1}$ [4], [14]. For fiber D and $\Delta\nu$ corresponding to $\Delta\lambda = 70$ nm, $\Delta L_d \sim 1.3$ cm at $\lambda = 1.0$ μm. At this wavelength, $L_p = 1.5$ mm and thus, light with a bandwidth of 70 nm will be depolarized after only ~9 beat lengths. For a bandwidth $\Delta\nu$ this length ΔL_d is just the fiber length required to produce a differential phase change of $\Delta\psi = 2\pi$

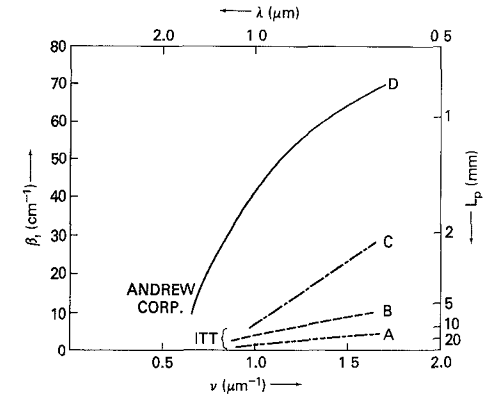


Fig. 2. Frequency dependence of the birefringence for the four fibers listed in Table I.

between the light at the extremities of the bandwidth in the two polarization eigenmodes. Hence, the $\Delta\nu_d$ discussed above as the distance between adjacent intensity maxima is also the bandwidth necessary to depolarize the light over some fiber length L. It follows then, that in order to measure the wavelength dependence of β_i, the measurement bandwidth $2\delta\nu$ must be $\ll \Delta\nu_d$. The relevance of ΔL_d will be discussed in Section III.

III. Random Polarization-Mode Coupling

The theory of random polarization-mode coupling has been formulated in terms of an ensemble of statistically equivalent fibers injected with monochromatic light polarized parallel to one polarization eigenmode of the fiber [3]. However, according to this formulation, an experimental evaluation of the polarization holding ability of the fiber is difficult as measurements on a large number of statistically equivalent fibers are required. As well, for any one fiber and for monochromatic light, difficulties arise in locating the fiber axes accurately and obtaining a reliable measure of the relative power in each polarization eigenmode. This is because the coherent interference between the light propagating in the two eigenmodes is very sensitive to environmental conditions, leading to large fluctuations in the power transmitted by the output polarization analyzer [4].

To overcome these problems, the theory of random polarization-mode coupling has been extended [4] to include a range of wave numbers $\Delta\nu$. In this case, and for the injection of linearly polarized light into one polarization eigenmode (x), the average power coupled to the cross-polarized eigenmode (y) as a function of the length L is given by

$$\xi = \{p_y\}/\{p\} = \tfrac{1}{2}\,[1 - \exp(-2h(\nu_o)L)] \tag{3}$$

where $h(\nu_o) = (k^2/4)\{|\Gamma(\beta_i)|^2\}$ is the polarization-holding parameter [3], [4]. Here, $\{\ \}$ denotes the spectral average over $\Delta\nu$ and p_y and $p = p_x + p_y$ are the spectral power densities. $|\Gamma(\beta_i)|^2$ is the power spectrum of the perturbing birefringences β_p evaluated at the spatial frequency of the fiber birefringence β_i and ν_o is the mean wave number in the interval $\Delta\nu$. Equation (3) shows that coupling between the polarization eigenmodes will be effected only by those perturbations whose spatial frequency is equal to β_i. The polarization holding parameter h describes the average rate of power transfer to the cross-polarized mode and is a measure of the power spectrum of the perturbing birefringences at the spatial frequency β_i. The relationship between this power spectrum and the actual perturbations is expressed by [3], [12]

$$\{|\Gamma(\beta_p)|^2\} = \int_{-\infty}^{\infty} R(u)\, e^{-i\beta_p u}\, du \tag{4}$$

where $R(u)$ is the autocorrelation function of some function $\gamma(z)$. This $\gamma(z)$ describes the strength, orientation, and distribution of all the birefringence perturbations along the fiber. Equation (4) shows that the average value of the power spectrum is just the Fourier transform of $R(u)$. The strength, distribution, and character of $\gamma(z)$ is, as yet, unknown but a knowledge of $|\Gamma(\beta_p)|^2$ is expected to provide some of this information.

The depolarization length ΔL_d discussed in Section II is also the fiber length over which the polarization coupling can be considered to be statistically independent [4], [15]. In this way, the spectral average expressed by (3) is equivalent to the ensemble average of Kaminow [3]. However, now it allows a determination of h from a measurement on a single fiber. In this case, we can consider the individual members in the ensemble average [3] to be stacked end-on-end along the single fiber rather than being separate fibers. The number of members [4] in the ensemble is just $N \sim L/\Delta L_d$ and a 100 m length of fiber D then has $N \sim 7.7 \times 10^3$ members if $\Delta\lambda = 70$ nm and $\lambda = 1\ \mu$m.

Experimental support of the theory of random polarization coupling in highly birefringent fibers is obtained by measuring the polarization holding performance of two elliptical-core fibers as a function of length [4]. The simple experimental layout is shown in Fig. 3. Light from a tungsten lamp is focused through a linear polarizer into the birefringent fiber. At the fiber output, the light is focused through interference filters and a linear analyzer onto either a silicon or cooled germanium photodiode and synchronously detected. The filters are primarily chosen to ensure operation of the fiber in its single-mode regime although they also allow evaluation of the polarization holding ability of the fiber as a function of frequency. The fiber axes are located by rotating both the input and output polarizers for minimum detected power. In this condition, the input polarizer is parallel to a fiber eigenmode (x) and the output analyzer is crossed to that eigenmode. Rotation of the analyzer through $\pi/2$ allows measurement of the extinction ratio $\eta = \{p_y\}/\{p_x\} = P_y/P_x$. P_y and P_x are the total broad-band powers in the two polarization eigenmodes. The sensitivity of the detected power to the orientation of the polarizer and/or the analyzer is shown in Fig. 4 for a 72 m length of Andrew Corporation [11] elliptical-core fiber with a beat length $L_p \approx 1$ mm at $\lambda = 0.83\ \mu$m. This fiber can hold polarization to 14.4 dB over 1 km. A misorientation of both the input polarizer and the output analyzer of $\leqslant 1°$ degrades the polarization holding parameter h from 3.6×10^{-5} m^{-1} to 4.2×10^{-5} m^{-1}, corresponding to a reduction of its *average* polarization holding ability over 1 km by $\leqslant 0.4$ dB. A $\leqslant 2°$ misorientation of both the polarizer and analyzer degrades the extinction ratio η by up to 2.8 dB over 1 km. This

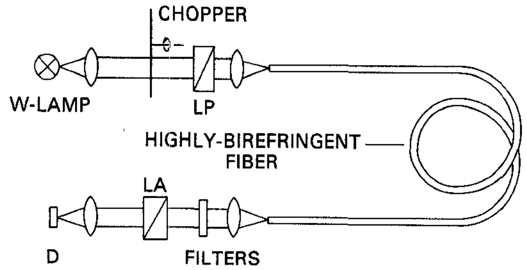


Fig. 3. Experimental arrangement for evaluating the polarization holding ability of highly birefringent fibers.

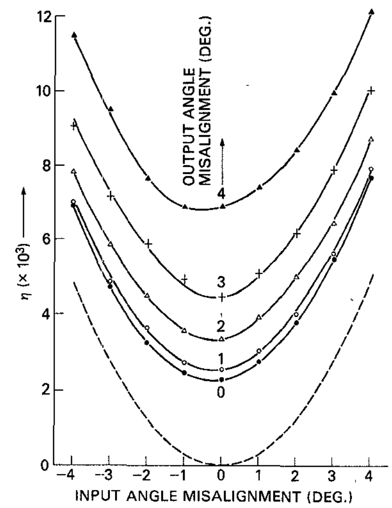


Fig. 4. Sensitivity of the extinction ratio η to a misalignment of the polarizer and analyzer. The zero input angle denotes the x eigenmode and the zero output angle denotes the y eigenmode. The dashed curve shows the extinction ratio sensitivity to a misalignment of two polarizers, without the fiber.

shows that, as expected, extremely precise orientation ($\ll 1°$) of the fiber at joints, splices, etc., may not be necessary in some applications. In the experimental arrangement, the extinction ratio measured after all the optics, i.e., lens, polarizers, etc., without the fiber is $\eta < 10^{-4}$, independent of angular alignment. For comparison, the dashed curve shows the extinction ratio expected after two misaligned perfect polarizers. The similarity in the shapes of the curves is clear.

For two ITT [10] elliptical-core fibers, the relative power in the cross-polarized mode (y) as a function of fiber length [4] is shown in Fig. 5 together with the best-fit theoretical curves given by (3). The fibers are loosely coiled on 1 m circumference drums, the mean wave number ν_o corresponds to $\lambda_o = 800$ nm wavelength and the bandwidth $\Delta\nu$ corresponds to $\Delta\lambda = 200$ nm [4]. We interpret the good agreement between the experimental points and the theoretical curves to be a sound confirmation of the theory of random polarization-mode coupling in highly birefringent fibers. As expected, the fiber with the larger birefringence ($L_p = 11$ mm and $h = 2.2 \times 10^{-3}$ m^{-1}) holds polarization better than the fiber with the smaller birefringence ($L_p = 22$ mm and $h = 4.3 \times 10^{-2}$ m^{-1}). The large difference between the polarization holding abilities of the two fibers is a little surprising as it indicates a very rapid falloff in the power spectrum of the birefringence perturbations with increasing spatial frequency. This interpretation is

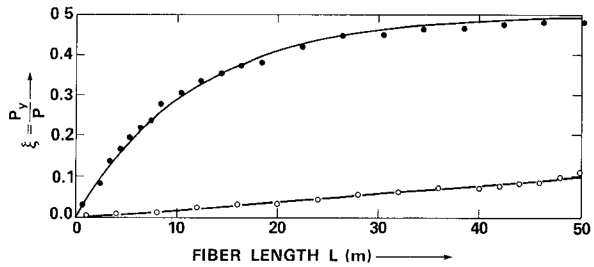


Fig. 5. Length dependence of the relative power in the unexcited polarization eigenmode (y) for two elliptical-core fibers. • $L_p = 22$ mm, $h = 4.3 \times 10^{-2}$ m^{-1}, ○ $L_p = 11$ mm, $h = 2.2 \times 10^{-3}$ m^{-1}.

a little misleading because, as will be discussed further in Section IV, the jacket on the fiber with $L_p = 22$ mm was Hytrel with ripple-defects which imposed substantial perturbations to the fiber.

IV. Birefringence Perturbations

External deformations of the fiber such as bends, clamps, etc., will introduce perturbing birefringences, but these can be avoided or reduced by careful handling of the fiber. Perturbations resulting from the fabrication process, that is, those internal to the fiber and those introduced by the fiber jacket will ultimately limit the polarization holding ability of the fiber. To optimize the fiber, they must be identified and, if possible, removed. The investigation here is limited to those perturbations present in the fiber structure. In some applications, for example sensors, external perturbations such as tightly coiling the fiber may ultimately limit the performance, but they are not addressed here. In all the measurements, the fibers are either loosely coiled under their own weight on 33 cm diameter drums or laid flat in an oven in loose 25 cm diameter coils. Care is taken to avoid all unnecessary bends, fiber crossings, etc., which would introduce additional birefringences. The high attenuations of these fibers limit the measurable fiber length to the 50-100 m range.

One source of these perturbations is the fiber jacket. Careful observation of Hytrel-jacketed fibers shows that the fiber is not always centrally positioned in the soft silicone primary jacket. When the Hytrel is extruded over the primary jacket and cured, it contracts and exerts noncircularly symmetric transverse stresses on the fiber. These transverse stresses are randomly distributed around and along the fiber and, when they are not aligned with the fiber axes, they will couple the polarization eigenmodes. Fig. 6 shows the polarization holding parameter h for three different ITT fibers as 50 m lengths of the fibers are heated slowly in an oven. For the Hytrel jackets, the stresses in the jacket relax at ~80°C and they remain relaxed after the fibers have cooled back to room temperature. The two Hytrel-jacketed fibers have similar beat lengths but for one fiber, a drawing defect resulted in the jacket being rippled with a period of 2-4 mm, accounting for the different h parameters. For these measurements, bandwidths $\Delta\nu \sim 300$ nm are used. Even for these relatively short beat lengths ~10 mm, the Hytrel jacket is responsible for degrading the h parameter by up to an order of magnitude and, as will be discussed shortly, possibly even more. The DeSoto 40 jacket behaves oppositely. As the jacket is heated it changes

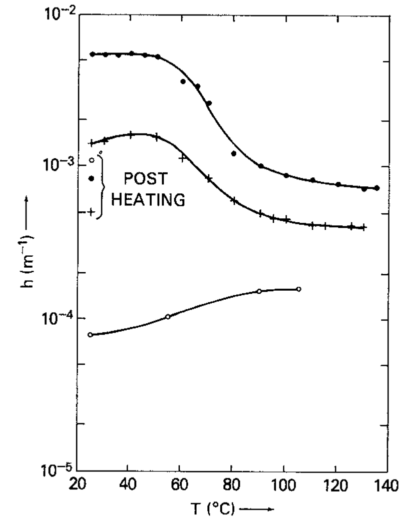


Fig. 6. Temperature dependence of the polarization holding parameter h for three elliptical-core fibers. • Fiber B, $L_p = 10.1$ mm, rippled Hytrel jacket; + $L_p = 10.5$ mm, Hytrel jacket; ○ fiber C, $L_p = 4.7$ mm, DeSoto 40 jacket.

from a clear color to dirty yellow and hardens. Again, if the fiber is not perfectly centered in the jacket, this hardening introduces perturbing birefringences. After the fiber has cooled to room temperature, the polarization holding ability of the fiber has degraded by more than an order of magnitude, even though the fiber had a beat length <5 mm. Here, attention is drawn to the possibly very large effect these jackets would have on the polarization state propagating through nominally low birefringence fibers.

For each fiber, a range of broad-band filters with a bandwidth $\Delta\lambda = 70$ nm is used to measure the frequency dependence of the h parameter. This bandwidth is sufficient to obtain a statistically meaningful measure of h because, as discussed in Section III, this bandwidth still results in 7.7×10^3 members per 100 m length of fiber D in the ensemble average. When combined with the frequency dependence of the fiber birefringence β_i discussed in Section II, this measurement gives the spatial frequency dependence of h which is just a measure of the power spectrum of the perturbing birefringences. That is, we obtain a measure of $|\Gamma(\beta_p)|^2$ for one fiber over a range of β_p. Fig. 7 shows these data for fiber A with various layers of its jacket heated and removed. Comparison of the curve for the unheated Hytrel jacket with that for the bare fiber shows that the birefringence perturbations degrade the polarization holding ability by at least an order of magnitude. The strength of the perturbations introduced by the Hytrel jacket is strongest at lower spatial frequencies and it decreases slightly with increasing frequency over the range of 1.5 cm^{-1} $< \beta_i <$ 4.0 cm^{-1}. Heating the Hytrel jacket to 135°C reduces the strength of the perturbing birefringences by up to an order of magnitude, particularly for the lower spatial frequencies, but sufficient jacket stresses remain to degrade the polarization holding ability by close to a factor of 5. These stresses originate in the Hytrel jacket. Careful stripping of the Hytrel so as to leave only the primary silicone jacket, removes all the jacket-induced perturbations. The h parameter for the fiber with the silicone jacket is indistinguishable from that for the fiber stripped com-

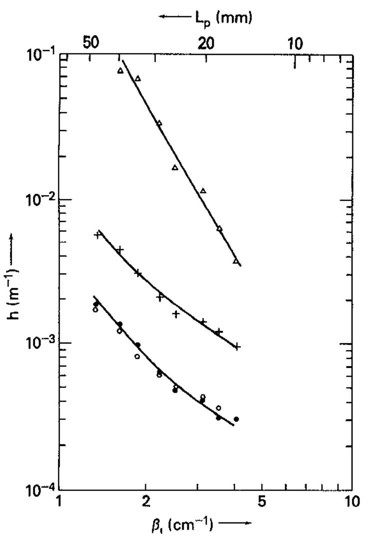


Fig. 7. Spatial frequency dependence of the polarization holding parameter h for fiber A with its Hytrel jacket: △ unheated fiber; + heated to 135°C; ○ Hytrel jacket removed, RTV jacket jacket only; ● bare fiber.

pletely bare. The only perturbing birefringences remaining at this stage are those internal to the fiber and the strength of these perturbations at the spatial frequency 4.0 cm^{-1} is almost an order of magnitude below the strength of the perturbations at the frequency 1.3 cm^{-1}. Over this range, the strength of the internal perturbations is reducing by an average factor of 4.4 for an octave increase in spatial frequency.

The strength of the perturbing birefringences (measured by the h parameter) as a function of the spatial frequency of the fiber birefringence β_i is shown in Fig. 8 for each of the four fibers, both with their respective jackets and stripped completely bare. All the jacket materials examined introduce additional perturbations to the fibers due to noncircularly symmetric transverse stresses. Initially, the DeSoto 40 jacket adds the smallest perturbations, but as discussed above, it degrades rapidly after heating. Only the soft silicone primary jacket does not introduce additional birefringences. This is consistent with expectations as, historically, silicone has been useful in reducing microbend losses. For single mode fibers, a silicone primary jacket is not sufficient to prevent the noncircularly symmetric transverse stresses from the hard plastic outer jacket being transferred to the fiber itself and introducing additional birefringences. For all the jacket materials, the troublesome ripples and bumps which introduce the perturbations can usually be both seen and felt, indicating that they are gross defects. For each jacket material, the curves representing the strength of the perturbations in the fiber with its jacket intact and after removal of the jacket are approximately parallel. This indicates that the power spectrum of the jacket-induced perturbations is approximately constant over this spatial frequency range.

The plots for the two fibers with highly elliptical cores, namely fibers C and D, exhibit a potentially disturbing trend. The strength of the perturbations appears to increase rapidly as the fiber birefringence increases. This is contrary to expectations and, if correct, would raise concerns for the prospects of fabricating good quality polarization holding elliptical-core fibers. While it is possible that the process adopted to increase

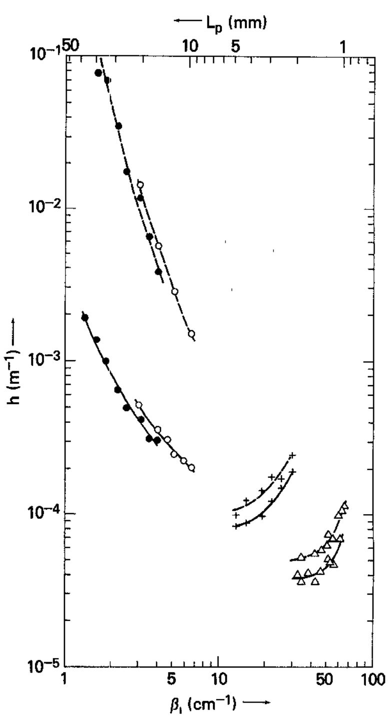


Fig. 8. Spatial frequency dependence of the polarization holding parameter h for the fibers with and without their respective jackets. ● Fiber A; ○ fiber B; + fiber C; △ fiber D; --- fiber with jacket; —— bare fiber.

the fiber birefringence may result in an increase in the strength of the perturbing birefringences as well, we think that this has not occurred here. We interpret this degrading of the h parameter to be evidence of the fiber becoming multimoded. For highly elliptical-core fibers, the higher order modes continue to propagate for lower V values than would be the case for nominally circular-core fibers [16]. For these fibers, the relevant normalized frequency is $V = 2\pi b\sqrt{n_1^2 - n_2^2}/\lambda$ where n_1 and n_2 are the refractive indexes of the core and cladding, respectively [5], [16]. Using the published cutoff curve [16] and the fiber parameters from Table I, the higher mode cutoff is found to be $\lambda_c \sim 1$ μm for fiber D and $\lambda_c \sim 0.8$ μm for fiber C. In the measurements shown in Fig. 8 for these two fibers, the V values were kept below $V = 2.2$ which is in the multimoded regime as $V_c \sim 1.4$ for these fibers [16]. Hence, only the lower few data points for the two fibers are truely representative of the fiber perturbations. For the other two fibers, namely fibers A and B, the V values over the wavelength range measured correspond to the single-mode regime of the fibers. This upturn in the h parameter can be interpreted as further confirmation of the V value at which the higher order modes of elliptical-core fibers cutoff [16]. This technique may be useful in experimentally determining the cutoff wavelength for elliptical-core fibers but the resolution of the measurement may be very limited. This same sharp upturn in the h parameter was observed in a stress-induced birefringence fiber as the wavelength was lowered below the cutoff, but this result was not previously reported [8].

In evaluating the polarization holding ability of the elliptical core fibers, the h parameters for the two polarization eigenmodes are found to be equal within the experimental accuracy. Also, no differential loss between the two eigenmodes is observed although the loss measurements made are only accurate to a few percent.

The spatial frequency dependence of the strength of the internal birefringence perturbations in these elliptical-core fibers is repeated in Fig. 9. As discussed in connection with Fig. 8, these fibers are stripped bare of their jackets and are handled carefully so as to avoid the introduction of any externally induced birefringences. The remaining perturbations are then internal to the fiber structure. One surprising characteristic is that the fibers fabricated in two different laboratories [10], [11] appear to lie on the same curve. This can be interpreted to indicate that the origin of the perturbations may be related to either the geometrical structure of the fiber or the general fabrication technique, namely the CVD method, and not directly related to minor differences in the fabrication procedures, drawing tower idiosynchrasies, etc. That is, in the fabrication of these elliptical-core fibers via the CVD method, a particular type of perturbation, which is independent of minor fabrication differences, may be introduced. Although, it is pointed out that the perturbation cannot result directly from the elliptical shape of the core as a perfectly uniform elliptical core would have no coupling perturbations. The strength of these perturbations decreases by close to two orders of magnitude over one and a half orders of magnitude increase in fiber birefringence. The slope of the curve starts to flatten out for $\beta_p > 10$ cm^{-1} and extrapolation of this curve indicates that very small beat lengths $L_p < 0.1$ mm will be necessary in order to achieve better polarization holding with $h < 10^{-5}$ m^{-1}. Obviously, this is not the desired approach. An identification and reduction in the strength of the perturbations would be more fruitful.

A comment is appropriate here concerning the measurement of the spatial-frequency dependence of the perturbations by changing the wavelength of the light in one particular fiber. As already discussed, varying the wavelength enables the strength of the perturbations to be determined for a range of fiber birefringences without the possibility of fabrication-related perturbations being introduced in different fibers which are fabricated differently so as to produce the range of fiber birefringence required. However, associated with this wavelength change is a change in the radial dimension of the mode within the fiber. Any variation of the radial distribution of the birefringence perturbations in the core/cladding region of the fiber would contribute to any changes observed in the power spectrum of the perturbations over the range of spatial frequencies measured. One way of avoiding this possible ambiguity would be to draw several fibers, each from the same preform, but with different diameters, so that the measurement could be made at a constant V value while, at the same time, covering a range of birefringence in fibers which are expected to have identical internal perturbations. Here, we assume that the radial distribution of the internal perturbations does not change significantly over the wavelength range scanned.

The strength of the perturbing birefringences in highly birefringent elliptical-core fibers has been experimentally determined. As yet, the origin of these perturbing birefringences is still unknown. It is clear that the perturbations must result from some mechanism or defect close to the core of the fiber. Core diameter variations are considered to be an unlikely cause as the speed at which fibers are drawn tends to preclude the possibility of significant diameter changes with a subcentimeter periodicity. As well, it is unlikely that a core diameter variation will introduce a birefringence effect which has its axes misaligned with those of the fiber. It is expected that diameter changes will only change the magnitude of β_i and not affect the orientation of the axes. Such a mechanism will not couple the polarization eigenmodes. Variations in the shape of the core ellipse along the fiber are an obvious possibility but they would need to occur at sufficiently large spatial frequencies. Slow twists or rotations of the core ellipse would not introduce substantial birefringence unless the outer shape of the fiber is far from circularly symmetric. In this case, a stress-induced birefringence with its axes not aligned with those of the core ellipse could be introduced.

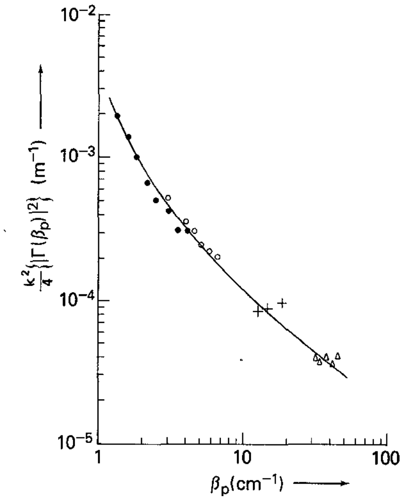


Fig. 9. Map of the average power spectrum of the intrinsic perturbing birefringences in elliptical core birefringent fibers. ● Fiber A; ○ fiber B; + fiber C; △ fiber D.

We consider that the most likely origin of these birefringence perturbations is a combination of core shape irregularities and the resulting stress perturbation. Elliptical core fibers are fabricated with rather large doping levels to achieve the required large index differences. This, together with the non-circularly symmetric core shape, must result in large stress asymmetries being present in the core and near-core cladding regions of the fiber. This has already been confirmed experimentally [7] and discussed in Section II. This stress birefringence then magnifies any core shape irregularity which is, itself, a perturbation of the geometrical shape birefringence. The shape irregularity disturbs the distribution of stress in the fiber cross section and the resulting stress birefringence will not, in general, have its principal axes aligned with those of the core ellipse. It will, thus, couple the polarization eigenmodes of the fiber. We suggest that core irregularities and the resulting stress birefringence perturbations are responsible for limiting the h parameter in state-of-the-art elliptical-core fibers to $\sim 4 \times 10^{-5}$ m^{-1} even though submillimeter beat lengths have been achieved. For comparison, a nominally circular-cored fiber fabricated so as to maximize the stress-induced birefringence exhibits an h parameter of 5.5×10^{-6} m^{-1} even though it has a beat length of ~2.5 mm [8]. It is unlikely that highly doped elliptical core fibers can be fabricated free of stress and thus, very good control of the geometrical shape of the core may be necessary in order to achieve good polarization holding in elliptical-core fibers. Preliminary experimental evidence tends to support this explanation, but further work is still necessary.

V. Conclusion

The polarization holding abilities of four highly birefringent elliptical-core fibers are evaluated with the experimentally simple spectral averaging technique [4]. Only the perturbing birefringences resulting from the fiber structure are considered as care is taken to avoid all externally induced perturbations. The four fibers are selected so that they span the range of birefringences fabricated to date, corresponding to beat lengths over the range 1 mm $< L_p <$ 55 mm. To extend the number of data points, and to ensure that the character of the internal perturbations does not change as the strength of the fiber birefringence is increased, the strong frequency dependence of the fiber birefringence is exploited to evaluate the polarization holding as a function of spatial frequency within each fiber. To do this, the wavelength dependence of the fiber birefringence is measured on short lengths of the fiber with a simple technique [7]. This measurement confirms that material stress birefringence as well as geometrical shape birefringence contributes to the fiber birefringence, but not in accordance with the simple theory describing low birefringence fibers [9]. For the first time, the power spectrum of the internal perturbations, that is the strength of the internal perturbing birefringences as a function of spatial frequency, is experimentally determined for highly birefringent elliptical core fibers. It is shown that commonly available fiber jackets can significantly degrade polarization holding in the fiber and care must be taken to ensure that the jacket is applied circularly symmetric with the fiber and free of bumps, ripples, etc. The strength of the birefringence perturbations decreases quite rapidly $\propto \beta_p^{2.2}$ for smaller spatial frequencies $\beta_p \sim 1.5$ cm^{-1}, but this rate slows $\propto \beta_p^{0.78}$ for $\beta_p \sim 40$ cm^{-1}. The actual nature and origin of these perturbations are still unknown but it is suggested that they result from core shape irregularities and the associated stress perturbations. This remains to be experimentally confirmed, but now, at least, the power spectrum of the perturbations is known which will facilitate identifying the origin of the perturbations. The data seem to support the predicted low-pass filter characteristic for the power spectrum [3] and the internal birefringence perturbations limit polarization holding in state-of-the-art high-birefringence elliptical-core fibers to $\leqslant$14.4 dB over 1 km.

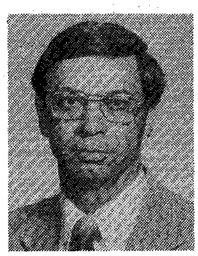
Acknowledgment

The authors acknowledge discussions with H. F. Taylor and R. Ulrich and thank F. I. Akers and R. B. Dyott for supplying fiber samples and relevant fiber data.

References

[1] A. Simon and R. Ulrich, "Evolution of polarization along a single mode fiber," *Appl. Phys. Lett.*, vol. 31, pp. 517–520, 1977.
[2] —, "Polarization optics of twisted single mode fibers," *Appl. Opt.*, vol. 18, pp. 2241–2251, 1979.
[3] I. P. Kaminow, "Polarization in optical fibers," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 15–22, 1981.
[4] S. C. Rashleigh, W. K. Burns, R. P. Moeller, and R. Ulrich, "Polarization holding in birefringent single mode fibers," *Opt. Lett.*, vol. 7, pp. 40–42, 1982.
[5] R. B. Dyott, J. R. Cozens, and D. G. Morris, "Preservation of polarization in optical fiber waveguides with elliptical cores," *Electron. Lett.*, vol. 15, pp. 380–382, 1979.
[6] R. H. Stolen, V. Ramaswamy, P. Kaiser, and W. Pliebel, "Linear polarization in birefringent single mode fibers," *Appl. Phys. Lett.*, vol. 33, pp. 699–701, 1978.
[7] S. C. Rashleigh, "Wavelength dependence of birefringence in highly-birefringent fibers," *Opt. Lett.*, vol. 7, pp. 294–296, 1982.
[8] S. C. Rashleigh and M. J. Marrone, "Polarization holding in a high-birefringence fiber," *Electron. Lett.*, vol. 18, pp. 326–327, 1982.
[9] W. Eickhoff, Y. Yen, and R. Ulrich, "Wavelength dependence of birefringence in single mode fiber," *Appl. Opt.*, vol. 20, pp. 3428–3435, 1981.
[10] Fabricated by ITT Electro-optical Products Division, Roanoke, VA, under contract to the Office of Naval Research.
[11] Fabricated by Andrew Corporation, Orland Park, IL.
[12] D. Marcuse, *Theory of Dielectric Optical Waveguides.* New York: Academic, 1974.
[13] S. C. Rashleigh and M. J. Marrone, "Stress and shape birefringences in polarization-holding fibers," in *Proc. 84th European Conf. on Opt. Commun.*, Cannes, France, Sept. 1982.
[14] S. C. Rashleigh and R. Ulrich, "Polarization-mode dispersion in single mode fibers," *Opt. Lett.*, vol. 3, pp. 60–62, 1978.
[15] R. Ulrich and S. C. Rashleigh, to be published.
[16] S. R. Rengarajan and J. E. Lewis, "First higher mode cutoff in two-layer elliptical fiber waveguides," *Electron. Lett.*, vol. 16, pp. 263–264, 1980.

Scott C. Rashleigh (S'72–M'74), for a photograph and a biography, see p. 511 of the April 1982 issue of this Transactions.



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Dr. Marrone is a member of the American Physical Society.