

Polarization Quality of High-Birefringence Single-Mode Fibers

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Coherent optical communications, integrated optics, and interferometric sensors require that single-mode fibers maintain a stable state of polarization. With a broadband source, wavelength averaging of the power in either orthogonally polarized HE_{11} mode permits a simple measurement of the power transfer to the cross-polarized state (the h value). Polarization-holding quality was measured on several single-mode fibers with strain birefringence that had been induced by a new preform deformation method or a gas-phase etching technique. The fibers exhibited h values from $2.3 \times 10^{-5} \text{ m}^{-1}$ (average polarization-holding to -24 dB) to $8.9 \times 10^{-4} \text{ m}^{-1}$ with beat lengths (at $\lambda = 632.8 \text{ nm}$) from 1.7 to 10 mm when the power is wavelength averaged over the 800- to 1100-nm range.

I. INTRODUCTION

Coherent optical communications,¹ integrated optics, and interferometric sensors require that single-mode fibers maintain a stable state of polarization over long propagation lengths. Environmental perturbations are one cause of cross-polarization coupling of the two orthogonally polarized HE_{11} modes²⁻⁴ resulting in an unstable state of polarization. The birefringent properties of polarization-maintaining fibers should be designed to be insensitive to environmental changes.

An important characteristic of single-polarization fibers is the average rate at which power is coupled into the cross-polarization state.

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With a broadband source, wavelength averaging of the power in either mode can allow a simple measurement of the power transfer to the cross-polarized mode.⁵ Following that approach, a statistically determined polarization-holding parameter, h , and beat lengths (at $\lambda = 632.8$ nm) were measured for several single-mode fibers. The strain birefringence was induced by a preform deformation method⁶ or a gas-phase etching⁷ technique. The power is wavelength averaged over the 800- to 1100-nm spectral range.

II. RATE OF TRANSFER OF CROSS-POLARIZATION

One parameter commonly used in describing birefringent fibers is the mode beat length defined by

$$L_p = \frac{2\pi}{\delta\beta} = \frac{\lambda}{B}, \quad (1)$$

where $\delta\beta$ is the difference between the propagation constants for the slow- and fast-polarization eigenmodes, λ is the wavelength of light, and B is the modal or normalized linear birefringence. The modal birefringence can be separated into a stress anisotropy component, B_s , and a geometrical, or shape, component, B_G .

Kaminow² obtained an analytical expression for the ensemble averages of the relative powers in the two polarization modes. Rashleigh⁵ et al. extended the random-coupling theory to incorporate a finite range of wave numbers on a single fiber since the random-coupling theory requires measurements of a large number of fibers. The rate of transfer of cross-polarization in a single-mode fiber is defined by

$$\zeta \equiv \{P_y\}/\{P\} = 1/2[1 - \exp(-2hL)], \quad (2)$$

where P_y indicates the power in the cross-polarization mode, $P = P_x + P_y$ is the total power, P_x is the power in the excited mode, and L is the fiber length. The inverse of the parameter h describes the characteristic distance for power transfer to the cross-polarization state.

The ensemble of N statistically equivalent fibers is directly proportional to the bandwidth $\delta\lambda$ of a broad bandwidth light source;⁵ i.e.,

$$N \approx \sigma L \delta\lambda \approx L/\Delta \ell, \quad (3)$$

where $\Delta \ell$ represents one member of an ensemble of equivalent fibers and

$$\sigma = \frac{1}{c} \frac{d(\delta\beta)}{dk_o} \equiv \frac{1}{c} \left[\frac{\delta\beta}{k_o} + k_o \frac{d(\delta\beta/k)}{dk_o} \right] \quad (4)$$

is the polarization-mode dispersion, the group delay difference between orthogonally polarized modes. The relative standard deviation of the

rate of power transfer to the cross-polarization state is of the order $N^{-1/2}$.

III. EXPERIMENTAL TECHNIQUE

Figure 1 shows a schematic for the measurement of the rate of power transfer to the cross-polarization state. The source for these experiments is white light from a xenon arc lamp that is chopped and then filtered by Corning glass filters 5-56 and 2-58. The combined filters produce a bandwidth of 800 to 1100 nm. The filtered light is linearly polarized and focused into the single-mode test fiber. Cladding-mode strippers are used to ensure that the light being examined is guided along the fiber core. The polarized fiber output light is focused through a linear analyzer and detected by a silicon avalanche photodiode. The detected signal is input to a lock-in amplifier and referenced to a synchronizing signal from the chopper. The lock-in function-output voltage is digitized and sent to a computer where P_x and P_y are averaged in time.

Stolen and Turner⁸ showed that the best polarization-holding azimuthal angle in a fiber can be determined by rotating the polarizer and analyzer until the detected power is minimum. At the minimum power, the measured output is in the cross-polarization state. To examine the power in the excited mode, the linear analyzer is rotated 90 degrees.

IV. RESULTS AND DISCUSSION

The rate of power transfer to the cross-polarization state and beat lengths (at $\lambda = 632.8$ nm) were measured and are presented in Table

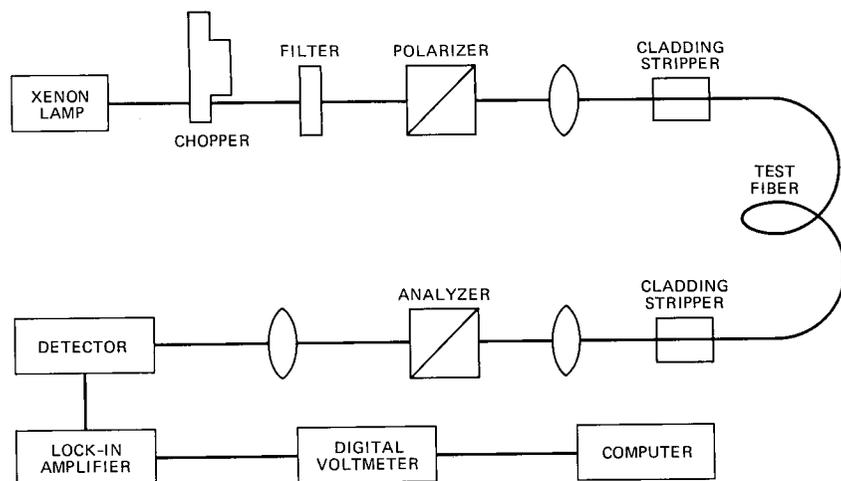


Fig. 1.—Measurement system for the rate of power transfer to the cross-polarization state.

I. Table I also shows the average polarization holding in decibels defined as $10 \cdot \log_{10} (h \cdot \text{fiber length})$. The measured fibers were all single mode for wavelengths longer than 800 nm.

Fibers 2 through 4 were fabricated with a cladding refractive index below that of the silica support tube (depressed index or W-type fiber design). The ellipticity of the stress-applying region (shown in Fig. 2) immediately surrounding the core gives rise to the birefringence observed. The stress resulting from this structure has been analyzed in detail by Stolen.⁹ Fibers 2 through 4 contain an $\text{Al}_2\text{O}_3\text{-SiO}_2$ core, $\text{B}_2\text{O}_3\text{-P}_2\text{O}_5\text{-SiO}_2$ stress region, and a fluorine-doped SiO_2 cladding. Two modes were present in these fibers at a wavelength of $0.63 \mu\text{m}$, and a high fundamental mode tunneling loss was observed in the $1.0\text{-}\mu\text{m}$ wavelength region.

Fiber 1 (shown in Fig. 3) was made by a gas-phase etching technique.⁸ It contained a $\text{GeO}_2\text{-SiO}_2$ core, a fluorine-doped silica stress region, and a SiO_2 cladding. This fiber has a core diameter of $3.6 \mu\text{m}$, and was multimode at $0.63 \mu\text{m}$. The long wavelength, leaky-mode loss edge was beyond $1.5 \mu\text{m}$.

The h values for the fibers listed in Table I vary from $2.3 \times 10^{-5} \text{ m}^{-1}$ to $8.9 \times 10^{-4} \text{ m}^{-1}$ with the beat lengths varying from 1.7 mm to 10 mm. There was no correlation between the changes in the h values and the beat lengths. This agrees with other results in the litera-

Table I—Average polarization-holding quality over 800- to 1100-nm spectral range

Fiber Number	Fiber Length (m)	h (m^{-1})	L_p (mm)	Polarization Holding (dB)	Core Diameter (μm)
1	96	6.2×10^{-4}	10	-12.2	3.6
2	50	8.9×10^{-4}	2.6	-13.5	4.3×11
3	450	1.5×10^{-4}	3	-11.7	5.8
4	174	2.3×10^{-5}	4.3	-24	6

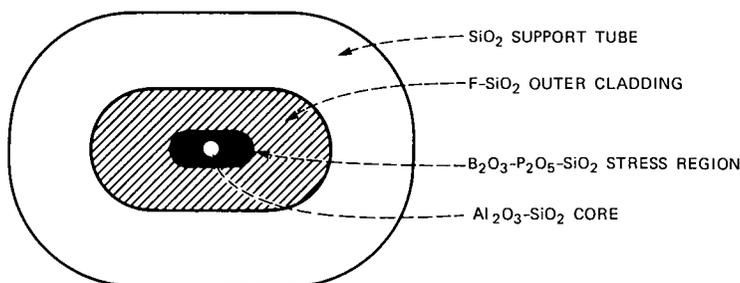


Fig. 2—Single-mode birefringent fiber cross section fabricated by a preform deformation.

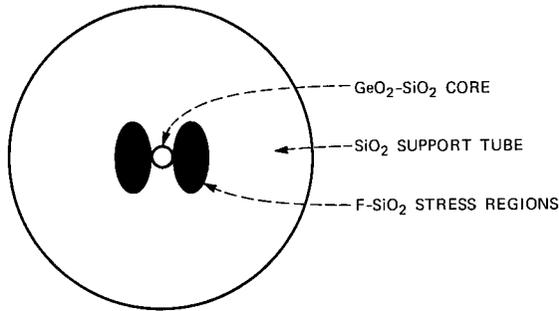


Fig. 3—Single-mode birefringent fiber cross section fabricated by a gas-phase etching technique.

ture.⁵⁻⁷ The fiber-core diameters are listed in Table I. Fiber 2 has shape-induced birefringence due to the elliptical core, but this effect is small compared to the stress-induced birefringence.

The coherence length, $\Delta \ell$, for lightwaves in a fiber is

$$\Delta \ell = \frac{\Delta \tau}{\sigma}, \quad (5)$$

where $\Delta \tau = \lambda_o^2/c\delta\lambda$ is the coherence time of the source and λ_o is the mean wavelength for the spectral width $\delta\lambda$. Using the definition for σ from eq. (4) and neglecting the second term (small for stress-induced birefringence), eq. (5) becomes

$$\Delta \ell = \frac{\lambda_o}{\delta\lambda} L_p. \quad (6)$$

As an example, fiber 1 has a beat wavelength, $L_p = 10$ mm, which results in a coherence length, $\Delta \ell = 3.2$ cm, for a source whose spectral width is $\delta\lambda = 300$ nm centered about $\lambda_o = 950$ nm. For fiber 1 in Table I, this measurement represents an average of $N \approx 3000$ independent samples with a relative standard deviation of $N^{-1/2} \sim 0.018$.

It has been shown that birefringent multimode fibers preserve the state of polarization.¹⁰ The observation was that in fibers supporting a moderate number of modes, all modes maintain linear polarization with the exception of one mode near cutoff. Multimode polarization holding measurements were made in the wavelength region from 500 to 900 nm. The multimode results for fiber 1 indicate polarization holding to -27 dB, corresponding to an h value of $2.2 \times 10^{-5} \text{ m}^{-1}$.

A 1-km length of high-birefringence fiber fabricated by Hitachi Cable Ltd. was reported in the literature¹¹ to have an h -value of $5.5 \times 10^{-6} \text{ m}^{-1}$ for an average polarization holding to -22 dB. These values are in the same range as those measured here. However, low-loss high-birefringence fibers have been reported to hold polarization to better than -30 dB.¹²

V. CONCLUSION

In conclusion, the polarization quality of high-birefringence single-mode fibers has been evaluated using a broadband source. The birefringent fibers were fabricated by a preform deformation method and a gas-phase etching technique. A statistical determination of the rate of power transfer to the cross-polarized state was made by wavelength averaging. The h values measured in the single-mode regime of the fibers varied from $2.3 \times 10^{-5} \text{ m}^{-1}$ to $8.9 \times 10^{-4} \text{ m}^{-1}$ with beat lengths from 1.7 mm to 10 mm. Polarization preservation was found in the multimode regime supporting a moderate number of modes, but it is not yet understood how mode mixing affects polarization performance.

VI. ACKNOWLEDGMENTS

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