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Degree of Polarization in the Lyot Depolarizer

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Abstract—**Analytic output equations for the degree of polarization of light exiting a Lyot depolarizer are derived from a coherency matrix representation. Design criteria are obtained for sources of different spectral shape.**

I. Introduction

LYOT DEPOLARZERS [1], [2] have recently attracted renewed attention due to the successful use of one in reducing polarization noise in a fiber-optic gyroscope [3]. Recently, such a device has been reported [4] which was constructed from birefringent single-mode fibers rather than the usual birefringent crystal plates.

The Lyot deploarizer classically consists of two birefringent crystal plates (X or Y cut), whose crystal axes are oriented at 45° with respect to each other, and whose thicknesses are in the ratio 1:2. The device is intended to be used with broadband light and may be viewed as performing a polarization conversion on the spectral components of polarized input light. At the output, each spectral component appears with a different polarization state, and upon averaging over bandwidth, the output is depolarized. The choice of a 45° angle between the plate axes is made so the depolarizer will be operative independent of the input polarization state. If depolarization is not achieved by the first plate, it will be achieved by the second.

Billings [2] analyzed the Lyot depolarizer by assuming sufficient birefringence to provide 2π of phase retardation over the source bandwidth in the first plate. His model for a rectangular-shaped source suggested that the plates should have an integer thickness ratio not equal to one. Loeber has treated the problem for a blackbody [5]. Recent approaches have focused on frequency decomposition of the output polarization states on the Poincare sphere [6], attempting to achieve a design that provides a uniform distribution of such output states [7], [8]. However, these approaches are not capable of providing quantitative design rules for Lyot depolarizers.

Rashleigh and Ulrich [9] have pointed out that polarization-mode dispersion in single-mode fibers leads to a group delay difference which causes the depolarization of broad-band light. The role of polarization dispersion as opposed to birefringence in depolarization has also been emphasized theoretically by Sakai *et al.* [10]. In this paper, we follow this approach to calculate analytic output equations for the degree of polarization of a Lyot depolarizer, as a function of the input polarization state, source bandwidth and band shape, and fiber or crystal group delay difference. This result will aid in the de-

Manuscript received April 18, 1983; revised June 6, 1983.
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sign of depolarization devices in applications. Our model has been presented qualitatively by Epworth [11]. We ignore mode coupling between polarization modes which has been treated in the paper by Böhm *et al.* [4].

II. Theory

We assume a configuration for the Lyot depolarizer as shown in Fig. 1. The birefringent sections may be crystal plates or sections of briefringent fiber, although we will use fiber terminology. We assume fiber-mode propagation constants β_x and β_y, which are functions of optical frequency ω. The fiber birefringent axes are denoted by X and Y in the first section of length L_1, and X' and Y' in the second section of length $L_2 (L_2 \geqslant L_1)$. The second section is rotated relative to the first by 45°. We assume an optical source with spectral intensity $|\nu(\omega)|^2$ and center frequency ω_0. The optical input to the depolarizer is assumed to be linearly polarized with input azimuth at an angle θ_p from the mode axis X. For unity power input, the time-dependent electric-field input to the fiber may then be represented

$$\begin{bmatrix} E_{0x}(t) \\ E_{0y}(t) \end{bmatrix} = \begin{bmatrix} \cos\theta_p \\ \sin\theta_p \end{bmatrix} e(t)\, e^{i\omega_0 t} \tag{1a}$$

where

$$\langle e(t)\, e^*(t) \rangle = 1 \tag{1b}$$

and $\langle\ \rangle$ signifies a time average. At the joint between the two sections, polarization-mode coupling will occur. The transfer matrix for such coupling is given by

$$\begin{bmatrix} E_{x'}(L_1) \\ E_{y'}(L_1) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} E_x(L_1) \\ E_y(L_1) \end{bmatrix} \tag{2}$$

Propagation in the fiber sections is governed by the frequency-dependent propagation constants $\beta_x \equiv \beta_x(\omega)$ and $\beta_y \equiv \beta_y(\omega)$. Employing the transfer matrix in (2), we can write the frequency-dependent output fields at the end of section L_2 as

$$\begin{bmatrix} E_{x'}(\omega) \\ E_{y'}(\omega) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} e^{-i\beta_x(L_1+L_2)} & e^{-i(\beta_y L_1 + \beta_x L_2)} \\ -e^{-i(\beta_x L_1 + \beta_y L_2)} & e^{-i\beta_y(L_1+L_2)} \end{bmatrix} \begin{bmatrix} E_{0x}(\omega) \\ E_{0y}(\omega) \end{bmatrix} \tag{3}$$

where $E_{0x}(\omega)$ and $E_{0y}(\omega)$ are the input fields at the frequency component ω.

The degree of polarization is defined as the fraction of optical power that is polarized [10], [12]. It is calculated from

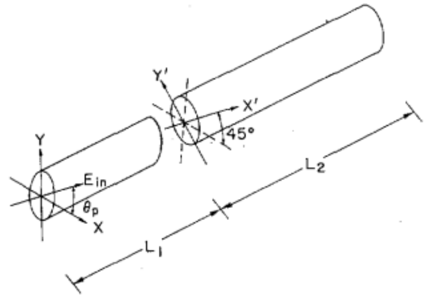

Fig. 1. Model for Lyot depolarizer formed with birefringent fibers.

the coherency matrix J

$$J = \langle E \cdot E^\dagger \rangle = \begin{bmatrix} \langle E_{x'} E_{x'}^* \rangle & \langle E_{x'} E_{y'}^* \rangle \\ \langle E_{y'} E_{x'}^* \rangle & \langle E_{y'} E_{y'}^* \rangle \end{bmatrix} \tag{4}$$

where † signifies the Hermitian transpose. To compute (4), we require time-varying electric-field outputs. We express time-varying electric fields in terms of a complex analytic signal in the usual way [10] by defining $e(t)$ in (1a) as

$$e(t) = 2 \int_0^\infty \nu(\omega)\, e^{i(\omega-\omega_0)t}\, d\omega \tag{5}$$

where $\nu(\omega)$ is the (complex) amplitude spectrum of the source. The output time-varying fields from the depolarizer are then given by

$$\begin{aligned} E_{x'}(t) = \frac{1}{\sqrt{2}} \{ &\cos\theta_p\, e^{i[\omega_0 t - \beta_{x0}(L_1+L_2)]}\, e(t - \beta'_{x0}(L_1+L_2)) \\ &+ \sin\theta_p\, e^{i(\omega_0 t - \beta_{x0} L_2 - \beta_{y0} L_1)} \\ &\cdot e(t - \beta'_{x0} L_2 - \beta'_{y0} L_1) \} \end{aligned} \tag{6a}$$

$$\begin{aligned} E_{y'}(t) = \frac{1}{\sqrt{2}} \{ &-\cos\theta_p\, e^{i(\omega_0 t - \beta_{x0} L_1 - \beta_{y0} L_2)} \\ &\cdot e(t - \beta'_{x0} L_1 - \beta'_{y0} L_2) + \sin\theta_p\, e^{i[\omega_0 t - \beta_{y0}(L_1+L_2)]} \\ &\cdot e(t - \beta'_{y0}(L_1+L_2)) \} \end{aligned} \tag{6b}$$

where $\beta_{x0} \equiv \beta_x(\omega_0)$, $\beta_{y0} \equiv \beta_y(\omega_0)$ and β' denotes differentiation of β by ω. To derive (6), we have used (3) and papers by Sakai *et al.* [10] and Burns *et al.* [13]. Using (6), we calculate the components of the coherency matrix by performing the necessary time averages

$$J_{x'x'} = \tfrac{1}{2} [S_0 + \sin 2\theta_p\, S_1(L_1) \cos \Delta\beta_0 L_1] \tag{7a}$$

$$J_{y'y'} = \tfrac{1}{2} [S_0 - \sin 2\theta_p\, S_1(L_1) \cos \Delta\beta_0 L_1] \tag{7b}$$

$$\begin{aligned} J_{x'y'} = \tfrac{1}{2} e^{i\Delta\beta_0 L_2} \{ &-\cos 2\theta_p\, S_1(L_2) \\ &+ \tfrac{1}{2} \sin 2\theta_p\, e^{i\Delta\beta_0 L_1} [S_1(L_1+L_2) \\ &- e^{-i2\Delta\beta_0 L_1} S_1(L_2 - L_1)] \} \end{aligned} \tag{7b}$$

$$J_{y'x'} = (J_{x'y'})^* \tag{7d}$$

where $\Delta\beta_0 = \beta_y(\omega_0) - \beta_x(\omega_0)$ and S_0 and $S_1(z)$ are defined by

$$S_0 = 8\pi \int_0^\infty |\nu(\omega)|^2 \, d\omega \tag{8a}$$

$$S_1(z) = 8\pi \int_0^\infty |\nu(\omega)|^2 \cos [(\omega - \omega_0)\delta\tau_g z] \, d\omega. \tag{8b}$$

To derive (7) and (8), we have assumed the source spectrum is symmetrical with respect to ω_0. In (8b), z is a length variable and $\delta\tau_g$ is the polarization-mode dispersion or group delay difference

$$\delta\tau_g = \frac{d(\beta_y - \beta_x)}{d\omega}. \tag{10}$$

The degree of polarization is obtained from the coherency matrix as [12]

$$P = \left[1 - \frac{4 \det J}{(trJ)^2}\right]^{1/2} \tag{10}$$

which yields $P(\theta_p)$ as a function of the input polarization azimuth. The result is

$$\begin{aligned} P(\theta_p) = (&\cos^2 2\theta_p \, \gamma^2(L_2) \\ &+ \tfrac{1}{2} \sin^2 2\theta_p \{\gamma^2(L_1) + [\gamma^2(L_1) \\ &- \gamma(L_1 + L_2)\, \gamma(L_2 - L_1)] \cos 2\Delta\beta_0 L_1 \\ &+ \tfrac{1}{2} [\gamma^2(L_1 + L_2) + \gamma^2(L_2 - L_1)]\} \\ &- \sin 2\theta_p \cos 2\theta_p \, \gamma(L_2) \, [\gamma(L_1 + L_2) \\ &- \gamma(L_2 - L_1)] \cos \Delta\beta_0 L_1)^{1/2} \end{aligned} \tag{11}$$

where $\gamma(z) \equiv S_1(z)/S_0$ is the degree of coherence [12].

III. Discussion

Equation (11) gives the output degree of polarization for the Lyot depolarizer. It depends on the degree of coherence $\gamma(z)$

$$\gamma(z) = \frac{\int_0^\infty |\nu(\omega)|^2 \cos [(\omega - \omega_0)\delta\tau_g z] \, d\omega}{\int_0^\infty |\nu(\omega)|^2 \, d\omega} \tag{12}$$

which depends on the source parameters ω_0 and $|\nu(\omega)|^2$ and the fiber parameter $\delta\tau_g$. We note that $\gamma(z)$ is a real, even function of z. For band shapes with spectral width $2\delta\omega$, Sakai *et al.* [10] has calculated γ for the following spectral shapes

$$\text{Rectangular:} \quad \gamma = \frac{\sin \alpha}{\alpha} \tag{13a}$$

$$\text{Gaussian:} \quad \gamma = \exp\left[-\left(\frac{\alpha}{2\sqrt{\ln 2}}\right)^2\right] \tag{13b}$$

$$\text{Lorentzian:} \quad \gamma = \exp(-\alpha) \tag{13c}$$

where $\alpha \equiv \delta\omega\delta\tau_g z$. These functions are compared in Fig. 2. For the Gaussian and Lorentzian cases, γ is a monotonically decreasing function of α. Experimental results have been given for rectangular- [9] and Gaussian- [14] shaped sources.

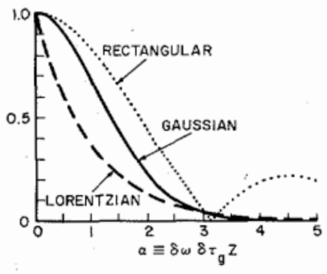

Fig. 2. Magnitude of the degree of coherence for sources with various band shapes. $\delta\omega$ is the spectral half-width at half-power, $\delta\tau_g$ the fiber group delay difference, and z the fiber length.

We first look at (11) for special cases of θ_p. For $\theta_p = 0$ the input is polarized parallel to the X-axis of the first section (L_1) and no depolarization occurs in this section. The input to the second section (L_2) is at 45° to its birefringent axes and we have $P(0) = |\gamma(L_2)|$. For $\theta_p = 45°$ depolarization will occur in the first section and the second section becomes unnecessary. We take $\theta_p = 45°$ and $L_2 = 0$ and obtain $P(45°) = |\gamma(L_1)|$. These results agree with the calculation for a single fiber length in the paper by Sakai *et al.* [10]. In general, we want $P(\theta_p) = 0$ for any θ_p. We assume $L_2 \geqslant L_1$ and a monotonically decreasing $\gamma(z)$. From inspection of (11), we require

$$\gamma(L_1) = 0 \tag{14a}$$

and

$$\gamma(L_2) = 0 \tag{14b}$$

which then implies $\gamma(L_1 + L_2) = 0$. We also require

$$\gamma(L_2 - L_1) = 0 \tag{14c}$$

which is satisfied if (14a) is satisfied and if $L_2 - L_1 \geqslant L_1$ or $L_2 \geqslant 2L_1$. The entire condition can then be stated as

$$\gamma(L_1) = 0 \tag{15a}$$

$$L_2 \geqslant 2L_1 \tag{15b}$$

to ensure $P(\theta_p) = 0$ for all θ_p with Lorentzian- or Gaussian-shaped sources. This yields a mathematical explanation for the original condition of $L_2 = 2L_1$ in a Lyot depolarizer. For a rectangular shaped source, which was assumed by Billings [2], the situation is more complicated because γ does not monotonically decrease with z. Following the argument above, we arrive at the condition

$$\gamma(L_1) = 0 \tag{16a}$$

$$L_2 = nL_1, \quad n \text{ integer} \neq 1 \tag{16b}$$

It is clear from Fig. 2 that precision in L_1 and L_2 is only required with a rectangular-shaped source.

The condition for low output degree of polarization is that the quantity $\delta\omega\delta\tau_g z$ be large ($\geqslant\pi$). We may express the group delay difference $\delta\tau_g$ in terms of the effective-index difference Δn_{eff} between the modes [9]. Since $\Delta\beta = \Delta n_{\text{eff}}\, \omega/c$, where c

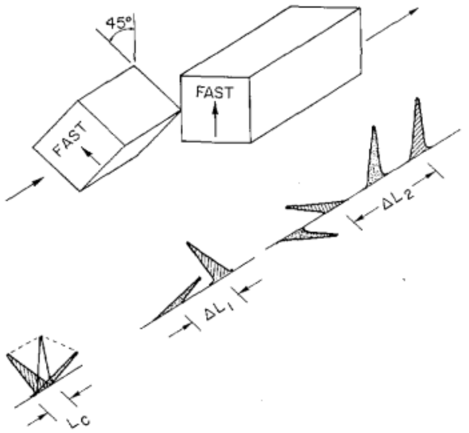

Fig. 3. Model for depolarization in a Lyot depolarizer of broad-band light with coherence length L_c. ΔL_1 and ΔL_2 are the group delay differences experienced in the first and second sections, respectively. For depolarization we require $L_c \ll \Delta L_1$ and $\Delta L_2 \sim 2\Delta L_1$. Depolarization is then independent of input azimuth.

is the light velocity, we have

$$\delta\tau_g = \frac{d\Delta\beta}{d\omega} = \frac{\Delta n_{\text{eff}}}{c} + \frac{\omega}{c}\,\frac{d(\Delta n_{\text{eff}})}{d\omega} \tag{17}$$

so that the dispersion of Δn_{eff}, when it is not negligible, contributes to depolarization as well as the index difference itself. This is the case, for example, in elliptically cored fibers.

Epworth [11] has given a useful physical picture of the mathematics presented here, following the original model of Rashleigh and Ulrich [9]. Broad-band light has a finite region of coherence [12]. Depolarization then occurs when a polarized input is evenly divided between two polarization modes, and the polarization-mode dispersion is sufficiently large that the resulting group delay is greater than the length of the coherent region. Using two fiber lengths with a relative axis rotation of 45° insures that this condition is met in one of the two sections for all linear inputs. An arbitrary input polarization state is then depolarized by superposition. The 1 : 2 length ratio of the sections avoids overlap of the coherent regions in the second section. We adapt this picture in Fig. 3, assuming a nonrectangular source.

Finally, we can compare our results here with the model used to analyze Lyot depolarizers by performing a spectral decomposition of output polarization states on the Poincare sphere [6]-[8]. The approach developed here points out the importance of spectral band shape and dispersion of Δn_{eff} to depolarization, factors which are not readily included in the Poincare sphere representation. The theoretical significance of a uniform distribution of output polarization states (spectrally decomposed) on the Poincare sphere, has not been rigorously defined. In constrast, depolarized light has been rigorously defined as light whose polarization state, viewed in a sequence of sufficiently short time intervals, does uniformly sample the surface of the Poincare sphere [15]; or as light whose Stokes parameters which describe polarization are zero [12], [15]. These criterion are directly related to the coherency matrix representation used above, and so must also be satisfied for any arrangement which gives zero degree of polarization as defined by (11).

Equations (11) and (15) predict that the degree of polarization with a given bandwidth source may be made as small as desired by using sufficient lengths of fiber with a large group delay difference. For a Gaussian source with half-width $\delta\lambda \simeq$ 7 nm and a fiber with $\delta\tau_g \simeq 1$ ns/km, a fiber length (L_1) of 0.5 m should be sufficient [14]. Of course the theory presented here will be limited by mode coupling between polarization modes, which was treated in the paper by Böhm *et al.* [4]. Experimentally, a value $P \sim 10^{-2}$ was achieved in a Lyot depolarizer [4], and a value $P \sim 10^{-3}$ in a single section of high-birefringence fiber [16].

IV. Conclusions

We have provided analytic output equations for the degree of polarization in Lyot depolarizers which can be applied directly to experimental arrangements. This derivation clearly points out the importance of source band shape and of group delay difference in the birefringent elements, and will allow quantitative device design. Our approach has been put in context with previous descriptions of the device. This analysis will be useful to device designers who will employ this important device in fiber gyroscopes.

Acknowledgment

The author appreciates helpful conversations with R. B. Smith on this subject.

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Low-Loss Coupling of Multiple Fiber Arrays to Single-Mode Waveguides

EDMOND J. MURPHY AND TRUDIE C. RICE

***Abstract*—A method for obtaining permanent low-loss coupling between arrays of single-mode fibers and Ti:$LiNbO_3$ waveguides is described. The technique, based on the use of silicon chip V-grooves, simplifies the coupling problem by simultaneously aligning the entire array and by providing a large surface area for a higher integrity adhesive bond. At $\lambda = 1.3$ μm, we measure an average 1.9-dB coupling loss (exclusive of propagation loss) for the assembled array. The average excess loss due to the fiber array is 0.8 dB.**

We present an analysis of the effect of various types of array misalignment on coupling efficiency. Angular alignment and array periodicity are found to be critical. If the fiber and waveguide periodicities are matched exactly, the fibers need only be placed within ±1.3 μm of their optimum position to maintain coupling efficiencies greater than 90 percent.

THE EFFICIENT COUPLING of light from a single-mode fiber into a single-mode waveguide (in glass or in an electrooptic material) is an important and formidable problem. Recent results [1], [2] demonstrate that through a careful choice of waveguide fabrication parameters, high efficiency can be attained. In this research, micropositioners were used to align one input and one output fiber to a single waveguide, in what amounts to a tedious and time-consuming manual operation. However, two important problems were not addressed. No attempt was made to simultaneously couple into more than one waveguide and no attempt was made to permanently attach the fibers. In this paper, we report our initial results on a multiple fiber coupling and calculate the influence of various misalignments on coupling efficiency.

There are several approaches to the solution of these problems that deserve consideration. Clearly, a technology which allows for a simple tongue-in-groove automatic alignment would be ideal. In principle, the tongue and groove could be formed by etching. Unfortunately, the submicrometer accuracy required here may preclude this possibility especially for chemically inert materials like lithium niobate. The other obvious and, in fact, more tractable approach involves the use of etched V-grooves in silicon. The etching of these grooves is well understood [3] and the grooves can be accurately placed by using standard photolithographic processes. Moreover, these chips are commonly used for other fiber alignment applications [4].

Several other authors have reported on permanent fiber-waveguide fixturing. The earliest work involved the "flip-chip" approach [5]. Ramer *et al.* reported on a 2 × 2 switch at $\lambda =$ 0.83 μm with attached fiber pigtails [6]. The excess loss due to fiber coupling was approximately 1.5 dB per fiber per interface. In the work by Kondo *et al.*, a pigtailed 1 × 4 switch array at $\lambda = 1.3$ μm is reported. In this case, a four-element Si chip array was used at the switch output with an excess loss of at least 1.0 dB per fiber.

The approach we utilize here is to fabricate arrays of fibers in Si chips and to align them to appropriately spaced waveguides in $LiNbO_3$. If the periodicities of the fibers and waveguides are equal, alignment of any two fibers will result in the alignment of all of the fibers. The Si chips used here are standard Western Electric twelve-groove chips used for multimode-fiber ribbon connectors [4]. The nominal groove spacing is 228.5 μm. We use a standard fiber for $\lambda = 1.3$ μm with a mode size (half width at $1/e$ amplitude) of 4.0 μm and a core eccentricity of 0.7 μm. The fiber array (see Fig. 1) is formed by stripping a small length of the fiber's plastic cladding and epoxying the fibers in a Si chip "sandwich." The chip is then cut and polished to an optically smooth finish.

For this experiment, waveguides were fabricated on a z-cut

Manuscript received April 18, 1983; revised June 16, 1983.
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0733-8724/83/0900-0479$01.00