The Use of the Principal States of Polarization to Describe Tunability in a Fiber Laser

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Abstract—A novel approach for the description of the tunability of a fiber laser using principal states of polarization is introduced. Upon comparing the theoretical predictions with experimental measurements, it has been found that for a 4-m fiber laser, the proposed description is valid for a wavelength range of 2 nm.

Index Terms—Erbium-doped optical fibers, optical fiber lasers, optical fiber polarization, polarization mode dispersion, principal states of polarization, tunable lasers.

I. INTRODUCTION

A N OPTICAL fiber, unlike other solid-state laser media, has complicated polarization characteristics, like random birefringence and polarization mode-coupling which are wavelength dependent [1]. These phenomena lead to polarization mode dispersion in fiber-optics communication systems, which may limit system performance [2]. In fiber lasers, they can influence the spectrum of the laser, as has been demonstrated by devices such as a tunable fiber laser with an intracavity polarizer [3] and a fiber laser with discrete lasing modes (a "comb-like" spectrum) [4]. The properties of these special fiber lasers can be described with the usual Jones calculus, as in [5]. This description is not convenient because in the Jones calculus, knowing the polarization matrix of the fiber in one wavelength does not help to predict its value in another wavelength, due to the complicated nature of the fiber birefringence and its wavelength dependence. In order to calculate the laser behavior in a given spectral range, the polarization characteristics of the fiber have to be measured in each wavelength of interest within that range.

In this article, we present, for the first time to our knowledge, the use of the principal states of polarization (PSP’s) to describe polarization-dependent phenomena in fiber lasers. These special polarization states are an important tool for the description and analysis of polarization mode dispersion in optical communication systems [6], [7]. The PSP’s make a useful basis as they do not change in wavelength to first-order [8], a property which makes it possible to approximate the behavior of the laser in a range of wavelengths, just from knowing the PSP at midrange. The device we describe here is a tunable fiber laser with a linear polarizer inside the cavity. The output wavelength of that laser can be changed by a rotation of the intracavity polarizer. In Section II, we describe how the round-trip transmission of the cavity can be calculated for different angles of the polarizer, using the PSP’s of the fiber. In Section III, we describe an experiment in which a tunable Er-doped fiber laser was built, and its PSP’s were measured, and in Section IV, we show that the laser tunability can be predicted from the measured PSP’s.

II. ANALYTICAL FORMULATION OF TUNING USING THE PRINCIPAL STATES OF POLARIZATION

For any optical system with polarization-independent loss, there exist two special pairs of orthogonal polarization states which are called the input and output principal states of polarization [8]. Light which enters the system aligned with an input PSP will emerge in its corresponding output PSP, independent of the wavelength to first order. Below we describe how the polarization-dependent transmission of a fiber laser with an intracavity polarizer can be calculated using the PSP’s. We show that the transmission can be found without knowing the polarization properties of the cavity in each optical frequency. Using this novel approach, the only information that is needed is the PSP’s at one frequency $\omega_0$, the phase difference between them, and its first derivative in that frequency, from which it is possible to calculate the transmission of the cavity in a range of frequencies around $\omega_0$.

A. Analytical Description

Fig. 1 represents the model of a fiber laser. A linearly polarized light with a polarization $\mathbf{e}_{\text{in}} = \hat{b}(\theta)$ as defined by the polarizer angle $\theta$, enters the fiber. The light propagates in the fiber, returns from the input coupler, and propagates back. The state of polarization changes due to the birefringence of the fiber, which is given by the Jones matrix $\mathbf{M}(\omega)$ for a round trip. The output polarization after a round trip in the fiber, $\mathbf{e}_{\text{out}}(\omega, \theta)$, is thus given by the following (we assume that the gain $G(\omega)$ is polarization independent, and there is no polarization dependent loss in the cavity excluding the polarizer):

$$\mathbf{e}_{\text{out}}(\omega, \theta) = \mathbf{M}(\omega) \cdot \hat{b}(\theta).$$

(1)
The polarization-dependent transmission of the cavity is given by the projection of \( \hat{\mathbf{c}}_{\text{out}}(\omega, \theta) \) on the intracavity polarizer:

\[
T(\omega, \theta) = \left| \mathbf{I} \right|^2 = \left| \mathbf{F}^\dagger(\theta) \cdot \hat{\mathbf{c}}_{\text{out}}(\omega, \theta) \right|^2 \tag{2}
\]

where \( \mathbf{I} \) stand for complex transpose conjugation. As can be seen, \( T \) is a function of both the optical frequency and the polarizer angle.

Let \( \hat{\mathbf{c}}_{\text{in}}^\pm \) represent the (orthogonal) input PSP’s of a round trip in the fiber at \( \omega = \omega_0 \). Following the notation of Poole et al. [9], any monochromatic light field \( V_{\text{in}} \) that enters the fiber, with an arbitrary state of polarization, \( \hat{\mathbf{c}}_{\text{in}} = \hat{\mathbf{p}}(\theta) \), can be written as a linear combination of the input PSP’s:

\[
V_{\text{in}} = V_\text{in} \hat{\mathbf{c}}_{\text{in}} = V_\text{in} [c_+ \hat{\mathbf{c}}_{\text{in}} + c_- \hat{\mathbf{c}}_{\text{in}}] \tag{3}
\]

where \( V_{\text{in}} \) is the complex amplitude of the light field and \( c_\pm \) are complex coefficients which are given by

\[
c_\pm = c_\pm^* \cdot \hat{\mathbf{c}}_{\text{in}}. \tag{4}
\]

The output field state of polarization, after a round trip in the fiber, is given by

\[
\hat{\mathbf{c}}_{\text{out}}(\omega_0) = \mathbf{M}(\omega_0) \cdot \hat{\mathbf{c}}_{\text{in}} = \left[ e^{i\phi_-(\omega_0)-\Delta\phi_0} \cdot [c_+ \hat{\mathbf{c}}(\omega_0)+ c_- \hat{\mathbf{c}}(\omega_0)] \right] \tag{5}
\]

where \( \hat{\mathbf{c}}_{\text{out}}(\omega_0) \) are the output PSP’s at \( \omega = \omega_0 \), \( \alpha \) is the loss per unit length (polarization-independent), \( L \) is the fiber length, \( \phi_-(\omega_0) \) is the optical phase gained by the “-” PSP, and \( \Delta\phi(\omega_0) \) is the phase difference between the PSP’s at the output. The formulation of the PSP’s [8] claims that to first-order in \( (\omega - \omega_0) \), \( \hat{\mathbf{c}}_{\text{out}}(\omega_0) \approx \hat{\mathbf{c}}_{\text{out}}(\omega_0) \), and

\[
\Delta\phi(\omega) \approx \Delta\phi(\omega_0) + \Delta\tau \cdot (\omega - \omega_0) \tag{6}
\]

where \( \Delta\tau \) is the group delay difference between the PSP’s (also called the polarization mode dispersion). Therefore, (5) can be extended to a wavelength region around \( \omega_0 \) to give

\[
\hat{\mathbf{c}}_{\text{out}}(\omega) = \mathbf{M}(\omega) \cdot \hat{\mathbf{c}}_{\text{in}} = e^{i\phi_-(\omega)-\Delta\phi_0} \cdot [c_+ \hat{\mathbf{c}}(\omega)+ c_- \hat{\mathbf{c}}(\omega)]
\]

\[
\tag{7}
\]

Thus, the only dependence on frequency, to first-order, of \( \hat{\mathbf{c}}_{\text{out}} \) is through the phase difference between the output PSP’s (obviously \( \phi_+ \) is also frequency dependent but it does not affect the state of polarization).

Using (7) and (4), we can write \( \hat{\mathbf{c}}_{\text{out}} \) as a function of the input and output PSP’s, the phase difference between them, and the angle of the polarizer. Substituting the result into (2) we get

\[
T(\omega, \theta) = \left| \mathbf{F}^\dagger(\theta) \cdot \hat{\mathbf{c}}_{\text{out}}(\omega_0, \theta) \right|^2
\]

\[
= \left| \mathbf{F}^\dagger(\theta) \cdot \left[ e^{i\phi_-(\omega_0)-\Delta\phi_0} \cdot [c_+ \hat{\mathbf{c}}(\omega_0)+ c_- \hat{\mathbf{c}}(\omega_0)] \right] \right|^2
\]

\[
= \left| e^{i\phi_-(\omega_0)} \cdot \left[ \hat{\mathbf{c}}(\omega_0) \otimes \mathbf{P}(\theta) \right] \cdot \mathbf{e}_{\omega_0}^0 \right|^2
\]

\[
= \left| \left[ \hat{\mathbf{c}}(\omega_0) \otimes \mathbf{P}(\theta) \right] \cdot \mathbf{e}_{\omega_0}^0 \right|^2 \tag{8}
\]

where \( \otimes \) stands for outer product and we marked the output PSP’s at the frequency \( \omega_0 \) by \( \mathbf{e}_{\omega_0}^0 \).

The last expression can be further simplified noting that \( \hat{\mathbf{p}}(\theta) \otimes \hat{\mathbf{p}}(\theta) \) is the Jones matrix \( \mathbf{P}(\theta) \) of a linear polarizer, rotated at an angle \( \theta \):

\[
T(\omega, \theta) = \left| e^{i\phi_-(\omega_0)} \cdot \mathbf{P}(\theta) \cdot \mathbf{e}_{\omega_0}^0 \right|^2.
\]

With this formulation, we will now prove that the maxima in the transmission spectrum depend on the polarizer angle, and hence the rotation of the polarizer induces tuning of the laser.

To find the extrema of \( T \), we require that its first derivative with respect to \( \omega \) is equal to 0 and get

\[
e^{-2i\Delta\phi(\omega_0)} = \frac{(\mathbf{e}_{\omega_0}^0 \cdot \mathbf{P}(\theta) \cdot \mathbf{e}_{\omega_0}^0)}{(\mathbf{e}_{\omega_0}^+ \cdot \mathbf{P}(\theta) \cdot \mathbf{e}_{\omega_0}^+)} \tag{10}
\]

In the special case of a cavity that contains just a simple retardation plate and a polarizer, the PSP’s coincide with the eigen vectors of the cavity (all coincide with the axes of the retardation plate). In that case, the input PSP’s \( \hat{\mathbf{c}}_{\text{in}}(\omega_0) \) are the same as the output PSP’s \( \hat{\mathbf{c}}_{\text{out}}(\omega_0) \), and the right side of (10) equals 1, independent of \( \theta \). As a result, rotation of the polarizer does not induce any tuning in that simple case. An example for that case is the laser described by Krasinski et al. [10], where indeed no tuning occurs. However, in the more general case of random birefringence, as is usually the case in optical fibers, the right side of (10) is a function of \( \theta \), so the frequency of maximum transmission is dependent on the polarizer angle. In that case, the peaks of the transmission change with the polarizer angle, and tuning of the laser’s output is achieved.

B. Description on the Poincare Sphere

To get a simple expression to the round-trip transmission of the cavity, it is useful to use the Poincare sphere representation of polarization [11]. When only first-order effects are considered, a slight change in the optical frequency cause the unit Stokes vector, \( \mathbf{S}_{\text{out}} \), that represents the output field state of polarization to rotate about a diameter defined by the unit Stokes vectors that represents the output PSP’s [7]. Mathematically, this rotation can be expressed as

\[
\frac{d}{d\omega} \mathbf{S}_{\text{out}} = \hat{\mathbf{S}} (\), \tag{11}
\]

where \( \hat{\mathbf{S}} \) is a vector in the direction of the output PSP and its magnitude represents the rotation rate of the output state.
rate of rotation is exactly equal to the rate of change of the 

\[ \frac{d\Delta \phi}{d\omega} = \Delta \tau_g \]  

(12)

In a small frequency band around \( \omega_0 \), the output state of 

polarization can be approximated by the Taylor expansion:

\[ \hat{S}_{\text{out}}(\omega_0 + \Delta \omega) \approx \hat{S}_{\text{out}}(\omega_0) + \frac{d \hat{S}_{\text{out}}}{d\omega} |_{\omega_0} \cdot \Delta \omega \]

\[ = \hat{S}_{\text{out}}(\omega_0) + [\hat{\Omega} \times \hat{S}_{\text{out}}(\omega_0)] \cdot \Delta \omega. \]  

(13)

As in (2), the transmission is given by the projection of 

the output polarization on the polarizer axis. In Poincare 

representation, it is given by

\[ T = \frac{1}{2} \cdot (1 + \hat{S}_{\text{out}} \cdot \hat{p}) \]  

(14)

where \( \hat{p} \) is a unit Stocks vector parallel to the polarizer axis.

Substituting (13) into the last expression gives

\[ T(\omega_0 + \Delta \omega, \theta) = T(\omega_0) + \frac{1}{2} \Delta \omega \cdot \hat{p}(\theta) \cdot [\hat{\Omega} \times \hat{S}_{\text{out}}(\omega_0)]. \]  

(15)

As in (9), this equation also represents the dependence of the 

transmission on \( \omega \) and \( \theta \). However, the Poincare sphere rep- 

resentation is more convenient in analyzing the experimental 

data. In summary, if \( \hat{\Omega} \) and \( \hat{S}_{\text{out}} \) are known in one frequency 

it is possible to express the cavity transmission in a frequency 

range around \( \omega_0 \) using (15). This approach was examined 

experimentally.

III. EXPERIMENT

The experiment contained two different parts. First, a tun-

able fiber laser was built, using an erbium-doped fiber as 

the gain medium and an intracavity polarizer for tuning. The 

spectrum of the laser was measured for different angles of 

the polarizer. In the second part, we measured the polarization 

properties of the fiber cavity (without the polarizer) in different 

wavelengths. From these measurements, we calculated both 

the Jones matrixes of the cavity and its PSP ’s for each wave-

length. The polarization-induced spectral loss for different 

angles of the polarizer was calculated in the direct way (using 

the Jones matrices) and also from the measured PSP ’s. The 

results were compared to the measured spectrum of the laser, 

to prove the proposed description of tunability.

A. A Tunable Er-Doped Fiber Laser 

with an Inter cavity Polarizer

The fiber laser is described in Fig. 2. We used a 4-m-long 

erbium-doped fiber as the gain medium. A 514-nm argon 

laser pumped a tunable Ti: Sapphire laser, which pumped the 

fiber through an input coupler. The Ti: Sapphire was tuned 

to give maximum overall efficiency, at 980 nm. Both the 

input and output mirrors were dichroic mirrors with high 

reflection at 1550-nm (\(~100\%\) and 60\%, respectively) and 

high transmission at 980 nm. The input mirror was butt-
coupled to the fiber end, whereas the output end of the fiber 

was imaged on the output mirror, allowing the introduction of 

a polarizer inside the cavity. The output end of the fiber was 

cleaved in an angle of about 7°, to reduce reflections into the 

cavity, which otherwise made an inner cavity and effected the 

output of the fiber laser.
The output spectrum of the laser was measured with an optical spectrum analyzer, for different angles of the polarizer. The measured spectra for some angles of the polarizer are plotted in Fig. 3. Two important facts may be noted.

1) Tuning occurs in the range of 7 nm, and it has the expected $90^\circ$ cycle [3] as a function of the polarizer angle.

2) Turning the polarizer affects not only the lasing wavelength but also the spectrum of the amplified spontaneous emission. As was shown above, the polarizer angle changes the transmission spectrum of the cavity, and as a result, the spectrum of the amplified spontaneous emission changes. Since the spontaneous emission spectrum of the fiber without a polarizer is smooth, its angle-dependent variations give good qualitative information about the polarization transmission of the cavity. In that way, it is possible to measure the polarization transmission not only for the lasing wavelengths but also for a wider wavelength range. The spectrum is slightly modulated because of reflection from both surfaces of the polarizer, which acted as a Fabry–Perot filter inside the cavity.

### B. Measurement of the Polarization Properties of the Fiber

In this measurement, we characterized the polarization properties of the fiber in the wavelength range 1545–1565 nm using a tunable laser. Light in different states of polarization and of different wavelengths was launched into the cavity, and the output polarization state, after a round trip, was measured. Using these results, it is possible to calculate the Jones matrixes of the cavity [12] and the PSP’s [9], [7]. Since the lasing medium is a three-level system, we had to pump the fiber in order to have a useful S/N. We used subthreshold pump power which was kept constant during the measurements.

The setup for the measurement of the polarization properties of the fiber cavity is described in Fig. 4. Since the Jones matrix of the fiber is wavelength dependent, we used a tunable laser as our source. The tunable laser was collimated and passed through a polarizer and a $\lambda/2$ or $\lambda/4$ waveplates, to change the state of polarization at the fiber’s input. The light was then passed through a beamsplitter and focused into the fiber. The output light from the fiber passed through the second path of the beamsplitter and entered a polarization analyzer, after which it was measured with an optical spectrum analyzer. Thanks to the use of the optical spectrum analyzer, it was possible to distinguish the output probe beam from the spontaneous emission with a high S/N even when its transmission through the polarization analyzer was very low. In these cases, the measurement accuracy is limited by reflections from the surfaces of the optical system, since these reflections are in different polarization than the light that passed through the fiber. The reflections were minimized by angle cleaving the fiber, as discussed above, and by using optics with a suitable antireflection coating wherever possible. We measured the fiber in the range 1545–1565 nm, with 0.5-nm intervals. During the measurements, the temperature in the laboratory was stable and the fiber was lying on an optical table. As long as the fiber was not disturbed, the results did not change significantly.

During the measurements, we found that the beamsplitter we used affects the polarization of the light. The polarization state of the light that is reflected by the beamsplitter is changed. As a result, the input polarization to the fiber is changed, and it affects the calculation of the polarization matrix. To solve the problem, we measured the polarization properties of the beamsplitter in the same way as we measured the fiber—replacing the fiber with a mirror. We used the results as a reference matrix and divided the measured Jones matrixes of the fiber with that reference to get the “pure” matrixes of the fiber. This normalization is possible since the polarization of the light that passes through the beamsplitter (after a round trip in the fiber) does not change. It is interesting to note that for the calculation of the PSP’s from the measurement (see Section III-C) this normalization is not needed since the results do not depend on the input polarization state. The only requirement is that the input polarization remains constant over the tuning range.

### C. Calculation of the Principal States from the Measured Data

To find the PSP’s from the measured data, we used a method which is similar to that described by Poole et al. in [9]. To improve accuracy, we used data from five input polarizations at a wavelength range of 2 nm and made a least squares estimation to find the output PSP’s in that range. The calculation was repeated in 2-nm steps to cover the whole measurement range. We actually found the common axis of a family of circles on the Poincare sphere which pass as close as possible to the measured output states. That method uses the fact that was discussed in Section II, that the output
polarizations in a limited wavelength range lie approximately on a circle on the Poincaré sphere, and the output PSP’s lie on diameter which passes through its center. To minimize the error, for every wavelength range we used only those polarization states which are not too close to the PSP. That requirement is the same as described in [9], namely

\[
|\hat{\Omega}_{\text{in}} \times \hat{\Omega}_{\text{f}}| > \sqrt{2}
\] (16)

where \(\hat{\Omega}_{\text{in}}\) is the calculated output PSP and \(\hat{\Omega}_{\text{f}}\) is a unit vector on one of the best-fit arcs. This process was repeated iteratively to select the set of polarizations for which the estimation error was minimized. For each wavelength range, at least three input polarizations could be used.

Fig. 5 illustrates the derivation of the output PSP’s in a 2-nm band. The symbols (×, ○, ©, and ●) mark the measured output polarizations and the solid arcs are parts of the best-fit circles. The output PSP’s (which are on the ends of the diameter that passes through the centers of the circles) are marked with dots. It can be seen that the output states for each input polarization do lie on a circle, that the centers of all those circles lie on the same diameter, and that its ends are the output PSP’s in that wavelength range.

The PSP’s estimation process enabled us to find also the rate of rotation of the output polarization, thus both the magnitude and the direction of \(\Omega\) were determined.

D. Measured Eigen Polarizations and Principal States

A state of polarization that repeats itself after a round trip in the cavity is called an eigen polarization of the cavity. The eigen polarizations of a cavity that has no polarization-dependent loss or gain are linear and lie on the equator in Poincaré representation [5]. The measured cavity eigen polarizations in the different wavelengths are shown in Fig. 6 on the Poincaré sphere. As expected, they lie close to the equator.

Fig. 7(a) shows the angle of the eigen polarization (the angle between the long axis of the polarization ellipse and the positive x direction) in the measured wavelength range. Fig. 7(b) shows the phase difference between the two eigen polarizations. A period of about 15 nm exists in the measured eigen polarizations. That period is also present in some of the measured emission spectra of the laser.
The PSP’s are shown in Fig. 8 on the Poincare sphere. Their three Stocks parameters $s_1, s_2, s_3$ [11] (components of $\Omega / |\Omega|$) are given in Fig. 9(a) as a function of the wavelength. The magnitude of $\Omega$ was found for all the different input polarizations in 2-nm intervals and is given in Fig. 9(b). Each point in the graph is an average of the values that were calculated for the different input polarizations. These values were found to be very close to each other, as expected. As can be seen, the PSP’s of the measured fiber depend on wavelengths in the 20-nm range. To estimate the range of wavelength for which the approximation of wavelength-independent PSP’s is valid, we can use Fig. 5. Since the best-fit arcs are close to the measured output states in the whole 2-nm range, we can use the PSP’s as constant on that range. The measured magnitude of $\Omega$ is almost constant over the 20-nm range. It is about 1.4 ps, which gives $\Delta B \cdot \Delta \tau = 0.07$, in agreement with [13] ($\Delta B$ is the frequency band in which the PSP’s are approximately constant).

IV. TRANSMISSION PREDICTION USING THE PRINCIPAL STATES

We used (15) iteratively to calculate the round-trip transmission of the cavity for different angles of the polarizer. The iteration step $|\Delta \omega|$ was 0.5 nm, and $\Omega$ was changed every 2 nm, according to the values in Fig. 9. The required output state of polarization in an initial frequency, $\delta_{\text{out}}(\omega_0)$, was found using the measured Jones matrix in $\lambda_0 = 1545$ nm.

The results are shown in Fig. 10(b) as a map of the transmission versus both the wavelength and the angle of the polarizer. These results are in good agreement with the measured amplified spontaneous emission spectra, which are shown in a similar representation in Fig. 10(a). The transmission spectrum was calculated also using the measured Jones matrixes and similar results were obtained.
V. CONCLUSION

A novel approach for calculating the polarization-dependent transmission of fiber laser cavities using PSP’s was described. We used that model for analyzing a tunable fiber laser with intracavity polarizer. In this model, the transmission spectrum of the cavity can be calculated in some wavelength range where the only parameters needed to describe the fiber’s birefringence are its PSP’s in one wavelength and the phase difference between them. The model was proved experimentally for an Er-doped fiber laser, where good agreement was achieved between the measured and calculated spectra for different angles of the polarizer. Since, experimentally, the method is based on a measured fixed pair of PSP’s, its applicability is obviously limited to those systems where the birefringence does not change significantly in time. This approach can be used for the analysis of other wavelength-dependent polarization phenomena in fiber lasers and as a tool in the design of devices based on these phenomena.

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REFERENCES


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Before receiving the Ph.D. degree, he spent five years in the Israeli Defense Forces. During the academic years 1981–1983, he was a Post-Doctoral Fellow (1981–1982) and then a Research Associate (1982–1983) at the Information System Laboratory and the Edward L. Ginzton Laboratory of Stanford University, Stanford, CA. At the Information System Laboratory, he studied speckle phenomena, various theories of wave propagation in random media, and asymptotic solutions of the fourth moment equation. At the Ginzton Laboratory, he participated in the development of new architectures for single-mode fiber-optic signal processing and investigated the effect of laser phase noise on such processors. He is presently a Professor of Electrical Engineering in the Faculty of Engineering at Tel-Aviv University, where he established a fiber-optic sensing laboratory. He has authored or co-authored more than 100 journal and conference technical papers with recent emphasis on fiber-optic bit-rate limiters, fiber lasers, fiber-optic sensor arrays, the statistics of phase-induced intensity noise in fiber-optic systems, and fiber sensing in smart structures.

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