Birefringence Mapping in an Optical Fibre by Using a Polarization-OTDR

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We propose a new analysis method of the Rayleigh backscattered field for the measurement of the birefringence spatial distribution in a single-mode optical fiber. The technique is based on a Polarization-OTDR set-up using a rotary linear polariser. We demonstrate that the birefringence distribution may be deduced from the measurement of the round-trip Mueller matrices derived from three POTDR traces corresponding to three different angles (0, π/4, π/8 rad) of the polarizer.

Introduction

Polarization Mode Dispersion (PMD) [1] has become the most serious limiting factor in high speed optical communication systems since the effect of the chromatic dispersion has been minimized by using appropriate types of fibers such as dispersion shifted and dispersion compensating fibers. The PMD takes his origin in the presence of asymmetries in the fiber such as an elliptical core or mechanical stress. When its cylindrical symmetry is broken, the fiber exhibits a small difference in refractive index for a particular pair of orthogonal polarization states (the principal states) which results in a difference in their propagation velocities. This phenomena is called birefringence and it results a differential group delay (DGD, $\Delta\tau$) between the two principal states. The PMD is then given by $\Delta\tau/\sqrt{L}$ where L is the fiber length. The PMD of a fiber depends on two parameters: the mean beat length (L_B), related to the birefringence and the mean coupling length (L_C) which gives the distance after which the principal states have moved significantly [2]. Measuring the distributed PMD therefore consists to measure the spatial distribution of L_B and L_C. In this paper, we describe a new analysis of the Rayleigh backscattered field for the distributed measurement of the birefringence in optical fibers. The measurement technique we have developed is based on a Polarization Optical Time Domain Reflectometer (POTDR) using a rotary linear polariser [4,5].

Theory

In general, an optical fiber exhibits axially-varying birefringence and can be represented by a series of homogeneous elements as illustrated in Fig. 1(a). Each element can be described by a Jones matrix which relates the input and the output states of polarization. The Jones matrix of the ith homogeneous trunk may be written as [3]

$$J_i = \begin{pmatrix} \cos\frac{\beta_i l_{el}}{2} + j\sin\frac{\beta_i l_{el}}{2}\cos 2q_i & j\sin\frac{\beta_i l_{el}}{2}\sin 2q_i \\ j\sin\frac{\beta_i l_{el}}{2}\sin 2q_i & \cos\frac{\beta_i l_{el}}{2} - j\sin\frac{\beta_i l_{el}}{2}\cos 2q_i \end{pmatrix} \tag{1}$$

where l_{el} is the element length, β_i is the birefringence, i.e. the phase delay expressed in rad/m between the two local polarization mode. q_i is the angle of the birefringence , i.e. the angle between the fast mode and an arbitrary Ox axes. Let us consider a double passage, forward and then backward, of the light into the fiber. The resultant birefringence for light propagating forward to the end of the i^{th} element and then backward to the launch end is given by the products of the relevant matrices (2) [3].

$$J_{Bi} = (J_i J_{i-1} \ldots\ldots J_2 J_1)^T (J_i J_{i-1} \ldots\ldots J_2 J_1) \qquad (2) \qquad\qquad \mathbf{V_{b1}} = L_e C_e^{-1} C_e L_e \mathbf{V_{in}} = L_e^2 \mathbf{V_{in}} \qquad (3)$$

J_i^T is the transpose of J_i. Let us now consider that we want to measure the birefringence β_i of the i^{th} element. All the concatenated preceding sections from 1 to i-1 can be modeled as a concatenation of a pure linear retarder described by a Jones matrix L_e and a pure rotator described a Jones matrix C_e as illustrated in Fig. 1(b). The Jones vector $\mathbf{V_{b1}}$, resulting from the light propagating forward to z_1 and then backward to the launch end can be written as in (3) because the sign of the rotation angle of the rotator is reverse for the back direction. $\mathbf{V_{in}}$ is the input Jones vector. The different round-trip Jones matrices described in (2) are therefore equivalent to a linear retarder and may be written by the following general form :

$$J_{B_i} = \begin{pmatrix} A_i + jB_i & jC_i \\ jC_i & A_i - jB_i \end{pmatrix} \quad (4) \qquad \text{with} \qquad A_i^2 + B_i^2 + C_i^2 = 1 \qquad (5)$$

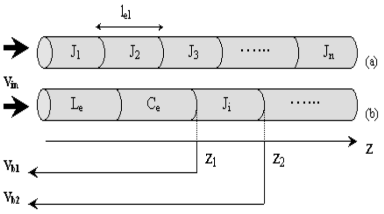

Fig.1 : Fibre modeling

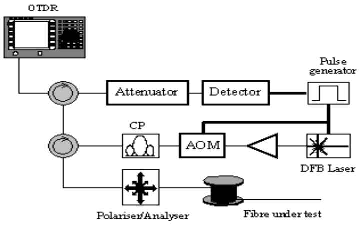

Fig.2 : Experimental set-up

If $\mathbf{V_{b1}}$ the Jones vector of the light backscattered at z_1 is measured, we can determine L_e from (3). The backscattered polarization state $\mathbf{V_{b2}}$, resulting from the light propagating forward to z_2 and then backward to the launch end is related to $\mathbf{V_{in}}$ by (6).

$$\mathbf{V_{b2}} = L_e C_e^{-1} J_i^2 C_e L_e \mathbf{V_{in}} \qquad (6) \qquad\qquad C_e^{-1} J_i^2 C_e = \begin{pmatrix} A + jB & jC \\ jC & A - jB \end{pmatrix} \qquad (7)$$

Hence the knowledge of $\mathbf{V_{b2}}$, $\mathbf{V_{in}}$ and L_e enables to calculate $C_e^{-1} J_i^2 C_e$. This matrix may be written in the Jones formalism by (7) [3], where $A=\cos(\beta_i l_{el})$. Hence, it appears that β_i can be determined after measuring $\mathbf{V_{b1}}$ and $\mathbf{V_{b2}}$ if we assume that $\beta_i l_{el}$ is comprised between 0 and $\pi/2$. This last condition supposes that the local beat length is bigger than 4m for a measurement resolution length of 1m which is usually the case for a telecommunication fiber. Measuring the distributed birefringence therefore consists to determine the A_i, B_i and C_i parameters related to the different round-trip Jones matrices described in (4).

Principle of measurement

Because it is not convenient to measure a Jones vector, the use of the Stokes formalism, which describes a state of polarization in terms of measured optical powers, is more suitable. It is why we will use this formalism for the following of this paper. A polarization state is then described by a four dimensional vector and the polarization properties of an optical device is described by a four-by-four Mueller matrix. The corresponding Mueller matrix of (4) may be written by (8).

$$M_{B_i} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & A_i^2+B_i^2-C_i^2 & 2B_iC_i & -2A_iC_i \\ 0 & 2B_iC_i & A_i^2+C_i^2-B_i^2 & 2A_iB_i \\ 0 & 2A_iC_i & -2A_iB_i & A_i^2-B_i^2-C_i^2 \end{pmatrix} \qquad (8) \qquad \mathbf{s}_{\mathbf{B_i}} = M_{B_i}\begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ A_i^2+B_i^2-C_i^2 \\ 2B_iC_i \\ 2A_iC_i \end{pmatrix} \qquad (9)$$

If we want to measure $\mathbf{V_{b1}}$ and $\mathbf{V_{b2}}$ for each element, we need to measure the complete polarization state evolution of the backscattered light. This is quite difficult to implement. An new analysis method [4] has therefore been developed and involves the use of a rotary polariser in a POTDR set-up as illustrated in the experimental set-up shown in fig. 2. The polariser is placed at the fiber input so that it is also used as the backscattered signal analyser. Let us consider the polariser/analyser imposing a 0° linear input state of polarization. The corresponding normalized Stokes vector at the fiber input is given by (1,1,0,0) and the resulting backscattered vector $\mathbf{s_{Bi}}$ is given by (9). The Stokes vector resulting from the passage of $\mathbf{s_{B1}}$ through the analyser $\mathbf{s_{P0}}$ is given by (10).

$$\mathbf{s_{P0}} = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \mathbf{s_{B1}} = \frac{1}{2}\begin{pmatrix} 1+A^2+B^2-C^2 \\ 1+A^2+B^2-C^2 \\ 0 \\ 0 \end{pmatrix} \qquad (10) \qquad P_0 = A_i^2 + B_i^2 \qquad (11)$$

The matrix multiplying $\mathbf{s_{Bi}}$ is the Mueller matrix of a 0 rad linear polarizer. Introducing (5), the resulting optical power (P_0) detected after the analyser is given by equation (11). In the same way, when the polariser/analyser imposes input linear states of $\pi/4$ and $\pi/8$ rad, the detected powers are respectively :

$$P_{45} = A_i^2 + C_i^2 \qquad (12) \qquad P_{22.5} = B_iC_i + (1 + A_i^2)/2 \qquad (13)$$

Introducing (5) in these three relationships, it appears that the measurement of the backscattered field evolution for three different positions of the polariser/analyser enables to determine the A_i^2, B_i^2, C_i^2 and B_iC_i values related to the different round-trip matrices described in (2). The sign ambiguities on A_i, B_i and C_i lead to two different possible solutions for each β_i. The value of β_i can then be determined by supposing that two successive β_i are close to each other. The experimental set-up is shown in Fig. 2. Since the coherence of an OTDR source is weak, the OTDR pulses are used to modulate a 1550 nm DFB laser via a pulse generator. The pulses are then launched into the fiber after amplification by an EDFA. An acousto-optic modulator (AOM) is used to suppress the ASE noise between two successive pulses. The rotary linear polariser is placed at the fiber input and a polarization controller (CP) is used to obtain the maximum power after the polariser. Light pulses are continuously Rayleigh-backscattered as the pulse propagates down the fiber and the emerging backscattered light is directed by the two circulators onto the OTDR detector. The three POTDR traces corresponding to 0, π/4 and π/8 rad are then recorded and analyzed by a computer which calculates the distributed birefringence. An example of result is show in Fig. 3 where the fiber under test was a conventional step-index fiber. The OTDR pulses were set to 10 ns in order to obtain a resolution length of 1m. The corresponding mean beat length value was found to be 29.6m which is a typical value for this fiber type.

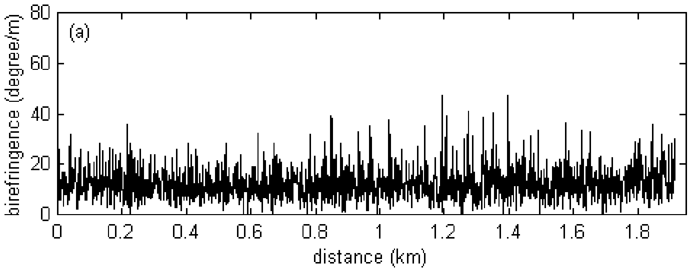

Fig. 3 : Example of results

Conclusion

In summary, we described a new analysis of the Rayleigh backscattered field for the measurement of the birefringence spatial distribution in a single-mode optical fiber. This analysis involves the use of a rotary linear polariser at the fiber input. We showed that the measurement of three POTDR traces, corresponding to three different angles of the polariser (0, π/4, π/8 rad), enables to determine the distributed birefringence of an optical fiber.

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