Quantum Electronics **49** (5) 514–517 (2019)

FIBRE OPTICS

https://doi.org/10.1070/QEL16832

Modelling of polarised optical frequency domain reflectometry of axially twisted anisotropic optical fibres

F.L. Barkov, Yu.A. Konstantinov, S. D. Bochkova, A.S. Smirnov, V.V. Burdin, A.I. Krivosheev, E.A. Nosova, O.Yu. Smetannikov

Abstract. **This paper presents a mathematical model that describes the influence of defects in an anisotropic optical fibre on its polarised frequency domain reflectograms. The model relies on the Jones matrix formalism. Calculated reflectograms are presented for a uniform axial twist of an optical fibre. As input data for simulation, we use real distributed optical parameters of the fibre determined by polarised light Brillouin reflectometry.**

Keywords: *polarised reflectometry, frequency domain, anisotropic optical fibre, axial twist of optical fibre.*

1. Introduction

Distributed fibre-optic sensors of physical parameters became an important, dynamically developing area of photonics long ago [1–3]. Initially, isotropic optical fibres, such as are employed in telecommunication systems, were used as sensors, but in recent years there were also reports on sensors based on anisotropic fibres [4, 5]. There is currently increasing practical interest in issues pertaining to both distributed control over anisotropy parameters of PM fibre sensors with the aim of improving their performance and directly to sensing technologies based on such fibres, namely, to obtaining a spatial representation of mode coupling. The polarisation holding parameter (h-parameter) and polarisation mode dispersion can be measured by various methods, including time domain reflectometry [6]. In practice, however, such methods are only applicable if there are sufficiently large anisotropy defects that cannot be detected, in particular if they are located in the region of so-called dead zones. In such a case, it is of interest to use frequency domain reflectometry [7–9], in particular, polarised one, because this method has essentially no dead zones and is polarisation-sensitive. The simplest schematic of an optical frequency domain (OFD) reflectometer is presented in Fig. 1.

It is of particular interest to study the behaviour of the output signal of an OFD reflectometer in the case of an axial twist of optical fibre, a rather widespread defect. It can be formed in the process of placing an anisotropic fibre sensor into an object to be studied and have an even more significant effect on the output signal of the device after the polymerisation of the potting material.

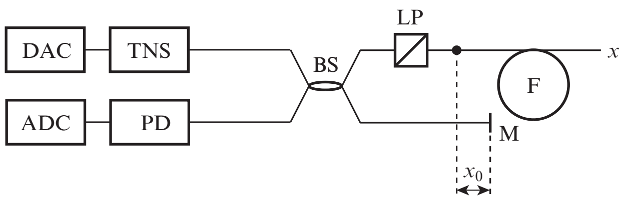

Figure 1. Simplified schematic of an OFD reflectometer with one photodetector:
(DAC) digital-to-analogue converter; (ADC) analogue-to-digital converter; (TNS) tunable narrow-band source; (PD) photodetector; (BS) beam splitter; (M) mirror; (LP) linear polariser; (F) test fibre.

Previously reported models for polarised frequency domain reflectometers are incapable of describing the range of desirable parameters in full detail. For example, Wegmuller et al. [10] studied the effect of various factors (including axial twist) on modal birefringence in an isotropic optical fibre. The efficiency of optical power transfer from a mode whose polarisation is directed along one axis of an anisotropic fibre to a mode with an orthogonal polarisation is difficult to calculate using the mathematical approach indicated. An approach based on Mueller matrices and proposed by Palmieri et al. [5] is better suited for solving the problem, but its real-time software implementation is rather complicated, and output data require further transformation to construct a classic OFD reflectogram. In this paper, we present a model for frequency-domain reflectometry whose output data clearly represent the effect of axial twist on reflectograms of anisotropic optical fibres. The model utilises a simple and intuitively clear algorithm which is easy to implement in real time using a standard performance computing system.

2. Modelling results and discussion

Processes that take place in OFD reflectometers have been described in the literature in different ways [11, 12]. This is

F.L. Barkov, Yu.A. Konstantinov Perm Federal Research Center, Ural Branch, Russian Academy of Sciences, ul. Lenina 13a, 614000 Perm, Russia; e-mail: fedor@bacup.ru;
S. D. Bochkova, A.S. Smirnov, V.V. Burdin Perm Federal Research Center, Ural Branch, Russian Academy of Sciences, ul. Lenina 13a, 614000 Perm, Russia; Perm National Research Polytechnic University, Komsomol'skii prosp. 29, 614990 Perm, Russia;
A.I. Krivosheev, E.A. Nosova Perm Federal Research Center, Ural Branch, Russian Academy of Sciences, ul. Lenina 13a, 614000 Perm, Russia; Perm National Research Polytechnic University, Komsomol'skii prosp. 29, 614990 Perm, Russia; JSC Perm Scientific Industrial Instrument Making Company, ul. 25 Oktyabrya 106, 614990 Perm, Russia;
O.Yu. Smetannikov Perm National Research Polytechnic University, Komsomol'skii prosp. 29, 614990 Perm, Russia

Received 5 October 2018; revision received 22 November 2018
Kvantovaya Elektronika **49** (5) 514–517 (2019)
Translated by O.M. Tsarev

due in part to the fact that different researchers pay attention to different aspects of such models. Nevertheless, based on the above-mentioned interpretations, we can construct a simple algorithm describing the backscattered power of an optical signal entering a photodetector:

$$E(\gamma t) = 2AK\cos(2\gamma t\,|x - x_r|), \tag{1}$$

where γ is the laser frequency at time t; x_r is the coordinate of the mirror (M) in the reference arm of the OFD reflectometer; x is the spatial coordinate along the fibre length at time t; the parameter A determines the level of the signal at point x (and depends, among other factors, on the refractive index of the mirror at point x_r, that of the fibre at point x and the scattering loss during time t); and the coefficient K characterises the polarisation state of the light. Systems that detect components for two mutually perpendicular polarisation states of input light (hereafter denoted by the subscripts x and y) have a slightly different configuration (Fig. 2) [12]. Relations for such systems have the form

$$E_x(\gamma t) = 2A_xK_x\cos(2\gamma t\,|x - x_r|), \tag{2}$$

$$E_y(\gamma t) = 2A_yK_y\cos(2\gamma t\,|x - x_r|), \tag{3}$$

where $E_x(\gamma t)$ and $E_y(\gamma t)$ are the interference signals obtained in photodetectors placed after the polarising beam splitter (PBS), which describe the variation in the electric field amplitude of the backscattered signal for the polarisation axes x and y, and the coefficients K_x and K_y are determined by polarisation nonuniformities in the test fibre and the polarisation state in the reference arm. Assume that such nonuniformities can be estimated using the Jones matrix formalism [13]. To this end, we represent an anisotropic optical fibre as a sequence of semitransparent phase plates inclined to each other, each having its own anisotropy.

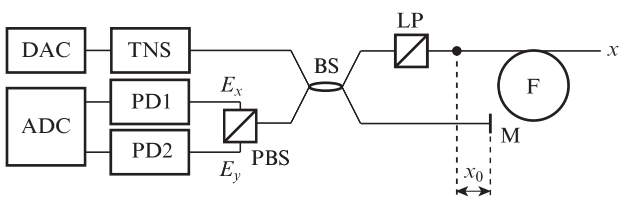

Figure 2. Simplified schematic of an OFD reflectometer with two photodetectors:
(PD1, PD2) photodetectors; (PBS) polarising beam splitter. The other designations are the same as in Fig. 1.

The Jones matrix of a phase plate of length L, having refractive indices n_1 and n_2 (in the mth segment of the fibre), in a coordinate system with axes parallel to those of the plate has the form

$$M_m = \begin{bmatrix} 1 & 0 \\ 0 & \exp(-i\Delta\varphi) \end{bmatrix},$$

where $\Delta\varphi = 2\pi L(n_2 - n_1)/\lambda$ is the phase delay of the slow component of the wave, due to the refractive index difference.

Since the fibre segment under consideration is twisted a certain angle θ_m (proportional to the distance from the fibre end to the mth segment, $\theta_m = \alpha L_m$, where α (rad km^{-1}) is the twist rate and L_m is the spatial coordinate of the mth segment), in a normal coordinate system the Jones matrix transforms in the corresponding way:

$$T_m = T_{\mathrm{rot}}(\theta_m)M_mT_{\mathrm{rot}}(-\theta_m), \tag{4}$$

where $T_{\mathrm{rot}}(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$ is the rotation matrix.

It should also be taken into account that, for a backward propagating wave, the fibre is twisted in the opposite direction, so the Jones matrix of the same fibre segment has a somewhat different form:

$$T_m^* = T_{\mathrm{rot}}(-\theta_m)M_mT_{\mathrm{rot}}(\theta_m). \tag{5}$$

As shown by Konstantinov and Kryukov [14], the backscattered power in such a coordinate system at time t_n can be represented as

$$E_{n-1} = F_0 b_{n-1}\prod_{i=1}^{n} f_i^2, \tag{6}$$

where E_{n-1} is the power backscattered in the $(n-1)$th fibre segment; F_0 is the input power; and the coefficients b and f determine reflection and attenuation parameters of this segment. Assume that a similar approach for treating a transient process can be applied to polarised reflectograms. The relation for backscattered linearly polarised light (in the case of zero input angle) then has the form

$$\begin{bmatrix} E_{x(0)}(z) \\ E_{y(0)}(z) \end{bmatrix} = \begin{bmatrix} \varepsilon_{\mathrm{pol}} & 0 \\ 0 & 0 \end{bmatrix}\prod_{m=1}^{z} T_m^* \prod_{m=z}^{1} T_m \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{7}$$

where $\varepsilon_{\mathrm{pol}}$ is the polarisation extinction ratio of the LP. It is reasonable to use the $E_{x(0)}(z)$ and $E_{y(0)}(z)$ thus obtained for calculating the backscattered signal in the case of frequency domain measurements. Relations (2) and (3) then take the form

$$E_x(t) = 2A_xkE_{x(0)}\cos(2\gamma t\,|x - x_r|), \tag{8}$$

$$E_y(t) = 2A_ykE_{y(0)}\cos(2\gamma t\,|x - x_r|), \tag{9}$$

where k is an empirical coefficient determined by the power of the signal launched into the test fibre. Clearly, analysis of the relation for $E_y(t)$ is of most interest to manufacturers of PM fibres and related sensors from the viewpoint of h-parameter measurement, because this relation includes $E_y(0)$. Usually, the following vector sum is calculated in an OFD reflectometer [11]:

$$r(t) = \sqrt{|E_x(t)|^2 + |E_y(t)|^2}. \tag{10}$$

As input data for simulation, we used real optical characteristics obtained for optical fibres by polarised light Brillouin reflectometry [15]. As in previous work [15], the Brillouin frequency shifts measured for x- and y-polarisations were used to calculate distributed refractive indices in a sensing Panda-type anisotropic optical fibre, which was used as a physical parameter sensor embedded in a structure from a composite material. The parameters of the optical fibre were as follows:

optical signal attenuation coefficient at the input wavelength (1550 nm), 1 dB km^{-1}; modal birefringence, 7×10^{-4}.

Figure 3 presents Fourier transforms of two signals corresponding to two polarisation states and the resultant reflectogram. The functions are slightly offset along the vertical axis for clarity (in real OFD reflectometers, the two signals are maintained at roughly equal levels by optical means).

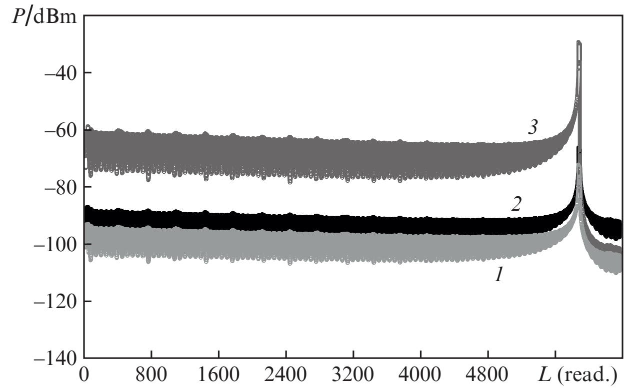

Figure 3. Calculated OFD reflectograms: (*1*) $E_x(t)$, (*2*) $E_y(t)$, (*3*) $r(t)$.

The three reflectograms are clearly seen to have some periodicity. This is understandable since the refractive index data set obtained for the two propagation axes of the Panda-type optical fibre using a real sample was modulated because the fibre was wound onto a spool and then embedded in a structure from a composite material. During sensor fibre winding, axial twist was strictly controlled. Thus, it is reasonable to assume that the fibre whose reflectogram is presented in Fig. 3 is free of axial twist. The fibre does not have any visible distortions, except for local changes in its refractive index. In a number of cases, however, there are fibre twists of the order of 1 rad km^{-1}, which lead to serious distortion of its polarisation properties. As an illustration, we introduce such twist in the Jones matrix multiplication step in the proposed model. Figure 4 shows two resultant reflectograms (vector sums) for two cases: twist angles of 0 and 1 rad km^{-1}.

Clearly, as a result of such signal processing, the reflectogram of an axially twisted fibre becomes distorted, because the error introduced into the measurements considerably exceeds the stated accuracy of such devices.

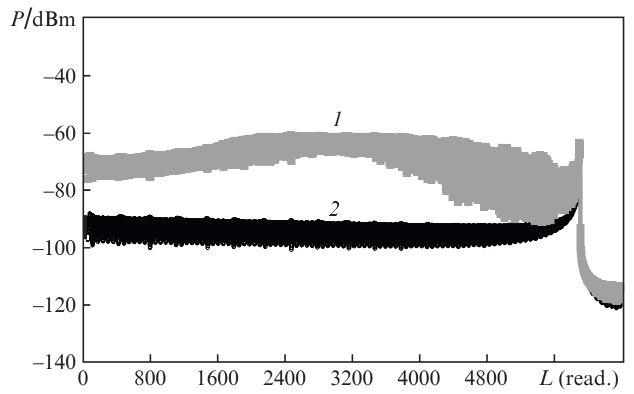

Figure 4. Calculated OFD reflectograms of an optical fibre (*1*) with and (*2*) without axial twist.

The present data can be considered in two aspects. First, they can shed light on the applicability of frequency domain reflectometry for assessing the quality of sensor fibre winding onto a spool or devices in a sensor. The model suggests that twisting a 500-m length of fibre at a constant rate of 1 rad km^{-1} shows up rather well in the corresponding reflectogram. Clearly, an appropriate software implementation of the model will allow any small fibre twist angles to be visualised, which will be impeded in practice by a rather large number of limiting instrumental factors. It is for this reason that the next step should be an experimental study. Such experiments were carried out previously, but with shorter lengths of fibre and larger twist pitches (for so-called spun fibre) [15].

Second, as to the problem of observing other physical quantities with such sensors, it is reasonable to conclude that, according to the simulation results, axial twist severely distorts a signal. We are thus led to infer that polarisation-sensitive optical frequency domain reflectometry techniques should have a more flexible mechanism for obtaining a resultant reflectogram than simple vector sum calculation (possible alternatives are simple averaging, reflectogram construction from a maximum signal and other approaches). In a number of cases, a possible solution is to take the reflectogram of a twisted fibre as a zero state.

3. Conclusions

We have described a new approach, based on the Jones matrix formalism, for modelling frequency domain reflectograms of polarisation-maintaining fibres having anisotropy defects.

As an example of a polarisation nonuniformity, we considered a uniform axial twist of an optical fibre and constructed model reflectograms. The results demonstrate that even a small twist of the order of 1 rad km^{-1} produces significant changes in frequency domain reflectograms.

The approach is applicable to modelling the influence of other polarisation defects on reflectograms. Practical utility of the proposed model is that it can potentially be used to identify changes in optical and geometric characteristics of real optical fibres by finding parameters at which calculated reflectograms will be identical to those observed in experiments.

Acknowledgements. We are grateful to our colleagues at the JSC Perm Scientific Industrial Instrument Making Company for providing the samples and for their assistance in the experimental work and to D. Claude, an engineer at the Laboratory of Photonics, Perm Federal Research Center, Ural Branch, Russian Academy of Sciences, for fruitful discussions.

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