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Fiber optic sensor for birefringence

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ABSTRACT

The paper covers an autocollimating fiber optic sensor for measuring the birefringence of bulk material based on the use of a pulsed laser and multimode optical fiber with a fiber delay line. The specimen birefringence is defined by measurement of the pulse intensities. The basic expressions that describe the operation of the sensor are presented. The suggested scheme can be used for studying the inner stress in transparent solid bodies, birefringence of crystals, or for measuring temperature, pressure, electrical and magnetic field strength, etc.

Keywords: polarimetry, birefringence, polarimetric fiber sensor

1.INTRODUCTION

Birefringence must often be monitored under conditions where direct illumination of the specimen is either impossible or difficult to arrange, e.g., when the specimen is placed inside various mechanical and chemical equipment or otherwise the measurement must be made remotely. In such cases it is possible to use an optical-fiber analog of return-path polarimeters[1,2]. Unlike traditional polarimeters[3], in the return-path instruments for measuring birefringence the probe beam incident on the specimen coincides with the beam reflected from this specimen. Realization of the optical-fiber birefringence sensor can be achieved with the use of a single fiber for transmission and receiving of radiation. In the general case we can use either a multimode optical fiber or a singlemode optical fiber for the sensor. But demands to the sensor with the multimode fiber and its cost less than the sensor with the singlemode fiber. Here we describe the birefringence sensor that is based on the use of the impulse laser diode and the multimode fiber.

2.DESCRIPTION OF THE SENSOR WITH LINEARLY POLARIZED PROBE PULSES

The configuration of the sensor optical scheme with linearly polarized probe pulses is shown in Fig.1. It consists of a transceiver **I**, a sensor unit **II** and a processing unit **III**. The transceiver contains a pulsed laser diode **LD**, the first polarization beamsplitter **PBS1**, a lens **L1** and a photodiode **PD**, which is mounted in the first body **B1**. Polarization of the laser diode beam is linear and parallel to the transmittance plane of the polarization beamsplitter **PBS1.** The elements of the sensor unit are as follows: the second body **B2**, the second polarization beamsplitter **PBS2**, a polarizer **P**, three lenses **L2**, **L3** and **L4** and a fiber optic coil **FOC** which is used as a delay line. The sensor unit can be rotated around the axis of the output beam. A multimode optical fiber **MMF** connects the transceiver and the sensor unit between them. The fiber optic coil **FOC** is also made of a multimode optical fiber. The photodiode is connected to the processing unit. An oscilloscope **Os** can be used as the unit. A specimen under investigation **S** is a transparent plane parallel plate. A plane mirror **M** is used for back reflection of the probe pulses.

The birefringence sensor works in the following manner. The linearly polarized pulse I_0 from the laser diode **LD** passes the first polarization beamsplitter **PBS1,** the lens **L1,** and the connecting multimode fiber **MMF**. There the radiation is decomposed into a great number of optical modes and depolarized completely[4]. The output radiation is collimated by the lens **L2** and is divided into two polarization components I_{1p} and I_{1s} by the second polarization beamsplitter **PBS2**:

$$I_{1p} = I_{1s} \approx 0.5 \cdot I_0 . \tag{1}$$

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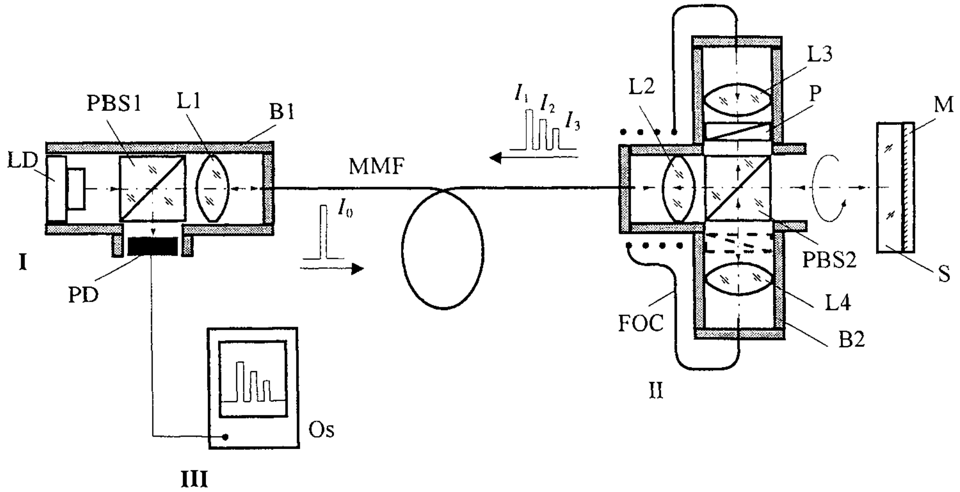

Fig.1. Configuration of the sensor optical scheme with linearly polarized probe pulses. **I**: transceiver; **II** sensor unit; **III** processing unit; **LD**: pulsed laser diode; **PBS1**: the first polarization beamsplitter; **L1**: the first lens; **PD**: photodiode; **B1**: the first body; **B2**: the second body; **PBS2**: the second polarization beamsplitter; **P**: polarizer; **L2**: the second lens; **L3**: the third lens; **L4**: the fourth lens; **FOC**: polarization-scrambling fiber optic coil; **MMF**: connecting multimode optical fiber; **Os**: oscilloscope; **S**: specimen under investigation; **M**: plane mirror; I_0: the initial pulse; I_1: the first return pulse; I_2: the second return pulse; I_3: the third return pulse.

The first p-polarized probe beam I_{1p} passes to the specimen. The second s-polarized output beam I_{1s} is reflected from the splitter coating. Further the pulse I_{1s} passes through the polarizer **P** and is launched into the first end of the fiber optic coil **FOC**. The specimen's birefringence causes a polarization modification of the probe pulse I_{1p}. Therefore the back reflected pulse is divided by the second polarization beamsplitter PBS2 into two pulses I'_{1p} and I'_{1s} with p- and s-polarizations respectively:

$$I'_{1p} = (\cos^2\Delta + \sin^2\Delta \cdot \cos^2 2(\varphi - \psi)) \cdot r \cdot I_{1p},$$
$$I'_{1s} = \sin^2\Delta \cdot \sin^2 2(\varphi - \psi) \cdot r \cdot I_{1p}. \tag{2}$$

Here Δ is the phase difference introduced into the beam by the specimen upon one passage of the pulse, φ is an angular position of a principal axes of the specimen, ψ is the polarization plane of the probe pulse.

The component I'_{1p} passes back through the second beamsplitter **PBS2** and is introduced into the connecting optical fiber **MMF** by the second lens **L2**. Thus the first return pulse I_1 will go by the connecting fiber:

$$I_1 = k_1 \cdot (\cos^2\Delta + \sin^2\Delta \cdot \cos^2 2(\varphi - \psi)) \cdot I_0, \tag{3}$$

where $k_1 \approx 0.5$ is a coefficient taking into account losses at beam passage in an optical scheme of the sensor unit.

The component I'_{1s} is reflected from the second beamsplitter **PBS2** and is launched through the lens **L4** into the second end of the fiber optic coil **FOC**. So the two pulses I'_{1s} and I_{1s} pass in the opposite directions through the fiber optic coil at the same time. These pulses are depolarized completely in the coil **FOC**. The pulse I'_{1s} goes out from the first coil end and is collimated by the third lens **L3**. Further the s-polarized pulse part passes through the polarizer and is reflected from the second polarization beamsplitter. The second lens **L2** introduces this pulse I'_{2s} into the connecting fiber **MMF**:

$$I'_{2s} \approx 0.5 \cdot I'_{1s}. \tag{4}$$

The pulse I_{1s} leaves the second coil end and is collimated by the lens **L4**. The polarization beamsplitter **PBS2** divides this pulse into two equal parts I_{2s} and I_{2p}:

$$I_{2p} = I_{2s} \approx 0{,}5 \cdot I_{1s}. \tag{5}$$

The pulse I_{2p} passes through the beamsplitter **PBS2** and then the polarizer **P** absorbs it. The pulse I_{2s} is reflected towards the specimen. The polarization plane of the second probe pulse I_{2s} is perpendicular to the polarization plane of the first probe pulse I_{1p}. The reflected back pulse has ***p***- and ***s***- polarized components I''_{2s} and I''_{2p}:

$$\begin{gathered} I''_{2p} = \sin^2\Delta \cdot \sin^2 2(\varphi - \psi) \cdot r \cdot I_{2s}, \\ I''_{2s} = (\cos^2\Delta + \sin^2\Delta \cdot \cos^2 2(\varphi - \psi)) \cdot r \cdot I_{2s}. \end{gathered} \tag{6}$$

The component I''_{2p} passes through the second beamsplitter **PBS2** and is launched into the connecting optical fiber by the lens **L2**. Thus the two returns pulse I'_{2s} and I''_{2p} enter the connecting fiber simultaneously at a time τ after the first pulse I_1. The delay time τ is equal:

$$\tau = L_{dl} \cdot \frac{n}{c}, \tag{7}$$

where L_{dl} is the length of the fiber in the coil **FOC**, *n* is a refractive index of the fiber's core, *c* is the speed of light in vacuum. Polarization planes of the pulses I'_{2s} and I''_{2p} are orthogonal and the pulses do not interference between them. Therefore the total intensity of the second return pulse I_2 is the following:

$$I_2 = I'_{2s} + I''_{2p} = k_2 \cdot \sin^2 2(\varphi - \psi) \cdot \sin^2\Delta \cdot I_0, \tag{8}$$

where $k_2 \approx 0.5$ is a coefficient taking into account losses at passage of the pulses in the sensor unit and the fiber optical coil.

The component I''_{2s} is reflected from the second beamsplitter **PBS2** in the direction of the second coil end. The lens **L4** launches the pulse I''_{2s} into the coil. Here the pulse is depolarized completely. Then the pulse goes out from the first coil end and is collimated by the third lens **L3**. The ***s***-polarized pulse passes through the polarizer **P** and is reflected from the polarization beamsplitter **PBS2**. The lens **L2** introduces this part of the pulse into the connecting fiber. So the third return pulse I_3 will enter the connecting fiber after a delay time 2τ after the first pulse I_1. An intensity of the third pulse is the next:

$$I_3 = 0.5 \cdot I''_{2s} = k_3 \cdot (\cos^2\Delta + \sin^2\Delta \cdot \cos^2 2(\varphi - \psi)) \cdot I_0, \tag{9}$$

where $k_3 \approx 0.125$ is a coefficient taking into account losses upon passage of the pulse through parts **II** and **I**.

The polarizer **P** removes the pulse, which has gone through the second polarization beamsplitter **PBS2** in order to eliminate additional repeated passage of the pulse in the fiber optic coil **FOC**. The polarizer **P** can likewise be installed between the second beamsplitter **PBS2** and the fourth lens **L4**; the result will be the same.

The return pulses I_1, I_2 and I_3 are depolarized in the connecting fiber. Half intensities of the pulses are reflected from the first polarization beamsplitter **PBS1** toward the photodiode **PD**. It is possible to measure the intensities of the return pulses I_1, I_2 and I_3 using an oscilloscope, for example.

Let assume that an orientation of the specimen's principal planes is unknown. Then we turn the sensor unit around the axis of the output beam in order to obtain the minimal intensity I_2. In the position found, the orientation of the principal planes of the specimen corresponds to the orientation of the principal planes of the second polarization beamsplitter:

$$\psi = \varphi. \tag{10}$$

Furthermore, we install the polarization plane of the probe beam is such a way that one makes an angle 45° with the fast axis of the specimen, i.e. $\psi = \varphi + 45°$. In this case:

$$\begin{aligned} I_1 &= k_1 \cdot I_0 \cdot \cos^2 \Delta, \\ I_2 &= k_2 \cdot I_0 \cdot \sin^2 \Delta, \\ I_3 &= k_3 \cdot I_0 \cdot \cos^2 \Delta. \end{aligned} \qquad (11)$$

Use of the following formulas enables us to find the specimen phase difference from intensities of the return pulses:

$$\Delta = \tan^{-1}\sqrt{\frac{I_2}{k_2}\frac{k_1}{I_1}} \quad \text{or} \quad \Delta = \tan^{-1}\sqrt{\frac{I_2}{k_2}\frac{k_3}{I_3}}. \qquad (12)$$

In many cases the azimuth φ is known in advance and it is not necessary to turn the sensor unit during measurement. Then we install angle $\psi = \varphi + 45°$ beforehand.

3.DESCRIPTION OF THE SENSOR WITH CIRCULARLY POLARIZED PROBE PULSES

The configuration of the sensor with circularly polarized probe pulses is shown in Fig.2. The sensor has an additional quarter wave plate **QWP**. It is not necessary to rotate the second body **B2** in order to determine the optical axes of the specimen unlike the sensor with linearly polarized probe pulses, which is described above. The quarter wave plate **QWP** is installed between the second polarization beamsplitter **PBS2** and the specimen **S**. The plate converts the probe pulses into circular polarizations. As with the previous sensor, there are three return pulses with intensities I_1, I_2 and I_3 with this alternate sensor. Owing to the fact that the probe pulses are circularly polarized, the intensities of the return pulses do not depend on the angular position of the principal axes of the specimen:

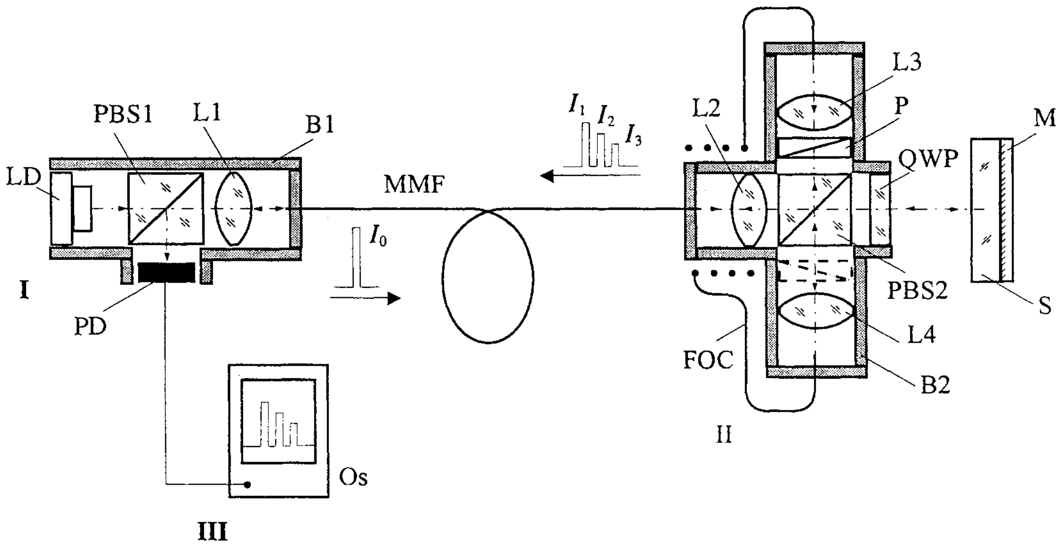

Fig.2. Configuration of the sensor optical scheme with circularly polarized probe pulses. **I**: transceiver; **II** sensor unit; **III** processing unit; **LD**: pulsed laser diode; **PBS1**: the first polarization beamsplitter; **L1**: the first lens; **PD**: photodiode; **B1**: the first body; **B2**: the second body; **PBS2**: the second polarization beamsplitter; **P**: polarizer; **L2**: the second lens; **L3**: the third lens; **L4**: the fourth lens; **QWP**: quarter wave plate; **FOC**: polarization-scrambling fiber optic coil; **MMF**: connecting multimode optical fiber; **Os**: oscilloscope; **S**: specimen under investigation; **M**: plane mirror; I_0: the initial pulse; I_1: the first return pulse; I_2: the second return pulse; I_3: the third return pulse.

$$
\begin{aligned}
I_1 &= k_1 \cdot I_0 \cdot \sin^2 \Delta, \\
I_2 &= k_2 \cdot I_0 \cdot \cos^2 \Delta, \\
I_3 &= k_3 \cdot I_0 \cdot \sin^2 \Delta.
\end{aligned} \tag{13}
$$

Here I_0 is an intensity of the initial probe pulse in the connecting fiber MMF, k_1, k_2 and k_3 are coefficients taking into account losses at passage of the pulses through parts **II** and **I**. The coefficients are: $k_1 \approx k_2 \approx 0.5$ and $k_3 \approx 0.125$. We can find the phase difference Δ after measuring the return beam intensities:

$$
\Delta = \tan^{-1}\sqrt{\frac{I_1}{k_1}\frac{k_2}{I_2}} \quad \text{or} \quad \Delta = \tan^{-1}\sqrt{\frac{I_3}{k_3}\frac{k_2}{I_2}}. \tag{14}
$$

4.CONCLUSION

Two kinds of the fiber optic sensors for birefringence are proposed. The sensor with the linearly polarized probe pulses allows defining a phase difference value and principal plane orientations of a specimen. This scheme demands a rotation of the sensor unit when the principal plane orientations are unknown. The sensor with the circularly polarized probe pulses enables the determination of phase differences only. A disadvantage of the last scheme is the lower precision because of an additional error caused by quarter wave plate.

The use of the pulse regime of a laser gives the possibility to realize a measurement system, which consists of one transceiver and several sensing units. The units with appropriate couplers are placed along one connecting multimode fiber. An optical time domain reflectometer can be used as transceiver in this case.

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