

Polarimetric optical fiber refractometer

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An optical fiber refractometer based on a photometric return-path birefringence sensor is proposed. For measuring the refractive index, the phase shift between polarization components on total internal reflection inside a refractometric prism is used. Several kinds of refractometric prism are described. It is shown that a refractive-index sensitivity of 0.0001 and higher for a wide range of index values is attainable. © 2001 Optical Society of America

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1. Introduction

Refractometers are widely used in science and industry. Most of them are based on measuring the ray deflection in a prism, on measuring the angle of total internal reflection, or on using interferometric or immersion techniques.¹ Using optical fibers for making refractometers allows for many advantages. For instance, the refractometers' accurate measurement range can be extended, remote measurements may be possible, and the refractometer may be used in various kinds of mechanical and chemical equipment and buildings. Earlier, an optical fiber refractometer with a Fabry–Perot etalon as a sensor head² and a refractometer based on a Mach–Zehnder interferometer³ were proposed. In a refractometer with a prismatic fiber face² and a refractometer with a polished core⁴ a change in the power loss caused by the disturbance of total internal reflection on the core surface in contact with a liquid is used. Here an optical fiber refractometer is described that is based⁵ on the differential phase shift between p and s components introduced after total internal reflection.

2. Description of the Refractometer Scheme

The configuration of the refractometer is shown in Fig. 1. It consists of transceiver I, sensor unit II, and processing unit III. The transceiver contains laser LD, polarization beam splitter PBS1, lens L1, and two photodiodes (PD1 and PD2), which are mounted in body B1. The elements of the sensor unit are as

follows: body B2, two lenses (L2 and L3), polarization beam splitter PBS2, 45-deg polarization rotator PR(45°), and refractometric prism RP. The prism is fastened to the outside of body B2. Beam splitter PBS2 is made from two rhombic prisms. The processing unit includes correcting amplifier CA, difference amplifier DA, summing amplifier SA, and divider DV. Optical cable OC, which contains two multimode optical fibers (MMF1 and MMF2), connects the transceiver and the sensor units. Photodiodes PD1 and PD2 are connected to the processing unit as shown in the figure.

The refractometer works in the following manner: The linearly polarized beam from laser diode LD passes through polarization beam splitter PBS1 then through lens L1 and is launched into multimode optical fiber MMF1. There the radiation is decomposed into a great number of optical modes and completely depolarized. The output radiation is collimated by lens L2 and is divided into two polarization components, I_p and I_s , by polarization beam splitter PBS2:

$$I_p \approx I_s \approx 0.5I_0. \quad (1)$$

The first, p -polarized, probe beam passes directly to the refractometric prism. The second, s -polarized, probe beam is reflected from the splitter coating. After reflection on the inclined rhombic prism side, the second beam is oriented parallel to the first probe beam. Rotator PR45° shifts the polarization planes of the beams by 45°. Two or three or N total internal reflections of the probe beams take place inside the refractometric prism. The axes of the beams are combined in this prism. The polarization of the beam becomes elliptical at total internal reflection because the initial polarization planes lie at a 45° angle to the incidence plane. The ellipticity value

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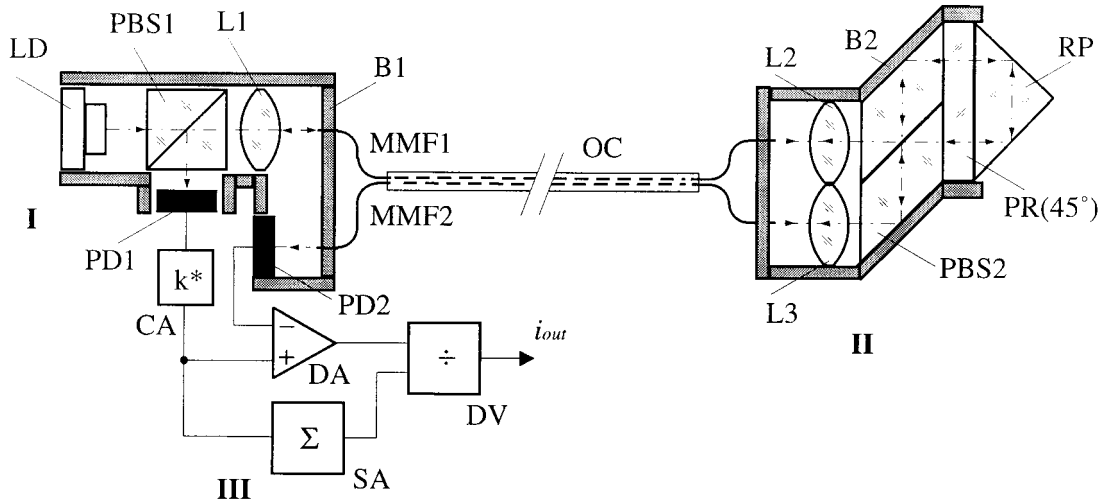


Fig. 1. Schematic of the polarimetric optical fiber refractometer. The components of transceiver I, sensor unit II, and processing unit III are defined in the text.

depends on the incidence angle and on the ratio between the refractive index of the prism and the experimental medium. The polarization ellipses of the return beams are shifted by -45° by the polarization rotator.

The first return beam is reflected by the side of the inclined rhombic prism and falls onto the splitter coating. Here the beam has two polarization components, I_p' and I_s' :

$$\begin{aligned} I_p' &= 0.5 \left[1 + \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_p, \\ I_s' &= 0.5 \left[1 - \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_p, \end{aligned} \quad (2)$$

where Δ_j is the phase difference at the j th reflection inside the refractometric prism and N is the number of reflections.

The second return beam has two polarization components, I_p'' and I_s'' , also:

$$\begin{aligned} I_p'' &= 0.5 \left[1 - \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_s, \\ I_s'' &= 0.5 \left[1 + \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_s. \end{aligned} \quad (3)$$

The splitter coating transmits the p -polarized component of the first return beam, I_p' , and reflects the s -polarized component of the second return beam, I_s'' , toward lens L3. These beams do not interfere with each other because they have orthogonal polarizations. Both beams are then introduced into fiber MMF2. In addition, the splitter coating reflects the s -polarized component of the first beam, I_s' , and transmits the p -polarized component of the second beam, I_p'' . Lens L2 introduces both beams into fiber MMF2. Thus the beams with intensities $I_s' + I_p''$ and $I_p' + I_s''$ pass back through into fibers MMF1 and MMF2, respectively. Beam splitter PBS1 reflects

beam I_1 in a direction of photodiode PD1. Intensity I_1 is equal to one half of the intensity of the return beam in the first fiber. Beam I_2 falls upon photodiode PD2:

$$\begin{aligned} I_1 &= k_1 \left[1 - \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_0, \\ I_2 &= k_2 \left[1 + \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_0, \end{aligned} \quad (4)$$

where $k_1 \approx 0.25$ and $k_2 \approx 0.5$ are coefficients that take into account losses at beam passages.

The correction amplifier has a coefficient k^* that accounts for the reflection loss at beam splitter PBS1. The input signals of the difference and summing amplifiers, i_1 and i_2 , are the following:

$$\begin{aligned} i_1 &= s_1 k_1 k^* \left[1 - \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_0, \\ i_2 &= s_2 k_2 \left[1 + \cos \left(\sum_{j=1}^N \Delta_j \right) \right] I_0, \end{aligned} \quad (5)$$

where s_1 and s_2 are sensitivities of the first and the second photodiodes, PD1 and PD2, respectively. Coefficient $k^* \approx 2$ such that $s_1 k_1 k^* = s_2 k_2$. Consequently we have a signal i_{out} on the divider output:

$$i_{\text{out}} = \frac{i_1 - i_2}{i_1 + i_2} = -\cos \left(\sum_{j=1}^N \Delta_j \right). \quad (6)$$

3. Description of the Refractometer Sensor Heads

The phase shift on total internal reflection at the sensor prism is determined as⁶

$$\Delta_j = 2 \tan^{-1} \frac{\cos \epsilon_j (n_{\text{rp}}^2 \sin^2 \epsilon_j - n_m^2)^{1/2}}{n_{\text{rp}} \sin^2 \epsilon_j}, \quad (7)$$

where n_{rp} is the refractive index of the refractometric prism glass, n_m is a refractive index of the experi-

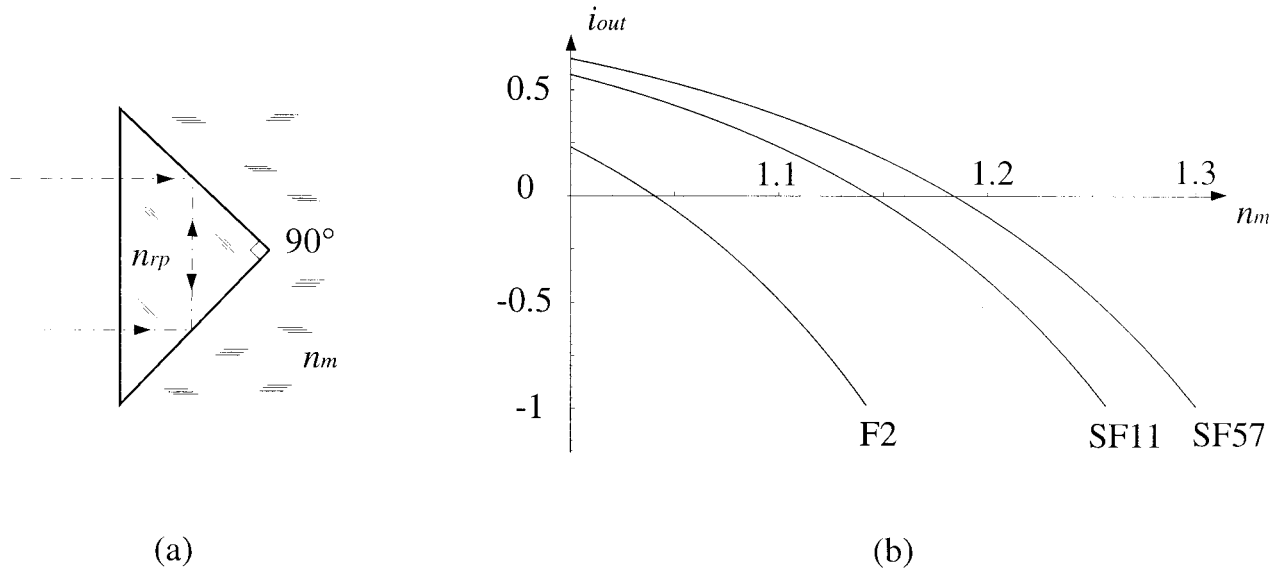


Fig. 2. (a) Schematic of the right-angle refractometric prism. (b) Dependence of the output signal on the refractive index of the experimental medium for the refractometric prisms made from Schott glasses F2, SF11, and SF57.

mental medium, and ε_j is an incidence angle for the j th reflection.

As follows from Eq. (7), the measurement range for refractive index n_m extends from 1 to \tilde{n}_m , where \tilde{n}_m is

$$\tilde{n}_m = n_{rp} \sin \varepsilon. \quad (8)$$

Output signal i_{out} is obtained by substitution of Eq. (7) into Eq. (6). In view of the complexity of the general equation it is convenient to get the formula for each specific prism.

A schematic of the right-angle refractometric prism and the passage of rays is shown in Fig. 2(a). As one can see, there are two reflections ($N = 2$) at incidence angle $\varepsilon_j = 45^\circ$. Phase shift Δ_j on single reflection is

$$\Delta_j = 2 \tan^{-1} \left[\frac{1}{n_{rp}} (n_{rp}^2 - 2n_m^2)^{1/2} \right]. \quad (9)$$

The measurement range for the refractive index of an experimental medium n_m is

$$1 \leq n_m \leq \frac{n_{rp}}{\sqrt{2}} \approx 0.707n_{rp}. \quad (10)$$

Output signal i_{out} is

$$i_{out} = 1 - \frac{2n_m^4}{(n_{rp}^2 - n_m^2)^2}. \quad (11)$$

Output signal i_{out} varies in the range [see Eq. (6)]

$$1 - \frac{2}{(n_{rp}^2 - 1)^2} \geq i_{out} \geq -1. \quad (12)$$

The output signal is equal to zero for

$$n_m = n_{rp} \sqrt{\sqrt{2} - 1} \approx 0.644n_{rp}. \quad (13)$$

The dependences of the output signal on the refractive index of the experimental medium for the right-angle refractometric prisms made from Schott glasses F2, SF11, and SF57 are shown in Fig. 2(b). Use of these diagrams enables us to find the medium's refractive index from the value of the output signal. For instance, when the refractometric prism is made from glass F2, the measurement range for refractive index n_m lies from 1 to 1.143. In this case the output signal changes from 0.23 to -1 . The output signal is equal to zero for $n_m = 1.040$. As follows from Fig. 2(b), the derivative $\partial n_m / \partial i_{out}$ is ~ 0.15 for an output signal close to zero. Therefore, to achieve a measurement error of $\delta n_m = 0.0001$, one needs to determine the output signal at a resolution of 0.07%.

A schematic of the trapezoidal refractometric prism and the passage of the rays appears in Fig. 3(a). As one can see, there are three reflections ($N = 3$) at incidence angle $\varepsilon_j = 60^\circ$. Phase shift Δ_j on single reflection is

$$\Delta_j = 2 \tan^{-1} \left[\frac{1}{3n_{rp}} (3n_{rp}^2 - 4n_m^2)^{1/2} \right]. \quad (14)$$

The measurement range for the refractive index of an experimental medium n_m is

$$1 \leq n_m \leq \frac{\sqrt{3}}{2} n_{rp} \approx 0.87n_{rp}. \quad (15)$$

Output signal i_{out} is

$$i_{out} = \frac{1}{2} \frac{(3n_{rp}^2 + 2n_m^2)(18n_{rp}^4 - 30n_{rp}^2n_m^2 - n_m^4)}{(3n_{rp}^2 - n_m^2)^3}. \quad (16)$$

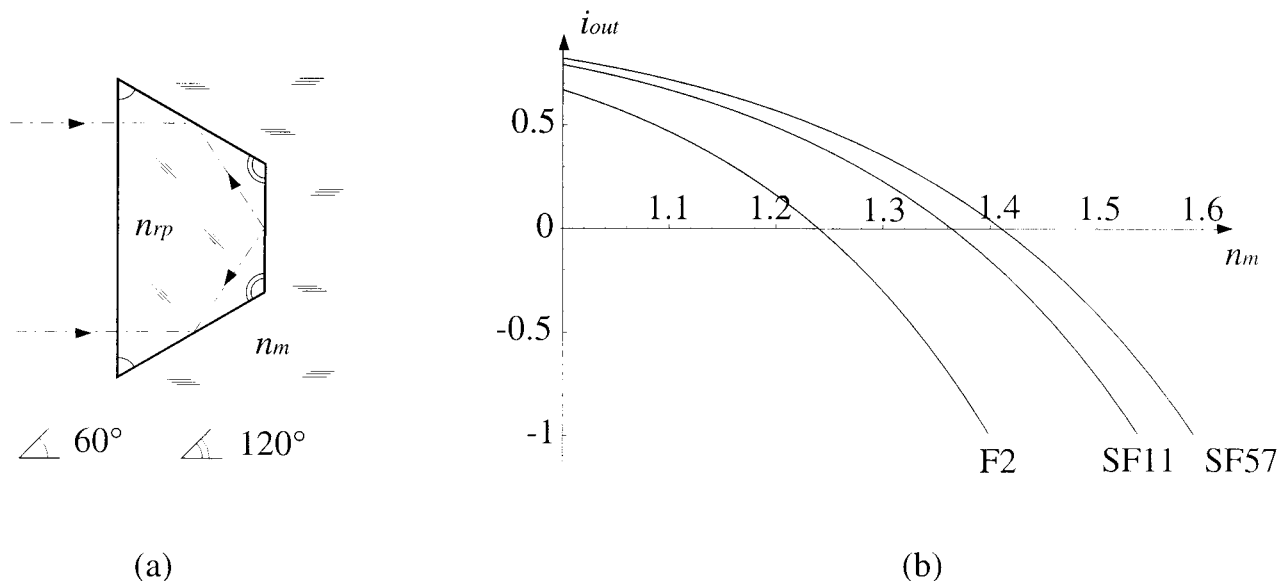


Fig. 3. (a) Schematic of the trapezoidal prism. (b) Dependence of the output signal on the refractive index of the experimental medium for the refractometric prisms made from Schott glasses F2, SF11, and SF57.

Output signal i_{out} varies in the range [see Eq. (6)]

$$\frac{1}{2} \frac{(3n_{rp}^2 + 2)(18n_{rp}^4 - 30n_{rp}^2 - 1)}{(3n_{rp}^2 - 1)^3} \geq i_{out} \geq -1. \quad (17)$$

The output signal is equal to zero for

$$n_m = n_{rp} \sqrt{9\sqrt{3} - 15} \approx 0.767n_{rp}. \quad (18)$$

The dependence of the output signal on the refractive index of the experimental medium for the trapezoidal refractometric prisms made from Schott glasses F2, SF11, and SF57 are shown in Fig. 3(b). For instance, when the refractometric prism is made from the glass SF11, the measurement range for refractive index n_m lies from 1 to 1.540. In this case the output signal changes from 0.79 to -1 . The output signal is equal to zero for $n_m = 1.364$. As follows from the diagram, a derivative $\partial n_m / \partial i_{out}$ is ~ 0.24 for the output signal close to zero. Therefore, for a measure-

ment error of $\delta n_m = 0.0001$ to be achieved, the output signal needs to be determined at a resolution of 0.04%.

Table 1 enables us to estimate and to compare parameters of the right-angle and the trapezoidal refractometric prisms, which are made from several kinds of optical glass. In practice, these parameters can differ slightly when there is soiling on the prism surfaces. Therefore it is necessary to calibrate the sensor head before measurement.

If there is a possibility of contamination of the interface between the refractometric prism and the sample medium during measurement we can detect the contamination by checking the sum signal from the summing amplifier. When there is contamination, the sum signal decreases. In this case the refractometer with two wavelengths can be used because the spectral dependence of the phase shift is sharper for a prism surface covered by a thin film.

4. Conclusions

The feasibility of a polarimetric optical fiber refractometer that allows one to measure a wide range of refractive indices with an accuracy of 0.0001 and higher has been shown. A sensor head in the form of a right-angle prism is optimal for analyzing media with low refractive indices, for instance, of pinched gases and cryogenic liquids. A trapezoidal refractometric prism is better suited for investigating liquids such as water solutions and petroleum products. For each specific case one can select an optimal shape for the refractometric prism and its glass and in addition can coat prism surfaces with thin films as necessary. The scheme also permits one to find the spectral dependence of the refractive index by using appropriate radiation sources.

Table 1. Parameters of Refractometric Prisms Made from Schott Glasses F2, SF11, and SF57^a

Glass	Right-Angle Refractometric Prism				Trapezoidal Refractometric Prism		
	n_{rp}	\tilde{n}_m	$n_m(0)$	$\frac{\partial n_m}{\partial i_{out}}$	\tilde{n}_m	$n_m(0)$	$\frac{\partial n_m}{\partial i_{out}}$
F2	1.61656	1.143	1.040	0.15	1.400	1.240	0.23
SF11	1.77862	1.258	1.145	0.17	1.540	1.364	0.25
SF57	1.83957	1.301	1.184	0.18	1.593	1.411	0.26

^a n_{rp} is the refractive index of the refractometric prism for wavelength 0.633 μm , \tilde{n}_m is the maximum measured value of the medium's refractive index, $n_m(0)$ is the medium's refractive index when the output signal is equal to zero, and $\partial n_m / \partial i_{out}$ is a derivative for the output signal close to zero.

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