Design of an optical-fiber refractometric transducer with hemispherical detection element

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We analyzed the performance of the optical-fiber refractometric transducer with hemispherical optical detection element. Specifically, we examined the effect of the light intensity distribution in the optical fibers on the transducer response to the refractive index of the surrounding media. In addition, we accounted for small local imperfections of the optical detection element surface. Accounting for these effects results in a significant accuracy improvement in the modeling of the described transducer.

Keywords: Optical fiber sensors; refractometry.

En el presente trabajo fue analizado el funcionamiento de un transductor refractométrico en fibras ópticas con un elemento óptico de sensibilidad de una forma semiesférica. Específicamente, fue examinado el efecto de la distribución de la intensidad de la luz en las fibras ópticas así como el efecto de las pequeñas distorsiones de la forma geométrica del elemento óptico de sensibilidad, sobre la respuesta del transductor al índice de refracción del medio externo. Al tener en cuenta estos efectos, se puede aumentar significativamente la exactitud del modelado del transductor mencionado.

Descriptores: Sensores en fibras ópticas; refractometría.

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1. Introduction

The refractive index is one of the principal characteristics of the optical medium. It relates to many other important physical and chemical characteristics, such as temperature, pressure, specific density, concentration, chemical composition etc. Because of this, the refractometric transducers find many applications in scientific research, industry and medicine. With the progress in the optical fiber technology, the optical-fiber refractometric transducers become a popular measurement tool.

Among different types of the optical-fiber refractometric transducers, the intensity-type devices have the following practical advantages: 1. The coherence and spectrum width of the optical source is not critical, 2. The multimode as well as monomode optical fibers can be used in the transducer, and 3. The signal detection and processing is relatively simple. On the other hand, there are many physical factors that affect the transducer precision, linearity, stability, and impose a limit on its operational range.

The optical-fiber refractometric transducer that we examine in this paper consists of two multimode optical fibers (the transmitting and the receiving one) and the transparent glass detection element of a hemispherical form. The operation of this transducer is based on the sensitivity of the internal reflection of light on the detection element surface to the refractive index of the surrounding medium. Therefore, the principal characteristic of this transducer is its optical transmission T versus the refractive index of the surrounding medium n. The particular form of the function $T(n)$ depends on the geometrical parameters of the transducer and material constants. In our previous works [1,2] we have examined the effect of the relative position of the optical fibers and the detection element as well as the effect of the optical fiber core diameter and numerical aperture on the transducer's transmission function $T(n)$. However, the light intensity distribution in the optical fibers was considered uniform in [1,2].

In this work, we examine the effect of different light intensity distribution in the transmitting and receiving optical fiber on the transducer transmission function $T(n)$. We account for the radiation pattern of the light source, the transmission properties of the optical fibers, the detection element's geometrical form, and the small imperfections of its surface.

2. Mathematical model

We employed the three dimensional geometrical optics model of the optical-fiber refractometric transducer. This model describes the elementary optical ray propagation from the transmission optical fiber to the receiving one via the multiple internal reflections from the detection element surface (Fig. 1). The detection element 1 is in the external medium of the refractive index n. The two optical fibers 2 and 3 have the same optical and geometrical parameters and are positioned on the detection element's plane surface symmetrically with respect to the transducer axis. The transmitting optical fiber is exited by the light source 4. The light intensity at the receiving fiber exit is measured by the photo receiver 5. We assumed a monochromatic, non-polarized and non-coherent light. We employed 100,000 elementary rays for the modeling of the optical beam. The ray starting point, the angle to the fiber axis and the azimuth were assigned in a random manner employing the Monte-Carlo method. The computational algorithm accounted for several serial reflections from the detection element's hemispherical surface. The Fresnel reflection coefficient was calculated at each reflection point and the resulting intensity was determined for each ray. Then, the relative transmission of the transducer $T^*(n) = I_2(n)/I_{2air}$ was calculated. Here, $I_2(n)$ is the transducer output light intensity (that is, the light at the receiving fiber exit), and I_{2air} is the transducer output light intensity when the surrounding medium is air.

In this model, we accounted for the following factors that had an effect on the light distribution over the transmitting fiber butt end: the refractive index profile of the optical fiber, the optical fiber length, the radiation pattern of the source, and the coupling between the light source and the optical fiber. In terms of the electromagnetic model, all together these factors determine the modal distribution in the optical fiber. Because of the well known difficulties of the determination of the mode coupling coefficients for the multimode optical fiber, in the calculations we employed the light intensity distributions, which were obtained experimentally for the transmitting and receiving optical fibers. These distributions were approximated by analytical functions that were then employed in the simulation of the transducer.

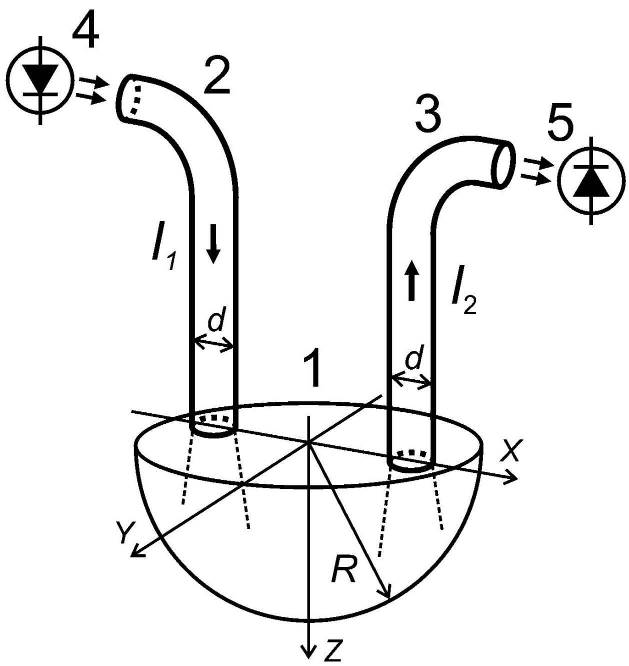

FIGURE 1. Optical-fiber refractometric transducer composed of the hemispherical transparent dielectric detection element (1), the transmitting optical fiber (2), the receiving optical fiber (3), the light emitting diode (4), and the photo diode (5).

3. Experiment

We employed the polymer step-index transmitting and receiving optical fibers of a core diameter $d = 1$ mm, core refractive index $n_c = 1.492$, numerical aperture in the air *NA*=0.47, and an optical loss $\alpha = 0.22$ dB/m (Agilent HFBR-R). For the receiving optical fiber, we measured the transmitted light intensity as a function of the angle of incidence of the input light beam. We employed the He-Ne single mode laser (Melles Griot 05-LHP-925) of a wavelength $\lambda = 633$ nm and of a power rating of $P = 17$ mW. The laser beam was collimated and chopped mechanically at a frequency of 1 kHz.

For the transmitting optical fiber, we determined the far-field radiation pattern at the optical fiber exit. We employed the light emitting diode (Agilent HFBR-1524) as a light source (the peak emission wavelength $\lambda = 665$ nm, spectral width $\Delta\lambda = 20$ nm, and an output power $P = 0.5$ mW). The light emitting diode was pulsed modulated at a frequency of 2 kHz. For a photo receiver, we employed a Si photo diode connected to a current amplifier.

The same light emitting diode and photo receiver was employed in the experimental exploration of the transducer relative transmission $T^*(n)$. The optical detection element was a hollow hemisphere of a radius R = 30 mm made of a borosilicate glass (Pyrex, $n = 1.471$ at $\lambda = 665$ nm). The glass hemisphere was filled with anhydrous glycerol of a refractive index $n = 1.470$ at $\lambda = 665$ nm. We employed water-glycerol mixtures of different concentration as the surrounding media of certain refractive index.

4. Results

The far-field light intensity distributions employed in the modeling of the transducer are shown in Fig. 2. The graph a is an ideal step-like light intensity distribution that is usually assumed for the multimode step-index fibers. The graphs b and d are the experimentally obtained distributions of light in the receiving and transmitting optical fiber, respectively. The graphs c and e are the best-fit approximations of graphs b and d respectively. The distributions c and e were obtained through numerical modeling of light propagation in the optical fiber. In the modeling, we used an analytical expression for the optical fiber local aperture $I(\theta)$ of the form

$$I(\theta) = I_0 \exp\left(-\left|\frac{\theta}{\theta_{1/e}}\right|^k\right)\cos\theta \quad ,$$

where I_0 is the light intensity in the longitudinal direction, $\theta_{1/e}$ is the exit angle which corresponds to the light intensity of I_0/e, k is a positive number.

We employed the distributions c and e in the modeling of the transducer relative transmission $T^*(n)$. In addition to the previously mentioned factors, we also accounted for some small local deviations of the detection element surface from the perfect hemispherical form. This was accounted for by introducing an optical beam divergence increase factor $\Delta\theta$.

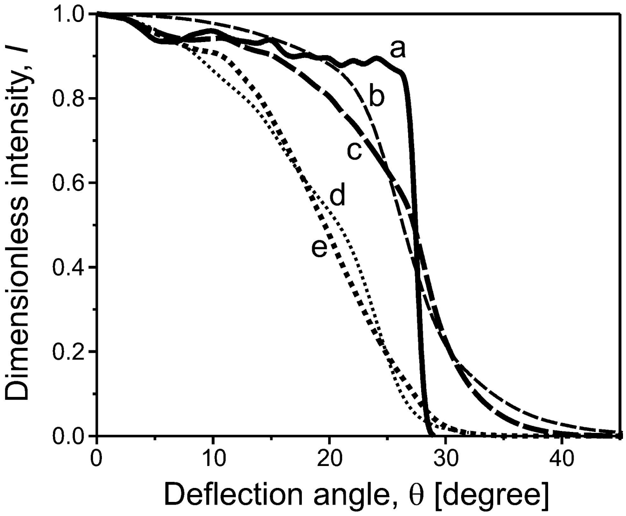

FIGURE 2. Far-field light intensity distribution obtained for the employed optical fibers: a) calculated distribution, which accounts for the guided modes only; b) experimental distribution in the case of receiving optical fiber; c) the best-fit approximation of graph b, which was obtained by numerical modeling of light propagation in the optical fiber; d) experimental distribution in the case of the excitation of the transmitting optical fiber by the light emitting diode; e) the best-fit approximation of graph d, which was obtained by numerical modeling.

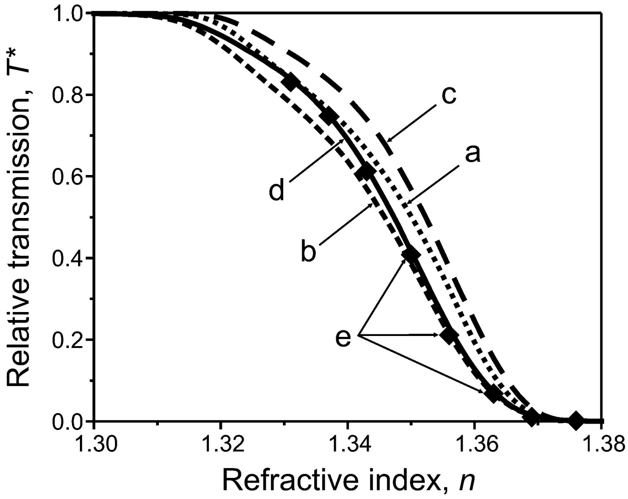

FIGURE 3. Transducer relative transmission $T^*(n)$: a) the case of the step-like distribution of light in the far-field of the multimode step-index optical fiber (graph a in Fig. 2) and the ideal geometrical form of the hemispherical detection element; b) the case of the step-like distribution of light and the non-ideal geometrical form of the detection element; c) the case of experimentally found light distribution (approximated by graph c and e in Fig. 2) and the ideal geometrical form of the detection element; d) the case of experimentally found light distribution and the non-ideal geometrical form of the detection element; e) experimental data.

The divergence increased at the internal reflection on the nonperfect detection element surface. The amount of this effect was accessed experimentally and was found to be of the order of $\Delta\theta g \cong 1^\circ$ typically at each reflection point.

The results of the relative transmission function simulation and the experimental results are plotted in Fig. 3. The predicted and observed behavior coincide well in the case of the theoretical graph d and the experimental graph e. As we mentioned earlier in this Section, the graph d was obtained under accounting both for the factual distribution of light in the transmitting and receiving optical fiber, and for the nonperfect form of the detection elements surface.

5. Conclusions

We disclosed some new factors that have an effect on the relative transmission function $T^*(n)$ of the optical-fiber refractometric transducer with the hemispherical detection element. In addition to the previously known effects of the optical fiber position, diameter, and numerical aperture, we have found that the light intensity distribution in the optical fibers as well as small imperfections of the detection element surface have a significant effect on the relative transmission function. Accounting for these factors allows one to improve the accuracy of modeling of the relative transmission function $T^*(n)$ by a factor of 3 approximately in comparison to the case when the mentioned factors are not taken into account.

Acknowledgements

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