Optical waveguide engineering: Joint Activity Detection based on Partial Internal Reflection by Using Optoelectronic Sensor

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Abstract:

The Thesis is devoted to the study of the dependence of the losses of transmitted energy in a bent fiber on the angle and radius of its bend. It presents an overview of the existing types of optical fiber, its production technologies, fiber-based optoelectronic sensors, including those based on changes in its properties during bending. An original experimental setup for studying this dependence is proposed. Experimental results are obtained, indicating a strong dependence of the studied properties on the type of optical fiber and its radius.

Key words: Optical wave, Internal reflection, Optical electron،

هندسة الدليل الموجي البصري: الكشف عن النشاط المشترك بناءً على الانعكاس الداخلي الجزئي باستخدام المستشعر الإلكتروني البصري

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خلاصة:

الرسالة مخصصة لدراسة اعتماد فقدان الطاقة المنقولة في الألياف المنحنية على زاوية ونصف قطر انحناءها. ويقدم نظرة عامة على الأنواع الحالية من الألياف الضوئية، وتقنيات إنتاجها، وأجهزة الاستشعار الإلكترونية الضوئية القائمة على الألياف، بما في ذلك تلك التي تعتمد على التغييرات في خصائصها أثناء الانحناء. ويقترح الإعداد التجريبي الأصلي لدراسة هذا الاعتماد. تم الحصول على نتائج تجريبية تشير إلى اعتماد قوي للخصائص المدروسة على نوع الألياف الضوئية ونصف قطرها.

الكلمات المفتاحية: الموجة الضوئية، الانعكاس الداخلي، الإلكترون الضوئي،

Introduction:

The Thesis consists of 3 parts. In the 1^{st} part literature review on optical fiber and fiber-based sensors is presented. Special attention is given to sensors based on fiber bending. The physics of fiber bending is discussed, especially the change in mechanical and optical properties of the fiber under different bending conditions.

Optical fiber is a glassy and thready material that makes use of the phenomenon of total internal reflection to guide light waves. In 1966 it was predicted theoretically [1] that optical fiber with extremely low loss could be produced, and its application to telecommunications was proposed. Combined with lasers, optical fiber made optical communication technology possible, which is now recognized as one of the bases of the modern information society.

Optical fibers are mainly of two different types: step-index fiber and gradient-index fiber. Step-index fiber usually consists of a core with refractive index n_1 and a cladding layer with refractive index $n_2 < n_1$. In a gradient-index fiber refractive index changes with radial distance r as

$$n(r) = \begin{cases} n_1\left[1 - \Delta\left(\frac{r}{a}\right)^p\right], & r \le a \\ n_1(1-\Delta), & r > a \end{cases},$$

where a is the core radius, $\Delta = \frac{n_1 - n_2}{n_1}$, $p > 0$. The main characteristics of the fiber include transmission loss (mainly due to Rayleigh scattering), number of modes (that is, the number of angles at which light waves can propagate into fiber), and chromatic dispersion (the dependence of refractive index on the light wavelength). The process of fabrication of optical fiber is based on modified chemical vapor deposition technology, where pure SiO_2 is produced from $SiCl_4$ and sintered to a silica preform at 1600^oC. After that, the preform is drawn into a fiber at high T. To obtain the difference in n between the core and the cladding, the pure silica is doped with GeO_2 or P_2O_5. Then the bare fiber is drawn into a plastic sleeve and packaged into a cable to strengthen it.

Stimulated by the development of optical fiber technologies, many different optical devices and components have been developed. One of the such device types is optical fiber sensor, which is considered to be an indispensable part of an information system.

Optical fiber sensors have experienced fast development and attracted wide attention both in fundamental research and in practical applications. Optical fiber in sensors plays the role of a sensing element itself. Compared with other types of sensors, fiber sensor technology is immune from electromagnetic interference, waterproof and resistant to chemical reactions. It has different advantages over conventional optical sensors – for instance, sensing can be combined with signal transmission. Fiber sensors have been used in different areas of industry, transportation, communication, security and defense. Basic physical conditions to which fibers are sensitive, include strain, stress and temperature. A bent fiber can be considered as a bent (and stretched) cylindrical silica rod. Inside the rod a neutral surface exists, on which there is neither axial extension nor compression, that is, the length of the neutral surface is equal to the original length of the fiber. The neutral surface divides the fiber into two parts: the part of the fiber closer to the center of bending is axially compressed, whereas the other part is stretched.

The basic effect found in bent fiber experimentally is birefringence. Is happens because the round rod is deformed to be elliptical, and asymmetric strain occurs around the center. The bending-induced birefringence depends strongly on the bending curvature $(1/R)$. It is observed in experiments that the birefringence becomes quite notable when the curvature radius reaches less than a few centimeters.

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Fiber bending not only induces birefringence but also causes propagation loss. Fiber loss is one of the main characteristics in fiber sensors [2].

It is evident that the bending will cause the peak of the mode to move from fiber center toward the outer circle, like shown in Fig. 1, and some energy of the guided mode may radiate out. Considering the fact that the curvature radius of bending, R_c, is usually much larger than fiber diameter, a commonly used approximation is to convert the curved fiber into a straight

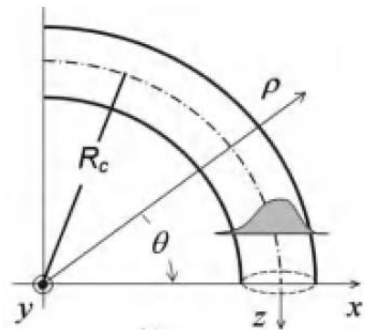

Figure 1. Bent fiber and coordinates used

waveguide with an equivalent index $n_{eq}(x)$, a function of position x, instead of the original uniform step index.

The mathematical concepts used in the work are given in works [4, 5]. We will give here the abridged version of the concepts. According to the symmetry of the problem, let's find the solution to Maxwell equations in the form of $E == E_\rho E_y \exp i\beta z$. Here β is the propagation constant, $i^2 = -1$, and the coordinate axes are given in Fig. 1. The azimuthal part can be rewritten as $\exp i\beta z = \exp i\beta R_c\theta = \exp iq\theta$, where $q = \beta R_c$. Substituting the solution into the Maxwell equations for electric field $\vec{\nabla} \times \vec{\nabla} \times \vec{E} = k^2 n^2 \vec{E}$ and $\vec{\nabla}\vec{E} = 0$, we get the following system of equations:

$$\left(\frac{\partial^2}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial}{\partial\rho} + \frac{\partial^2}{\partial y^2} - \frac{q^2}{\rho^2} + k^2 n^2\right)\frac{\rho}{R_c}E_\rho = -\frac{2}{R_c}\frac{\partial E_y}{\partial y}$$

$$\left(\frac{\partial^2}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial}{\partial\rho}+\frac{\partial^2}{\partial y^2}-\frac{q^2}{\rho^2}+k^2n^2\right)E_y=0$$

$$\left(\frac{1}{\rho}+\frac{\partial}{\partial\rho}\right)E_\rho+\frac{\partial E_y}{\partial y}+i\frac{q}{\rho}E_\theta=0$$

As the bending radius is so large that the RHS in the first equation can be neglected, the first and second equations in the system have the same form and are coupled with each other. If we convert the coordinates to Cartesian from the center of the fiber (let $\rho=R_c+x$) and introduce new functions $\psi_\rho(x,y)=\left(\frac{\rho}{R_c}\right)^{\frac{3}{2}}E_\rho(\rho,y)$ and $\psi_y(x,y)=\left(\frac{\rho}{R_c}\right)^{\frac{1}{2}}E_y(\rho,y)$, the two equations can be rewritten into one

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+n_{eq}^2(x)k^2\right]\psi_{\rho,y}(x,y)=0,$$

where the equivalent refraction index (depending on *x*) is

$$n_{eq}^2k^2=n^2k^2+\frac{1-4\beta^2R_c^2}{4(R_c+x)^2}\approx\left(n^2-n_{eff}^2\right)k^2+\beta^2\frac{2x}{R_c}=\beta_t^2+\beta^2\frac{2x}{R_c}.$$

As the equivalent refraction index depends on *x*, it can be shown that there is a critical position of x_c beyond which the equivalent index is larger than the effective index of the straight fiber; the optical wave in the region becomes a radiating wave, resulting in fiber bending loss.

These losses can be estimated by finding the propagation constant; the procedure is described in [4]. By using some simplifications and approximations, the propagation constant for the fundamental mode can be deduced as

$$\beta_{i,0}=\frac{\beta_{t1}^2}{4\mathrm{V}^2}\sqrt{\frac{\pi}{R_c\beta_{t2}^3}}\frac{1}{K_1^2(\beta_{t2}a)}\exp\left(-\frac{2\beta_{t2}^3}{3\beta^3}\beta R_c\right).$$

As it is evident from the formula above, the bending loss is proportional to $R_c^{-0.5}\exp -CR_c$. The objective of the work is to try to confirm the formula, or, in other words, to study whether the absorption of the input power and radiation losses in optical fibers bent at different angles and radii can be the actual indicator of the bending angle. To reach this objective, several tasks need to be completed: experimental setup must be designed and created, experiment must be carried out, data obtained as a result of the experiment must be analyzed.

Figure 2. Outer view of the setup

The 2nd part of the Thesis contains the information on the proposed experimental setup. The setup consists of a wooden box with the dimensions 420×500×170 mm (Fig. 2) which was painted with matt black coating from the inside in order to reduce environmental lighting and to avoid reflections that might occur. Inside the box a second bottom surface holding the light source and the bending area was made. The second bottom can be levelled horizontally using supplied levelers, as it stands on four springs with four thumbscrews in the corners of the box.

The bending area consists of two wooden circles attached to each other concentrically; they can rotate around the same axis. That axis can be locked tight by friction with a big thumbscrew. This guarantees that none of the circles will move while getting the output results. The optical fiber is

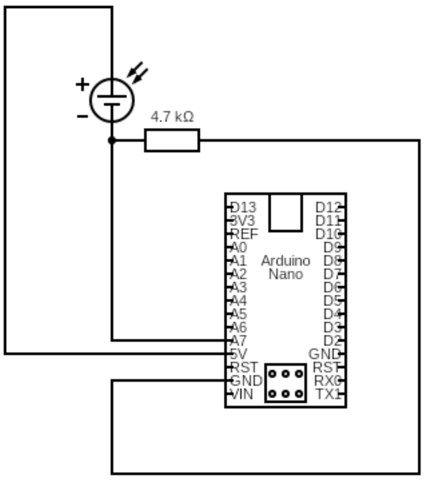

Figure 3. Electronic circuit

guided using steel nails and metallic jaws during bending. The losses arisen from the bending are found using the light dependent resistor connected to Arduino Nano microcontroller with an electric circuit shown in Fig. 3.

The 3rd chapter of the Thesis is devoted to discussing the results of the experiment. The fibers taken for the experiment were of different lengths and radiuses. The first fiber that was tried was 5m long and 0.3mm in diameter. The results obtained with this fiber were of insufficient quality: almost all transmitted power was lost. Other fibers that I used was 35 and 45 cm long and 0.9 mm in diameter. These fibers were too thick: they were wrapped in an insulating material that prevents light from escaping in the bending spot. The third set of fibers were 35 and 45 cm long and 0.3mm thick; from these fibers we were able to extract experimental results, that are presented in Fig. 4, 5 and 6.

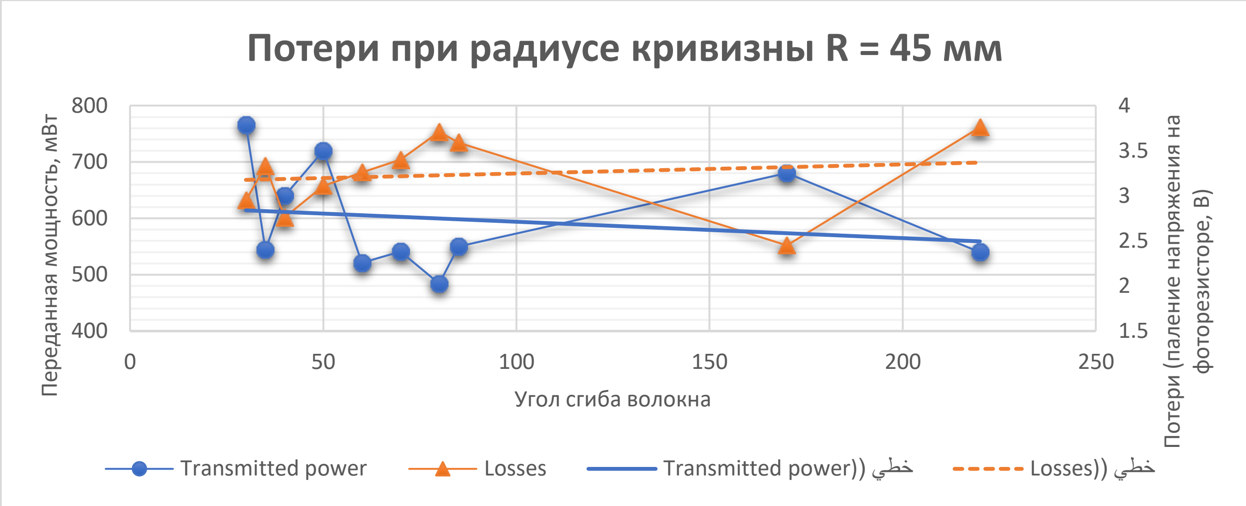

Figure 4. Dependence of the transmitted power and the power loss on the bending angle for R_c = 45 cm

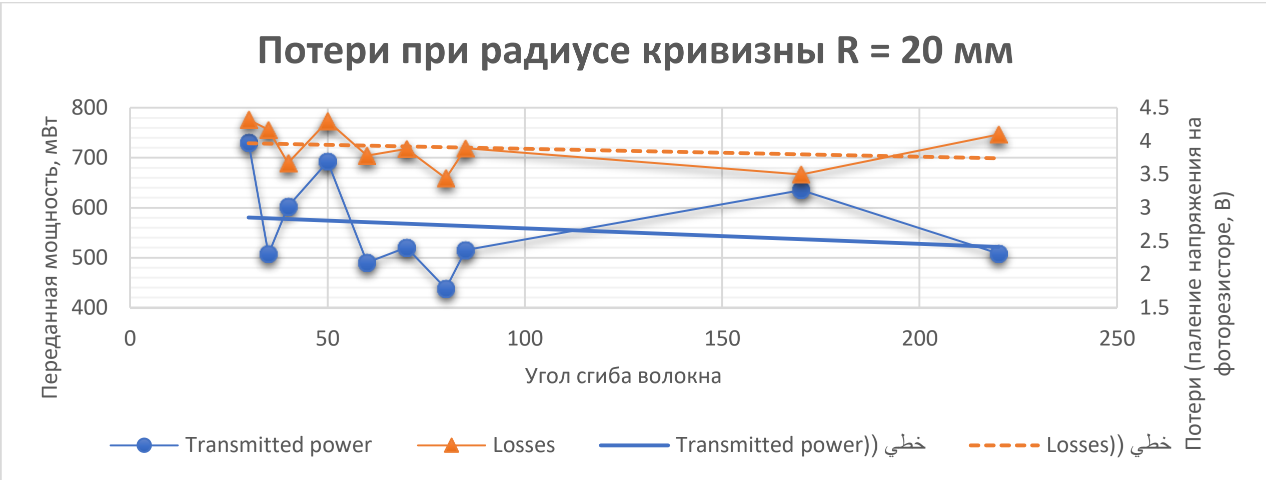

Figure 5. Dependence of the transmitted power and the power loss on the bending angle for Rc = 20 cm

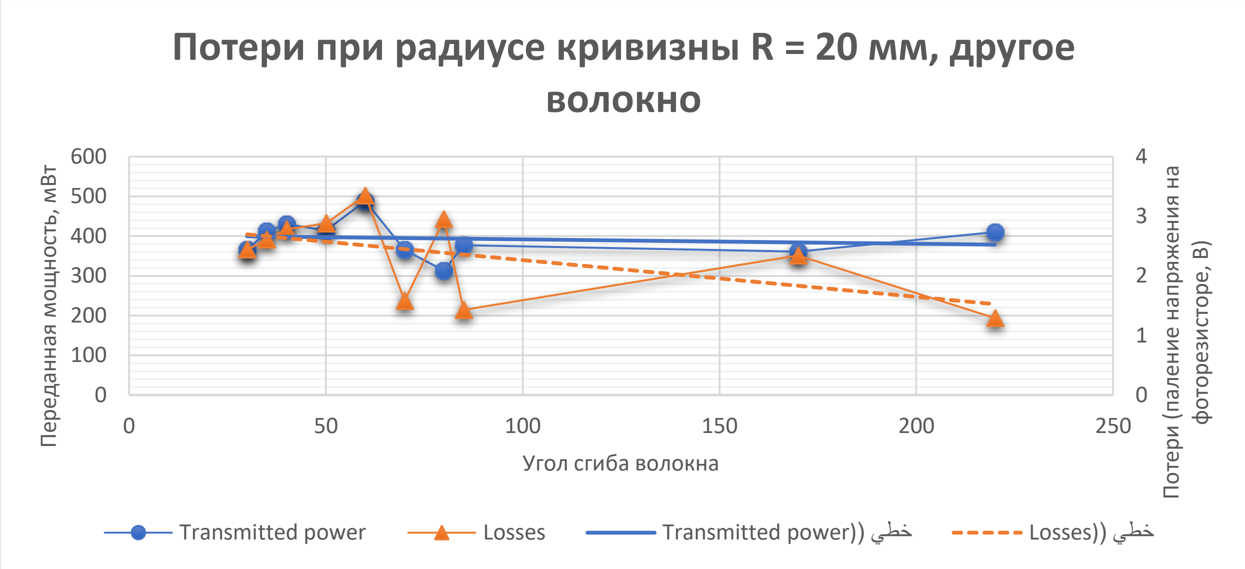

Figure 6. Dependence of the transmitted power and the power loss on the bending angle for Rc = 20 cm (another optical fiber, same characteristics)

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