Research Article

Sensitivity Enhancement of Heterocore Macrobend Fiber Optics by Adding a ZnO Film

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Optical fibers with high sensitivity are in demand due to their great potential in sensor application. Semiconductors, such as ZnO, are good materials. Using them as a second cladding offers opportunities in realizing next-generation multimaterial fiber optics. COMSOL Multiphysics is used to simulate heterocore macrobend fiber optics with the same curvature radius but different values of refractive index and thickness of ZnO films. The optimum thickness of ZnO films is identified by determining the loss of optical fibers. Macrobend heterocore fiber optics by adding ZnO thin film has been established by simulating and interpreting the relationship in terms of transmission and refractive index in the evanescent field. These results will provide a reliable fundamental to guide the performance in practice.

1. Introduction

Bending in an optical fiber can result in a loss of power output, which means the output light intensity is smaller than the intensity of the light source [1]. As the bend becomes more acute, more light leaks out. Bending can be utilized in an intrinsic optical fiber sensor, and it can be categorized using a modulation principle in terms of shift intensity, phase, or wavelength [2]. Basically, shift intensity can be recognized by detection of attenuation signal output from the optical fiber. Simple attenuation is bending on the optical fiber, which uses only mechanical disorder. The sensitivity characteristics of fiber optics can then be realized. A heterocore fiber also generates attenuation. This condition can be related to evanescent theory, in which propagation light is coupled out of the core road. The use of a heterocore fiber is an inexpensive method compared with removing fiber cladding via a chemical process. Combination of bending and heterocore fiber has already been studied by researchers. Relevant research is important and helpful for scientists to create a suitable application from this.

At present, semiconductor optical fibers are an emerging platform for the fiber optic world and thus become an important class of fiber. With the advancement of technology, nanomaterials play an important role in fabrication sensors. Hence, researchers have studied various semiconductors coated on fiber optics to enhance the sensitivity of current sensor-based fiber optics. Examples are ZnO materials. The high refractive index and carrier mobility of ZnO cause it to be a highly attractive material for optoelectronic application [3–7]. From previous research, ZnO is used for sensitivity enhancement, which increases the interest in ZnO, especially ZnO coated on fiber optics. Here, we simulate and design a ZnO film with a small thickness and high sensitivity of fiber optics at 1550 nm. We then determine the correlation between bending in optical fiber sensors and the heterocore effect.

2. COMSOL Multiphysics Simulation

The wave optic module of COMSOL Multiphysics has been used for boundary mode analysis and optical loss simulations. Once the geometries are set, refractive indices are

given to the core and cladding materials. In this simulation, a wavelength of 1550 nm is used as a source. The specifications for the proposed fiber are provided in Table 1.

Figure 1 is the geometric model on plane XY in this simulation with Port 1 is the input terminal while Port 2 is the output terminal. Port 2 is a function of detecting the transmission light intensity. In this simulation, 1550 nm is used as a light source. Region 2 is the macrobend heterocore portion of the evanescent field. A mapped meshing element is used to evaluate the output from this simulation. The governing equation in this problem is the wave equation for the electric field [8, 9]

$$E(r) = E_1(r)e^{(-jk_1 \cdot r)}, \quad (1)$$

for the wave vector set to unidirectional, where E_1 is a slowly varying field envelope function and approximates the propagation phase for the wave. Inserting this electric field formulation into Maxwell's equation results in the following wave equation for the envelope function [1, 8]:

$$(\nabla - jk_1) \times ((\nabla - jk_1) \times E_1) - k^2 E_1 = 0. \quad (2)$$

3. Results and Discussion

3.1. Impact on Refractive Index. Propagation of light in a fiber can form evanescent waves, which can also be transmitted to the external of the fiber. This might be occurred due to the structure of fiber optic such as macrobend fiber optic or heterocore fiber optic. By combination of the structure, it might be formed double values of evanescent waves in evanescent field. Different refractive indices of silica fiber optic with different size of core will impact on influences on the penetration depth and energy of evanescent waves. Due to this situation, it finally changes the output intensity of the optical fiber. Therefore, we can justify the evanescent field characteristics due to the structure and refractive index of fiber optic by analyzing the transmission intensity at the receiving port of the optical fiber. Figure 2 shows the visual map of the electric field along heterocore macrobend fiber optics for different refractive indices. The figure depicts that light intensity is basically concentrated in the core area but has a loss in the evanescent field and bending effect. The values of power flow and electric field at Ports 1 and 2 are depicted in Figure 3. The refractive index is considered the effect on the output. The transmission loss of light is changed by setting different refractive index media and then measuring the output at the receiving end.

From both figures, we can determine that the change in refractive index media can cause a change in energy loss. Power flow is high at Port 2 when the refractive index medium is air ($n_{\text{air}} = 1$). When the fiber cladding is removed, the power flow along the heterocore macrobend fiber optics is much higher compared with the two others. The total internal reflection is achieved because n_{air} is much smaller than n_{core} of fiber optics. Snell's law is obeyed when n_{ZnO} is larger than n_{core} of fiber optics. Basically, with the high refractive index of cladding than that of core, the light tends to couple out. Then, the power flow of that situation at Port 2

TABLE 1: List of parameters of fiber optics.

Parameter	Single mode fiber (μm)	Multimode fiber (μm)
Core diameter	9	50
Cladding diameter	125	125

FIGURE 1: The structure of optical fiber based on bend loss.

is less than the power flow of standard fiber optics. To overcome this phenomenon, the general equation of evanescent wave penetration depth is used [10, 11]:

$$dp = \frac{\lambda}{2\pi \sqrt{(n_{\text{core}}^2 \sin^2 \theta^2 - n_{\text{clad}}^2)}} \quad (3)$$

where λ is the length of the incident wave, n_{core} is the refractive index of the fiber core, and n_{clad} is the refractive index of the fiber cladding. Figure 4 shows the penetration depth for different refractive indices of cladding. As the refractive index increases, the penetration depth also increases.

As the foundation principle, light in the fiber optic propagates in a total internal reflection way and extends to the cladding region due to structure and refractive index of fiber optic. Maxwell's equation defines the wave extending to the cladding region as standing wave. If the incident angle is measured from a normal direction at the interface of core and cladding, then the evanescent wave will transmit along the vertical axis and decline exponentially [10]. However, the refractive index of a material impacts the propagation of light. When light propagates through the evanescent area, its energy will be lost. Thus, the greater the light loss is, the smaller energy the receiver perceives. The characteristics of the evanescent field can be analyzed using the light intensity at the output terminal. The results could be described by the relationship between the evanescent light and the characteristics of the refractive index of fiber optic. For further justification, heterocore macrobend optics with different thicknesses of ZnO film is simulated. Figure 5 shows the result of this situation. The thickness of the ZnO film influences the propagation of light along the structure fiber optics. As the ZnO layer increases, the losses decrease. This result can be related to the tunneling optic properties of the refractive index. It can be proven by previous research [12],

FIGURE 2: The electric field propagating along the macrobend heterocore of fiber optic when the refractive index of cladding is (a) $n_{\text{silica}} = 1.4612$, (b) $n_{\text{air}} = 1$, and (c) $n_{\text{ZnO}} = 1.709$.

which mentioned that the energy of ZnO films decreases as the film thickness increases. The decrease in energy with the increment in film thickness is attributed to the improvement in film quality. Light trapping occurs in media of high refractive index. Light inside a medium of large refractive index is often difficult to be extracted into air, especially if the medium surface is parallel. This phenomenon occurs because certain light undergoes multiple total internal reflection without extraction into air.

3.2. Impact on the Thickness of ZnO Film. The electric field propagates along the structure of fiber optics with added ZnO film on the macrobend heterocore portion, as shown in

Figure 6. To determine the optimum fiber geometry, the propagating light is then simulated as a function of ZnO film thickness. The result is shown in Figure 7. A low loss starting from $5.0 \mu\text{m}$ exists, and the loss increases at the smallest thickness of the ZnO film because the evanescent wave extends into the cladding region. The effect of introducing additional second cladding is significant in terms of reducing optical propagation losses without an etching process by using a chemical reagent or a costly process. ZnO has a more significant effect in reducing the loss because the refractive index difference is larger compared with that in a silica fiber. Consequently, some light will propagate out to the surroundings along the transmission. The refractive index causes relative tunneling with increasing ZnO thickness, as

FIGURE 3: Graph of electric field and power flow at Port 1 (input) and Port 2 (output) when the refractive index of cladding is (a) $n_{\text{silica}} = 1.4612$, (b) $n_{\text{air}} = 1$, and (c) $n_{\text{ZnO}} = 1.709$.

mentioned in [12]. The relationship between refractive index n and energy gap E_g can be determined as [13]

$$n^2 = 1 + \left[\frac{13.6}{E_g + 3.4} \right]^2. \quad (4)$$

FIGURE 4: Evanescent wave depth penetration for different refractive indices of cladding.

(a) FIGURE 5: Continued.

FIGURE 5: Electric field and power flow for cladding diameter of ZnO film. (a) 25 μm , (b) 65 μm , and (c) 105 μm .

FIGURE 6: The electric field for different ZnO thickness.

The transmission output for each structure is shown in Figure 8. The output clearly shows that, at a certain ZnO thickness, a high loss occurs. Figure 8(a) illustrates the

unclad fiber and ZnO as a cladding. ZnO as a second cladding without the original cladding is shown in Figure 8(b). Comparison between these structures indicates

FIGURE 7: Transmission simulated as a function of ZnO thickness.

(a)

(b)

FIGURE 8: Structure of heterocore macrobend fiber optic with its transmittance graph: (a) ZnO as a cladding and (b) ZnO as a second cladding.

that, for the thickness of ZnO, a high loss appears at less than 10 μm without etching silica cladding. By contrast, with ZnO as a first cladding, the transmission output is unstable until 105 μm of ZnO thickness. However, both simulations showed the similar effective mode index with the value is 1.4819.

4. Conclusions

We have investigated the design of future fiber optics based on a ZnO optical fiber. The structure and refractive index of its fiber optic proved the impact of evanescent waves in which loss is directly proportional to the refractive value. The thickness of the ZnO film is varied to optimize fiber performance. The loss is greater when the thickness is less than 10 μm for double-cladding fiber optics. This finding can provide a theoretical basis for us to design high-performance heterocore macrobend fiber optics for different purposes in the future.

Data Availability

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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