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Evanescent wave analysis and experimental realization of refractive index sensor based on D-shaped plastic optical fiber

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ABSTRACT

A simple D-shaped plastic multimode fiber optic sensor is proposed and demonstrated for refractive index testing. The D-shaped fiber is fabricated using the wheel side-polishing method. Experimental results exhibit a good linear relationship between the receiving optical power and the refractive index of the test medium. Different parameters, such as the depth, the length and the bending of the D-shaped region, are taken into account to analyze and optimize the sensitivity of the sensor. Normalized transmittance intensity decreases 13.4% with the refractive index increasing from 1.333 to 1.455 when the depth and length are 500 μm and 2 cm with excurvature radius of 5 cm and optical source wavelength of 652 nm. For different refractive indices of the test medium, we simulate the energy distribution of the D-type structure by using Finite Element Method, which achieves a good agreement between the experimental and theoretical results. Such a low-cost and easily fabricated structure will be competitive for remote and continuous measurement of refractive index in chemical, biological, and biochemical sensing areas.

1. Introduction

Fiber-based refractive index (RI) sensors have attracted considerable interest in recent years due to their compactness, light weight, convenience for remote measurements. The traditional fiber based RI sensors include photonic crystal fibers (PCFs) [1,2], long period fiber grating technology [3,4], optical fiber Mach–Zehnder or Fabry–Perot interferometer technology [5–8], surface plasmon resonance (SPR) technology [9,10], etc. However, most of these RI sensors are either expensive or hard constructed or highly sensitive to environmental temperature changes.

Plastic optical fiber (POF) is now widely recognized to offer various important advantages, compared with the silica fiber sensing. Except for being inexpensive and easy to handle, the POF are always with good flexibility, tensile strength, immune to electromagnetic interferences and big modulus of elasticity [11,12]. Additionally, POF based sensing structures are more stable for multi-sensor scheme or can be employed under harsh conditions without significant sensor performance deterioration [13]. Therefore, POF based refractive index sensor attracted much attention of researchers in recent years. Several schemes of POF based refractive index sensors have been proposed so far, such as tapered structure, in-line hole based structure. Teng [14] reported a tapered micro/nano RI POF sensor, the resolution is 7.96×10^{-5} for the RI range from 1.332 to 1.391 at the wavelength of 635 nm, however, the cladding of the POF limits the measurement range of the RI. Shin, etc. [15] proposed a compact refractive index sensor by microdrilling an in-line submillimeter hole in POF directly. For a 0.35 mm-radius hole, transmittance has been measured at 670 nm with the RI changing from 1 to 1.5, such a novel structure may need an expensive fabricating system.

This paper presents a D-shaped plastic optical fiber RI sensor by polishing the surface of the fiber to expose the evanescent field to the external environment. Interaction between the evanescent wave of the surface of the D-shaped fiber and the external environment results in an optical transmission attenuation. The refractive index of the external environment is measured by detecting a change in transmitted light power. The depth, the length and the bending type of the D-shaped region, are taken into account to analyze and optimize the sensitivity of the sensor, achieving a refractive index sensor with good linearity and sensitivity. Additionally, theoretical analysis based on finite element method is in accordance with the experiment. Such a low-cost and easily fabricated structure will be competitive for remote and continuous measurement of refractive index in chemical, biological, and biochemical sensing areas.

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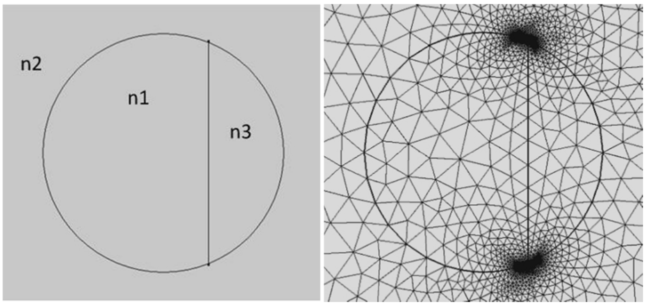

Fig. 1. D-shaped optical fiber sensor geometry and mesh dividing.

2. Theoretical bases and simulation

The operating principle of sensing is based on attenuated total internal reflection (ATR) via multiple internal reflections along the fiber, which forms a decayed evanescent field in the interface of fiber-optic probe and the external environment. Different modes propagating through the fiber has different evanescent fields. The evanescent field will increase as the order of the mode increases, thus higher order modes have a larger distribution of the optical power in the evanescent area. The expression of V-number that describes the number of modes in a D-shaped fiber can be expressed as [16]:

$$V_D = V_{\mathrm{eff}} = \frac{2\pi r_{\mathrm{eff}}(d)}{\lambda}\sqrt{n_{\mathrm{co}} - n_{\mathrm{ext}}} \quad (1)$$

where λ is the wavelength of transmitted light; n_{co}, n_{ext} are, respectively, the refractive index of the core and external environment; and r_{eff} is the effective radius of the D-shaped fiber related to the D-shaped depth of the fiber. Obviously, the fiber's normalized frequency V_D changes with the RI of the environment around the D-shaped region changing, and as a consequence, the optical power distribution ratio of the fiber core to external part will be changed simultaneously. It is viable to detect the RI of the external environment by analyzing the optical power's change.

Finite element method (FEM) is usually used to simulate physical phenomena by solving the partial differential equation (single field) or partial differential equations (Multi-fields). In this letter, FEM is utilized to study the D-shaped structure's effect of optical fiber sensor [17]. In order to reduce the computational complexity of mode field analysis for the large aperture plastic optical fiber, a non-standard multimode fiber with a 16 μm core and a 40 μm cladding thickness is chosen as a model for simulation analysis. The sensor geometry and mesh dividing is shown in Fig. 1. It is defined that the core refractive index n_1 is 1.492 and refractive index of the cladding n_2 is 1.417, which represents the RI of the PMMA core and fluorinated polymeric cladding. The incident wavelength of light is 652 nm and meets the scattering boundary conditions in simulation. The circle arc at the right side is defined as the testing medium, making refractive index n_3 change from 1.33 to 1.44. Both the core and the test medium are defined as loss-free dielectric to analyze the guided mode field based on the above-mentioned model.

For different refractive index of the test medium, we analyze and simulate the energy distribution of the light field inside and outside the D-type regions. As shown in Fig. 2(a), we choose the different

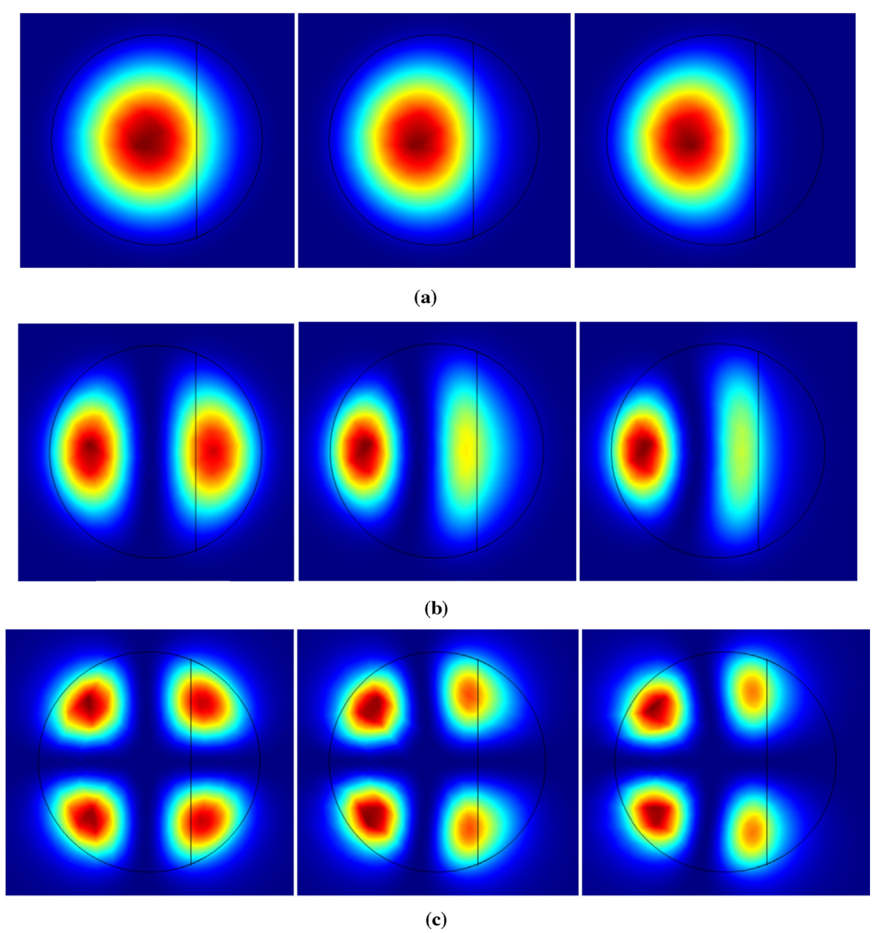

Fig. 2. Typical modes' energy distribution in D-shaped fiber for different RI.