Optik - International Journal for Light and Electron Optics 170 (2018) 237–241

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Depressed index clad fiber as a highly sensitive low-cost refractive index sensor

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ARTICLE INFO

Keywords:
Optical fiber
Refractive index
Sensor
Resolution

ABSTRACT

We present a simple, compact, low cost and ultra high sensitive refractive index sensor based on depressed index clad fiber. The leakage loss of the fiber is highly sensitive to the variations in the refractive index of the outermost leaky layer. We utilize different portions of leakage loss curve to design sensors in different ranges, with different resolutions and for specific applications. One of such designed sensor work in the range 1.4573250–1.4573500, which corresponds to the refractive index of jojoba oil. The resolution within this range is of the order of 4×10^{-7} which is the maximum resolution of the sensor. The fabrication of the sensor only requires etching of some portion of the cladding of the fiber and does not require costly methods of wavelength or polarization interrogation.

1. Introduction

Measurement of refractive index of various biological and chemical samples is important for detecting several physical and biological parameters. Biological or chemical events are exactly the change processes of particular substances and cause refractive index change. The sensor community has, therefore, paid considerable attention towards the refractive index sensors. Several methods have already been reported for measurement of refractive index of various types of materials including biological samples Refraction of light by turbid colloidal dispersions has been of interest to physical chemists for more than 50 years [1]. Yet, only a few reports have appeared hitherto on the measurement of refractive index of colloidal spheres. The classical methods of measuring refractive index from critical angle and Brewster angle are not suitable for absorbing and turbid liquids [2]. For sensing refractive index of biological sample there is a need to measure small changes in refractive index in small volumes of liquid. Traditional bulk refractometers are inconvenient for such measurements. In view of the above there is a need for development of alternative refractive index sensors. An optical fiber refractive index sensor provides a good alternative for a compact lightweight and highly sensitive refractive index sensor. An optical fiber refractometer is also suitable for remote sensing and in otherwise inaccessible places. In addition, it is usable for sensing liquids or polymer composites. The amount of sample needed to carry out the measurement can also be very small. Currently, metal-coated fibers employing surface plasmon resonances [3,4] and fiber Bragg grating (FBG) are being widely studied as highly sensitive refractive index sensing devices for biological and chemical fields [5]. Tapering of fiber and stripping of the fiber cladding have also been used as another alternative for refractive index sensors [6,7]. Long period grating (LPG) [8] and untapered fully cladded fibers with thin films overlays [9] have also been used as refractive index sensors. Villatoro et al. have proposed a low cost optical fiber refractive index sensor based on core diameter mismatch [10]. The sensor has been formed by splicing a short section of single mode fiber (SMF) to a multimode fiber. Recently, we have also proposed a low cost core diameter

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https://doi.org/10.1016/j.ijleo.2018.05.105
Received 23 March 2018; Received in revised form 23 May 2018; Accepted 23 May 2018
0030-4026/

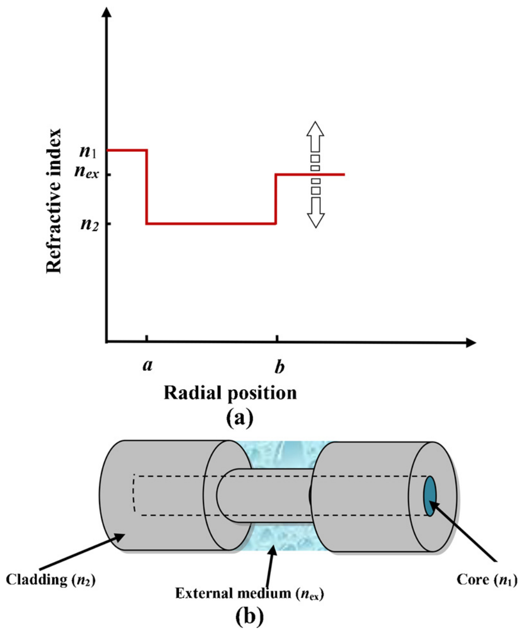

Fig. 1. (a) Refractive index profile and (b) Schematic representation of a DIC leaky fiber.

mismatch based sensor in a single-mode fiber [11]. Wang et al. have reported a very high resolution refractive index sensor with sensitivity 2×10^{-7} RIU [12]. However the choice of technique employed is a tradeoff between fabrication cost, practicality, robustness, simple manufacturing processes, sensitivity, and sensing range.

Here we present an optical fiber sensor that combines simplicity, compactness, high resolution, low cost and competitive sensing range. The sensor is based on a depressed index cladding (DIC) type leaky fiber. Leakage loss in such fibers can be highly sensitive to the variations in refractive index of the outermost leaky layer. We show that for a particular value of refractive index of the leaky layer there can be resonant leakage of power and one obtains a peak in a leakage loss curve as a function of refractive index. The regions near the peak can be utilized in designing a highly sensitive short-range refractive index sensor. The regions away from the peak are less sensitive to the variations in refractive index and can be utilized as large- range refractive index sensors.

2. Fiber structure

The refractive index profile of the proposed DIC leaky fiber structure is shown in Fig. 1, where a is the core radius and b defines the radius of the inner cladding of the fiber. n_1 and n_2 are the refractive indices of the core and the inner cladding of the fiber respectively. n_{ex} is the refractive index of the outermost layer and corresponds to the refractive index of the material to be sensed. The sensor can be realised by etching out a portion of the cladding of a step-index optical fiber and placing the test material in the etched region. The width of the outermost layer is assumed to be infinitely extended. In such a DIC fiber the outer cladding refractive index is higher than that of the inner cladding and the modes of the fiber can be leaky. Calculation of this leakage loss of the fiber is extremely important for studying the performance of the sensor. We considered single mode DIC type fiber in which we varied the refractive index of the outermost cladding and studied the corresponding leakage loss and effective index of the mode by using transfer matrix method [13]. From leakage loss we have calculated corresponding transmittance in a certain length of the fiber.

3. Sensing mechanism

The sensing mechanism of the sensor described here relies on the fact that guiding of the leaky modes only occur over a fraction of a degree for in-coupling angle of the light for a given refractive index. This occurs when the angle of incidence is greater than the critical angle. At the same time, an evanescent wave is produced in the cladding of the fiber. The evanescent wave propagates parallel to the core-cladding interface, and decays exponentially from the interface. If the thickness of the inner cladding layer is comparable to the penetration depth of the evanescent field of the mode, tunneling of the power in the outer cladding of the fiber takes place. Any variation in the refractive index of the outer medium (n_{ex}) changes the amount of power it can trap and thus, changes the transmittance of the fiber. The structure can, therefore, work as a refractive index sensor. This tunneling of energy into the outermost region can be very strong for a particular value of n_{ex} due to resonance effect and the variation of transmittance of the fiber with n_{ex} near this value can be very strong. In this region the fiber can work as a highly sensitive refractive index sensor. For higher values as the refractive index of the external medium increases, leaky modes are more confined and we get decrease in leakage loss. This region of higher refractive index can be used for designing less sensitive refractive index sensor.