Novel Optical Fiber Sensor Based on SGMS Fiber Structure for Measuring Refractive Index of Liquids and Gases

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In this paper a single mode-gap-multimode-single mode fiber structure (SGMS) as refractive index sensor is demonstrated. A beam propagation method (BPM) for the circular symmetry waveguide is employed for numerical simulations of the light propagation performance in such fiber devices. The multimode interference effect is revealed to design optical fiber sensor with reasonable linearity in wide range of refractive indices. A simple way to predict and analyze the spectral response of the SGMS structure is presented with the derived approximated formulations. The proposed sensor is realized by using standard optical fibers.

Results indicate that the proposed SGMS structure can be exploited for measuring a broad refractive index range with reasonable high resolution. The results achieved for refractive indices in the range of 1.1 to 1.43 have best linearity with correlation coefficient 0.9991 at wavelength of 1550 nm. Therefore, it can be suggested that the SGMS structure fibers are attractive for measuring refractive index of both gases and aqueous solutions such as chemical liquids, biological, and biochemical sensing.

Keywords: Optical fiber sensor, Multimode interference, Refractive index, Self-imaging
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1. Introduction

Optical fiber based refractive index (RI) sensors have attracted considerable interest in recent years, because of their many excellent characteristics, including corrosion resistance, immunity to electromagnetic interference, high precision, small size, the potential for remote operation. These advantages are important for applications in areas like biomedical measurement and environmental protection [1,2]. Recently many ways to implement RI sensing is appeared, for example using a SMS fiber based refractometer [2], tapered graded-index polymer optical fibers [3], a Fabry-Perot interferometer [4], a multi-D-shaped optical fiber [5], and holey fiber tapers with resonance transmission [6]

A single mode-gap-multimode-single mode (SGMS) fiber structure is a combination of two different types of optical fiber, where a short length of multimode fiber (MMF) and very short gap are sandwiched between input and output single mode fibers (SMFs) as shown in Fig. (1). The light injected into the input SMF pass throught the gap toward the MMF. Then the light excites multiple modes propagating in the MMF. Interference occurs between these modes (multimode interference "MMI") and as a result, the nature of the light reaching the output SMF is dependent on a number of physical parameters, such as refractive index of gap, refractive index of core, core diameter and the length of the MMF section. This dependence gives SGMS fiber structures great potential for use as sensors, such as refractive index measuring sensor [7,8].

Multimode interference (MMI) in multimode waveguides has interesting self-imaging properties, which have extensively investigated and utilized in many integrated optical devices. Self-imaging can defined as a property of multimode waveguides by which an input field profile is reproduced due to constructive interference to form single or multiple images of the single mode input field at periodic intervals along the propagation direction of the guide. In SGMS fibers structure, the MMI in the multimode section leads to the formation of a self-image of the single mode fiber excitation onto the output single mode fiber core [9].

This paper presents a novel type of optical fiber sensor for measuring refractive index based on an SGMS fiber structure. The simulation of optical field propagation in SGMS fiber structures is obtained by the beam propagation method (BPM). Self-imaging in symmetrically excited multimode optical fibers is simulated to explore the effects of change refractive index in gap on SGMS fiber device characteristics. The SGMS fiber structure is optimized to provide high precision optical fiber sensor for measuring refractive index of fluids.

2. Modeling of Light Propagation in SGMS Structure

The proposed optical fiber sensor consists of SMF, short gap, MMF and SMF. The laser light injected through input SMF then it passes through the gap into MMF fiber. The MMI effect takes place

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when light is coupled into the SMF and excites all the modes supported by the MMF. Single images of the SMF input signal will appear along the MMF at periodical intervals along its axis, due to the interference between the modes as they propagate along the MMF [4, 5]

With certain length of MMF, the coupling loss of the SGMS fiber structure depends strongly on the refractive index of gap material but it is also wavelength sensitive. The structure of the proposed optical fiber sensor is shown schematically in Fig. (2). It can note that the gap between the input SMF and MMF and the gap is supposed to be filled by the medium whose RI is to be measured.

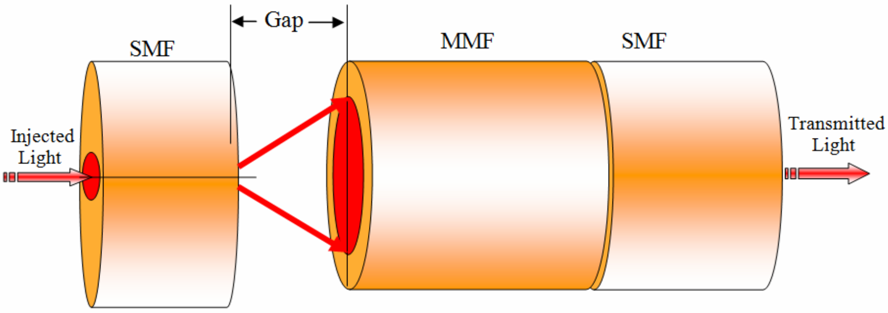

Fig. (1) Single mode-gap-multimode-single mode (SGMS) fiber structure

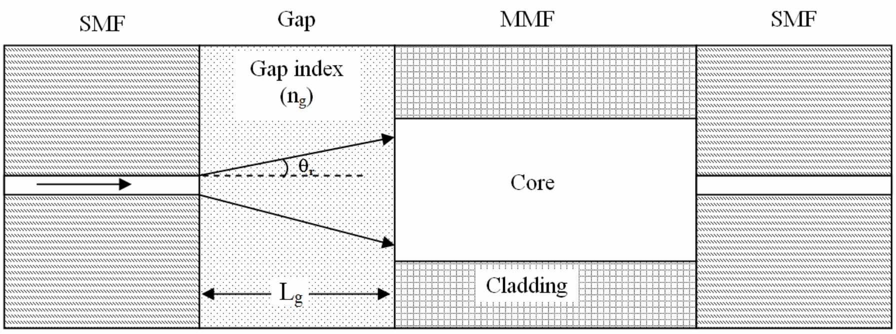

Fig. (2) The structure of the proposed optical fiber sensor

To study the light propagation in SGMS structure, it can assume that the SGMS consist of two sections. First section formed from single mode fiber and gap. Second section formed from whole multi mode fiber and output single mode fiber. In first section, the light pass through the SMF is emitted into the gap according to geometry of optical fiber.

Now consider the geometry of Fig. (2), where a refraction at the fiber–gap interface is occurs, the ray bends faraway from the normal on fiber axis. The angle θ_r of the refracted ray is given by [10]:

$$n_g \cdot \sin\theta_r = \sqrt{n_{SMF}^2 - n_{CLS}^2} \quad (1)$$

and;

$$\theta_r = \sin^{-1}\left(\frac{\sqrt{n_{SMF}^2 - n_{CLS}^2}}{n_g}\right) \quad (2)$$

where n_{SMF} and n_{MMF} are the core refractive index of both SMF and MMF respectively.

It can be calculate the field at end of gap (incident field on the multimode fiber) depends on the input field, the surface areas of the fiber aperture and transmitted beam at end of gap. Therefore, it can express as in the following equation.

$$E_g = E_i \frac{S_f}{S_g} \quad (3)$$

and;

$$S_g = \pi \cdot \left(L_g \cdot \tan(\theta_r)\right)^2 \quad (4)$$

$$S_f = \pi \cdot r_{SMF}{}^2 \quad (5)$$

where E_i is the input field, E_g is the field at end of gap, S_f is Surface area of fiber aperture, S_g is Spot surface at end of gap, r_{SMF} is the radius of the single mode fiber core and L_g is the length of gap

The second section formed the multimode interference. Multimode interference (MMI) in multimode waveguides has interesting self-imaging properties. Therefore, the transmission of multimode–single mode fibers structure can be calculated by [7,9]:

$$L_S(z) = 10\log_{10}\left\{\left|\sum_{m=1}^{M} c_m^2 \exp\left[-i\left(\frac{(2m+1)(2m-1)\pi}{\overline{L_z}}\right)z\right]\right|^2\right\} \quad (6)$$

where c_m is the excitation coefficient of each mode and M is excited mode number of the multimode fiber. It can calculate by:

$$m = V/\pi \quad (7)$$

and,

$$V = \frac{2\pi \cdot a\sqrt{n_{MMF}^2 - n_{cl}^2}}{\lambda} \quad (8)$$

where V is the normalized frequency, a is the radius of the multimode fiber core and n_{cl} is refractive index of multimode fiber cladding, and λ is the wavelength of light in the free-space

By substituting in the approximation (6), then it can be rewritten as below:

$$L_s(z) = 10\log_{10}\left(\left|\sum_{m=1}^{M} c_m^2 \exp\left(-i(2m+1)(2m-1)\pi\right) g(\lambda,z)\right|^2\right) \quad (9)$$

$$\overline{L_z} = \frac{16\, n_{MMF}\, a^2}{\lambda}$$

where $g(\lambda,z) = \lambda z / 16\, n_{co} a^2$, and;

$$c_m = \frac{\int_0^\infty E_g(r,0) F_m(r) r dr}{\int_0^\infty F_m(r) F_m(r) r dr} \quad (10)$$

where $E_g(r,0)$ is the input light to the multimode fiber and F_m is the field profile of LP_{0m} [9]

According to MMI theory, the peak wavelength of a MMI device is given by [8]:

$$\lambda_o = 4p\frac{n_{MMF} \cdot a^2}{L} \quad \text{with p=1, 2, 3} \quad (11)$$

where, L is the length of the MMF and p is the self-image number

As shown in Eq. (11), the peak wavelength response of the MMI section can be selected by simply changing the length of the MMF. An additional advantage when changing the length of the MMF for optimizes the optical response of refractive index sensor where a linear sensing response of the MMI device is obtained.

3. Simulation Results

The proposed SGMS structure formed from standard silica optical fibers. The standard single mode fiber (SMF-28) is chosen as the single-mode fibers, of which the parameters are: the refractive index for the core and cladding is 1.4504 and 1.4447, respectively, at wavelength 1550 nm and 8.3/125 µm core/cladding diameters [9]. The standard multimode fiber has a 62.5µm core/cladding diameters with group index of refraction of 1.491 at 1310 nm [11].

The simulation is done by using BMP software to numerically simulate optical field propagation in different gap length of SGMS fiber structures. According to the simulation results, the MMF length is further optimized to L = 11 mm in order to achieve the best linear characteristics and wider refractive index range at wavelength of 1550 nm.

Figure (3) shows three curves represent the relationship between the power transmission and refractive index with three gap lengths. It can note that, the curve with gap length of L_g=1.5 mm is best linearity over refractive index range of 1.1-1.43. While the curve with gap length of L_g=1 mm has less linearity over refractive index range of 1.26-1.43. Also curve with gap length of L_g=0.75 mm has less linearity over refractive index range of 1.1-1.26. A linear regression method employed to analyze the relationship between sensor response and refractive index changes. This method calculated the best-fitting linear equation (straight line) for the observed data using the least squares approach. Figure(3) shows a linear fit with correlation coefficient R=0.9991 to the plot of sensor response as a function of the refractive index for a sensing fiber with gap length of 1.5 mm. Others curves has correlation coefficients of R=0.9976 and R=0.9991 for gap lengths 1 mm and 0.75 mm, respectively.

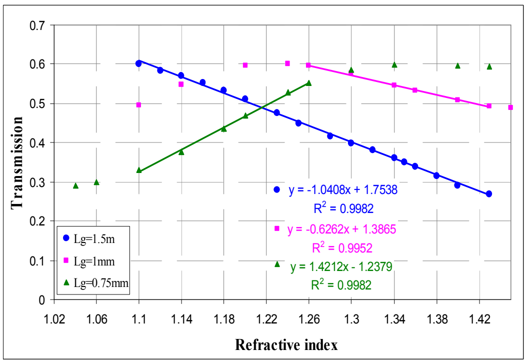

Fig. (3) The relationship between the ratio of power transmission and refractive index with three gap lengths

Figure (4) shows the spectra response of optical sensor with gap length of 1.5 mm as a function of wavelength from 1500 nm to 1600 nm for four refractive indices. It can see that all peaks shift to longer wavelengths as the refractive index of gap is decreased. The shift of the peaks is more remarkable for lower indices. In that range of indices, the intensity of the peaks changes with the refractive index, but their shape approximately remains constant.

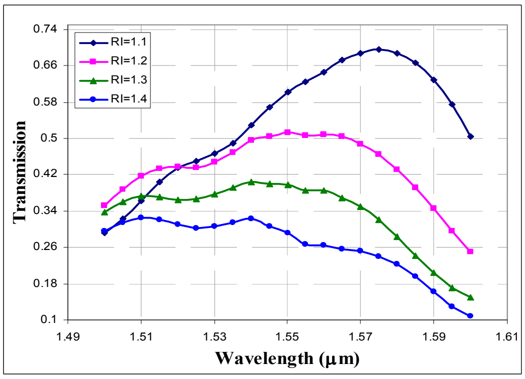

Fig. (4) Power transmission versus the wavelength with various refractive indices for gap length of 1.5mm

The relationship between the power transmitted over the SGMS structure and the refractive index of gap with different wavelength for gap length of 1.5mm is shown in Fig. (5). It can note that the response of optical sensor depends on the wavelength due to the MMI effect. By using a linear regression method to analyze the relationship between sensor response and refractive index changes, it can note that, the sensor response curve with wavelength of 1550 nm is best linearity over refractive index range of 1.1-1.43 with correlation coefficient R=0.9991. While the sensor response curve with wavelength of 1540 nm has less linearity with correlation coefficient R=0.99237. In addition, the sensor response curve with wavelength of 1560nm has less linearity with correlation coefficient R=0.99594. Therefore it can conclude that the proposed optical sensor is operate better at wavelength of 1550 nm with wide range (1.1 -1.43) and best linearity.

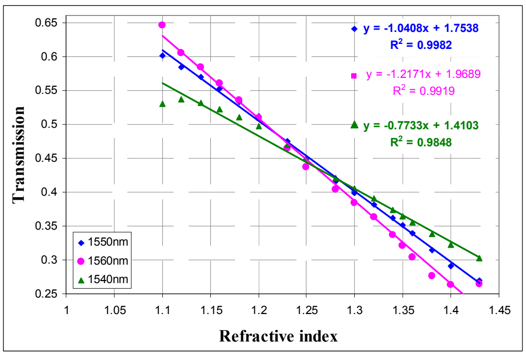

Fig. (5) Power transmission versus the refractive index with different wavelength for gap length of 1.5 mm

Figure (6) represent the field propagation through the SGMS structure for proposed optical sensor (length of MMF is L=11 mm and length of gap is) at wavelengths of 1550 nm with different refractive index of gap. It is clear that (in MMF section) self-imaging of the input field takes place so that at periodic intervals, a single image of the input field is reproduced. This occurs at distances of 3250μm, and 7150 μm measured from input end of MMF fiber at wavelength of 1550 nm. Multi-fold images of the input field can also be found at 1300 μm, 5000 μm, and 8900 μm. Therefore, It can be conclude that, the self-imaging occur at specific lengths only for certain wavelengths.

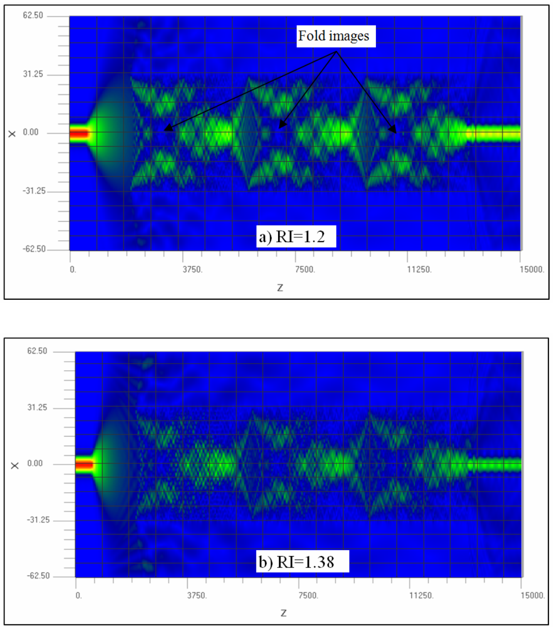

Fig. (6) Propagating fields through proposed optical sensor (a) Propagating fields at 1550 nm with gap refractive index of 1.2 (b) Propagating fields at 1550 nm with gap refractive index of 1.38

Figure (7) shows three curves represent the relationship between the power transmission and refractive index with three multimode fiber lengths at gap length of 1.5 mm over refractive index of 1.1-1.43. It can note that, the curve with MMF length of L=11 mm has best linearity, while the curve with MMF length of L=10.9 mm has less linearity. Also curve with MMF length of L=11.1 mm has less linearity.

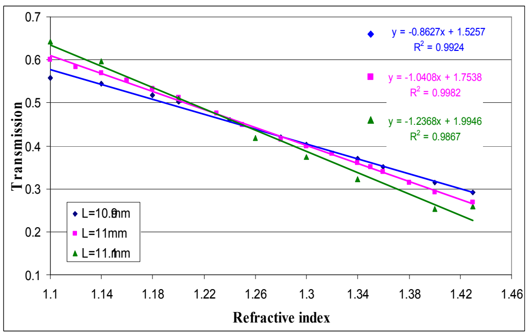

Fig. (7) Represent the relationship between the power transmission and refractive index with various multimode fiber length

By applying a linear regression method to obtain the best-fitting linear equation for the simulated data using the least squares approach. Figure (7) shows a linear fit with correlation coefficient R=0.9991 to the plot of sensor response as a function of the refractive index for a sensing fiber with MMF length of 11 mm. Others curves has correlation coefficients of R=0.9962 and R=0.9933 for MMF lengths 10.9mm and 11.1mm respectively. That is the reason why the length of the multimode fiber is chosen equal to 11 mm rather than 10.9 mm or 11.1 mm for proposed optical filter.

4. Conclusion

In conclusion, a simple optical fiber sensor for refractive index measurements based on the MMI phenomenon of self-imaging was demonstrated. The optical sensor was utilized compose of single mode-gap-multimode-single mode fiber structure. The power transmission of optical fiber sensor was plotted, from which the device was found to be suitable for refractive index sensor.

The proposed refractive index sensor is utilized standard optical fibers; therefore, the light source and the fiber used in sensor are compatible with the low-cost 1550nm optical communication technology. Additionally, the device is quite simple and relatively inexpensive when compared with other optical sensor techniques. The results reported here demonstrate that the SGMS fiber sensor is attractive for chemical, biological, and biochemical sensing with aqueous solutions further than it may used in gas refractive index sensing.

References

[1] Z.L. Ran et al., "Laser-micromachined Fabry-Perot optical fiber tip sensor for high-resolution temperature independent measurement of refractive index", *Optics Express*, 16(3) (2008) 2252-2263.

[2] Q. Wu et al., "High sensitivity SMS fiber structure based refractometer – analysis and experiment", *Optics Express*, 19(9) (2011) 7937-7944.

[3] J. Arrue et al., "Analysis of the use of tapered graded-index polymer optical fibers for refractive index sensors", *Optics Express*, 16(21) (2008) 16616-16631.

[4] Y. Tian et al., "A Miniature Fiber Optic Refractive Index Sensor Built in a MEMS-Based Microchannel ", *J. Sensors,* 11(1) (2011) 1078-1087.

[5] C.-H. Chen et al., "A Multi-D-Shaped Optical Fiber for Refractive Index Sensing", *J. Sensors*, 10(5), (2010) 4794-4804.

[6] V.P. Minkovich et al., "Holey fiber tapers with resonance transmission for high-resolution refractive index sensing", *Optics Express*, 13(19) (2005) 7609-7614.

[7] L.B. Soldano and E.C.M. Penning, "Optical Multimode Interference Devices Based on Self-Imaging: Principles and Applications", *J. Lightwave Technol.*, 13(4), (1995) 615-627.

[8] A. Castillo-Guzman et al., "Widely Tunable Erbium-Doped Fiber Laser Based on Multimode Interference Effect", *Optics Express*, 18(2) (2010) 591-597.

[9] Q. Wang et al., "Investigation on single mode-multimode-single mode fiber structure", *IEEE J. Lightwave Technol.*, 26(5) (2008) 512-519.

[10] G.P. Agrawal, **"Fiber-Optic Communication Systems"**, John-Wiley & Sons Inc., (2002), Ch. 2, p. 25.

[11] Draka.com, "C02: General purpose multimode 62.5μm fiber", www.draka.com/communications, C02_e, 2010, version 10.

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