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Long Period Fiber Grating for Refractive Index Sensing

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ABSTRACT

Refractive index (RI) sensors are very valuable in first level detection of changes to the environment. In this project an optical fiber-based sensor is proposed to detect changes in surrounding RI. Most optical fiber sensors require tapering to be done to enhance the light interaction with the surrounding. This causes the fiber to become fragile and difficult to handle. In this research, optical fibers with long period gratings (LPG) are proposed to overcome this issue. Zinc Oxide (ZnO) nanomaterial was deposited over the LPG region using seeding method to enhance the performance of the sensor. The LPG fiber sensor was then used to investigate RI changes in the environment. A broadband laser source was used as the input and an optical spectrum analyser was used to observe the output light spectrum of the LPG sensor for different refractive index mediums. The ZnO coated LPG showed a sensitivity of 428.57 nm/RIU over an RI range of 1 – 1.3578.

1. Introduction

Optical fiber-based sensors are gaining huge popularity in the research community in recent years. Optical fibers, which were conventionally used in the telecommunication industry, to carry data and signals, have proven to be very versatile due to their numerous applications in other areas such as in imaging, surgery, illumination and sensing [1,2]. Optical fibers as sensors offer great advantages over conventional electrical or electronic sensors due to their flexibility to be inserted in tight spaces, non-electrical making it safe from shorting or sparking, robust and non-corrosive. Being a transmission channel itself, there is no need to convert the signal from the sensing device to be transmitted to a remote location. Optical fiber sensors have been applied for sensing of both physical parameter such as stress and strain, temperature and pressure as well as in chemical and biological sensing applications [3,4]. These properties make optical fiber sensors increasingly popular for sensing investigations.

Various methods for optical fiber-based sensing have been reported such as absorbance, reflectance, intensity, wavelength and polarization-based techniques [5-7]. Most methods require

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some modification to the optical fiber cable such as tapering, bending, twisting or adding gratings. Optical fiber gratings are currently gaining popularity as they are highly sensitive and do not require the fiber to be tapered as tapering makes the fiber very fragile. Optical fiber gratings such as Fiber Bragg Gratings (FBGs) and Long Period Gratings (LPGs) had been conventionally employed as sensors to detect physical parameters such as stress, strain and temperature [8,9]

Currently LPG sensors have been also gaining popularity in chemical and biological sensing [10,11]. In this research, we explore the LPG for refractive index (RI) sensing applications. This would be preliminary research towards further work in LPG sensors for chemical and biological sensing applications. Most chemical and biological sensors require some form of sensitive layer to enhance the sensing capability [12]. Zinc oxide nanoparticles have been gaining a lot of attention in sensing [13,14]. In this research we use a Zinc Oxide (ZnO) layer as the sensitive layer. The sensor is investigated towards various RI values by introducing dipping the sensing region into various mediums with different RI values. This simple method will prove the ZnO coated-LPG sensor can be used as an RI sensor without tapering or modifying the dimensions of the optical fiber.

Korposh *et al.,* [15] used an LPG with a Silicon Oxide (SiO2) mesoporous coatings to develop an RI sensor. This mesoporous coating was deposited using layer-by-layer (LbL) technique on LPGs. The transmission spectrum was observed by immersing in two different types of solutions for characterizing the sensitivity of coated-LPG for resonant wavelength. The solutions used were different concentration of silica colloidal solutions and sugar solutions. This technique yielded highly accurate result; however, the deposition process was quite tedious and complicated. Tan *et al.,* [16] reported an LPG deposited with carbon nanotubes (CNTs) for refractive index detection in liquids. The deposition of the CNTs were done using a spraying technique. The developed sensor demonstrated high sensitivity of approximately 40 dB/RIU during their experimental work. This study shows great promise for further work in LPG based sensing in an aqueous environment.

2. Sensing Principle of LPG with ZnO Layer

A long period grating is an optical fiber which has had the core modified to have periodic refractive index variations using laser radiation. An LPF is basically a wavelength selective filter where the transmission spectrum is characterized by the coupling between the core mode and the copropagating cladding modes at a resonance wavelength which is given in Eq. (1)

$$\lambda_{res} = \left(n_{co}^{eff} - n_{cl}^{eff}\right)\Lambda \tag{1}$$

where λ_{res} is the resonant wavelength and n_{co}^{eff} and n_{cl}^{eff} are the effective index of the core and cladding respectively. Λ is the grating period.

The ZnO deposited LPG works on the principle of light absorbance of the cladding modes of the light travelling through the fiber with ZnO layer. The fundamental core mode (LP01) couples with the cladding modes (LP0m) when it meets the phase matching conditions in Eq. (2)

$$\beta_{01} - \beta_{clad}^{m} = \frac{2\pi}{\Lambda}, \;\; m = 1,2,3 \ldots \tag{2}$$

where β_{01} and β_{clad}^{m} are the copropagating constants of the fundamental modes and mth cladding modes respectively.

When the RI of the surrounding medium, (n3) is lower than the cladding, n2, any increase in n3 will cause a corresponding increase in the effective index of the cladding resulting in a blue shift of the resonant wavelengths when the surrounding RI increases. This is derived from Eq. (3) which shows the resonant wavelengths.

$$\lambda_{m,res} = [n_{eff,core}\ (\lambda_{m,res}\ , n_1, n_2) - n_{eff,clad}\ (\lambda_{m,res}\ , n_2, n_3)]\Lambda \quad (3)$$

where $n_{eff,core}$ and $n_{eff,clad}$ are the effective RIs of the core and cladding and $\lambda_{m,res}$ is the resonant wavelength due to coupling of the core and cladding mode.

Therefore, when n3 is higher than the cladding RI, there phase matching is no longer achieved. This will cause the total internal reflection conditions to be not met, resulting in leaky cladding modes. This will cause some of the light to be reflected and transmitted, while some light will be lost out of the fiber. The ZnO layer over the LPG acts as a four-layer waveguide where the transmission spectrum is based on the calculations of the long period modes and the cross and self-coupling coefficients. The RI sensing of the LPG can be observed from the spectrum of the attenuation bands of the sensor.

3. Methodology

3.1 LPFG Sensor Fabrication and Preparation

Several LPFGs were fabricated with the electric-discharge technique [17,18]. This technique is very simple, does not require special optical fibres and specific preparations (as hydrogen loading). The polymer coating has been removed on a portion of a standard single-mode fibre (ex. SMF 28). This portion is placed in between the electrodes of a commercial fibre fusion splicer. A white light source and an optical spectrum analyser (OSA) are connected in both ends of the fibre sample for monitoring LPFG's growth. After each electric discharge, the fibre is translated by a translation stage to a distance equal of the grating pitch. Distinct dips are formed in the transmission spectrum corresponding to resonance wavelengths where the fundamental mode is coupled to a specific higher order mode. The fabrication process is stopped when the isolation of the dip at targeted wavelength is maximal. The LPGs were coated with ZnO using a seeding method and connected to an ASE broadband light source (BBS) as the input and an Optical Spectrum Analyzer (OSA) model MS9740A from Anritsu for collection of data.

3.2 Zinc Oxide Seeding Method

ZnO was deposited LPG region of the fiber optic sensor using the seeding method. The seeding solution was made by mixing Zinc acetate dehydrate [$Zn(CH_3CHOO)_2.2H_2O$] and Sodium Hydroxide (NaOH) were each mixed with 120 ml and 60 ml ethanol respectively. The Sodium Hydroxide solution is dropped into the Zinc acetate dehydrate solution drop by drop to obtain a constant pH value. The pH value is significant as it affects the morphology of the ZnO over the fiber [19,20]. To grow the ZnO nanoparticles, the seeding solution is first kept in an 80°C oven for 3 hours. Then, the stripped LPG was immersed into the seeding solution for 1 hour, while slowly stirring to make the first layer of the nanomaterial on fiber surface. Then the coated fiber undergoes an annealing process at 70°C for 30 minutes. Finally, Zinc hexahydrate ([$Zn(NO)_3]_2$) and Hexamethylenetetramine [$(CH_2)NH_4$] were mixed together with 250 ml of deionized (DI) water to make the growth solution, and the stripped fiber was dipped into the growth solution and kept in an oven for 2 hours at 70°C.

3.3 Optical Sensing Setup

The fabricated sensor was then connected to a broadband light source at the input and an OSA at the output. The experiment was carried out with both uncoated and ZnO coated LPGs. The sensors were immersed in different concentrations of ethanol which had different RIs and the spectral response at the OSA was recorded. The block diagram of the sensing experiment shown in Figure 1.

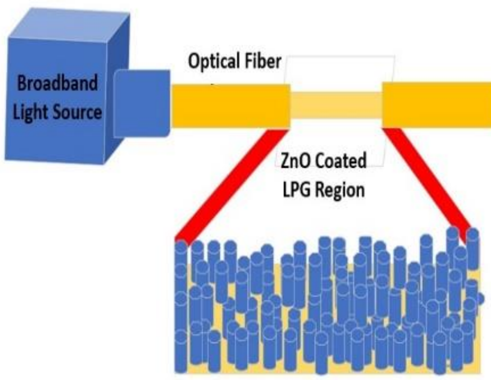


Fig. 1. Experiment Setup

4. Results

The deposition of ZnO on the LPG sensor was characterized by using Scanning Electron Microscopy (SEM). The was done to study the morphology of the ZnO nanostructures around curved structure of the fiber surface. Figure 2 shows the SEM image of the ZnO coated fiber. It can be observed that the ZnO coating has fully coated the fiber and is adhering well.

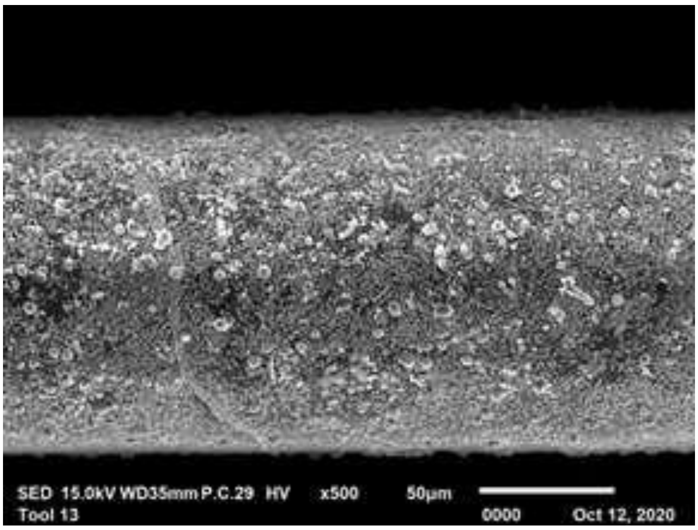


Fig. 2. SEM image of ZnO deposited on LPFG

In Figure 3, further magnification of 15000 was performed to study the structure of the ZnO nanoparticles. It can be seen clearly the ZnO has formed nanorods with approximate diameters of 0.5µm. The ZnO nanorods were found to be distributed evenly throughout the coated region and further investigation around the coated region yielded similar results without any significant uncoated or damaged areas.

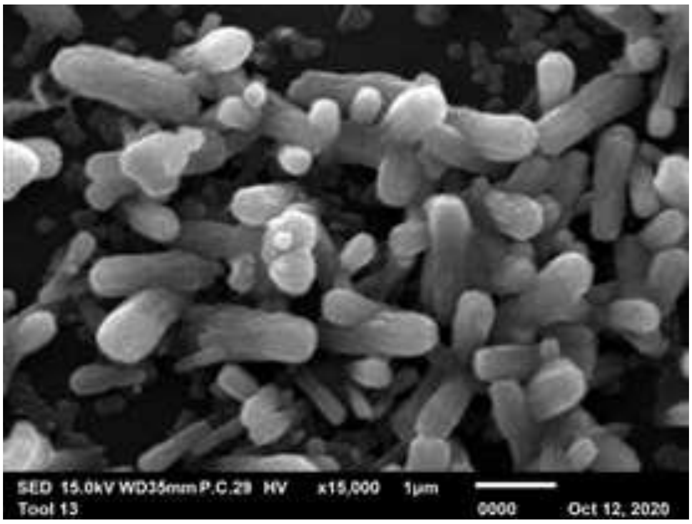
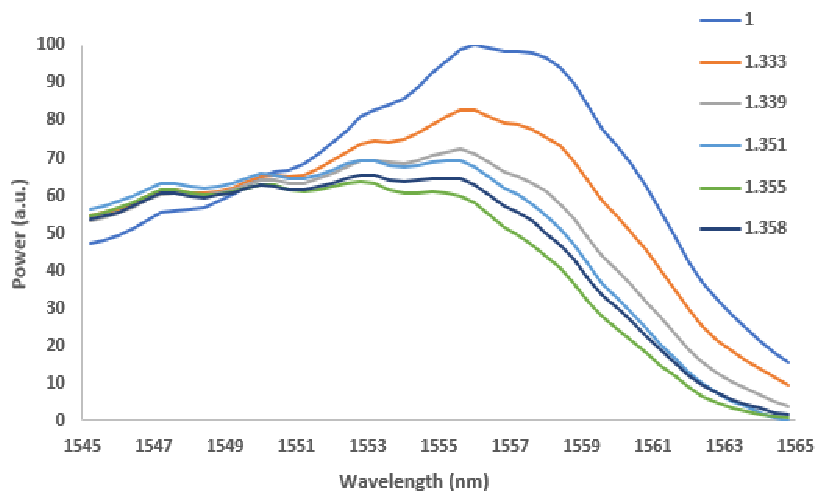


Fig. 3. SEM of ZnO in crystallization shapes

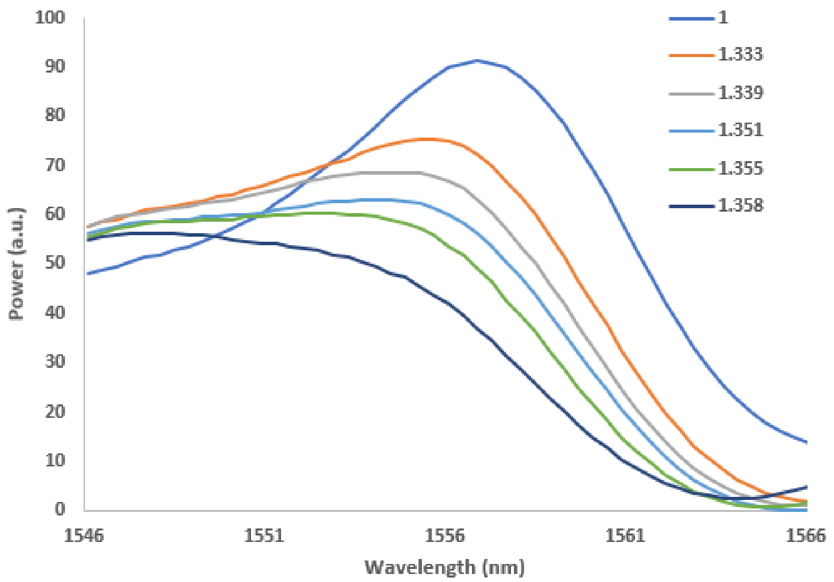
The output spectrum of the uncoated and ZnO coated LPG sensor when immersed in liquids of different RIs are presented in Figure 4(a) and Figure 4(b) respectively. It can be observed that as the RI increased, a corresponding drop in output power occurred for both the uncoated and ZnO coated LPG sensor. A blue shift in the spectrum is also observed for both the uncoated and the ZnO coated LPG sensor when immersed in liquids with increasing values of RI when immersed in liquids of different RI.

The change in the surrounding RI showed significant effect on the transmission of light through the fiber. The observed outputs agree with previous studies reported by other researchers [19,20]. Figure 5(a) and Figure 5(b) presents the graph of the RI versus the output power and wavelength respectively. From both graphs, it can be observed that the ZnO coated LPG sensor demonstrated higher sensitivity towards changes in the surrounding RI. The output power at 1556 nm for different values of RI was plotted in Figure 5(a). Output power was normalized in order to perform better comparison. Both sensors demonstrated high linearity of higher than 90% in their correlation graphs. It was observed that the ZnO coated LPG sensor had a sensitivity that was 35% higher that the uncoated LPG sensor.

The wavelength shifts of ZnO coated LPG sensor also demonstrates a significant increase in sensitivity when compared to the uncoated LPG sensor. A sensitivity of 160 nm/RIU was recorded for the uncoated LPG sensor while a sensitivity of 276 nm/RIU was recorded for the ZnO coated sensor. Form the data obtained, it can be concluded that the ZnO coating significantly increases the sensitivity of the LPG based RI sensor. This is due mainly to the ZnO layer, which has a higher RI than the cladding, causes light that is propagating in the cladding to be extracted from the cladding. This is due to the face that the total internal reflection conditions are no longer met. Changes in the RI values around the ZnO layer in turn causes the effective index of the layer to change. This change in turn affects the light spectrum at the output of the fiber.

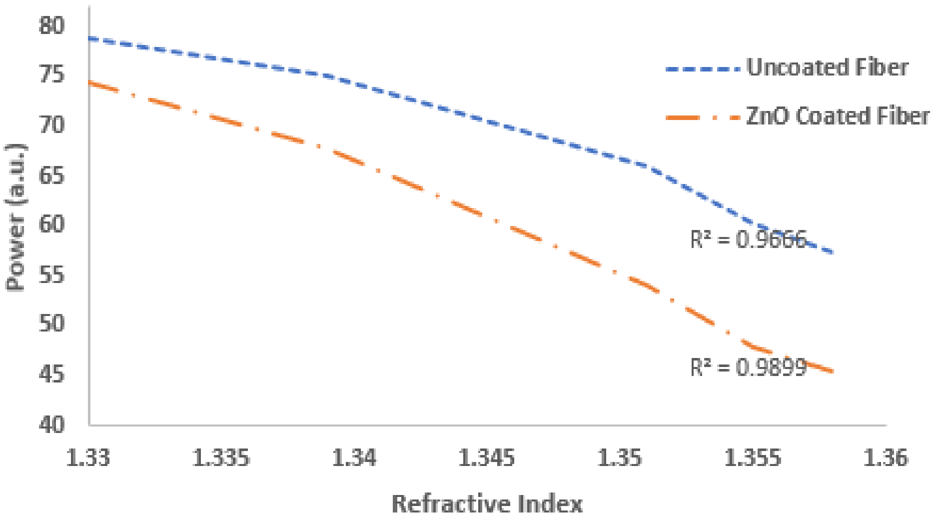


(a)

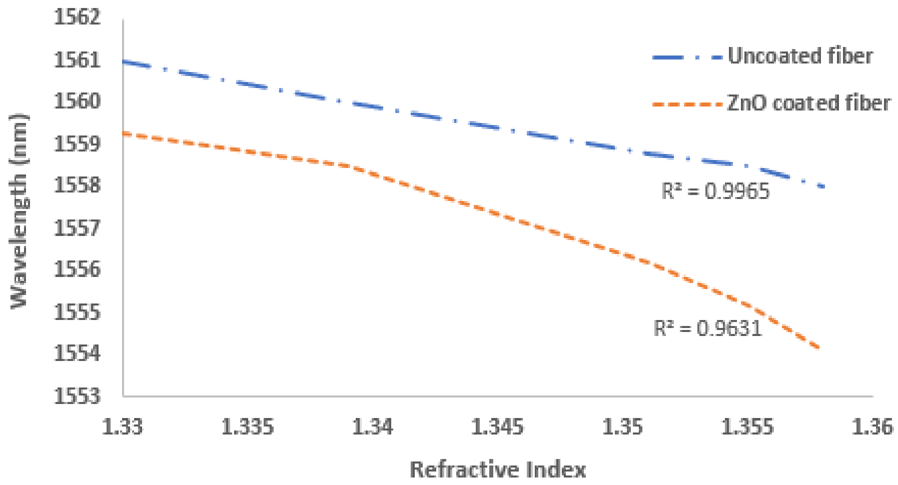


(b)

Fig. 4. Spectrum of the LPG with different surrounding RI (a) Uncoated (b) ZnO coated



(a)



(b)

Fig. 5. (a) RI against output power (b) RI against wavelength

5. Conclusions

In conclusion, an LPG fiber sensor deposited with ZnO nanomaterial was successfully developed and tested with liquids of varying RIs. The seeding method used proved to be effective in producing an even and consistent layer with good adherence to the curved surface of the fiber. Results obtained from this research adds strength to the current trend in the application of nanomaterial coatings to improve the performance of optical sensors.

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