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TEMPERATURE SENSING BY SIDE COUPLING OF LIGHT THROUGH ZINC OXIDE NANORODS ON OPTICAL FIBERS

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ABSTRACT

A temperature sensor fabricated by light side coupling through spirally patterned zinc oxide (ZnO) nanorods coated directly on plastic optical fiber (POF) is reported. A significant response to temperature changes from 20 °C to 100 °C based on extinction concept due to the attenuation of light by scattering and absorption was used. Sensitivity increases by a factor of 1.3 in spirally patterned coatings compared to optical fibers with continuous coating. The simplicity and economical sensor fabrication process for the swift and sensitive detection of temperature changes using visible light source show potential in environmental and biomedical applications.

1. Introduction

Light side coupling in optical fibers through the growth of single crystalline zinc oxide (ZnO) nanorods directly on plastic optical fibers was introduced in our previous work [1]. In this concept, the light scattering due to the incident angle of incident light greater than the critical angle posed by the surrounding and optical fiber core is applied. In this configuration, usually, light propagation inside optical fiber occur through the ZnO nanorods but the intensity of guided light is often low due to the leakage of light through the core mode [2]. This problem was suitably addressed by using large core plastic optical fiber (POF) to increase scattering area [3]. Further improvement was achieved by reducing the net area of ZnO nanorods coating through a structured growth on the POF's [4]. POF's are physically robust and suitable for operation in the visible light regime as compared to glass optical fibers (GOF's). Generally, most optical sensing applications operate with laser light source by launching light from one end of the optical fiber and output signal is collected from other end [5]. This is more complex and often expensive due to the needs of coupling the light in the optical fiber to align the laser beam. Coherent sources with small beam sizes when coupled through ZnO nanorods coating would provide lower sensitivity caused by the inequality of beam structure as it will have different distribution of intensity along the ZnO coating [6] and more importantly the laser beam can only focuses on specific coating area instead of entire coating area.

Conventional temperature sensors have their limitations if large distances have to be covered such as in many distributed measurements, electromagnetic interference leads to the loss of signal to noise ratio, explosive environments does not allow safe use of resistive devices and often in a plurality of applications they do not match when light-weight structures are desired. The fiber optic sensors market is a multi billion dollar business which is prognosed to grow further and fiber optic based temperature sensors are an important class therein as they are immune to electro-magnetic interference and are thus robust and accurate in high-RF environments. Several measurement principles have been described in the literature for measuring temperature sensors such as inten-

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sity modulated fiber optic displacement sensor (FODS) [7], lifetime measurements [8], microfiber loop resonator (MLR) [9], stimulated brillouin scattering [10], interferometer [11] and multicore fiber structure [12]. Although, the temperature sensing using polymer-coated microfiber interferometer reported by Romano et al. has a high sensitivity but it is not able to sense temperature changes at higher range due to low melting point of the polymer. In order to be economically advantageous, an optical fiber temperature sensor must be robust, easy-to-use, fast, accurate, stable over a wide measurement range and suitable for a large variety of applications [13]. In an application, many commercial electronic components can be damaged due to exposure to high temperature (>70 °C) and some can be damaged by exposure to low temperatures (<0 °C) [14]. Semiconductor devices and LCDs (liquid crystal displays) are examples of commonly used components that are susceptible to large temperature variations. In these cases, temperature sensing is indeed important so that appropriate measures can be incorporated to prolong the life of these devices. Optical fiber based temperature sensors are the only possibility in the presence of electromagnetic fields such as in microwave fields, power plants or explosion-proof areas and wherever measurement with electrical temperature sensors is not possible such as in high tension cable lines, airplanes, spacecrafts, electrical motors etc [15].

In a previous report, temperature sensing was demonstrated using ZnO thin films where spectral absorption changes in ZnO was monitored [16]. In this work we present optimized simple yet sensitive spiral patterned ZnO nanorod coatings on POF based temperature sensor capable of utilizing ambient light coupled through the nanorods into the fibers for sensing. Sensing performances of ZnO nanorod coatings, spirally patterned on POF fibers are presented and the results are compared to the sensing characteristics of the unpatterned fibers. Uncoated POF (bare) were not considered for this application since it does not show any scattering effects due to side coupling of light [3,4].

2. Fiber Preparation

POF fiber spiral patterning and ZnO nanorod seeding and synthesis procedures were described in detail in previous works [4,17,18]. Standard polymethyl methacrylate (SK-80 POF fibers from Mitsubishi Rayon Co., LTD; Japan) were utilized in these experiments to serve as control. The jacket of the POF were mechanically stripped off to expose the fiber over a length of 100 mm. Fig. 1 shows how self-adhesive plastic tape was wrapped to create spiral pattern on POF. Fully coated POF (100 mm) were also fabricated to complete the validation.

The fiber length of 100 mm was chosen in this work in order to have a full illumination of light beam on the stripped fiber from a light source with diameter of 30 mm that was placed in parallel at an optimal distance of 30 mm from the POF surface. Tape-patterned and unpatterned POFs were then placed in a ZnO seed solution and subsequently into the growth solution to form ZnO nanorods. Scanning Electron Microscopy (SEM) was performed by a Hitachi, 3400N SEM system operating at 20 kV.

3. Experiment

The proposed temperature sensor is schematically illustrated in Fig. 2. For maximal temperature detection, an aluminum rod with dimension of 0.3 and 10 cm in length was used. The aluminum rod is placed vertically on a hot plate and in closed contact with the physical POF coated with ZnO nanorods. For temperature monitoring, a thermocouple (type J) was fixed in closed contact with the POF. The thermocouple has a resolution of 1 °C and is able to measure the temperature within a range of 0 °C to 500 °C. A modulator circuit was used to minimize the noise in the measurement, the white-light LED current driver was modulated with a periodical pattern signal generated by a signal generator.

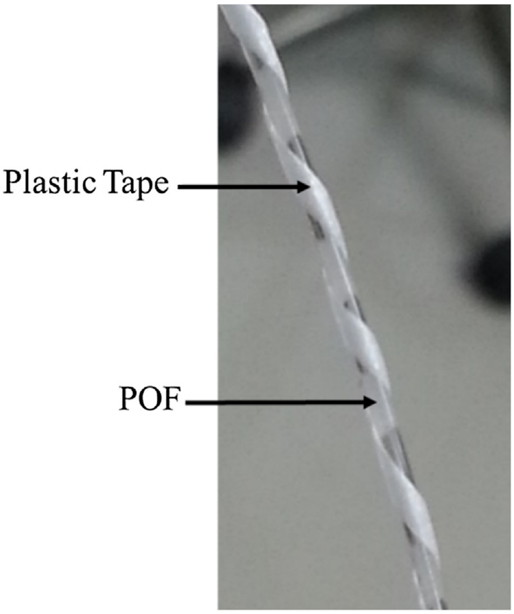

Fig. 1. Spiral Structured on POF using self-adhesive plastic tape for ZnO nanorods coating.

The magnitude of light side coupling was measured by connecting one of the POF to photodector and displayed in millivolt (mV) on oscilloscope under illumination of the modulated visible white light source. The other one of the POF tip was covered during the experiments to avoid light entering directly through the tips. Then, temperature sensing measurement was carried out by varying temperature from 20 °C to 100 °C. Five readings were recorded for each measurement. The sensitivity (S) was obtained through the slope of sensing response for spirally patterned and unpatterned ZnO nanorod coated POF devices.

4. Result and Discussion

ZnO nanorods coating: Fig. 3 shows the SEM image of unpatterned and spirally patterned coating of ZnO nanorods for temperature sensing. The SEM image in Fig. 3(a) and (b) clearly shows the unpatterned and spiral patterned ZnO nanorods coating on POF, respectively. In Fig. 3(c), ZnO nanorods can be seen growing perpendicular to the surface of the POF, an important geometry to enhance the light scattering mechanism for light side coupling into the POF. Moreover, the uniform high density growth of ZnO nanorods (85 nanorods/3.62×10^{-12} m^2 $\sim 23 \times 10^6$ nanorods/μm^2) on POF surface can be observed from Fig. 3(c) and Fig. 3 (d).

4.1. Temperature Sensing

The real time responses of the ZnO nanorod coated optical fiber sensor to temperature changes from 20 °C to 100 °C were recorded towards light side coupling. The measurements were conducted by exposing the spirally patterned and unpatterned ZnO nanorods coated POFs to temperature under visible light illumination. It was found that the both coating schemes showed obvious output voltage changes upon exposure to temperature as depicted in Fig. 4. It is well known that the thermo-optic coefficient of the POF is an order of magnitude higher than that of GOF, and the refractive index (RI)