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3D-printed Tilt Sensor based on an embedded Two-mode Fiber Interferometer

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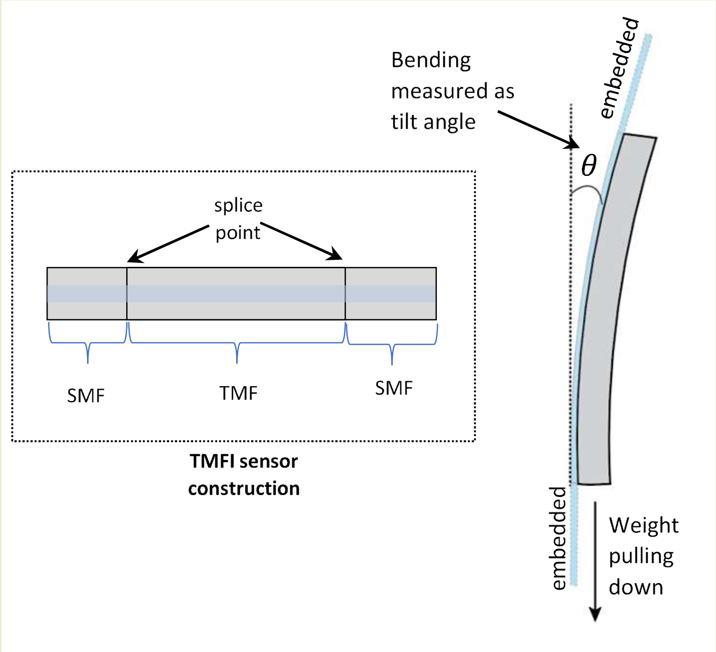

***Abstract*— A 3D-printed tilt fiber sensor using a two-mode fiber interferometer (TMFI) as the sensing mechanism has been demonstrated. The TMFI was constructed by splicing single-mode fibers (SMF-28s) at both ends of a two-mode fiber (TMF) to generate a comb-like interference spectrum that is sensitive to bending. A 3D-printed cantilever with a weight attached to one end was used to induce bending as the structure was tilted and by embedding the TMFI onto the 3D printed cantilever, different tilt angles can be measured, as a result of the bending of the fiber. The TMFI exhibited a linear response towards the tilt angles, θ, with a responsivity of 1 × 10^{-2} nm/deg at negative θ (0 to -90°) and 5 × 10^{-3} nm/deg at positive θ (0 to 90°), respectively. The sensor was able to detect small angle changes in increments as small as 1° and it performs better than embedded FBG sensors. The tilt sensor proposed has a small form factor and simple design, as well as being cost-effective and light-weight, thus showing significant potential for a variety of civil engineering applications.**

***Index Terms*—Fused deposition modelling, tilt sensor, two-mode fiber**

I. INTRODUCTION

Fused deposition modelling (FDM), which utilizes the melt extrusion method to deposit thermal plastic filaments in a pre-programmed pattern, has shown significant potential for the fabrication of various structures, in comparison to conventional machining, particularly with advantages in time, cost, and materials being seen. Currently, the FDM method is utilized in 3D-printing machines to assure fast prototyping, better customization, and high precision at a comparatively low cost [1-3], making the 3D printing process a promising alternative for the fabrication of various prototype components, and allowing rapid design iterations.

In the field of optoelectronics, 3D-printing has significant potential for the fabrication of high performance sensing elements by encapsulating the optical sensor into 3D printed structures [4-6]. Schmitz et. al [7] have successfully demonstrated this in a low cost novel 3D-printed tilt and motion smart sensor, by embedding liquids inside the printed structure. As such, a similar method can be used to embed the optical element inside the printed material during the 3D-printing process [4, 8, 9]. In traditional methods, fiber sensors are usually directly bonded onto the surface of a structure, by using glue or epoxy resin. This, however, may not be suitable for applications where it would be exposed to severe conditions such as high temperature and humidity. [10-12]. Therefore, by embedding the fiber into a 3D structure, more secure and compact designs allowing better fiber optic sensors can be realized [4].

The applications focus of this work is in the development of simple, easy to fabricate and use tilt sensors, which are devices that can measure movements in terms of the angle of tilt and are essential elements of civil engineering projects for a variety of applications such as measuring the angle of drilling in boreholes, monitoring ground or wall movement and tracking landslide movement [11, 13, 14]. Commercial tilt sensors rely on changes in electronic properties, such as resistivity [15], capacitance [16], and induction [17-19]. While adequate for many applications, these electronic sensors

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are not particularly well suited for use in harsh environments, in particular for applications that would see them being exposed to electromagnetic interference or other hazardous conditions, such as excessive moisture and dampness which can cause short circuiting or where there are hazardous or corrosive materials present. Therefore, optical methods, specifically those based on fiber optics, are of significant interest, as they are intrinsically safe as no currents flow at the sensor head. They are also light weight and can readily be networked. To date, most fiber optic tilt sensors involve the detection of strain by placing the fiber on a pendulum [20-22], while by contrast Bajić et. al [23] demonstrated a simple and low cost tilt sensor based on the refraction of light. However, these designs are relatively bulky and thus may not be suitable for real-world, in-the-field applications.

In this work, a 3D-printed tilt fiber sensor using a Two-Mode Fiber Interferometer (TMFI) as the sensing mechanism is proposed and its operational efficacy demonstrated. By embedding the TMFI into the 3D-printed structure, different tilt angles can be measured as a result of monitoring the bending of the fiber. The tilt sensor proposed is small and simple to design, low hysteresis, easy to fabricate, light-weight and cost-effective to use.

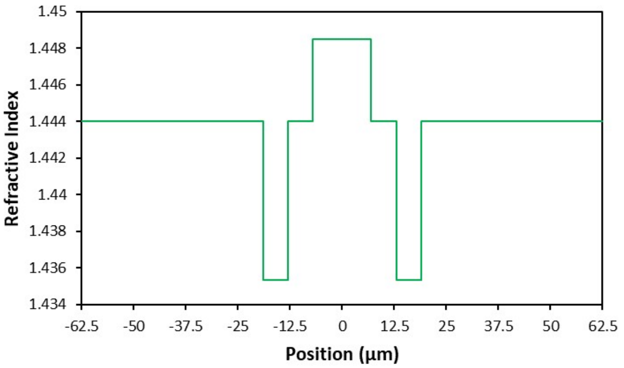

Fig. 1. Refractive index profile of the Two-Mode Step-Index Fiber (TMF) as a function of position

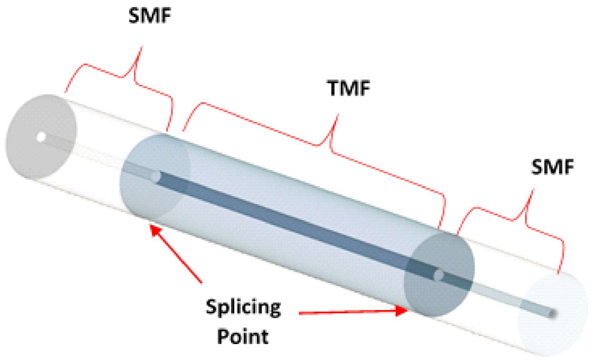

Fig. 2. Structure of the Two-Mode Fiber Interferometer (TMFI) showing the Single Mode Fiber (SMF) and Two Mode Fiber (TMF) sections

II. EXPERIMENTAL SETUP

A. TMFI fabrication

The TMFI structure was fabricated by fusion splicing a 2.5 meter long Two-Mode Step-Index Fiber (TMF) between two SMF-28 single-mode fibers (SMF-28s), one at each end of the TMF. The TMF supports the fundamental (LP_{01}) and second-order (LP_{11}) modes that were seen in the interferometer thus created. A schematic of the TMF refractive index profile, at a wavelength of 1550 nm, is given in Fig. 1, while the TMF structure developed, shown in the form of a 3D drawing is illustrated in Fig. 2. The TMF section, (colored blue), is sandwiched between two SMF fibers to provide the input and output to the system. The splicing between each cleaved end of the TMF was done with a FITEL 178A AUTO Multimode fusion function.

In operation, light from the SMF (SMF-28 fiber) enters the TMF section purely as a LP_{01} mode. As it crosses the first SMF-TMF boundary, the LP_{01} mode partly couples to the LP_{11} mode within the TMF section; the two modes interfere and only a fraction of the light is recoupled back into the LP_{01} at the next TMF-SMF interface, creating an interference effect that appears as a comb-like pattern in the optical transmission spectrum, as shown in Fig. 3. The evolution of the transmission spectra can be expressed as the cosine function of the phase difference between the LP_{01} and LP_{11} modes, based on the two-mode interference theory, whereby:

$$I = I_{LP01} + I_{LP11} + 2\sqrt{I_{LP01} I_{LP11}} \cos\phi.$$

Here ϕ is the phase difference between the two guided modes and can be defined as:

$$\phi = \frac{2\pi n_{eff} \Delta L}{\lambda}$$

where $\Delta L = L_{LP01} - L_{LP11}$ is the effective propagation length difference between the two linearly-polarized modes. As the value of L is disturbed, the phase difference changes and alters the transmission output as a function of the wavelength shift. The value, L, can be manipulated by applying a stress or strain, i.e. by bending or pulling the fiber. In this setup, the fiber bends as the sensor is tilted, inducing strain and thus causing shifts in the transmission peaks. The characterization of the transmission spectrum of the TMF fabricated is shown in Fig. 4. The measurement was done using an in-house built erbium-doped fiber (EDF) light source to provide the signal, while an AQ6370C Optical Spectrum Analyzer (OSA) was used to record the spectra obtained. The transmission spectrum (Fig. 3) shows a clear comb-like pattern, with a free spectral range (FSR) of 1 nm and an extinction ratio (ER) of 6.5 dB.

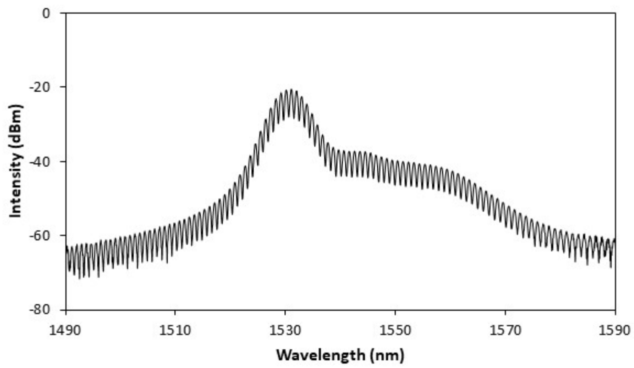

Fig. 3. Transmission Spectrum of the TMFI over the wavelength range 1490 to 1590 nm

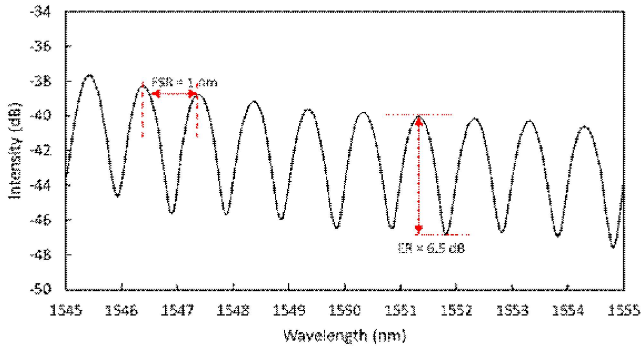

Fig. 4. Characterization of the transmission spectrum of the TMFI over the wavelength range 1545 to 1555 nm

B. Tilt sensor device and experimental setup

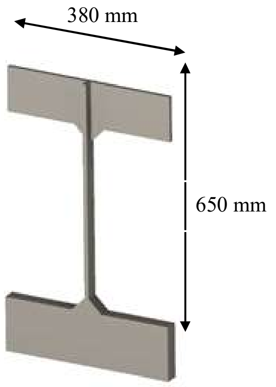

Fig. 5(a). 3D Design of the tilt sensor device design developed using Autodesk Fusion 360 Software

The tilt sensor was fabricated using an Ultimaker 2+ 3D printer and Polylactic Acid (PLA) as the filament material, with a 20% infill density. The sensor was based on a cantilever design, with a small and narrow flat shaft acting as the bending cantilever. The upper part of sensor can be clamped, while the bottom can be used to secure weights and thereby induce bending. The sensor had been designed using the Autodesk Fusion 360 software, with a photograph of the 3D model developed shown in Fig. 5 (a) and the schematic and critical dimensions of the design shown in Fig. 5 (b). The width of the shaft was 10 mm with a total length of 400 mm and a thickness of 30 mm.

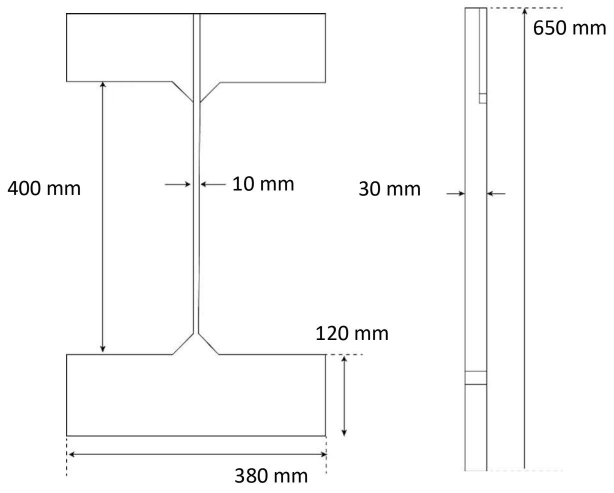

Fig. 5(b). Schematic design of the tilt sensor device showing the dimensions of the device

In order to integrate the TMFI into the 3D structure, the printing process was paused halfway through. One end of the TMFI was placed on the top part of the design, while the other end was placed on the bottom part, as shown in Fig. 6. A part of the sensor was left exposed and was touching the shaft of the tilt sensor to ensure maximum bending. The experiment to monitor the tilt was carried out by clamping the top part of the sensor on a retort stand and applying a weight of 30 g directly onto the bottom part of the sensor. The tilt was applied manually, by twisting the head of the clamp to cause a shift in the angle. The measurement of the tilt angle, with respect to the negative ($-\theta$) and positive ($+\theta$) angles, is shown in Fig. 7. As the sensor was tilted, the weight pulled the sensor down and caused a bend in the shaft. This bend was detected using the OSA, seen as a shift in the transmission spectrum of the TMFI. The amount of tilt was measured in degrees, using a protractor that has minimum angle measurement of 1°. It is worth noting that as the sensor was tilted at $-\theta$, compression stress occurs on the fiber while tilting at positive angles of θ results instead in a pulling tension. It is expected that the sensitivity of the device would vary, depending on the direction of the tilt.

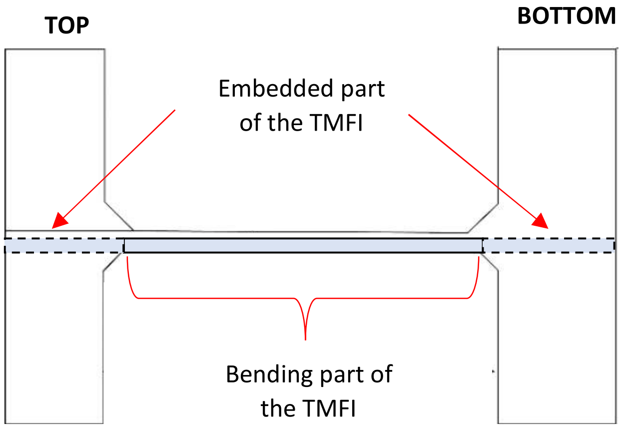

Fig. 6. Illustration of the placement of the fiber onto the 3D printed structure

III. RESULTS AND DISCUSSION

In an evaluation of the performance of the sensor system, Fig. 8 shows the shift of the transmission spectrum as a function of the change in tilt angle. The spectrum was recorded at 30° intervals, from 0° to -90°. Fig. 8 shows that the transmission peaks 'blueshifts' for increasingly negative values of the angle θ. Fig. 9 illustrates the wavelength shift, shown against the tilt angle, giving a linear response. However, there is a noticeable difference observed between the sensitivity, S, of the TMFI at the negative and positive angles: where S = 1 × 10-2 nm/deg for -90°<θ<0; while S= 5 × 10-3 nm/deg for 0<θ<90°. It can be inferred, based on the results obtained, that the TMFI sensor constructed is more sensitive for compression, as opposed to what is seen for tension.

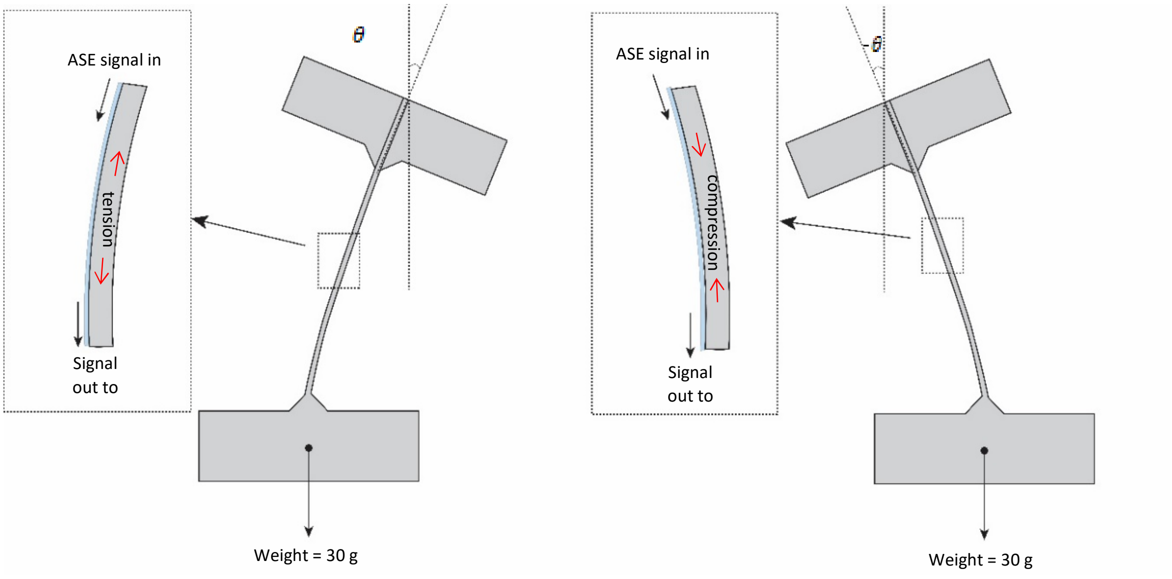

Fig. 7. Illustration of the angle measurement with the tilt sensor

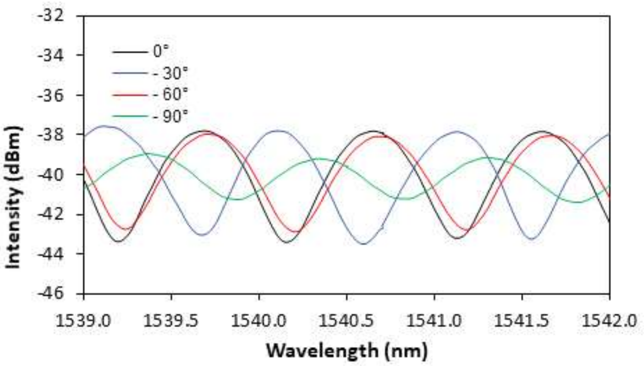

Fig.8. Transmission spectrum of the TMFI in response to tilt angle for angles 0°, -30°, -60° and -90° over the wavelength range 1539.0 to 1542.0 nm

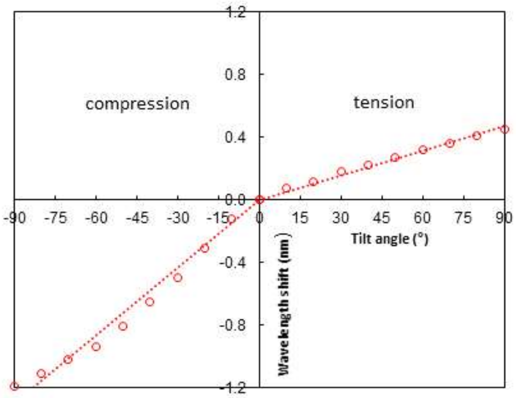

Fig.9. Wavelength response (shift in nm) of the TMFI in response to tilt angle, illustrating the difference between the compression and the tension situations (over the angles -90° to + 90°)

The sensing capabilities of the TMFI were further evaluated for the detection of small angles, at 1° increments. With every degree increase in the tilt angle, the transmission spectrum was recorded, with the results obtained being displayed in Fig. 10. The recorded results show that even with using small angles, of 1° increments, the shift in the spectrum is differentiable and measurable by using the OSA. In a way similar to what is seen in Fig. 8, the transmission spectrum 'blueshifts' as it is tilted at a negative angle. The relationship between the wavelength shift and the angle tilt is shown in Fig. 11. Based on the results seen at small tilt angles, S~1 × 10^{-2} nm/deg, which is similar to the data shown in Fig. 9. It should be noted that measurements were taken using a protractor, measuring with an uncertainty of ~0.5°.

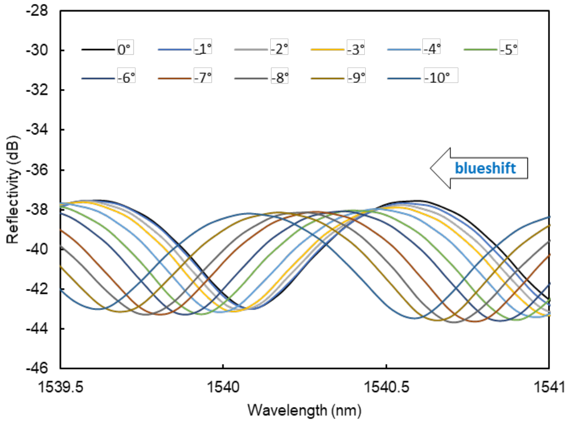

Fig.10. Transmission spectrum of the TMFI in response to 1 degree angle increment in the tilt angle (over the range 0° to -10°, seen over the wavelength range 1539.5 to 1541.0 nm)

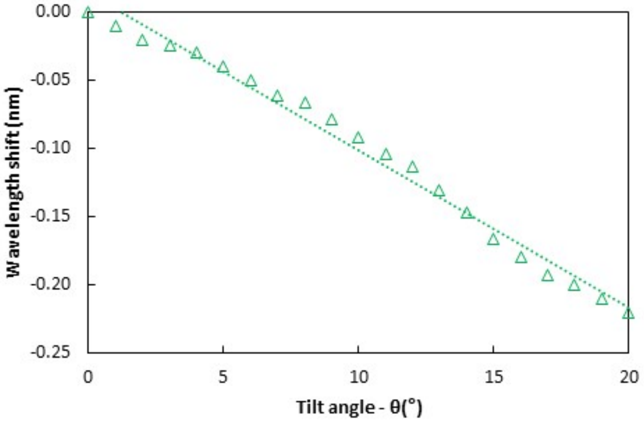

Fig.11. Wavelength response of the TMFI in response to 1 degree angle increment, over the tilt angle 0° to -20°

A similar experiment was carried out using an FBG as the basis of the sensing mechanism, in which the FBG was embedded into the structure using the same method. The result of the experiment carried out using the FBG sensor was compared with that from the TMFI, as shown in Fig. 12. In the positive angle direction, the results show that the use of the FBG gave results which were only slightly better than those seen with the TMFI, with S~6 × 10^{-3} nm/deg. On the other hand, for negative angles, the FBG—based approach performs poorly, at S~2 × 10^{-3} nm/deg. This was to be expected as the FBG can react differently, based on whether it sees the tension or compression modes [24]. These results confirm the very satisfactory TMFI performance, by comparison to that from the FBG.

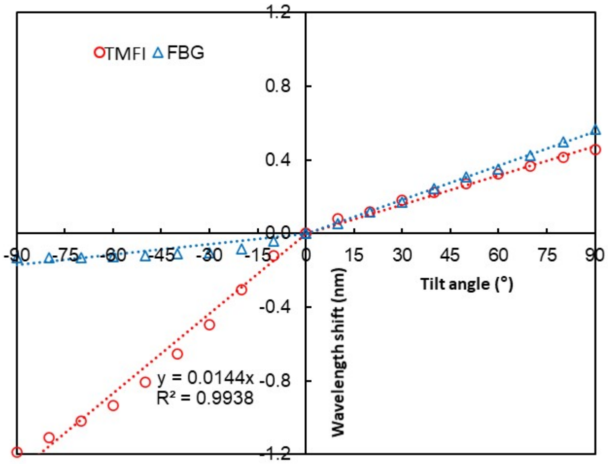

Fig.12. Comparison of the TMFI and the FBG sensor

Furthermore, the hysteresis profile of the TMFI was investigated for forward and backward tilt angle measurement at positive angles. Based on the results shown in Fig. 13, the hysteresis of the sensor was determined to be 0.66%. This slight hysteresis could be attributed to the lack of precision resulting from the manual adjustment of the tilt angle

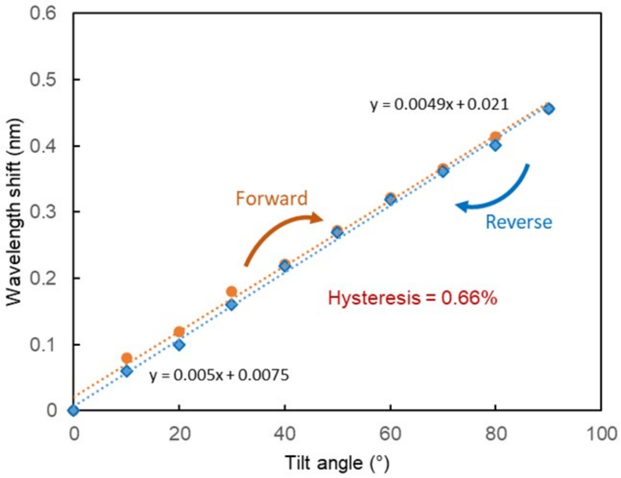

Fig.13. Hysteresis characteristic of the TMFI sensor

The influence of temperature on the performance of the TMFI performance was examined by immersing the sensor at a tilt angle of 0° in a water bath, with the temperature varied from 21°C to 50°C. The relationship between the temperature change and the wavelength shift is shown in Fig. 14, and from the obtained graph the temperature sensitivity of the sensor was determined to be 2.6 x 10^{-3} nm/°C. This indicates that the surrounding temperature has only a minimal influence on sensor reading.

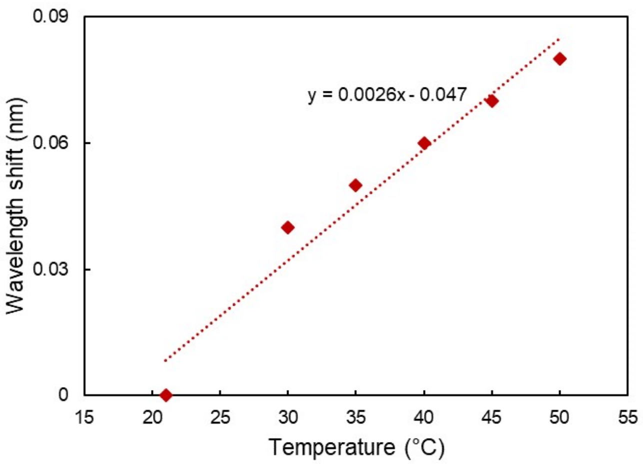

Fig.14. Wavelength response (shift in nm) of the TMFI in response to temperature

IV. CONCLUSION

An inexpensive and easy to produce, 3D-printed tilt fiber sensor that used a TMFI as the sensing mechanism has been designed, fabricated and its performance successfully demonstrated. The TMFI was constructed by splicing a sample of TMF to two SMFs (type SMF-28) to generate a comb-like spectrum, that was sensitive to bending. By embedding the TMFI thus created into the 3D printed structure, different tilt angles could be measured as a result of the bending of the fiber. The TMFI response, at negative angles ($-90^{\circ}<\theta<0$) was S= 1 × 10^{-2} nm/deg which was better that that (S~ 5 × 10^{-3} nm/deg) observed at positive angles ($0<\theta<90^{\circ}$). The research carried out showed that the sensor was also capable of measuring small angle increments, of 1 degree, and it performed well when compared to the results obtained from an embedded FBG sensor. This new tilt sensor has shown that it could have significant potential for a wide range of civil engineering applications. Further improvements can also be made by replacing the PLA material with high durability, high weather resistance and high heat resistance materials for long-term strain measurement.

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