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Research Article

Enhancing Temperature Sensitivity Using Cyclic Polybutylene Terephthalate- (c-PBT-) Coated Fiber Bragg Grating

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A polybutylene terephthalate (c-PBT) coating for enhancing the temperature sensitivity of a fiber Bragg grating- (FBG-) based sensor is proposed and demonstrated. The coating is seen to increase the sensitivity of the proposed sensor by a factor of approximately 11 times as compared to a bare FBG, giving a Bragg wavelength shift of 0.11 nm/°C with an operating temperature ranging from 30°C to 87°C. The proposed sensor is also easy to fabricate as compared to other similarly coated FBG sensors, giving it a significant advantage for field applications with the added advantage of being easily reformed to fit various housings, making it highly desirable for multiple real-world applications.

1. Introduction

Fiber Bragg gratings (FBGs) optical fiber components that have a number of highly promising sensor applications, particular those pertaining to the detection of strain and temperature [1, 2]. The principles of fiber Bragg gratings has been discussed in great length by Othonos and Kalli [3] and a good reading has been given by Kashyap [4], and the application of FBG-based sensors have have been thoroughly discussed due to their substantial advantages over conventional mechanical and electronic sensors. This is primarily due to their robust and compact form factors and easy fabrication process as well as the ability to be multiplexed, saving tremendous cost when multiple sensors are required [5, 6]. Furthermore FBG sensors, unlike other optical sensors, are inherently immune to electromagnetic interference at large and are also spark safe, allowing them to be used in hazardous environments such as in the oil and gas industry [7, 8]. There are also cases where optical sensors can be made to interact with electromagnetic waves based on the polarization rotation effect when the light travels within the core of the optical fiber, thus enabling new applications to be realized.

Among the most popular uses for FBGs is as a temperature sensor, which has been demonstrated successfully in numerous works [9–14]. However, most bare FBGs have a limited temperature response, due to the low thermal expansion coefficient of silica against temperature [15–17] in which most commercial FBGs are fabricated on. As such, research efforts have turned towards improving the performance of FBG-based temperature sensors by using temperature-sensitive materials as a coating to the FBG [18]. Among the techniques explored for this purpose include depositing or coating the FBG with metal or polymer layers [19–22], such as that reported by Chenari et al. [23] which coated the FBG with polydimethylsiloxane (PDMS) layers of different cross-sectional areas. While significantly increasing the sensitivity of the FBG, this method

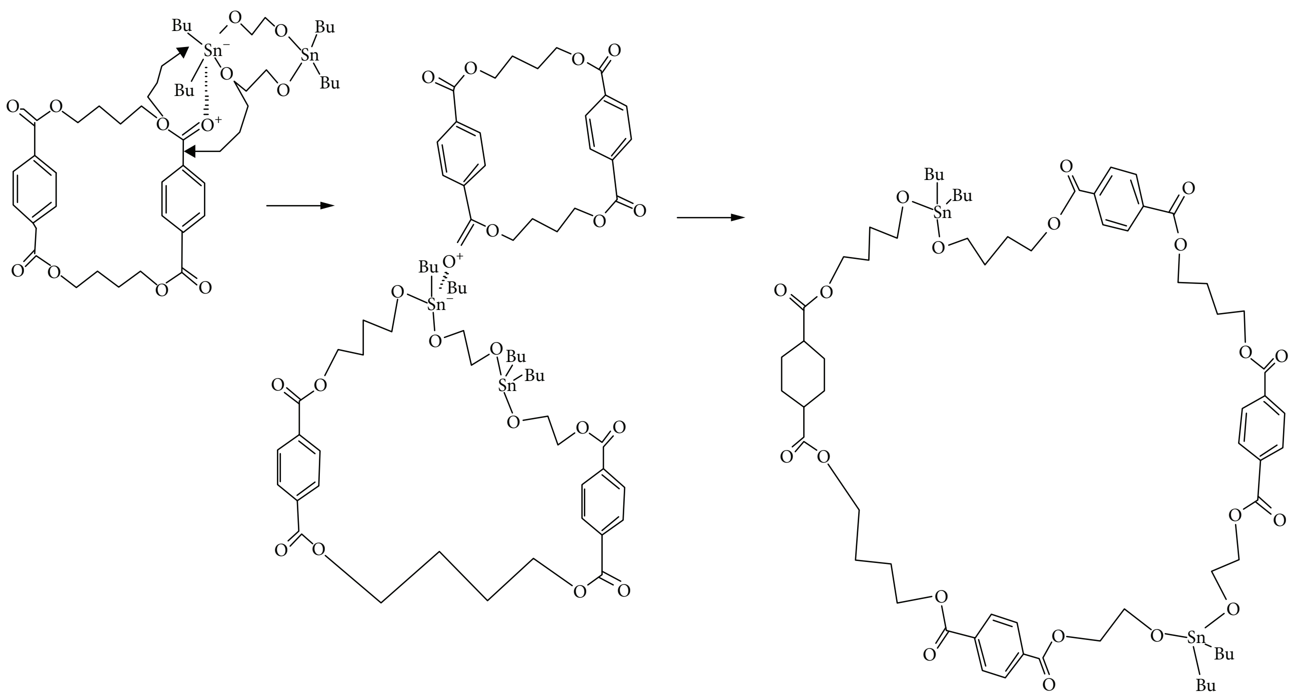

Figure 1: Ring expansion polymerization of CBT using stannoxane [26].

required many preparatory steps including pretreating the FBG cladding surface with oxygen plasma, thus making this approach commercially impractical. Similarly, Park et al. [24] reported the deposition of nickel on an FBG by electroless plating which again required substantially complex steps for fabrication. However, the improvement realized by the intermediate material was significant; the nickel-coated FBG recorded a temperature sensitivity of 25.86 pm/°C, and proved the sensing capabilities of the FBG.

In this work, a cyclic polybutylene terephthalate (c-PBT) polymer is proposed as a coating for an FBG-based temperature sensor. The proposed c-PBT polymer is easy to fabricate and provides a highly temperature-sensitive intermediate material for the FBG. The proposed sensor would have significant applications where temperature sensing in hazardous or dangerous environments is required.

2. Fabrication of the Cyclic Polybutylene Terephthalate (c-PBT) Polymer Coating

Polybutylene terephthalate (PBT) is an engineered thermoplastic and vastly used in many industrial and consumer applications. Macrocyclic PBT, also known as c-PBT, is produced from the ring expansion polymerization of CBT oligomers [25] as given in Figure 1. This process can be completed within a time frame of a few minutes over a relatively low temperature range of 140°C to 200°C [26] as compared to other similar polymers. The c-PBT produced by ring expansion polymerization with stannoxane initiators has a higher molecular weight, greater crystallinity, and better crystalline morphology than linear PBT, thus making it more sensitive to temperature changes [25, 27].

Figure 2: The c-PBT polymer after the heating process.

Prior to the grating inscription process, single mode (SMF-28) fibers were soaked in a highly pressurized chamber for two weeks to achieve hydrogenation and the photosensitization of the fibers. During the FBG fabrication process, 10 mm Bragg gratings were inscribed on SMF-28 fibers using a 193 nm argon fluoride (ArF) excimer laser with a phase mask. A laser pulse duration and pulse energy of ~10 ns and 8 mJ, respectively were used in the grating inscription process to achieve the desired grating reflectivity for each fiber. The transmission spectrum of the FBG was monitored using a Yokogawa AQ6370B optical spectrum analyzer (OSA) during the laser irradiation process. Subsequently, the fabricated FBGs were placed in an oven at 80°C for a period of 8 hours to out-diffuse any residual H_2 inside the FBG and to stabilize the spectral properties of the grating. This process produces an FBG with a reflectivity of 99%, a 3 dB bandwidth of approximately 0.3 nm, and a center wavelength of 1542.31 nm at 30°C.

The c-PBT is deposited on the fabricated adiabatic tapered FBG using the hydrofluoric (HF) acid etching process. The tapered FBG is adiabatic as it forms a gradual

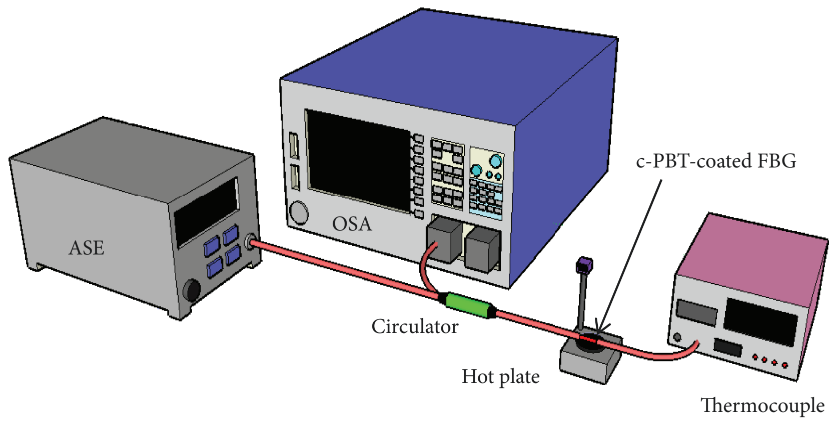

Figure 3: The experimental setup for the c-PBT-coated FBG temperature sensor.

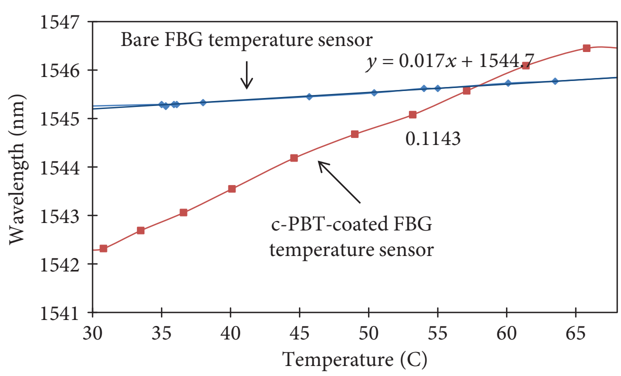

Figure 4: The wavelength shift of the c-PBT-coated FBG temperature sensor and bare-FBG temperature sensor.

taper, leading to a thin waist before returning to its original diameter. This confines most of the light travelling in the core of the optical fiber. Generally, in an adiabatic tapered fiber, the light modes remain primarily in the core as it propagates along the tapered region. In the case of a non-adiabatic tapered fiber, some high-order modes will travel in the cladding and then couple with the core mode as they propagate along the tapered region. The grating area of the SMF-28 fiber is cleaned with isopropyl alcohol before it is dipped into a 48% HF acid for 15 minutes [23]. During this process, no change in the Bragg wavelength has been observed. The estimated diameter of the adiabatic FBG is around 75 μm, below which the fiber may break during the polymer coating process. The thickness of the coating is roughly estimated to be about 300 μm. As explained in the Introduction, the powder form of c-PBT is spread on top of the adiabatic FBG before it is heated to its melting temperature of 140°C. The image of the c-PBT polymer after the heating process is shown in Figure 2. The FBG is tapered so as to enhance its temperature sensitivity, as the FBG's polymer cladding has a low thermal expansion coefficient. Tapering the FBG allows for a better interaction of the surface area of the FBG to the heat source due to the reduced cladding diameter, thus increasing the sensitivity of the fiber. This is due to a larger portion of the evanescent wave being able to interact with the heat source.

3. Experimental Setup of c-PBT-Coated FBG as a Temperature Sensor

Figure 3 shows the experimental setup of the c-PBT-coated FBG temperature sensor. A C-band amplified spontaneous emission (ASE) spectrum is generated by a 3 m long Fibercore Ltd. M12 erbium-doped fiber (EDF) pumped at 100 mW by a 980 nm laser diode. The ASE is used as the signal source for the proposed sensor, and is connected to port 1 of a 3-port optical circulator (OC). The OC is used to create a bidirectional optical path so that the reflection of the c-PBT-coated FBG, which changes as the FBG expands or contracts, can be captured by the Yokogawa AQ6370B OSA that is connected to port 3 of the OC.

The c-PBT-coated FBG is placed on a Thermo Fisher Scientific SP131 hotplate that serves as the source of heat for the experiment. The hotplate is capable of generating a temperature of between 30°C and 65°C. One end of the FBG is connected to port 2 of the OC, while the other end of the FBG is left unconnected. A Fluke 714 thermocouple calibrator is also placed on the hotplate to provide a reference measurement for temperature. For comparison purposes, the c-PBT-coated FBG is replaced with a conventional bare FBG, and the experiment repeated. The resulting responses from both FBGs are discussed in the Experimental Results.

4. Experimental Results

Figure 4 shows the wavelength shift of the c-PBT-coated FBG as well as a the bare FBG over an increasing temperature range of 30°C to 65°C. It can be seen from the figure that as the temperature increases, the Bragg wavelength of the c-PBT-coated FBG shifts by approximately 0.11 nm against a temperature rise of 10°C, with the highest shift of 4.13 nm obtained at the maximum temperature of 65°C. This gives a Bragg wavelength shift rate of about 0.11 nm/°C. On the other hand, the bare FBG is significantly less responsive towards the rising temperature, resulting in a Bragg wavelength shift rate of only 0.0178 nm/°C. From this, it can be seen that the c-PBT-coated FBG has a Bragg wavelength shift per °C response approximately 11 times larger

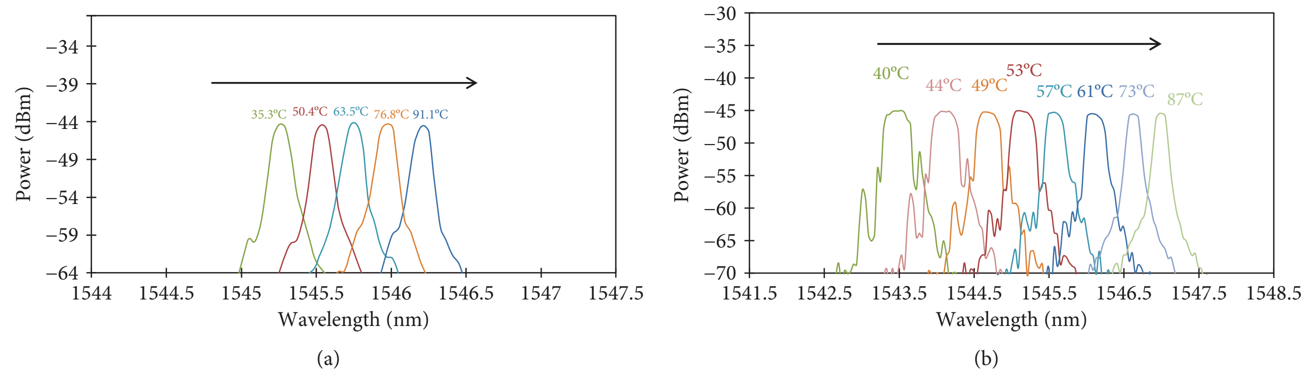

FIGURE 5: Reflection spectra of the (a) bare FBG and (b) c-PBT-coated FBG against a temperature range of 40°C to 87°C.

than that of the bare FBG. It can also be seen from Figure 4 that the c-PBT-coated FBG has an almost linear response against the rising temperature, with only a slight drop being seen at higher temperatures. This is attributed to the c-PBT film reaching its thermal expansion limit, and thus further increases in temperature would result in a smaller increase in the FBG wavelength.

Figure 5 shows the spectral response of the c-PBT-coated FBG against the rising temperature. A noteworthy observation is the narrowing of the bandwidth of the reflection from the FBG as the temperature increases. This arises due to the uneven stress in the polymer during the coating and curing process, and as a result of this, the stress in the polymer relaxes and the reflection curve of the FBG slowly changes to its original bandwidth as the temperature increases. Decreasing the temperature increases the stress, resulting in the bandwidth broadening again as the polymer is cooled to room temperature. The conversion of the CBT oligomers to a c-PBT polymer via heating will produce a significant change in the molecular weight (MW) of these polyesters, shifting it from low MW to higher MW material. This is because the molecular contents are denser and more compact, giving the higher MW in the resulting polymer. This gives more restriction and distraction to the grating upon penetrating the polymer coating. The side lobes of the FBG spectrum are also observed to change due to the uniformity of the gratings within the FBG changing during the heating process. The error of the wavelength reading is given by the manufacturer to be ±0.02 nm.

Figure 6 provides the 3 plots of the 3 dB bandwidth against the temperature range, and it can be seen that as the temperature increases from 40°C to 87°C the 3 dB bandwidth reduces from 0.4 nm to 0.13 nm. Figure 7 shows the response of the sensor during the heating and cooling cycles from 30°C to 65°C and vice versa. The response of the sensor to the heating and cooling process shows the same sensitivity, and these results are repeatable.

Table 1 provides a performance comparison of the c-PBT-coated FBG sensor of this work against other coated FBG-based temperature sensors.

From the table, it is immediately clear that the performance of the c-PBT-coated FBG is far from that of the PDMS- or nickel-coated FBGs, which have temperature resolutions of 0.042 nm/°C and 0.025 nm/°C. This means that the aforementioned sensors are almost 4 times more sensitive as compared to the c-PBT-coated FBG sensor. However, compared to the other proposed FBG-based sensors in Table 1, the c-PBT-coated FBG of this work is remarkably easy to fabricate, and can be done so in a time period of a few minutes. This means that the c-PBT-based

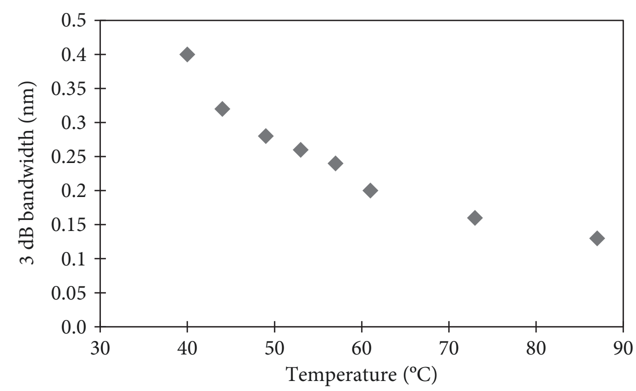

FIGURE 6: Effect of temperature to the 3 dB bandwidth.

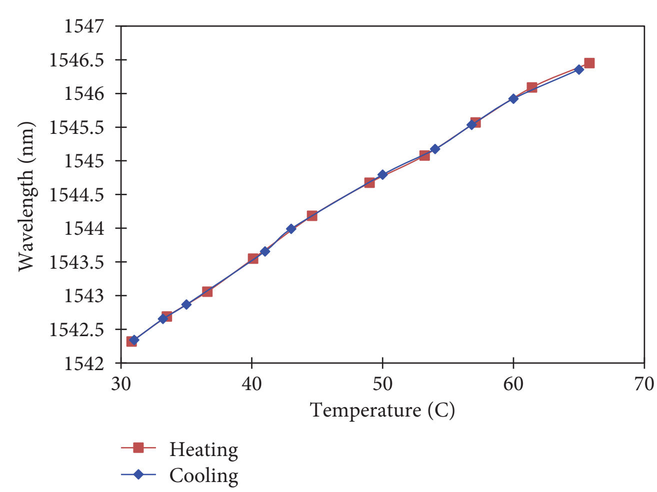

FIGURE 7: Heating and cooling cycles of the c-PBT-coated FBG sensor.

Table 1: Comparison of coated FBG temperature sensors with sensitivity and temperature range.

Type of coating	Sensitivity	Temperature range tested
PDMS coated [24]	0.042 nm/°C (with a cross section of 400 mm^2)	30°C–120°C
Nickel coated [25]	0.025nm/°C (with a thickness of 337.5 μm)	20°C–300°C
Polymer-coated fiber Bragg grating [28]	0.048 nm/°C	25°C–180°C
This work	0.11 nm/°C	30°C–85°C

FBG can even be fabricated in the field if needed, as compared to other coated FBG sensors which would require more stringent conditions, such as the use of a clean room or other similarly regulated environments. The c-PBT also has the added advantage of being easily remolded, allowing the coating to be changed to fit different housings. Furthermore, while the melting point of the c-PBT polymer coating is 140°C, the glass fiber itself does not show any significant expansion above a temperature of 87°C. This is effectively the maximum temperature that the sensor can measure. Taking these two factors into account makes the proposed sensor highly viable for real-world applications.

5. Conclusion

An FBG temperature sensor with a c-PBT polymer coating for enhancing sensitivity is proposed and demonstrated. The proposed sensor has a sensitivity approximately 11 times larger than that of a bare FBG with a Bragg wavelength shift of 0.11 nm/°C. The optimum operating temperature for the c-PBT-coated FBG spans from 30°C to 87°C, with the Bragg wavelength shifting linearly towards the longer wavelength region as the temperature is increased. At the same time, the 3 dB bandwidth of the reflected spectra decreases from 0.4 nm to 0.13 nm over the same temperature range. The proposed sensor has significant real-world applications, owing to its substantial ease of fabrication as well as the ability to reform the c-PBT polymer, allowing it to be adapted to multiple housings.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

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