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DOI: 10.15199/48.2025.05.21

Temperature sensitivity of polymer optical fiber: a study of PMMA, PVDF, and PI in fiber to the home network

Wrażliwość na temperaturę światłowodu polimerowego: badanie PMMA, PVDF i PI w światłowodzie do sieci domowej

***Abstract**: This study investigates the use of Polymer Fiber Bragg Grating (P-FBG) sensors for environmental temperature detection, focusing on the temperature-effective index effect in various polymers specifically polymethyl methacrylate (PMMA), polyvinylidene fluoride (PVDF), and polyimide (PI). Through simulations conducted in Fiber to the Home network using Optisystem 21.0 software, each polymer's reflected power response to temperature variations is tabulated and evaluated. The findings reveal that PMMA exhibits a stronger and linearly proportional thermo-optic response to temperature changes, compared to the nonlinear responses of PVDF and PI. This characteristic makes PMMA the most effective material for temperature-sensitive P-FBG applications, offering enhanced sensitivity and accuracy in temperature detection due to its predictable thermo-optic behavior. Consequently, PMMA stands out as the preferred polymer for P-FBG sensors within FTTH networks.*

***Streszczenie:** W tym badaniu zbadano zastosowanie czujników z siatką Bragga z włókna polimerowego (P-FBG) do wykrywania temperatury otoczenia, koncentrując się na efekcie współczynnika załamania światła w różnych polimerach, w szczególności w polimetakrylanie metylu (PMMA), polifluorku winylidenu (PVDF) i poliimidzie (PI). Poprzez symulacje przeprowadzone w sieci Fibre to the Home przy użyciu oprogramowania Optisystem 21.0, zestawiono i oceniono reakcję mocy odbitej każdego polimeru na zmiany temperatury. Odkrycia pokazują, że PMMA wykazuje silniejszą i liniowo proporcjonalną reakcję termooptyczną na zmiany temperatury w porównaniu z nieliniowymi reakcjami PVDF i PI. Ta cecha sprawia, że PMMA jest najskuteczniejszym materiałem do zastosowań P-FBG wrażliwych na temperaturę, oferującym zwiększoną czułość i dokładność wykrywania temperatury dzięki przewidywalnemu zachowaniu termooptycznemu. W związku z tym PMMA wyróżnia się jako preferowany polimer do czujników P-FBG w sieciach FTTH.*

Keywords: Temperature sensing, polymer, fiber Bragg grating, Optisystem
Słowa kluczowe: Wykrywanie temperatury, polimer, siatka Bragga z włókna, Optisystem

Introduction

In the rapidly advancing field of optical communications, the integration of environmental sensing capabilities into Fiber to the Home (FTTH) networks offers significant potential for enhancing system performance and reliability. This study focuses on evaluating the temperature sensing characteristics of three polymer materials namely Polymethyl-Methacrylate (PMMA), Polyvinylidene Fluoride (PVDF) and Polyimide (PI) by simulating their application within an FTTH network. The primary aim is to identify which polymer exhibits the most promising sensitivity for environmental temperature monitoring and showing linearly proportional response. By analyzing the relationship between temperature and effective index for each polymer and analyzing the reflected spectrum of the Fiber Bragg Grating (FBG), this research provides valuable insights into the suitability of these materials for integrating temperature sensors into FTTH networks. The findings from this study are expected to guide the selection of optimal polymer materials, thereby enhancing the effectiveness of environmental sensing in future implementations.

a. Polymer Optical Fiber (POF)

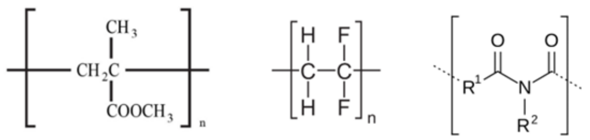
Polymer Optical Fibers (POF) have been investigated as a feasible replacement to silica-based fibers. POF consists of plastic, generally in the form of polymer. POF possesses a greater core diameter and a reduced effective index compared to traditional silica optical fibers[1]. One advantage of POF is its flexibility, allowing it can be bent without fracturing, thus making it more appropriate for applications requiring routing through confined places or around edges and corners[2]. This renders it ideal for distant locations, mountainous areas, and severe environmental conditions. The growing interest in Polymer Fiber Bragg gratings (P-FBG) emerges from the diverse material properties and sensing capabilities that polymers offer in comparison to silica[3]. Polymer fibers exhibit almost double the temperature sensitivity of silica fibers and enhanced strain sensitivity[4]. Polymer fibers provide greater elasticity, resulting in an expanded operational range for physical flexibility. Their organic characteristics facilitate various chemical processes for the development of biochemical sensors, with the implications of fiber breakage in situ being less detrimental than those associated with silica. Regarding expenses, P-FBG may have a comparable manufacturing cost to glass optical fibers, nevertheless, they could be more economical in terms of handling and maintenance[5]. The growing interest in P-FBG emerges from the diverse material properties and sensing capabilities that polymers offer in comparison to silica. Polymer fibers exhibit almost double the temperature sensitivity of silica fibers and enhanced strain sensitivity[6]. Polymer fibers provide greater elasticity, resulting in an expanded operational range for physical flexibility equations.

b. PMMA, PVDF and PI

Polymethylmethacrylate (PMMA) is a synthetic polymer composed of methyl methacrylate monomers containing carbon, hydrogen, and oxygen atoms in strong covalent bonds, imparting PMMA with transparency, rigidity, and UV resistance. Its optical clarity, lightweight, and thermal stability make PMMA ideal for optical and sensing applications, particularly in temperature monitoring. It can withstand temperatures from -40°C to 85°C without significant degradation[7], due to its glass transition temperature (Tg) of around 105°C[5]-[6], below which PMMA retains clarity and structural integrity.

Polyvinylidene fluoride (PVDF) is a semi-crystalline polymer of vinylidene fluoride monomers, known for its thermal, mechanical, and electroactive properties, which suit it for temperature sensing in fiber optic sensors. PVDF remains stable from -40°C to 150°C and has a Tg of -35°C, where it maintains flexibility, and a melting point of 177°C[10]-[11]. PVDF can be integrated with Fiber Bragg Gratings (FBG) to enhance temperature detection through wavelength shifts.

Polyimide (PI) is a high-performance polymer of imide monomers, characterized by thermal stability, chemical resistance, and mechanical strength. PI's thermo-optic coefficient enhances fiber optic sensors' temperature sensitivity. PI-coated FBG sensors operate across -200°C to 400°C due to their Tg around 360°C[12]-[13], maintaining flexibility and stability even in extreme environments.



PMMA PVDF PI

Fig. 1. The chemical structure of PMMA, PVDF and PI

Methodology

a. Integrating P-FBG into FTTH network

Simulating the incorporation of polymers into fiber-to-the-home (FTTH) networks facilitates an in-depth examination of the thermal response characteristics of polymers like PMMA, PVDF and PI under various temperature. The reflected spectra of Fiber Bragg Gratings (FBG) integrated with PMMA, PVDF, and PI can be systematically examined and compared. This comparative analysis will yield significant insights into the most optimal polymer-FBG combination for enhancing temperature sensitivity and precision in actual applications.

b. Effective Index Vs Temperature Variations

The variations in the effective index of PMMA, PVDF, and PI with temperature establish a key mechanism for the development of fiber optic temperature sensors. Utilizing the consistent correlation between temperature and effective index, these sensors provide accurate, dependable, and continuous temperature monitoring. The response profiles of PMMA, PVDF, and PI against temperature variations were obtained from published studies that used experimental settings for all three polymers. These data are critical for the simulation since it requires real-world data on the effective index of polymers at temperatures ranging from 30 to 200 degrees Celsius. The effective index value can be utilized to integrate the FBG parameters into the simulation, yielding the true FBG spectrum for the specified temperature. Figure 1, Figure 2 and Figure 2 shows the relationship between the effective index of all three polymers PMMA, PVDF and PI against temperatures while Table 1 tabulated the polymer effective index data extracted from graphs in the Figure 2.

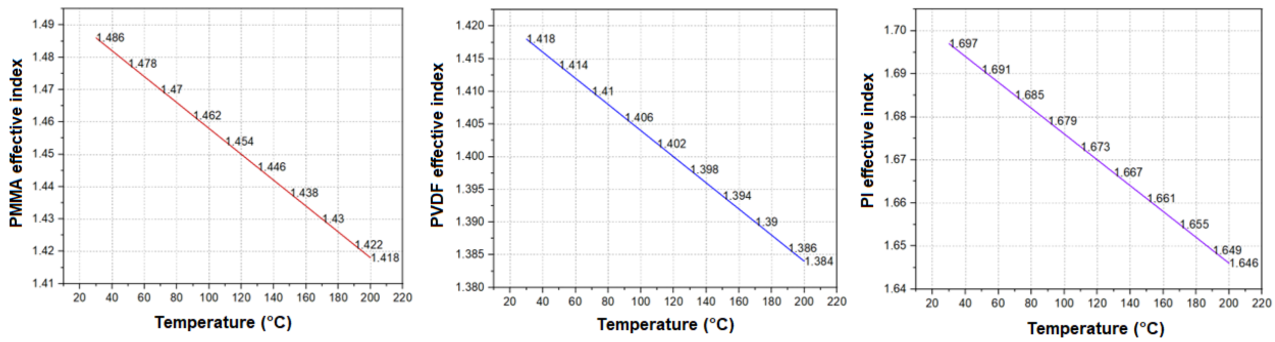


Fig.2. Effective index of three polymers (PMMA, PVDF and PI) versus Temperature from 30°C to 200°C

Table 1. Polymer effective index with temperature variations

Temperature (°C)	Effective Index		
	PMMA)	PVDF	PI
30	1.486	1.418	1.697
50	1.478	1.414	1.691
70	1.470	1.410	1.685
90	1.462	1.406	1.679
110	1.454	1.402	1.673
130	1.446	1.398	1.667
150	1.438	1.394	1.661
170	1.430	1.390	1.655
190	1.422	1.386	1.649
200	1.418	1.384	1.646

The data in Table 1 shows effective index data at temperatures ranging from 30°C to 200°C with 20°C increments. This data is critical for simulating P-FBG in Optisystem 21.0 software during tests at all temperatures (30°C to 200°C).

The P-FBG can be simulated by manipulating the effective index based on the temperature values. This process is depicted in Fig.3 where the effective index is manipulated for all three FBG by inserting the data in FBG parameter's setting in Optisystem 21.0.

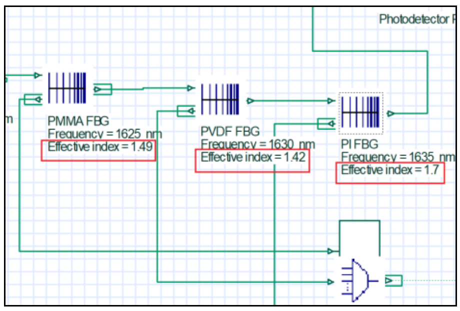


Fig. 3. Manipulating parameter of P-FBG effective index

Integrating P-FBG into the FTTH Network Model

Integrating a polymer Fiber Bragg Grating into the existing infrastructure is critical for emulating P-FBG in the fiber-to-the-home (FTTH) network. Internet data is sent from the ISP's office and monitored at the customer's Optical Network Terminal (ONU). Three FBG are strategically placed prior to the ONU. We may simulate the properties of P-FBG at different temperatures by varying the refractive indices of the individual FBGs and analyzing the resulting reflected spectrum using the Optical Spectrum Analyzer (OSA).

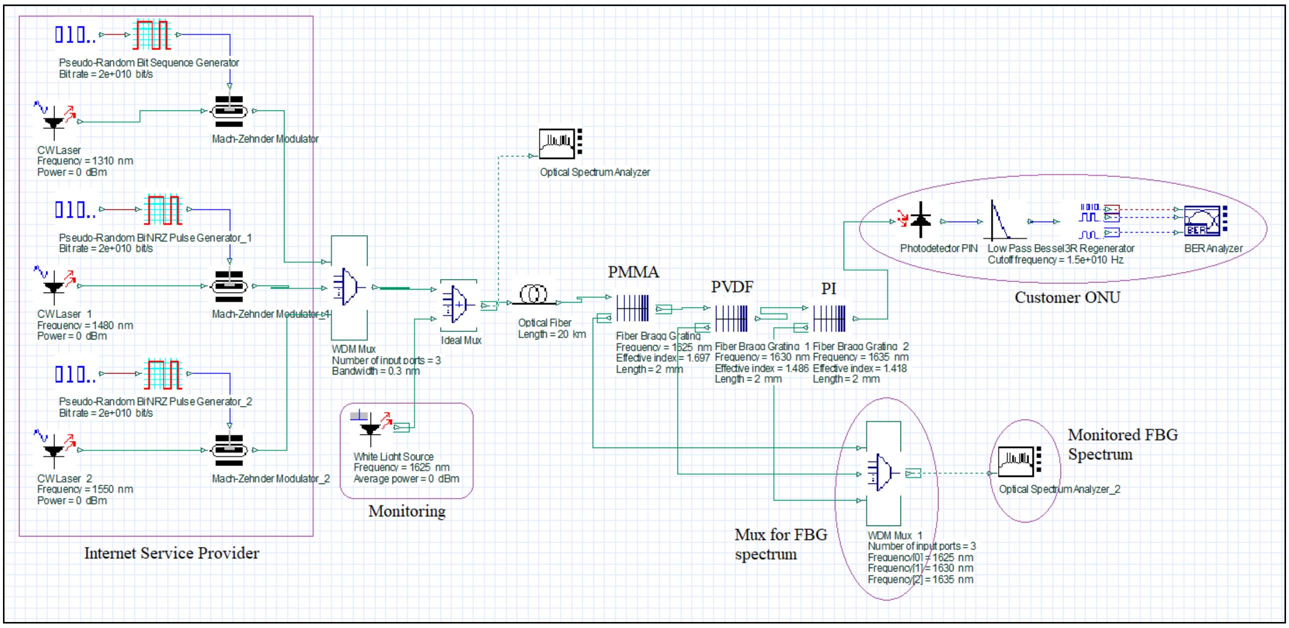


Fig. 4. Simulation of FTTH network with integrated P-FBG in Optisystem 21.0

The peak values represent the power reflected for each polymer PMMA, PVDF and PI. These values are labelled (A, B and C) in Figure 5. These was the power values which was monitored throughout the temperature ranges from 30°C to 200°C.

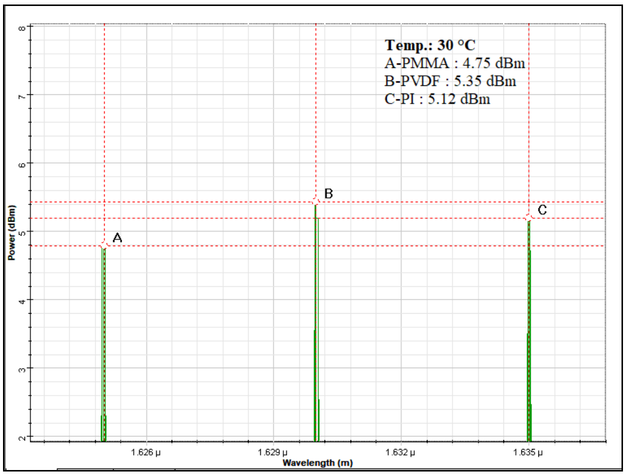


Fig. 5. Measuring peak of PMMA, PVDF and PI by Optical Spectrum Analyzer (OSA)

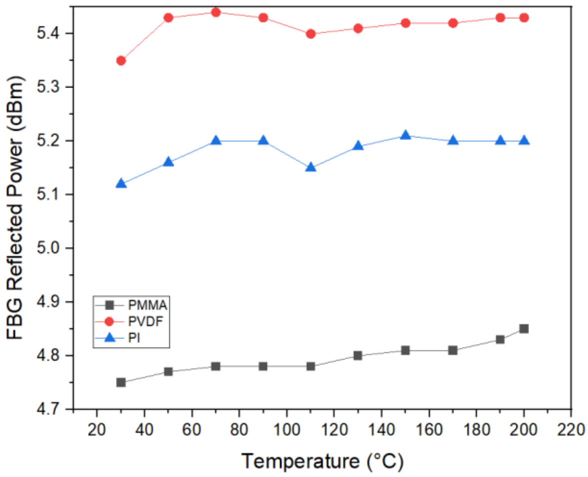


Fig. 6. Summary of PMMA, PVDF and PI reflected power against temperature

Result and Discussion

The outcome demonstrates the relationship between FBG reflected spectrum and temperature for PMMA, PVDF, and PI within the temperature range of 30°C to 200°C (Fig. 6). This graph indicates that the reactions of PVDF and PI to temperature elevation are not proportional. The maximum power value for PVDF is 5.44 dBm (at 70 °C), whereas the peak power for PI is 5.21 dBm (at 150°C). PVDF and PI exhibited power reductions at 110°C, measuring 5.40 dBm and 5.15 dBm, respectively. This indicates that the graph does not exhibit a linear proportional relationship, as it fails to show a constant rate of change with temperature. In the case of PMMA, the reflected spectrum increases linearly with temperature. The minimum power is 4.75 dBm (at 30°C), and the maximum power is 4.85 dBm (at 200°C).

Table 2. The P-FBG reflected spectrum (dBm) at temperature 30°C until 200°C

Temperature (°C)	Reflected Power (FBG)		
	Poly-methyl methacrylate (PMMA)	Poly-vinylidene fluoride (PVDF)	Polyimide (PI)
30	4.75	5.35	5.12
50	4.77	5.43	5.16
70	4.78	5.44	5.20
90	4.78	5.43	5.20
110	4.78	5.40	5.15
130	4.80	5.41	5.19
150	4.81	5.42	5.21
170	4.81	5.42	5.20
190	4.83	5.43	5.20
200	4.85	5.43	5.20

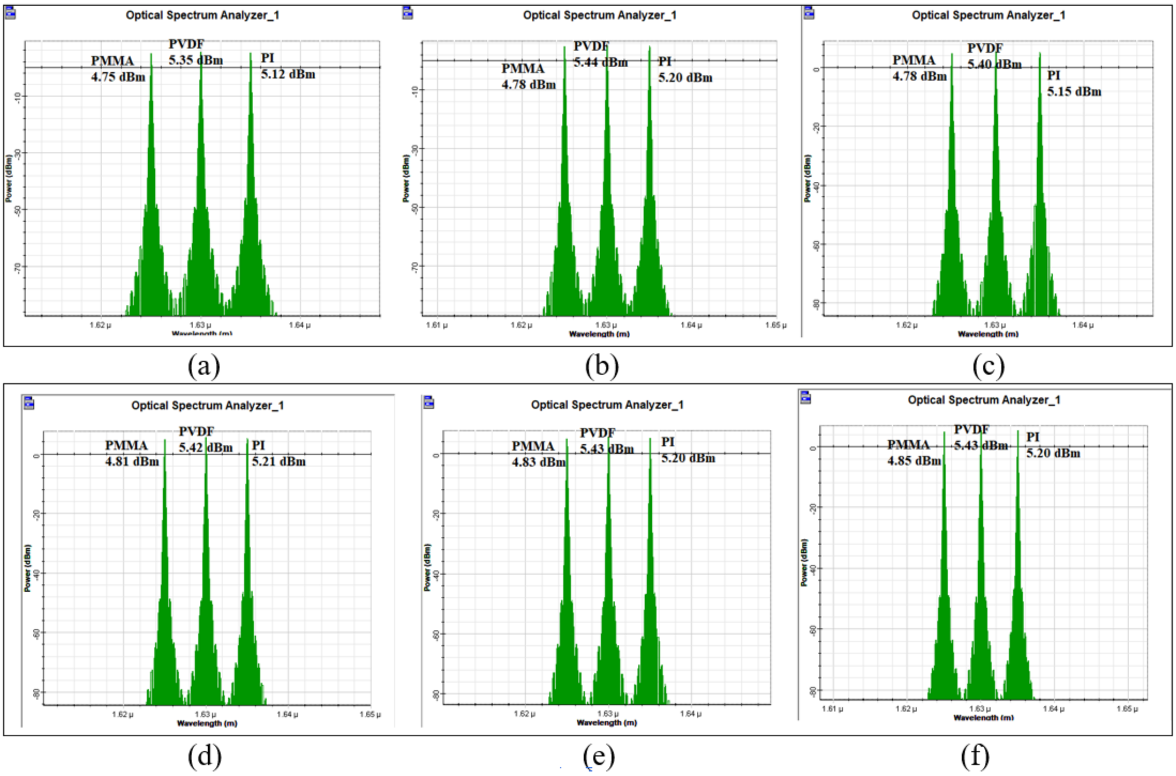


Fig. 7. The FBG reflected spectrum thru WDM Mux and monitored by OSA: (a) Spectrum at 30°C, (b) Spectrum at 70°C, (c) Spectrum at 110°C, (d) Spectrum at 150°C, (e) Spectrum at 190°C, (f) Spectrum at 200°C

Conclusion And Future Task

Polymer integration into Fiber Bragg Grating sensors requires careful consideration of a number of essential parameters, including the polymer's thermal, mechanical, and optical properties, as well as its environmental stability and cost-effectiveness[14]. This work has produced significant results for polymer reactions when used as sensing materials in FBG. The results indicate that PMMA exhibits excellent and promising characteristics as an effective temperature sensor in optical networks. Future research efforts should focus on the development of innovative polymer formulations, detailed characterization investigations, and the investigation of hybrid sensor designs for improved performance. Furthermore, long-term durability studies and interdisciplinary collaboration will be crucial in tackling the issues of polymer integration.

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