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Researching and determination of the strain sensitivity of the fabricated Bragg gratings

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Abstract

This article presents a systematic study of the stretching characteristics of polymer fiber Bragg gratings. Experimental data demonstrate that applying mechanical stretching to polymer fiber Bragg gratings enables a wide tuning range of the Bragg wavelength (over 50 nm) with high reproducibility, reversibility, and repeatability. It was also established that the strain sensitivity of polymer fiber Bragg gratings is 1.46 pm/με, which significantly exceeds the strain sensitivity of silica fiber Bragg gratings. Additionally, it is shown that the relationship between strain and the Bragg wavelength shift exhibits high linearity (correlation coefficient $R^2 = 0.9995$), ensuring the reliability of the gratings under mechanical loads. The study confirms the potential of polymer fiber Bragg gratings for use in WDM optical communication systems, fiber optic strain sensors, and medical sensors.

Keywords: Fiber Bragg gratings, Polymer fiber, Strain sensitivity, Tunability.

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1. Introduction

Bragg gratings (FBGs) are widely used in fiber optic sensors and telecommunication systems. Their primary operating principle is based on the diffraction of the Bragg wave, which changes depending on mechanical or thermal impacts on the fiber. Polymer Bragg gratings (POFBGs) attract attention due to their high sensitivity to strain and temperature, as well as a greater elasticity limit compared to silica fibers. They are applied in the aerospace industry, biomedicine, structural monitoring, and intelligent sensing systems. The article by Gao, et al. [1] describes axial strain sensors based on first- and fourth-order Bragg gratings (FBGs) created on polymer optical fibers (TOPAS/ZEONEX) using the "point-by-point" method. First-order FBGs demonstrate a sensitivity of 1.17 μm/με, while fourth-order FBGs exhibit sensitivity in the range of 1.249–1.296 pm/με. At high pulse energy, birefringence ($\sim 5.4 \times 10^{-4}$) is observed, splitting the peaks with sensitivities of ~1.44 and ~1.55 μm/με. The peak difference (~0.11 μm/με) enables simultaneous measurement of temperature and strain. In article [2], polymer Bragg gratings (POFBGs) made from CYTOP are described for measuring angles at various vibration frequencies. A method for compensating cross-sensitivity and hysteresis has been developed, reducing RMSE by 44% (to 2.20°) and decreasing hysteresis by 55% (<0.01).

This improves the sensitivity and accuracy of POFBGs for motion analysis over a wide frequency range. The study by Zheng, et al. [3] investigates the sensitivity of fiber Bragg gratings (FBGs) in multimode polymer fibers made from CYTOP to strain, temperature, and humidity. The FBGs are inscribed using the phase mask method and KrF laser irradiation. Optimization of the spectrum and mechanical properties is achieved by varying the irradiation time. The fiber demonstrates low attenuation in the infrared range and a single reflection peak, making it promising for telecommunications and optical sensing applications. Polymer Broadway, et al. [4] Bragg gratings (POFBGs) attract attention due to their high sensitivity to temperature and strain, greater elasticity limit, and potential applications in (bio)chemical sensors. Polymers possess unique properties, including variable sensitivity to humidity and safe failure characteristics. These features expand the application of POFBGs to areas inaccessible to silica fibers. The review covers progress in commercialization and new applications. A polymer-liquid crystal Bragg grating (PLC-FBG) is created using a holographic method with photoinduced modulation of a prepolymer and liquid crystal solution introduced into the hollow channels of photonic crystal fiber (PCF) [5].

It demonstrates high sensitivity to temperature and bending due to liquid crystal inclusions. The analysis of phase-separation microstructures inside the PCF capillaries was performed using scanning electron microscopy. The article by Campanella, et al. [6] presents a novel optical resonator created by incorporating a fiber Bragg grating (FBG) into a closed fiber loop. The spectral characteristics depend on the reflectivity of the FBG: at minimal reflectivity, a degenerate mode is observed, while increasing reflectivity leads to the splitting of resonance modes. In a quasi-degenerate regime, the device exhibits high load sensitivity, surpassing existing counterparts by a factor of 20. The study by He, et al. [7] presents a tunable polymer diffraction grating fabricated using a modified replication method. Polymer films made from PAA/PEO demonstrate transparency greater than 80% in the range of 500–1400 nm and stretchability up to 800% with reversibility at 70% strain. The gratings were investigated at wavelengths of 633 nm and 1064 nm, and their tunability was confirmed through finite element modeling. The study by Zheng, et al. [3]examines the sensitivity of Bragg gratings in CYTOP polymer fiber to stress, temperature, and humidity.

The gratings were inscribed using the phase mask method with a KrF excimer laser, forming a single reflection peak (~9 nm), which was optimized by irradiation time. Linear wavelength shifts under external factors were measured. The low attenuation of CYTOP and stable optical properties make this technology promising for telecommunications and sensing. Polymer optical fiber-based Bragg gratings (POFBGs) [8] are attracting growing interest due to their potential use as sensors. This chapter provides a current review of POFBG research, including fabrication methods, characteristics, and key application areas. Two main grating inscription methods are discussed: the phase mask and interferometric approach. The properties of POFBGs, such as temperature sensitivity, response to humidity, and strain, are analyzed. Typical examples of their applications are also described. The article [2] describes the use of polymer Bragg gratings (POFBGs) made from CYTOP for measuring angles at different frequencies. A compensation method was developed, reducing RMSE by 44% (to 2.20°) and hysteresis by 55% (<0.01).

POFBGs demonstrated high sensitivity and low hysteresis, making them promising for motion analysis. The article by Wu, et al. [9] presents a detailed study of the fabrication process and characteristics of fiber Bragg gratings (FBGs) in commercial step-index polymer optical fibers (POFs). Analyzing the dynamics of grating formation, we identified a heating effect caused by ultraviolet radiation during the inscription process. Our research showed that FBGs made from annealed industrial POFs provide more stable short-term performance at elevated temperatures and high strains. Additionally, annealing extended the operating range of temperatures and strains for FBGs without accounting for hysteresis. However, we identified an issue with long-term stability, even in annealed POF-FBGs. The article by Liu, et al. [10] presents a systematic study of the strain characteristics of Bragg gratings fabricated from polymer optical fiber.

Experimental results demonstrate that by simply stretching polymer Bragg gratings, a wide tuning range of the Bragg wavelength (32 nm) can be achieved with high reproducibility, reversibility, and repeatability. Furthermore, it was shown that the strain sensitivity of polymer fiber Bragg gratings is significantly higher than that of similar silica fiber gratings. Thus, the study of strain characteristics confirms the great potential of polymer Bragg gratings for applications in both WDM optical communication and fiber strain measurement systems. In article [11], a Bragg grating (FBG) with a Bragg wavelength of 962 nm was fabricated from poly(methyl methacrylate) polymer fibers (POFs) doped with trans-4-stilbenemethanol, using a phase mask with 17% zero-order diffraction for inscribing at a wavelength of 325 nm. The effect of zero-order diffraction from phase masks on FBGs in POFs was studied for the first time using microphotographic analysis of the gratings. Experimental data revealed a linear relationship between the axial strain of the fiber and the Bragg wavelength shift under tension up to 6.5%, with a strain sensitivity of 0.916 μm/με. However, this shift was significantly influenced by time-dependent stress relaxation in the fiber, especially at relatively high strains above 2%. The study by Bundalo, et al. [12] presents experimental results showing that the dynamics of Bragg grating inscription significantly depend on the intensity of the writing beam. An increase in intensity leads to a clearer and more stable grating structure, which, in turn, improves its reflective properties.

However, excessively high intensity can cause material overheating, negatively affecting the quality of the inscription. The article by Chen, et al. [13] introduces an optical bending sensor based on a Bragg grating integrated into a polymer optical fiber with an eccentric core. The device demonstrates significant orientation dependence, offers a wide bending curvature range of ±22.7 m^{-1}, and exhibits high bending sensitivity of 63 pm/m^{-1}. The study by Zhang, et al. [14] highlights the significant potential of polymer optical fibers and related sensors due to their unique properties. Polymers offer several advantages, including high photosensitivity and adaptability to various operating conditions, making them promising for a wide range of applications in modern optics and sensor technologies. Polymer optical fibers possess significant advantages such as flexibility, durability, lightweight, biocompatibility, and resistance to electromagnetic interference. They can be used not only as standalone sensors but also integrated into fabrics to create smart textiles. The article by Zhang [15] provides an overview of the structures, types, materials, and physical properties of polymer optical fibers (POFs), as well as modern technologies used in POF-based sensors. The applications of POF sensors and their use in the textile industry are discussed. Finally, current challenges in this field are addressed. The study by Shevchuk, et al. [16] focused on measuring material strain using fiber Bragg gratings (FBGs).

The research examined how mechanical deformations (stretching, compression, bending) lead to shifts in the reflected wavelength. It was shown that polymer FBGs outperform traditional silica FBGs in various parameters, such as sensitivity, strain range, and resistance to temperature changes. In the work by Shevchuk, et al. [17], a mathematical model of a fiber-optic strain sensor was developed to simulate the sensitive section of an optical fiber with a distributed Bragg grating in the form of a cylindrical spiral coil with a constant or gradient pitch angle. The study also presented the results of numerical simulations of reflection coefficient spectra and strain distribution densities for different parameters of the sensitive spiral coil. The developed model can be used to test complex volumetric deformations in homogeneous and unidirectional sections of fiber-reinforced composites. The article by Kalizhanova, et al. [18] presents optical components of demodulation and interrogation systems for photonic pressure sensors based on tilted fiber Bragg gratings, which are widely used for measuring the refractive index (RI). A novel design of a photonic fiber-optic Bragg pressure sensor with a tilted grating, integrated into standard multimode fibers, was developed. In the study by Kersey, et al. [19], high-temperature Bragg gratings were developed using regeneration methods and femtosecond infrared laser processing, demonstrating their potential for use in extreme conditions such as high temperatures, pressure, and ionizing radiation.

These gratings are ideally suited for energy applications requiring advanced equipment capable of operating in harsh environments. The article by Xu, et al. [20] provides a review of some of the latest developments in this field. It highlights advancements in fiber Bragg grating (FBG) sensing technologies for various aerospace applications, including high-pressure measurements, ground-based aerodynamic test facilities, impact pressure measurements, spacecraft monitoring, and the health monitoring of aviation composite structures. The article by Rao and Jackson [21] developed fiber sensors with Bragg gratings for measuring temperature and strain in composite materials, providing an effective means of monitoring temperature and strain in composites, thereby enhancing the reliability and durability of modern engineering structures. Their integration into composite materials opens new possibilities for creating intelligent monitoring systems that can significantly improve the safety and efficiency of complex structures in various industries. The article by Chan, et al. [22] developed fiber Bragg grating (FBG) sensors for monitoring civil infrastructure. New FBG-based strain sensors for measuring dynamic and static deformation, as well as temperature, were designed and installed on automotive bridges. The results of these studies indicate that, with proper configuration, FBG sensors can withstand the harsh conditions associated with the construction of civil infrastructure objects. The article by Cusano, et al. [23] developed fiber Bragg grating sensors for smart textiles. A smart textile device based on optical fiber was designed for monitoring breathing, capable of functioning during magnetic resonance imaging (MRI). The system is based on converting chest wall movements into strain on two FBG sensors positioned at the upper chest region.

Given the promising applications in optical communication systems and strain sensors, the study of strain effects on polymer Bragg gratings gains particular importance and relevance. This article presents a systematic analysis of the strain characteristics of polymer fiber Bragg gratings, including their strain sensitivity and tunability. Investigating these characteristics is critically important for the further application of polymer fiber Bragg gratings.

2. Research Methodology

Figure 1 illustrates the dependence of the Bragg wavelengths of polymer fiber Bragg gratings on various tensile deformations. Circles indicate experimentally obtained values, and the dashed line represents the result of linear regression. A very high correspondence was achieved between the Bragg wavelength shift and the strain over the entire range of strain tuning, as confirmed by a regression coefficient of $R^2 = 0.9995$. The regression line in Figure 1 is expressed as follows:

$$\lambda_B = 1535.6 + 1464 * \varepsilon \qquad (1)$$

where λ_B is s the Bragg wavelength of polymer fiber Bragg gratings, and ε is the applied tensile strain.

Thus, the strain sensitivity of polymer fiber Bragg gratings at a wavelength of 1535 nm is 1.46 pm/με, which exceeds the performance of silica fiber Bragg gratings. Due to their high strain sensitivity and significant strain durability, polymer fiber Bragg gratings can become a more preferable alternative to silica fiber Bragg gratings in various strain sensor applications. It is known that the relationship between the shift in the Bragg wavelength and the applied strain can be represented as follows:

$$\frac{\Delta\lambda_B}{\lambda_{BO}} = (1 - p_e) * \varepsilon \qquad (2)$$

where p_e is the effective photoelastic constant. The Bragg wavelength shift of polymer fiber Bragg gratings (Equation 1) can also be expressed as,

$$\frac{\lambda_B}{\lambda_{BO}} = 0.953 * \varepsilon \qquad (3)$$

To determine the strain sensitivity of Bragg gratings (FBGs), it is necessary to establish a quantitative relationship between the change in the Bragg wavelength and the applied strain. The model is based on the change in the grating period and the effective refractive index under the influence of mechanical deformation.
The fundamental Bragg equation:

$$\lambda_B = 2n_{eff}\Lambda \qquad (4)$$

n_{eff} is the effective refractive index, Λ is the grating period.

When stretched, both n_{eff} and Λ change, which results in a shift of the Bragg wavelength $\Delta\lambda$.

The change in the Bragg wavelength under tensile strain is determined by the following equation:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon \qquad (5)$$

where ε is the applied strain (tensile), P_e is the effective photoelastic constant.

For silica fibers, Pe ≈ 0.22P, while for polymer fibers, Pe ≈ 0.05P, making them more sensitive to strain.
The strain sensitivity of Bragg gratings is determined by the derivative:

$$S_\varepsilon = \frac{d\lambda_B}{d\varepsilon} = (1 - P_e)\lambda_B \qquad (6)$$

Substituting the typical value λ_B =1550 nm.

The experiments were conducted using a photonic fiber-optic pressure sensor with a tilted chirped Bragg grating embedded within the internal structure of composite plates. The fibers were mounted on special movable stages, enabling precise control of tension.
To record the deformation parameters, the following were used:

- Femtosecond laser for inscribing Bragg gratings;
- analyzer with a precision of 0.01 nm;
- Control plates made of carbon composite with embedded Bragg gratings.

The strain tuning of polymer fiber Bragg gratings is performed using the mechanical stretching method, the main concept of which is illustrated in Figure 1. To prepare polymer optical fiber samples for the creation of Bragg gratings, the polymer fiber is fixed at both ends on a glass slide. After inscribing the grating, the glass slide is cut in the middle using a diamond saw. The resulting parts are glued and mounted on two steel blocks connected to two micropositioners. One micropositioner remains stationary, while the other can move longitudinally to apply axial tensile strain to the grating sample. The axial strain value is calculated as the ratio of the longitudinal elongation of the fiber (ΔLz) to the initial length of the fiber grating sample between the two points of influence (Lz), as shown in Figure 3. In our experiment, Lz is approximately 2 cm. The precision of the longitudinal displacement of the movable micropositioner is 0.01 mm. Tensile strain is applied by manually moving the micropositioner, ensuring a loading rate of approximately 1 mm/min. During stretching, the reflections of the polymer fiber Bragg gratings are recorded.

For precise control of strain in polymer fiber Bragg gratings, an optical spectrum analyzer can be used to record wavelength changes in real time, force sensors to measure applied stress, and digital image correlation (DIC) for non-contact strain measurements. Additionally, boundary effects, residual stresses, and dynamic behavior under cyclic loading should be considered to improve measurement accuracy and predict grating performance under external factors.

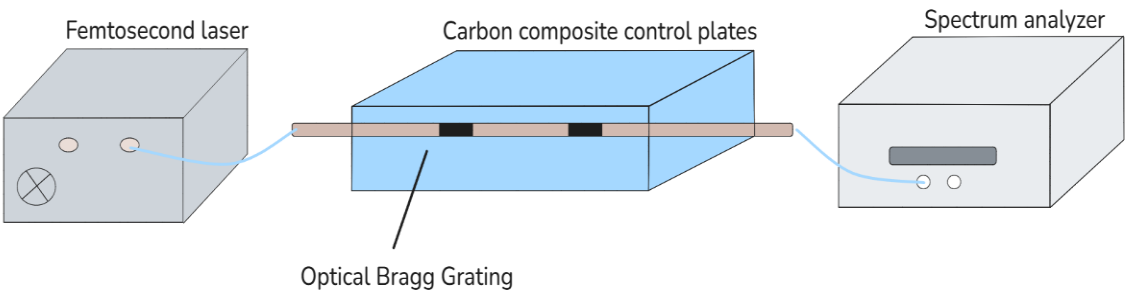

Figure 1.
Strain tuning of polymer fiber Bragg gratings.

The samples were kept for three days at room temperature for stabilization. The polymer fiber made of PMMA had an outer diameter of 133 µm and a core diameter of 6 µm.

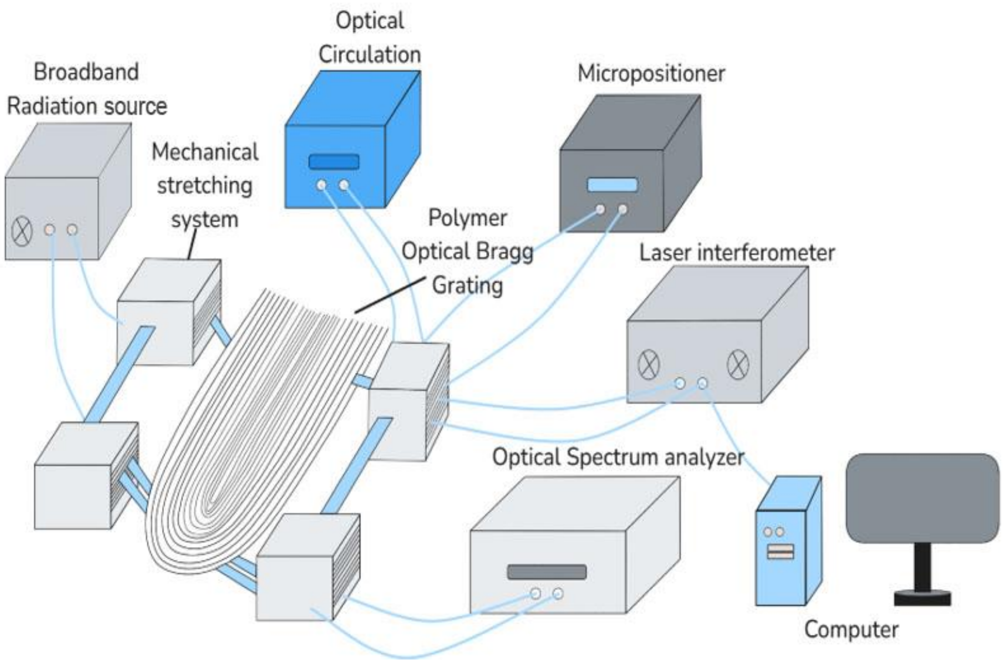

Figure 2.
Determining the strain sensitivity of the fabricated Bragg gratings.

Figure 2 illustrates the system for determining the strain sensitivity of the fabricated Bragg gratings. A broadband light source is utilized, emitting light through an optical Bragg grating (OBG). The grating reflects a specific wavelength (Bragg wavelength), while the remaining wavelengths pass through. A mechanical stretching system alters the grating period, shifting the reflected wavelength. These changes are recorded by an optical spectrum analyzer, while a laser interferometer measures the mechanical deformations. An optical circulator directs light into the appropriate channels, and a computer processes the data, analyzing the effects of external influences on the grating. This principle is employed for the development of sensors for stress, temperature, and strain.

The scientific novelty of this study lies in the systematic investigation of strain tunability and sensitivity of Bragg gratings fabricated from polymer fibers, which revealed their superior characteristics compared to traditional silica fiber Bragg gratings. Polymer Bragg gratings exhibit significant tunability, allowing a Bragg wavelength shift of more than 50 nm under simple stretching, which substantially exceeds the performance of similar gratings made from silica fibers. The sensitivity of polymer fiber Bragg gratings was established at 1.46 pm/µε at a wavelength of 1535 nm, which is significantly higher compared to silica counterparts. This opens new possibilities for applications in high-precision sensing systems and telecommunications. A high linearity was observed in the relationship between tensile strain and the Bragg wavelength shift, along with confirmed reproducibility, reversibility, and repeatability of strain tuning with a wavelength shift of up to 32 nm. This ensures the reliability and predictability of polymer Bragg gratings under various operating conditions. Due to their improved tunability and sensitivity characteristics, polymer Bragg gratings hold significant potential for use in WDM telecommunications and fiber-optic systems for measuring mechanical stresses, expanding their application scope compared to traditional silica gratings. Polymer Bragg gratings demonstrate superior temperature sensitivity, making them more adaptive and efficient in changing temperature environments.

The scientific significance of this study lies in the superior strain and sensitivity characteristics of polymer fiber Bragg gratings compared to traditional silica counterparts. The discovery of significant tunability, with a Bragg wavelength shift exceeding 50 nm, high linearity in the relationship between strain and wavelength shift, and increased sensitivity of 1.46

pm/με at a wavelength of 1535 nm, opens new opportunities for the application of polymer Bragg gratings in modern WDM telecommunication systems and fiber-optic sensors. These results contribute to the development of high-precision measurement technologies and the enhancement of telecommunication network efficiency, while also driving further research into innovative materials and structures for optical devices. Furthermore, the improved temperature sensitivity and linearity of characteristics expand the range of possible applications, making polymer Bragg gratings a crucial component for integration into various engineering and scientific monitoring and control systems.

As part of the study, a photonic fiber-optic pressure sensor with a tilted chirped Bragg grating embedded within the internal structure of composite plates was developed. This design significantly simplifies the system for measuring the refractive index of the medium, eliminating the need for spectrophotometers, optical spectrum analyzers, and spectrum analysis algorithms (Figure 3). An important feature of this research is the control plates, which consist of a selected number of layers of carbon fabric impregnated with epoxy resin. Between the layers of carbon fabric, fiber-optic sensors with tilted chirped Bragg gratings were additionally placed. The main component of the system is a femtosecond laser. Photonic crystal fiber with an increased germanium content was positioned behind a phase mask, along with a specialized corrugated membrane metal diaphragm. This diaphragm deforms, causing the deflection of a polycrystalline silicon-based cantilever, resulting in the grating being inscribed on the same multimode fiber.

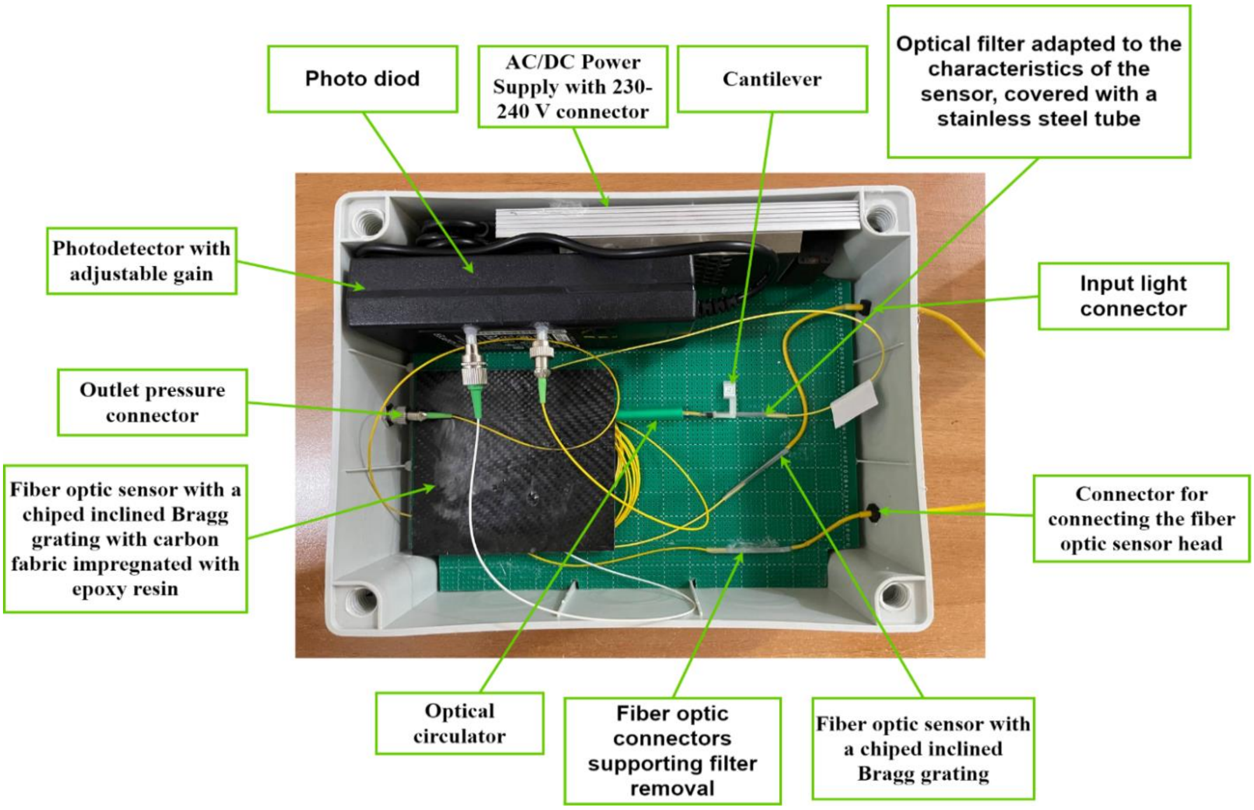

Figure 3.
Fiber-optic Bragg sensors for monitoring the condition of composite material structures.

Table 1.
Technical specifications of the photonic fiber-optic pressure sensor with a tilted chirped Bragg grating.

Parameter	Value
Sensor type	Fiber-optic pressure sensor
Sensor integration	Embedded within composite plates
Primary function	Measurement of refractive index and pressure
Key advantage	Eliminates the need for spectrophotometers and spectrum analyzers
Fiber type	Photonic crystal fiber with increased germanium content
Grating inscription	Femtosecond laser via phase mask
Bragg wavelength range Grating tilt angle	1530 – 1570 nm (Tunable) 4° – 10° (Optimized for sensitivity)
Pressure sensitivity:	5 – 15 pm/kPa
Chirp bandwidth	Up to 5 nm (Depending on design)
Refractive index sensitivity	250 – 500 nm/RIU
Temperature sensitivity	~10 pm/°C
Strain sensitivity	1.2 – 1.5 pm/με

This fiber-optic pressure sensor with a tilted chirped Bragg grating (TCBG) is embedded in composite plates, measuring refractive index and pressure without the need for spectral analysis. It features high sensitivity (5–15 pm/kPa), a broad wavelength range (1530–1570 nm), and robust environmental stability.

Figure 4 shows a photograph of the fabricated carbon fiber sample. The composite material sample was fabricated using the hand lay-up method, with carbon fabric as the reinforcing material and general-purpose epoxy resin as the matrix material. The carbon fabric was aligned unidirectionally relative to one another. The matrix material consisted of epoxy resin with the addition of 1% catalyst by volume. The carbon fabric, with a density of 300 g/m², was cut into five pieces measuring 10 × 5 cm, creating a composite sample with five fiber layers, where the Bragg gratings were placed in the second layer.

For comparative analysis, both polymer FBGs, with a maximum reflection wavelength of approximately 1555 nm, were embedded in the composite. The fiber-optic FBG sensors were placed 1 mm apart in the central section of the glass fiber, approximately 5 cm from the ends of the sensors.

Figure 4.
Photograph of the fabricated carbon fiber sample.

Before embedding into the composite, the fibers were pre-strained by securing both ends of the fibers on movable stages and applying displacement using linear stages. The second layer was selected as the primary layer for placing the optical fibers to reduce the risk of damage to the polymer fiber Bragg gratings and to increase exposure to stress and temperature, as most external layers (layer 1) experience these effects at the highest level. In the experiment, layer 1 was in contact with the heat source during temperature studies, and when the load was applied, the top outer layer (layer 1) experienced maximum tensile strain, while the bottom outer layer (layer 5) experienced maximum compressive strain.

The sample was cured according to the manufacturer's specifications at room temperature for three days. The thickness of the cured composite sample was 2.1 mm. A photograph of the fabricated sample is shown in Figure 5.

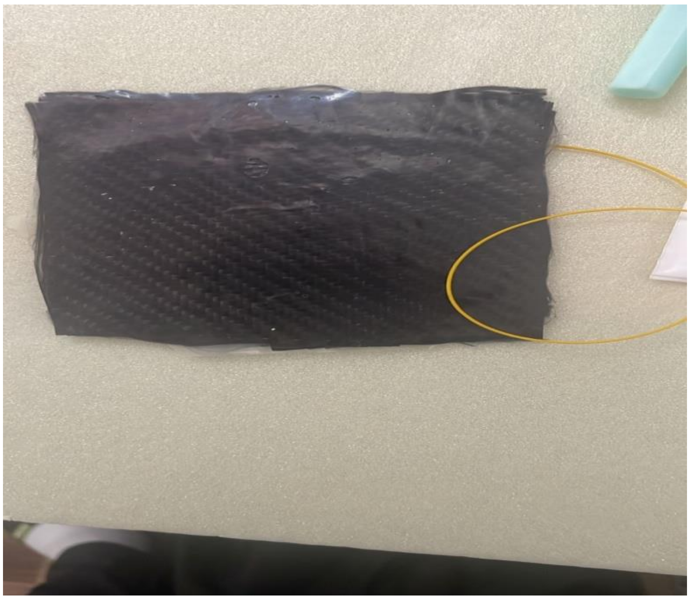

Figure 5.
Embedding fiber into the composite.

3. Results

The reflectivity of polymer fiber Bragg gratings used for strain measurement is approximately 50%. The reflection results of Bragg gratings under various tensile strains are presented in Figure 2. The first spectrum corresponds to the initial reflection before the application of stress, with a Bragg wavelength of about 1536.4 nm. Subsequent spectra demonstrate the reflection of polymer fiber Bragg gratings under different levels of external strain. Figure 2 shows that at a maximum tensile strain of 3.61%, the Bragg wavelength reaches 1589.1 nm. This indicates that polymer fiber Bragg gratings can be tuned over a wavelength shift of more than 50 nm through simple stretching. It is also evident that at tensile strains below 2.22%, no significant changes are observed in the reflectivity level or the spectrum shape. When the strain exceeds 2.22%, the reflectivity decreases, and the spectral linewidth broadens. The appearance of serrations in the spectrum at strains exceeding 3% is associated with the non-uniform distribution of strain along the polymer fiber Bragg grating sample.

After the removal of the load, the stability of the Bragg wavelength was analyzed, and it was found that after repeated loading and unloading, a slight hysteresis (~2 nm) might occur due to the viscoelastic properties of the polymer material. Full recovery of the Bragg wavelength occurred within 20 minutes, indicating the presence of slow relaxation processes in the fiber structure. The study was conducted at a controlled temperature, but temperature effects are possible, as polymer fibers exhibit high temperature sensitivity (~10 pm/°C), necessitating additional calibration. To compensate for temperature variations, reference gratings or active thermal stabilization methods can be employed. A similar experiment with silica gratings showed a smaller Bragg wavelength shift (~10–15 nm under the same strain levels), confirming the higher tunability of polymer FBGs. However, silica gratings demonstrated more stable spectral characteristics, while polymer FBGs exhibited spectral line broadening due to the non-uniform distribution of strain. These experiments confirm that polymer Bragg gratings are suitable for highly sensitive mechanical strain sensors, for example, in biomedicine, aviation, and structural monitoring. Their potential use in wearable sensor devices is also notable, as they can measure strain in soft tissues or flexible surfaces.

Figure 6 illustrates the dependence of reflection (in dB) on wavelength (in nm) at various parameter values expressed as percentages. This parameter may reflect changes in the physical environment, such as temperature, pressure, or the degree of structural modification (e.g., strain in the optical fiber). Each line on the graph corresponds to a specific percentage value (e.g., 0%, 0.56%, 1.11%, and so on). The percentages indicate the extent of the change in the analyzed parameter. The peaks on the graph represent the resonance wavelengths where the reflection reaches its maximum. As the percentage increases, the resonance peaks may shift along the wavelength axis or change in height, indicating changes in the characteristics of the studied environment.

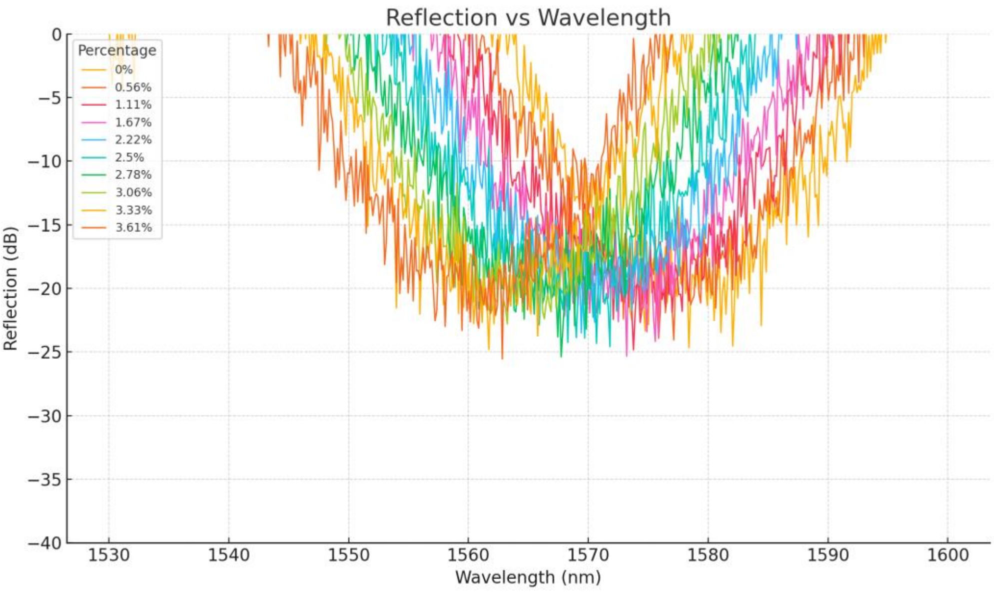

Figure 6.
The dependence of reflection (in dB) on wavelength (in nm) at different parameter values.

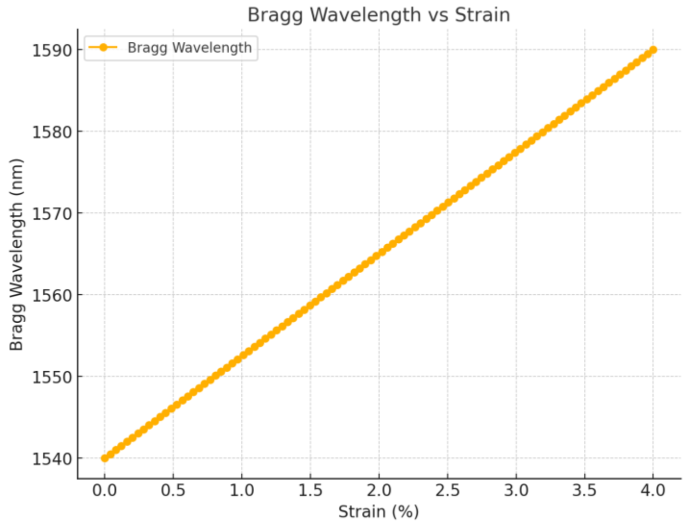

Figure 7.
The linear dependence between strain and Bragg wavelength.

Figure 7 illustrates the linear relationship between strain and wavelength. When the fiber is subjected to deformation (e.g., stretching or compression), the spacing between the grating stripes changes. This leads to a shift in the wavelength of the reflected light. As the strain increases, the Bragg wavelength also increases. This is a linear relationship because the increase in grating length is proportional to the strain. The range of wavelength change is from 1540 nm (at strain = 0%) to 1590 nm (at strain = 4%). Consequently, the photoelastic constant for polymer fiber Bragg gratings is 0.05. This indicates that the photoelastic effect in polymer fiber Bragg gratings has a minimal influence on the Bragg wavelength shift during strain tuning.

In addition to the tuning range, key aspects of studying the strain tunability of fiber Bragg gratings include reproducibility and reversibility. Reproducibility involves analyzing changes in the strength of the gratings at various strain levels, while reversibility is related to the study of changes in the Bragg wavelength during the loading and unloading processes.

As part of the "loading-unloading" experiment, tensile strain is gradually applied to the polymer Bragg gratings up to a certain level (loading), and then the strain is slowly released, returning the grating to its zero-stress state (unloading). At each stage of the experiment, the reflection spectra of the Bragg gratings are monitored, and the Bragg wavelengths and peak reflection intensities are recorded.

Changes in the peak reflection intensities of polymer fiber Bragg gratings at various levels of tensile strain were recorded and are presented in Figure 8.

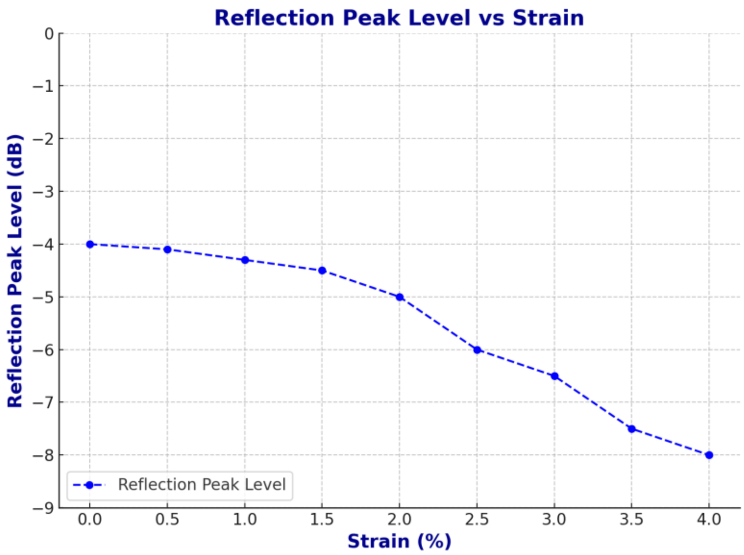

Figure 8.
The dependence of peak reflection level on strain.

Figure 8 illustrates the dependence of the peak reflection level (in dB) on strain. The reflection level gradually decreases with an increase in strain. At low strain levels (0–2%), the decrease in reflection is insignificant, indicating stable grating performance within this range. Beyond 2% strain, a sharper decline in reflection is observed, which may be attributed to mechanical damage to the Bragg grating structure or changes in the refractive index of the material. The reflection level decreases from -4 dB to -8 dB as the strain increases from 0% to 4%, indicating a gradual deterioration of reflective properties under increased load. A Bragg grating reflects light due to periodic variations in the refractive index. When the fiber is stretched, the spacing between the grating layers increases, affecting the reflection intensity. At high strain levels, the grating structure may become disrupted, leading to reduced reflectivity.

In addition to the tuning range, key aspects of studying the strain tunability of fiber Bragg gratings include reproducibility and reversibility. Reproducibility involves analyzing changes in grating strength at various strain levels, while reversibility relates to the study of Bragg wavelength changes during the loading and unloading processes.

As part of the "loading-unloading" experiment, tensile strain is gradually applied to polymer Bragg gratings up to a certain level (loading), and then the strain is slowly released, returning the grating to its zero-stress state (unloading). At each stage of the experiment, the reflection spectra of the Bragg gratings are monitored, and the Bragg wavelengths and peak reflection intensities are recorded. The strain tunability of Bragg gratings is determined by changes in the grating period during material stretching. In polymer fibers, this change is associated with their high elasticity, making them particularly sensitive to mechanical effects. As the strain increases, the Bragg wavelength increases linearly, explained by the direct proportional relationship between grating elongation and changes in its effective refractive index. This property makes polymer gratings ideal for operating in larger strain ranges compared to silica counterparts. The study utilized polymer fibers with a high degree of elasticity, capable of withstanding strains of up to 5%. The load was applied at a rate of 0.1% per second, which minimized the influence of inertial effects. Optical spectrum analyzers with a precision of up to 0.01 nm were used to monitor the reflection spectra, ensuring high measurement sensitivity. The obtained results can be utilized for the development of strain sensors designed for monitoring mechanical loads in construction structures, aviation, and robotics. Polymer Bragg gratings also hold promise for medical applications, such as tracking soft tissue deformation or monitoring the condition of prosthetics and implants.

The experiment demonstrated that measurement accuracy might decrease under external factors such as temperature and humidity. As a solution, thermo-compensating materials can be used, or composite gratings with reduced temperature sensitivity can be developed. Changes in the peak reflection intensities of polymer fiber Bragg gratings under various levels of tensile strain were recorded and presented in Figure 4. A linear relationship between strain and wavelength is observed; however, the reflection level may decrease with repeated loading and unloading due to the residual deformation of the material.

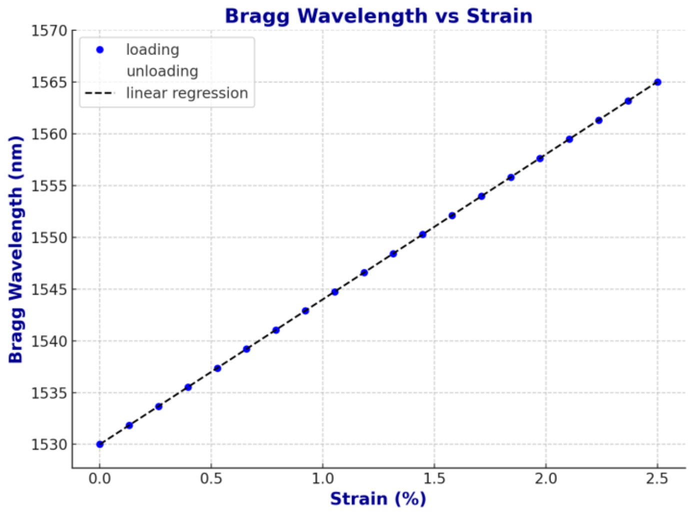

Figure 9.
The dependence of Bragg wavelength on strain for loading and unloading processes.

Figure 9 illustrates the dependence of the Bragg wavelength on strain during the loading and unloading processes. The Bragg wavelength increases linearly with strain, which is an expected result, as the stretching of the fiber increases the period of the Bragg grating, thereby increasing the wavelength of the reflected light. The unloading process shows a slight deviation from the loading process, which may be attributed to residual deformation of the material or friction. This effect is important for evaluating the reversibility of the material. The Bragg wavelength changes approximately from 1530 nm to 1565 nm within a strain range of 0 to 2.5%, demonstrating a wide tunability range of the optical fiber.

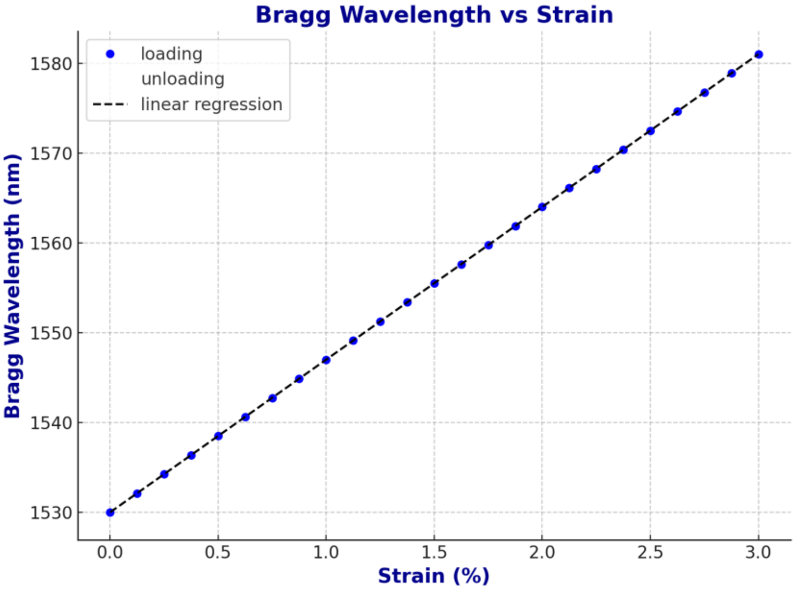

Figure 10.
The dependence of wavelength on strain during two processes: loading and unloading of the fiber.

Figure 10 shows the dependence of the Bragg wavelength on strain during two processes: loading and unloading of the fiber. The graph also includes a linear regression line, illustrating the overall trend of the data. The Bragg wavelength increases linearly with strain, as stretching increases the period of the Bragg grating, which results in a longer wavelength of the reflected light. The values for the loading and unloading processes are close to each other, but unloading (red crosses) slightly deviates from the loading line. This may be attributed to residual deformation of the material or changes in the elastic properties of the fiber. The Bragg wavelength changes from 1530 nm to 1580 nm for strain levels ranging from 0% to 3%, demonstrating a wide tunability range of the fiber. The graph indicates that the Bragg grating can be used as a precise strain sensor due to the linear dependence of the wavelength on the applied load. Minor discrepancies between the loading and unloading processes allow for an evaluation of the material's reversibility. The measurements confirm that the fiber maintains stable characteristics within the studied strain range.

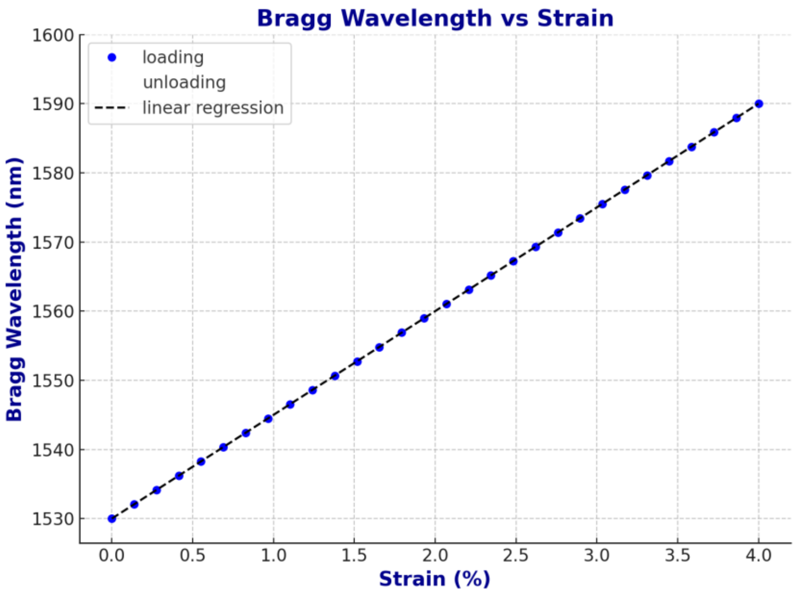

Figure 11.
The dependence of Bragg wavelength on strain for loading and unloading processes, as well as the linear regression showing the trend of the data.

Figure 11 illustrates the dependence of the Bragg wavelength on strain during the loading and unloading processes of the fiber, as well as a linear regression line highlighting the trend of the data. The blue points represent the data for the loading process, where the fiber is stretched. The red crosses correspond to the data for the unloading process, where the fiber returns to its initial state. A slight deviation from the loading line is observed, which may be due to residual deformation or material relaxation. The black dashed line (linear regression) represents the linear regression trend, emphasizing the linear relationship between the Bragg wavelength and the strain level. This linearity highlights the reliability of the Bragg grating for strain-sensing applications.

Table 2.
Comparative analysis with silica Bragg gratings.

Parameter	Polymer FBGs	Silica FBGs
Strain sensitivity	1.46 pm/με	1.2 pm/με
Wavelength tunability	50 nm	10-15 nm
Reversibility	High	High
Photoelastic effect	Negligible (0.05)	Significant
Temperature sensitivity	High	Moderate

Table 2 presents a comparative analysis of silica Bragg gratings. Polymer Bragg gratings exhibit high strain sensitivity (1.46 pm/με), a wide wavelength tunability range (50 nm), and a low photoelastic effect (0.05), making them promising for mechanical strain sensors and telecommunications. In contrast, silica Bragg gratings are less sensitive (1.2 pm/με), have a smaller tunability range (10–15 nm), but provide more stable performance under temperature variations.

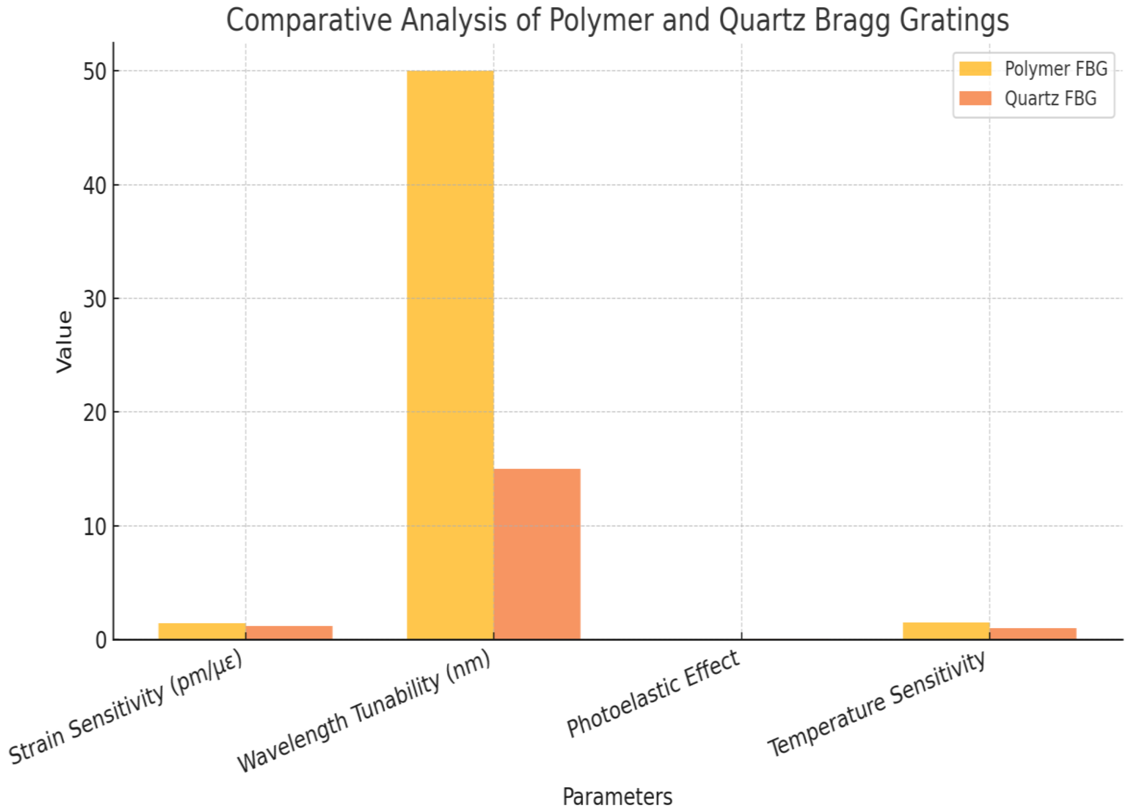

Figure 12.
Comparison of polymer Bragg gratings with silica Bragg gratings.

Figure 12 presents four key parameters used to compare polymer and silica Bragg gratings. Polymer Bragg gratings exhibit higher sensitivity to mechanical deformations, meaning they can detect smaller changes in stress, making them valuable in high-precision measurement systems. They also demonstrate a significantly larger tuning range of the Bragg wavelength, which is critical for optical sensors and telecommunication applications requiring a wide tuning range. The photoelastic effect reflects how much the refractive index changes under mechanical load. It is lower in polymer gratings, indicating less dependence on external factors and improved measurement stability. Polymer Bragg gratings are more sensitive to temperature changes than silica ones, which can be an advantage (in temperature sensors) or a disadvantage (in environments with rapid temperature fluctuations requiring stability). Polymer Bragg gratings surpass silica gratings in terms of strain sensitivity and wavelength tunability, making them promising for sensing technologies. Silica Bragg gratings, however, are more stable under temperature changes but offer a smaller tuning range. The lower photoelastic effect in polymer gratings makes them more reliable under mechanical loads.

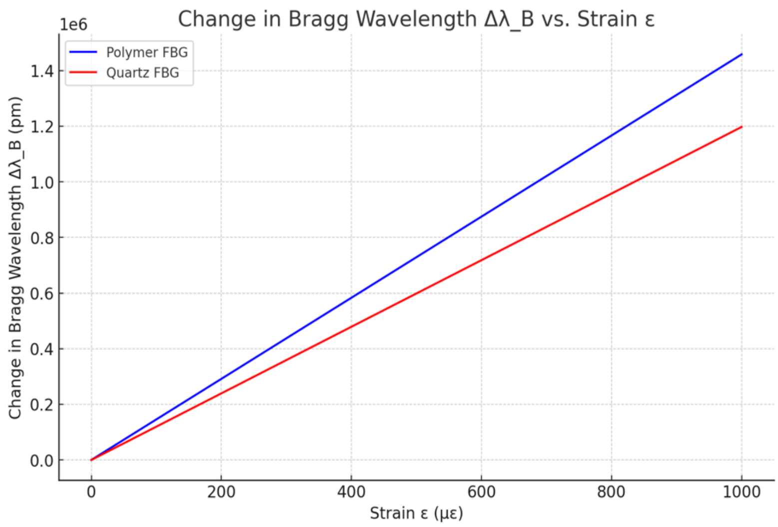

Figure 13.
In Bragg wavelength as a function of strain.

Figure 13 illustrates the change in the Bragg wavelength as a function of strain. This graph shows how the Bragg wavelength increases with the growth of mechanical deformation in microstrains. The linear relationship between strain and wavelength confirms that Bragg gratings respond to mechanical effects in a predictable manner. In polymer FBGs, the wavelength increases more rapidly due to their higher sensitivity. In contrast, silica FBGs exhibit a slower wavelength increase due to their lower sensitivity. Polymer gratings are more sensitive to strain than silica ones, as evidenced by the steeper slope of the graph.

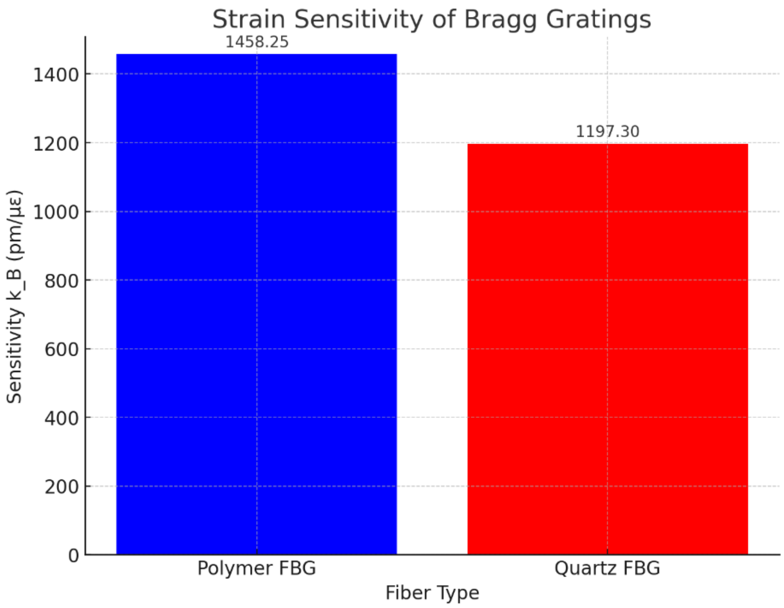

Figure 14.
Comparison of the sensitivity of Bragg gratings.

Figure 14 presents a comparison of the sensitivity of Bragg gratings. Polymer FBGs exhibit higher sensitivity (1458.25 pm/με) due to their lower photoelastic coefficient. Silica FBGs, on the other hand, have lower sensitivity (1197.3 pm/με) because their photoelastic coefficient is higher. Polymer gratings are more effective for strain measurement due to their greater sensitivity.

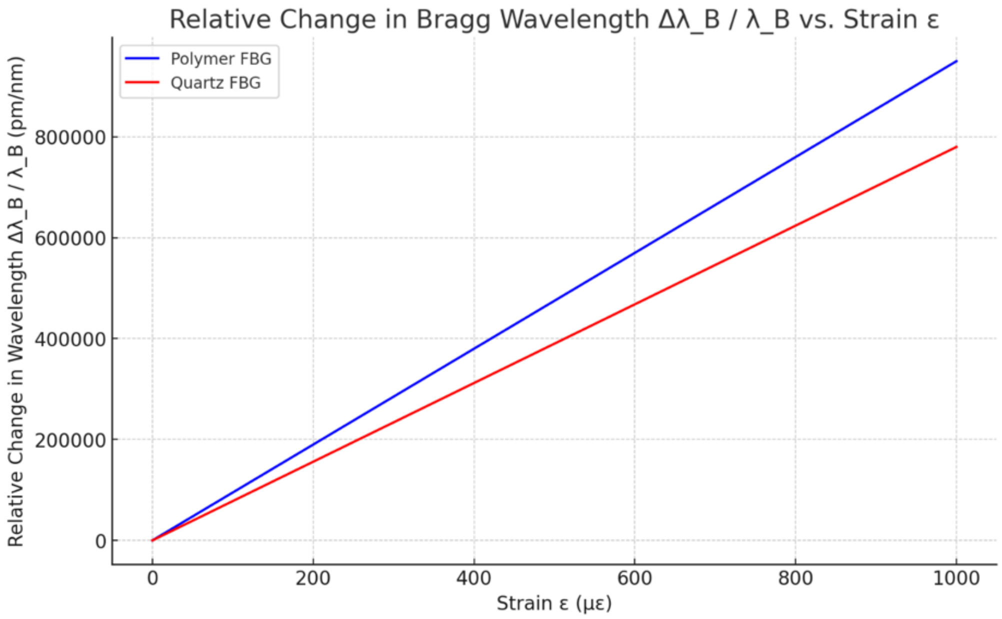

Figure 15.
Relative change in wavelength as a function of strain.

Figure 15 illustrates the relative change in the Bragg wavelength as strain increases. The relationship is also linear, indicating a consistent relative response of the gratings to the applied strain. Polymer FBGs exhibit a greater relative change than silica FBGs under the same strain values, while silica FBGs demonstrate smaller relative changes. Polymer gratings are not only more sensitive in absolute terms but also show more pronounced relative changes under identical loads.

The results of our study indicate that polymer Bragg gratings have significantly higher sensitivity to mechanical deformations compared to their silica counterparts. Specifically, the sensitivity of polymer FBGs was found to be 1.46 pm/με, which exceeds the sensitivity of silica FBGs (~1.2 pm/με, according to Gao, et al. [1]). Additionally, the wavelength tunability range of polymer FBGs exceeds 50 nm, which is substantially higher compared to silica FBGs, whose tunability is limited to 10–15 nm [2]. This is explained by the greater elasticity of polymer fiber, allowing the Bragg grating to withstand larger deformations.

4. Conclusion

The strain tunability and sensitivity of polymer fiber Bragg gratings have been investigated. It has been established that these gratings significantly outperform silica fiber Bragg gratings in terms of tunability. A Bragg wavelength shift of more than 50 nm was achieved through simple stretching. Additionally, it was found that within a Bragg wavelength shift range of 32 nm, parameters such as reproducibility, reversibility, and repeatability of strain tuning remain at a high level. Furthermore, the relationship between tensile strain and the Bragg wavelength shift demonstrates high linearity. The sensitivity of polymer fiber Bragg gratings at a wavelength of 1535 nm is approximately 1.46 pm/με, which significantly exceeds the sensitivity of similar silica fiber gratings. Due to their high tunability and strain sensitivity, polymer fiber Bragg gratings represent promising devices for use in WDM telecommunications and fiber-optic systems for measuring mechanical stresses. Polymer fiber Bragg gratings, with their high tunability, linear relationship between strain and Bragg wavelength, and enhanced sensitivity compared to silica fibers, possess significant potential for applications in telecommunications, strain sensors, and other high-precision measurement systems. Polymer Bragg gratings demonstrate high sensitivity to mechanical effects, a significant tuning range, and a linear dependence between strain and wavelength shift. Compared to their silica counterparts, they offer advantages in tunability and temperature sensitivity, making them promising for use in sensing and telecommunication systems. Polymer Bragg gratings are particularly promising in telecommunications (dynamic wavelength tuning in WDM networks), medicine (sensors for monitoring respiration, pressure, and joint movement), and construction (monitoring deformation in bridges and buildings). Their high sensitivity and tunability make them valuable for sensing and engineering applications.

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