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Optimizing signal conversion in uniform FBGs with InGaAs photodetectors for medical sensors

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ABSTRACT

This study experimentally interrogates the spectral response of uniform fiber Bragg gratings (FBGs) with varying reflectivity levels of 30%, 50%, 70%, and 90% under controlled environmental stimuli. The objective is to elucidate the influence of reflectivity on the wavelength shift behavior of FBGs and to inform the optimal interrogation of these elements with indium gallium arsenide (InGaAs) photodetectors in high-performance sensing systems. Utilizing high-precision measurement procedures and specialized instrumentation, the experiments revealed that the magnitude and pattern of wavelength shifts are significantly influenced by FBG reflectivity. Specifically, lower reflectivity enhances sensitivity, while higher reflectivity contributes to greater spectral stability. These findings highlight the critical role of reflectivity in shaping the spectral modulation characteristics of FBGs, establishing a critical theoretical framework for precision optical sensor systems. The outcomes give significant contributions to the design and calibration of FBG-based sensors, particularly biomedical applications where precision and responsiveness are paramount.

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1. INTRODUCTION

Fiber Bragg gratings (FBGs) have become the most significant technology and well-established usage in fiber optic sensors. They work by creating periodic changes in Fiber's refractive index through photo-inscription. Compared with conventional sensors, FBGs are beneficial due to their anti-electromagnetic interference, lightweight, small size, reusability, and adaptability to harsh environments such as high-temperature voltage fluctuations [1], [2]. The key factor affecting the performance of FBG sensor devices is the accurate demodulation of FBG sensor signals. The research on FBG sensors until the 2000s prominently sharpened on standard optical sensing and fabrication of gratings using direct inscription through picosecond laser pulses [3], [4], interferometer set-up [5], and a phase mask. There is the progressive standardization of their interrogation with tunable lasers and low-cost spectrometers [6]. More figures of researchers have studied the graph fiber of Fabry-Perot interferometry to detect photodetector signals [7]–[10], but the material must be optimized; meanwhile, the signal direction entirely depends on the effectiveness of the material. This dependence caused the sensor output to limit the detection direction and different angles. It is necessary to improve the figure of sensors to detect photodetector signals at all reflectivity and location in the transformer. The shortcoming is that a wide range of photodetector signals can be covered by the sensor's narrow bandwidth.

However, real experimental measurement using various FBG reflectivity is rarely reported because, till now, theoretical calculation methods such as coupled mode theory have been the primary methods to detect the reflectivity of FBG.

Previous research conducted by Lei and Chen [5] has used cavity ring-down (CRD) spectroscopy technology to measure the laser resonator loss, including geometric diffraction loss, output mirror loss, scattering loss, and transmission loss. The transmission loss is related to the reflectance of the cavity mirror, which can be determined with CRD spectroscopy, which uses the relationship between the reflectance of the cavity mirrors and the transmission loss of the cavity [5]. Previously, Gong *et al* [11] measured high-reflectance mirrors using CRD technology and achieved reflectances up to 99.925%. However, this takes too much time and causes misalignment of the optical elements. The different types of fiber designed were developed by Michelson and Sagnac interferometers [12]–[14]. Mandrel also developed FBG using the frequency bandwidth, but different resonating modes cover the wide bandwidth [15], [16]. To accomplish this, uniform FBGs are developed in conjunction with indium gallium arsenide (InGaAs) photodetectors to amplify the signals in this research. This research presents a new solution to our research, which focuses on the inquiry of the peak Bragg wave shift caused by the conversion process with various reflectivity. FBG sensors are stable and reliable, exhibit linear responses to sensing parameters, and have been used for various parameters such as strain, vibration, pressure, and temperature. FBGs were designed with specific parameters to optimize detection [17].

Our study focused on fabricating and characterizing uniform FBGs with controlled parameters to assess their effectiveness in optical-to-electrical signal conversion. Optical signals were transmitted through the FBGs and detected using InGaAs photodetectors, demonstrating high sensitivity and accuracy [18]–[20]. This successful conversion process was crucial for enhancing the precision and reliability of medical sensors. By examining Bragg wavelength shifts and the performance of uniform FBGs with InGaAs photodetectors, the research establishes a strong foundation for developing advanced medical sensor systems.

A notable research gap remains in exploring the dynamics of peak Bragg wavelength shifts during the conversion of optical signals into electrical signals, particularly within the context of medical sensing technologies. This study addresses that gap by extending prior findings. Earlier interrogations have demonstrated the utility of chirped FBGs in strain detection, reflecting the adaptability of FBGs across various sensing [21]. Similarly, other work has shown that uniform FBGs can effectively be applied in temperature sensing, emphasizing their role in optical signal translation [22]. This paper showed the key aspects of our research, including the work description, the approach utilized for optical-to-electrical signal conversion, the significance of research for medical sensor development, and its relation to existing works in the field. By interrogating the peak Bragg wave phenomenon using FBGs with InGaAs photodetectors, we aim to advance state-of-the-art medical sensor systems.

2. METHOD

The experimental set-up was designed to interrogate the wavelength shift characteristic of FBG with various reflectivities, as shown in Figure 1. A comprehensive set-up involving specialized equipment and precise measurement techniques was employed to accurately measure and analyze the wavelength shift, as shown in Table 1.

FBG with varying reflectivities were fabricated using established techniques [23] and used as the injection pulse signal source. A tunable laser controls temperature to gain the precision Bragg. The voltage between 0 to 5 V in the InGaAs photodetector was used to achieve the linear response of signal conversion. The FBG parameters could be observed in Table 2. The FBG reflectivity strongly depends on the lateral extent of FBG. Each guided mode had a different spatial distribution within the fiber core [24].

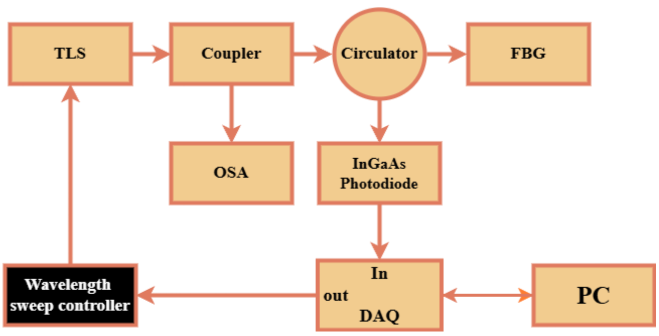

Figure 1. Experimental set-up of interrogating the wavelength shift of FBGs

Table 1. Proposed materials and equipment

Material	Specifications
Circulator	Direct the optical signal through the FBG sensor set-up
FBG uniform	Reflectivity levels: 30%, 50%, 70%, 90%
InGaAs	Selected for its sensitivity to infrared wavelengths
LabVIEW	Data acquisition and signal processing. Provides real-time monitoring and control
Data acquisition (DAQ)	Interfaces with LabVIEW to capture, process, and store data from the photodetector
Optical spectrum analyzer (OSA)	Spectrum monitoring
Interrogator	Measure and interpret the FBG wavelength shift
Tunable laser source (TLS)	Laser source

Table 2 demonstrates that FBG extended uniformly across the cross-sectional area of the fiber core, each guided mode was reflected equally, and the total reflectivity increased. These FBG were precisely designed and fabricated on optical fibers with accurate control over the grating period and refractive index modulation to achieve the pertinent reflectivity characteristics.

Table 2. Uniform parameter

FBG	L_B (nm)	Bandwidth (nm)	SLR (dB)	Reflectivity (%)
FBG 1	1549.974	0.147	18.48	30
FBG 2	1549.936	0.176	14.99	50
FBG 3	1549.895	0.216	14.18	70
FBG 4	1549.962	0.284	20.26	90

The photodetectors used in the interrogator system were typically designed to operate in the relevant wavelength range of the FBG reflections. The peak responsivity is achieved when the photon energy surpasses the bandgap energy. Figure 2 illustrates a responsivity value of InGaAs photodetector at 1.04 A/W. It could efficiently convert the optical power of the reflected signals into corresponding electrical currents, providing a reliable representation of the spectral information encoded in the FBG [25], [26].

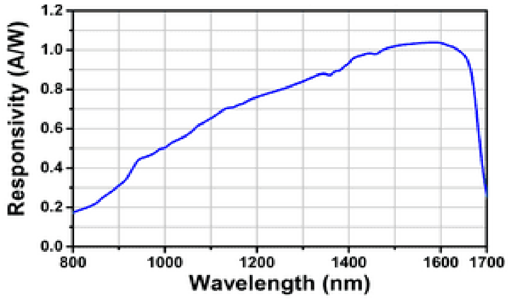

Figure 2. Responsivity of InGaAs photodetector

An OSA was used to monitor the wavelength shift using high-resolution spectral analysis. A tunable laser source (TLS) provided a controlled optical signal in 1543–1555 nm. Precise tuning of TLS ensures that the optical signal corresponds to the wavelength range of interest and enables characterization of the spectrum reflected by the FBG. TLS was integrated into a system alongside the photodetector, DAQ, system, and LabVIEW for signal processing, as shown in Figure 1. OSA was used to verify the spectral characteristics and was not part of the main system. The acquired data were analyzed using appropriate signal processing techniques, allowing measurement and quantification of the wavelength shifts exhibited by the FBG with different reflectivities.

3. RESULTS AND DISCUSSION

In this work, a swept wavelength from the TLS laser was used as the input, and when the light was irradiated onto the FBG, it was transmitted through the FBG and directed to the converter, enabling the obtained results to be read by DAQ system and LabVIEW for the DAQ interface. The usage of the DAQ begins by reading the photodetector input voltage, which is then converted to current and transformed into voltage. This voltage could be output as the DAQ's input voltage at the DAQ's axis output connector. This converts optical signals into electrical signals as a wavelength versus input voltage curve.

3.1. Converter system

The elemental principle of this conversion is the photovoltaic effect, where incoming light induces a voltage within a material. In this case, the light from the FBG was directed into an InGaAs photodetector, which absorbed the FBG light into its InGaAs material and generated a current proportional to the optical power of the signal. The shifted wavelength variations after conversion are shown in Table 3.

Table 3. Photon to current conversion spectrum in photodetectors

FBG	$\Delta\lambda_b$ Optical signal in interrogator (nm)	$\Delta\lambda_b$ Electrical signal in InGaAs (nm)
FBG 1	0.02392	0.05013
FBG 2	0.02226	0.02926
FBG 3	0.01622	0.04292
FBG 4	0.01298	0.02580

Reflectivity was calculated from the FBG transmission spectrum. On the contrary, the interrogator used an interferometer to measure reflection without transmission. The FBG produced this shifted wavelength from Table 3 because of precision detection from the interrogator and InGaAs. A light source (1549–1551 nm) was coupled into the fiber to measure the reflection spectrum. The maximum reflectance was calculated from the minimum transmission at the Bragg wavelength. The ambient temperature was 26.5 °C. The interrogator's original spectral data obtained by acquisition was preprocessed by algorithm, extraction to reflectance spectrum, and intercept to obtain ideal spectral data. However, it was challenging to determine the value of the converted reflectance because it included random noise due to various factors such as the optical path, circuit, and temperature system [27].

The reflectance of FBG was determined by the strength of the grating structure's refractive index modulation. The figure of higher reflectance signifies a more pronounced refractive index modulation within the FBG, leading to a stronger interaction with external stimuli like strain or temperature. Table 3 shows the number of wavelength shifts from the least reflectivity, which was slightly decreased since the weaker reflectance level corresponds to less pronounced grating structures, which could result in smaller changes in the Bragg wavelength for a given stimulus. FBGs with 30% reflectance had a weaker grating structure and exhibited a higher wavelength shift due to their increased sensitivity to external factors. In contrast, the FBG with 90% reflectance, possessing a stronger grating structure, might experience a smaller wavelength shift as it was less responsive to changes in strain and temperature. Table 3 shows an FBG 70% reflectance had a higher wavelength shift than 50% reflectance due to the balance between sensitivity and strength of the grating structure. 70% reflectance could provide a substantial response to external stimuli while maintaining a certain level of stability, resulting in a higher wavelength shift compared to FBG with lower reflectivity variations.

The precise measurement of small wavelength shifts was especially important. Reflectivity and bandwidth were the main parameters that significantly impacted FBG's accuracy and sensing capability. Strain-induced wavelength shift occured as a result of the deformation effects exerted on the grating, which could be mathematically described by a specific formula:

$$\Delta\lambda_b = \frac{\lambda_b(n_{eff}(\Delta\varepsilon)-\Delta n)}{n_{eff}} \tag{1}$$

where $\Delta\varepsilon$ represents the strain variation, Δn corresponds to the refractive index changes due to strain, λ_b represents Bragg wavelength, and n_{eff} represents the effective refractive index.

Table 3 also represents the $\Delta\lambda_b$ shifted values. This enables monitoring Bragg property changes due to mechanical strain variations and temperature fluctuation. The alterations in peak wavelength values at maximum intensity exhibit substantial spectral broadening arising from the spectral response of the photodetector and light dispersion. Chromatic dispersion became a substantial influencing factor due to variations in the speed of light with different wavelengths as they propagated along the fiber. As a result, diverse spectral components of the optical signal reach the photodetector at different times, leading to both broadening and shifting of the wavelength peaks. The spectral response represented the efficiency of the photon-to-electron conversion process. Non-uniform spectral response in the photodetector prevents the complete conversion of all wavelengths, thereby resulting in changes to the peak wavelength of the electrical signal. When the FBG peak was detected using an interrogator, the FBG exhibited characteristics such as temperature sensitivity, leading to small changes and wavelength shifts. Variations in temperature cause thermal expansion and contraction of the FBG, thereby altering the integrating spacing and inducing wavelength shifts in the FBG.

Wavelength variations were mainly caused by stress-induced shifts due to applied pressure during measurement. Environmental factors like pressure and humidity also affected the FBG's grating and spectral response. The interrogator detected the Bragg grating and showed a narrow reflection peak. Based on the grating, period, and refractive index, this peak is shown in Figure 3.

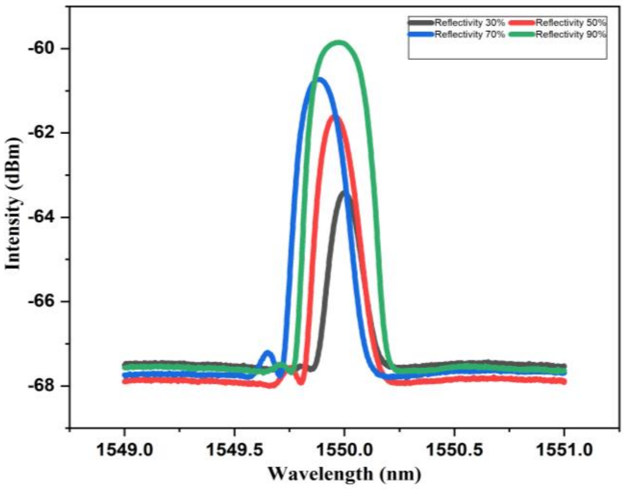

Figure 3. Optical spectrum signal

Wavelength shifts occurred as photons interacted with the FBG, altering its refractive index and generating electron-hole pairs in the InGaAs detector. To sum up, variations in reflectivity could cause variations in the amount of light coupled into the grating structure, leading to inconsistent responses and fluctuations in detected signals. This results in an error in the reflectance calculated from the transmission spectrum of the grating. This could complicate the grating selection in fiber laser design. Nevertheless, in the FBG measurement process, various factors had certain effects on the spectrum, such as fiber type, the quality of splices, and the test environment.

3.2. Wavelength variation

The peak wavelength variation of the uniform FBG was influenced by photodetector linearity, temperature changes, responsivity and wavelength-to-voltage conversion. The accuracy of this conversion directly affected the consistency of the electrical signal. Any non-linearity in the photodetector could cause wavelength shifts. These factors impacted the reliability of the FBG output [28]. The variations in the peak wavelength of the uniform FBG after conversion were attributed to multiple factors, including the linearity of the photodetector, temperature changes, responsivity, and the wavelength-to-voltage conversion process.

The diversity of gratings with narrow spectral bandwidths provided an inherent advantage in terms of sensitivity [9], [29]. A narrower spectral bandwidth increases refractive index sensitivity, facilitating precise detection of small environmental changes. Figure 4 shows the correlation between the wavelength and power in the uniform FBG. The reflected wavelength reached about 30% of the incident power at the Bragg wavelength. The reflected light power diminished as the wavelength deviated significantly from the Bragg wavelength.

In Figure 4, differences in the curves and wavelength shifts of optical signals were converted into electrical signals caused by various factors during the signal conversion process. The most important reason for the wavelength shift was the change in the Bragg wavelength of the laser grating due to alterations in the effective mode index caused by modulation techniques such as direct modulation. In direct modulation, a laser source was biased near its threshold, driven by an electrical bitstream, and the applied current was increased well above the laser's threshold, producing light pulses representing the signal modulation. The two rate equations must be solved numerically. Due to the laser's limited modulation bandwidth, the light pulses did not have sharp rising and falling edges. Significant delays occur because it took time for the optical power to rise.

From the graph, both of them had strengths and weaknesses. 90% reflectivity was suitable for applications where high sensitivity to external factors was desired since it had a stronger interaction with external stimuli, leading to a more pronounced wavelength shift, whereas it also leads to a smaller change in wavelength shift for a certain stimulus since possessing a stronger grating structure, which mad a smaller wavelength shift as it was less responsive to changes like strain or temperature. Hence, a larger wavelength shift compared to higher reflectivity FBG in the 30% reflectivity. Its made suitable for applications where a higher sensitivity to external factors was desired, meanwhile, it had a weaker interaction with external stimuli, which could result in a smaller wavelength shift compared to FBGs with higher reflectivity. However, based on the general principles of optical sensing monitoring, a higher reflectivity of 90% was more beneficial because it had the potential to provide a reliable signal and stability. Higher reflectivity could enhance the interaction with external stimuli, leading to a more pronounced and consistent signal acquisition.

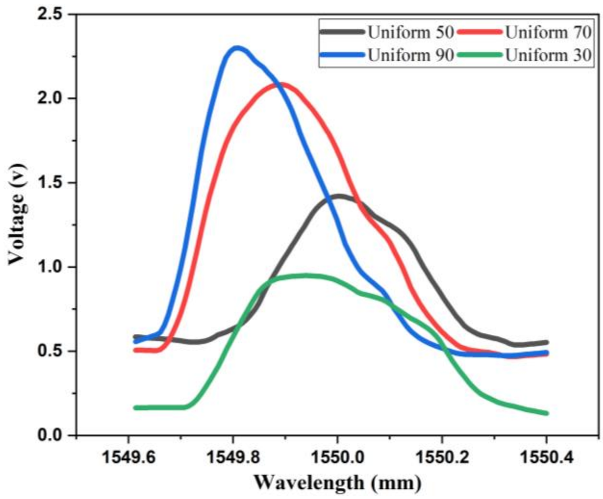

Figure 4. Peak detection with InGaAs

The voltage on the curve was related to the photoelectric effect. The wavelength of a wave could affect the energy of the electrons emitted by the wave. A system that measured the intensity of light using photodetectors that were sensitive to different wavelengths of light. The photodetectors converted the optical signal into a current signal, which was then converted to a voltage signal using a trans-impedance amplifier. The voltage signals for each current detection were combined and converted to digital data using an analog-to-digital converter. The curve showed the Gaussian pattern. The most prominent Gaussian for the best FBG sensor was shown by uniform 90%. This design offers optimized reflectivity and lower sidelobe strength, then making it ideal for sensing applications. The ideal sensor based on the Gaussian pattern respectively was shown by maximum reflectivity.

3.3. Human heart rate detection

Exemplify research was the measurement of the human heart rate. Detection of minute strain variations induces wavelength shifts in Bragg grating, and the utilization of a narrow spectral bandwidth enables more precise measurements of these shifts. This value was obtained as the transmitted light detects the identical wavelength as it passes through [30], [31]. An additional benefit of a narrow spectral bandwidth was mitigating interference from other optical signals. The reduced spectral bandwidth minimizes the potential for overlap with other optical signals, thereby preserving the accuracy of measurements. In addition, the narrow spectral bandwidth of uniform FBG rendered them less vulnerable to fabrication errors and variations, leading to more stable and reproducible measurements. This research demonstrated this characteristic, where FBGs with narrow spectral bandwidths showed superior suitability as sensors due to their high sensitivity, excellent stability, and minimal interference [32].

The measurement of cardiac pulsation could be ascertained by assessing the wavelength magnitude in three distinct states of activity, namely motionlessness, ambulation, and sprinting [24], [29]. Consequently, wavelength magnitude could be converted into a voltage value through a converter system linked with FBG. The voltage range employed spanned from zero to five volts to achieve linearity in the outcomes. Thus, each wavelength value should have possessed a voltage magnitude proportionate to the above range. FBG sensors were used to monitor heart rate during exercise, as they were immune to electromagnetic interference, as shown in Figure 5. The highest heart rate detection of FBG in humans when running was shown by the blue graph in Figure 6. It was caused by cardiovascular exercise that increases heart rate. Heart rate was a good measure because it indicated a higher level of physical activity. The peak fluctuations that occurred when running when detecting heart rate with FBG were due to cardiovascular drift.

Cardiovascular drift referred to the natural increase in heart rate when running with little or no change in pace. The increase in heart rate was mainly caused by the natural increase in core body temperature when running [27], which elevates the heart rate the same way running in hot conditions does. Therefore, it was important to understand the effect of cardiac drift on heart rate detection when using heart rate to measure easy and long runs, to train more effectively, and to maximize potential.

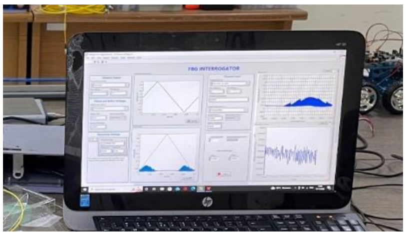

Figure 5. Heart rate detection

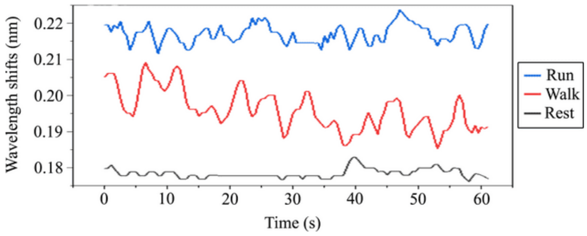

Figure 6. Human heart rate detection using the currently proposed FBG system

The red graph in Figure 6 significantly decreased towards the end of 60 seconds compared to the less fluctuation in resting heart rate shown by the black graph since when walking, the heart rate increases as the body demands more oxygen and energy to support the physical activity. Furthermore, the heart rate stabilizes to meet the activity's oxygen and energy requirements, leading to a relatively consistent heart rate during sustained walking. Toward the end of 60 seconds of walking, the body started adapting to the exercise, becoming more efficient in oxygen utilization and energy production. It caused a slight decrease in heart rate as the body adjusts to the workload. The black one reflected the baseline cardiovascular activity when the body was at rest and not under physical stress. It had less fluctuation since minimal external factors influenced heart rate variability, making it more stable than when engaging in physical activities like waking. The wavelength shift in this experience generally affected the grating structure's refractive index modulation due to the interaction between light waves and the grating structure.

Integration of FBGs, as described in Figure 6 for heart rate detection, holds promising implications for healthcare monitoring. The non-invasive nature of FBG-based sensing and the ability to detect heart rate with high accuracy and reliability make it a valuable tool for cardiovascular assessments. The real-time monitoring capabilities of FBGs, combined with their compatibility with wearable devices, enable continuous heart rate tracking, potentially leading to early detection of cardiovascular abnormalities and improved patient care.

3.4. Advantages and disadvantages

The optical-to-electrical signal conversion method using InGaAs photodetectors in FBGs offers several significant advantages. One of its main strengths is its high sensitivity to wavelength shifts, allowing precise detection of physical changes such as temperature or pressure [28]. Additionally, InGaAs photodetectors have a broad spectral response within the near-infrared wavelength range, making them highly suitable for medical applications like real-time body condition monitoring. The spectral response of these photodetectors depends on the number of photons captured and converted to electrons, with quantum efficiency playing a crucial role in this process. This flexibility and sensitivity make the method ideal for optical sensor applications in various monitoring systems.

However, the method also has certain limitations. One primary challenge is its susceptibility to environmental noise, affecting signal conversion accuracy, particularly in applications requiring high precision [33]. Additionally, dirty or contaminated gratings can obstruct photon detection, reducing the system's sensitivity and complicating accurate signal conversion. Furthermore, fluctuations in equipment temperature can introduce mode looping, leading to inconsistencies in the optical path and impacting sensor performance. This dependence on external factors necessitates better control to achieve more consistent results. Although the high sensitivity is a considerable advantage, further optimization is still required to mitigate the impact of uncontrollable environmental variables.

4. CONCLUSION

Our findings revealed a correlation between FBG reflectivity and wavelength shifts, indicating that reflectivity variations affect the reflected wavelength detected by the photodetector. This was measured as a voltage shift, demonstrating photon-to-current conversion demonstrated across different reflectivity levels. The system successfully detected heart rate by measuring the reflected light into voltage, which was then filtered, amplified, and analyzed. These findings enhance understanding of reflectivity-dependent behavior in FBGs, aiding optical signal processing, healthcare, and communications. Graphs illustrated how FBG reflectivity modulates wavelength shifts. Future research should explore environmental factors like pressure and humidity for FBG stability and performance improvements, especially in precise medical applications. Advanced noise reduction and signal processing, potentially using machine learning, could mitigate environmental noise and optimize sensor stability.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships, ideological that could have influenced the work reported in this paper. There are no conflicts of interest related to the research presented in this manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Bunga Meyzia upon reasonable request. Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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