Study the effect of refractive index on Transmission wavelengths of modified TFBG based on Surface Plasmon Resonance

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Abstract

In this paper, the characteristics of the Silica TFBG type of optical fiber, which has a wavelength of 1550 nm, were investigated and enhanced. Specifically, the refractive index was used to sense various sodium nitrate concentrations. The optical fiber's thickness was then lowered chemically using 10% hydrofluoride acid, and gold film was applied using the SPR technique. The findings demonstrated a shift in the wavelengths of the transmitting light spectrums, as well as an increase in power and, consequently, sensitivity .

1. Introduction

The effect of refractive index (RI) on the transmission wavelengths of modified tilted fiber Bragg grating (TFBG) sensors based on surface plasmon resonance (SPR) is a subject of significant interest due to its implications for enhancing sensor sensitivity and range. TFBG-SPR sensors exhibit a linear relationship between RI sensitivity and the grating period, with sensitivity slightly increasing with larger tilt angles(Moreno *et al*., 2023). The use of multi-angle TFBG structures, particularly those coated with a gold film, has been shown to improve the RI measurement range and maintain high linearity, achieving sensitivities of 523.41 nm/RIU over a range of 1.30 to 1.42(Chen et al., 2018) (Zhang *et al*., 2016). The deposition of a gold film on TFBG enhances RI sensitivity dramatically, with increases from 1.5 nm/RIU to 500 nm/RIU, and the sensitivity of the gold-coated TFBG-SPR is significantly higher than that of bare TFBG (Jiang & Lv, 2013). Additionally, the use of silver nanowire coatings on TFBG sensors can further increase sensitivity by 3.5 times compared to uncoated sensors, due to the excitation of surface plasmons by orthogonally polarized cladding modes (Bialiayeu *et al.*, 2012). These modifications allow TFBG-SPR sensors to detect a wide range of RIs, from 1.15 to 1.43, making them highly suitable for chemical and biochemical sensing applications (Zhang *et al.*, 2016). Overall, the integration of SPR with TFBG, through various structural and material modifications, significantly enhances the sensor's ability to detect changes in the refractive index, thereby broadening its application potential.

Tilted Fiber Bragg Gratings (TFBGs) are specialized optical fiber structures characterized by their grating planes being slanted relative to the fiber axis, which disrupts the cylindrical symmetry and enhances light coupling from the core to the cladding, exciting numerous cladding modes(Jiang & Zhao, 2023). These gratings are particularly useful in sensing applications, such as measuring the refractive index of liquids, where high accuracy and the ability to distinguish between similar refractive indices are crucial. This is achieved through demodulation methods that analyze the shift of cladding mode groups using cross-correlation algorithms and spectral analysis techniques (Cięszczyk *et al.*, 2024). TFBGs also find applications in detecting trace elements like cadmium ions, where they are coated with gold films and functionalized with glutathione to enhance sensitivity through localized refractive index changes, achieving a detection limit significantly lower than other fiber grating-based sensors(Ren *et al.*, 2023). The orientation of TFBGs is critical for accurate measurements, as their sensitivity to various parameters like vibration and pressure is direction-dependent. This orientation can be determined by observing asymmetrical amplitude modulation of cladding resonances when the fiber is rotated on a planar substrate(Xie *et al.*, 2023). Additionally, the transmission spectrum characteristics of TFBGs, such as minimum, width, and energy, exhibit linear dependencies on the environmental refractive index, which can be leveraged in sensor systems(Tolegenova *et al*., 2023). The integration of nanomaterials on TFBGs further enhances their spectral modulation and sensing capabilities, offering a promising approach to overcoming the limitations of the fiber's one-dimensional structure (Jiang & Zhao, 2023).

Materials and Methods

The experimental setup for the suggested refractive index sensor device is shown in Figures (1). The 2 cm TFBG is submerged or incubated in several solutions with refractive indices ranging from 1.3333 to 1.3456 . The transmission power detection experiment uses a laser source at wavelength 1550nm was used to illuminate the TFBG, allowing for the observation of minute changes in the optical characteristics of the fiber transducer, and an optical spectrometer an optical spectrum analyzer (OSA Thor-Lab), transmission spectra were measured with a resolution of 0.01 nm for spectrum monitoring. Use Five NaNO3 salt in water solutions were made for this article's purposes. Refractive index of water solutions with $NaNO_3$ contents ranging from 0% to 50%

Preparation of TFBG:

Fabrication: Fabricate the modified TFBG, ensuring it has a suitable coating to support SPR phenomena. TFBG can be created through methods like phase mask or point-by-point writing (An et al., 2023).

TFBGs are coated with a thin gold film to facilitate SPR, which is essential for biosensing applications like detecting NY-ESO-1 antibodies, where the TFBG is tilted at 18° and coated with a 50-nm-thick gold layer (Qu *et al*., 2023). This coating enhances the sensor's sensitivity and specificity, as seen in the detection of mercury ions using a TFBG-SPR DNA-biosensor, where the TFBG is used to excite SPR and detect surface perturbations caused by specific DNA interactions (Duan *et al*., 2021).

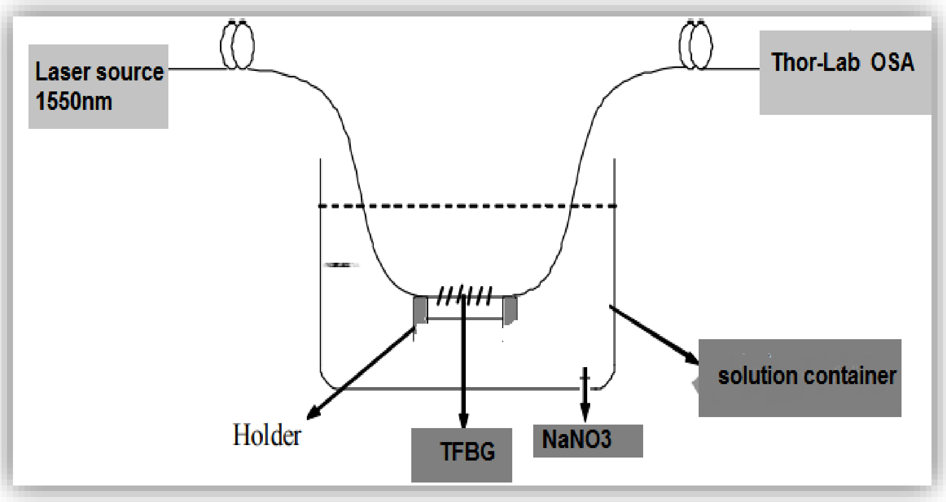

Figure (1) Diagram of measurement setup for TFBG submerged in solutions with various RI transmission spectra

The Results

Transmitted Modes of (TFBG) Sensor at different of prepared Solutions (without coated)

The spectra transmitted from the Bragg grating sensor when the refractive index of the solution changes with the change of concentrations can be seen in Figure (2). The patterns of the spectra to the left represent all the concentrations of the solution, while the spectra curve between the highest and lowest concentrations appear to the left. As concentration increases, the intensity of the peaks also increases, indicating greater absorption of light at certain wavelengths. The peaks around 1644-1648 nm suggest specific absorption bands characteristic of the analyte.

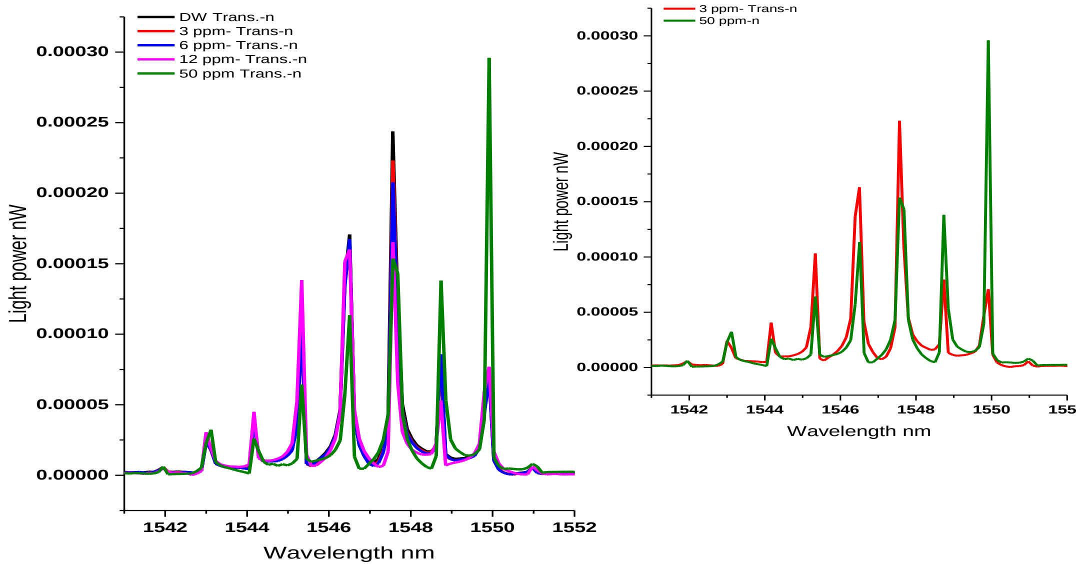

Figure (2) Transmitting spectra for all concentrations in the left figure, while the right spectrum is for the highest and lowest concentrations without coating sensor.

4-2Transmitted Modes of (TFBG) Sensor at different of prepared Solutions (with coated)

The transmission spectrum of the gold-coated Bragg grating fiber sensor with different concentrations appears in Figure (3). A spectrum to the right shows the relationship between the wavelength and the ability to transmit to the highest and lowest concentration. The effective spectra for each concentration of the pollutant, sodium nitrate, with a concentration of (a) pure water (b) 3 ppm (c) 6 ppm (d) 12 ppm (e) 50 ppm .

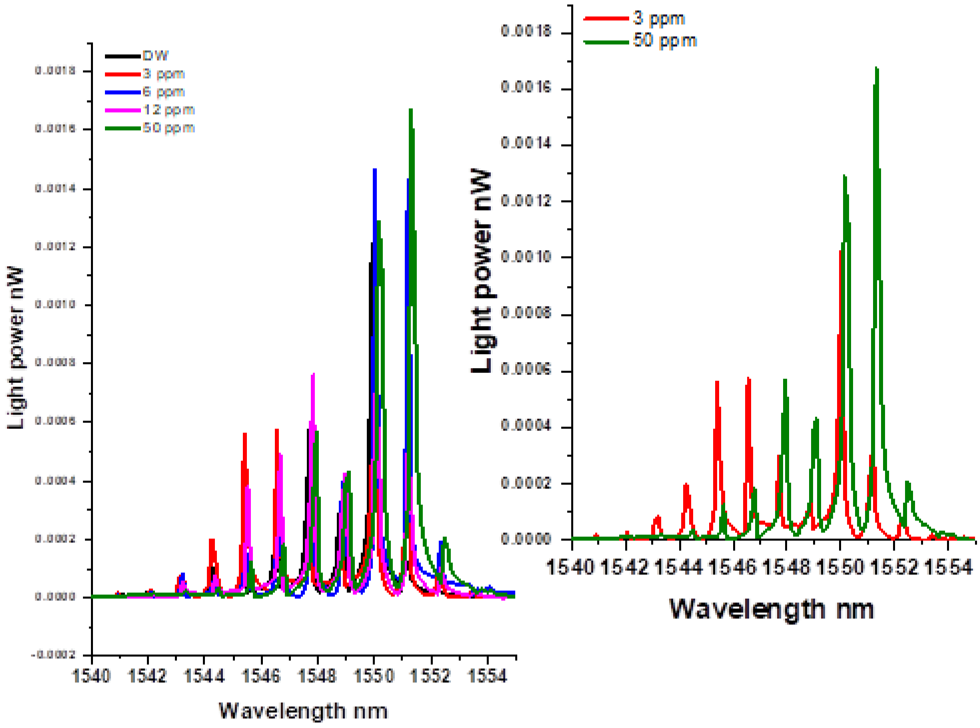

Figure (3) Transmission spectrum of the gold-coated Bragg grating fiber sensor with different concentrations.

the patterns resulting from the transmission spectrum of the Bragg grating sensor coated with a Nano-gold film when testing solutions of different concentrations, in other words, variable refractive index. It was observed that the first and second patterns disappeared for a concentration of 50 ppm. The sixth pattern disappeared for concentrations (50 and 12) ppm. As for distilled water and (3 and 6) ppm, the seventh pattern disappeared. The tenth pattern did not appear in distilled water and concentration 3 ppm. All of this description is documented.

Discussion

the integration of TFBGs with other fiber grating structures, such as long-period gratings (LPG) and standard fiber Bragg gratings (FBG), can improve the sensitivity and accuracy of multi-parameter sensors, as demonstrated in the hybrid LPG-TFBG-FBG sensor for ocean environment monitoring(Yan et al., 2022). These diverse applications highlight the versatility and adaptability of TFBGs in various sensing technologies, driven by precise fabrication and strategic integration with other optical components

Tilted fiber Bragg grating (TFBG) sensors exhibit unique transmission modes that are highly sensitive to changes in the refractive index (RI) of surrounding solutions, making them effective for solution concentration measurements without the need for coatings. The cladding modes in TFBG sensors are particularly responsive to variations in the refractive index, as demonstrated by the linear relationship between the resonance peak shifts and the solution's RI(Harasim, 2022) (Jiang *et al.*, 2013). For instance, in experiments with aqueous solutions, high-order cladding modes showed both a shift in central wavelength and a change in transmission minimum, with a sensitivity of 0.012 nm/RIU for cane sugar solutions (Harasim, 2022). Additionally, the nonuniformity of the grating period in TFBG can lead to irregular side mode fringes, which are useful for characterizing solution concentration through dip intensity changes, achieving a sensitivity of −0.471 dB/% for glycerol solutions(Yang et al., 2023) ("TFBG Side Modes and Fresnel Reflection-Based Sensing System for Solution Concentration Measurement", 2023). The bare TFBG sensors, when compared to those with gold coatings, still demonstrate significant sensitivity, although the latter enhances sensitivity dramatically due to surface plasmon resonance (SPR) effects(Jiang *et al.*, 2013) (Jiang & Lv, 2013). The linearity of the resonance peak shifts with RI changes is consistently high, with correlation coefficients exceeding 0.99, indicating reliable performance across different solution types (Jiang *et al.*, 2013). These characteristics underscore the versatility and effectiveness of TFBG sensors in measuring solution concentrations through transmitted modes without additional coatings.

Tilted fiber Bragg grating (TFBG) sensors exhibit diverse transmitted modes when coated with different materials, enhancing their sensitivity and specificity for various applications. The integration of graphene coatings on TFBG sensors significantly boosts their sensitivity and stability, as demonstrated in DNA hybridization detection, where the graphene layer enhances probe loading and molecular capture, allowing for real-time quantitative analysis of single base mutations(Yang et al., 2022). Similarly, the use of a hybrid coated structure combining long-period fiber grating (LPG), TFBG, and fiber Bragg grating (FBG) enables the simultaneous measurement of conductivity, temperature, and depth in ocean environments, with distinct transmission peaks corresponding to different environmental parameters(Yan et al., 2022). Partially-coated TFBGs with gold films have shown potential in biosensing by detecting changes in the surrounding refractive index, which is crucial for identifying environmental perturbations and enhancing signal-to-noise ratios in the detection of cancer biomarkers like HER2 proteins(Zhu et al., 2022). Graphene-coated TFBGs also demonstrate improved strain sensitivity, which is 1.6 times higher than that of bare gratings, although their temperature sensitivity remains unchanged(Xiao et al., 2022). Furthermore, the application of zinc oxide nanoflowers on TFBG sensors significantly increases refractive index sensitivity, making them highly effective for biosensing due to their enhanced electron transfer and adsorption capabilities(Sun et al., 2021). These studies collectively highlight the versatility and enhanced performance of TFBG sensors when coated with various materials, making them suitable for a wide range of sensing applications.

Conclusion

The transmission spectra of the Bragg sensor of reflective index appear for some concentrations and to show the patterns more clearly, the sensitivity of transmitted spectrum increasing after coated the TFBG sensor by Nano-Au film

, the transmission spectra varies with concentration, enabling analysis of the analyte's behavior in solution.

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