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WATER QUALITY MONITORING USING REFRACTIVE INDEX SENSING E-FBG SENSORS

Abstract. The need to protect the environment has stimulated the development of numerous analytical techniques for detecting pollutants in natural ecosystems, including methods for determining nitrate concentrations in source water. In this context, the present study introduces an experimental approach for water quality assessment based on etched fiber Bragg gratings (e-FBG). Specifically, the method relies on monitoring the shift in the Bragg wavelength, which occurs as a result of variations in the refractive index of water caused by changes in its chemical composition. Moreover, we proposed a water quality monitoring strategy employing e-FBG sensors, which provides high sensitivity to fluctuations in the optical properties of the surrounding medium. The applicability of the proposed sensor is demonstrated through the detection of low concentrations of nitrates in aquatic environments. The e-FBG sensor exhibits several notable advantages. In particular, it offers high resolution for wavelength shift detection, a high optical signal-to-noise ratio of 40 dB, and a narrow bandwidth of 0.02 nm, which collectively enhance the accuracy and reliability of peak wavelength measurements. Furthermore, the sensor supports optical remote sensing, making it suitable for real-time environmental monitoring. Therefore, the experimental results strongly suggest that the proposed e-FBG sensor holds significant potential for pollutant detection in practical field applications.

Keywords: water quality monitoring, e-FBG sensors, fiber Bragg gratings, refractive index.

1. Introduction

Pollution of water resources remains one of the most pressing environmental challenges of our time. A wide range of substances enters aquatic ecosystems as a result of intensive agricultural fertilizer use, industrial wastewater discharge, and domestic waste. Elevated nitrate concentrations, for instance, lead to eutrophication of water bodies, disturb the balance of aquatic ecosystems, and pose serious risks to human health [1], [2]. Traditional methods of nitrate detection, such as ion chromatography, spectrophotometry, and electrochemical sensing, provide high accuracy but are associated with significant limitations [3]. They require sophisticated laboratory equipment, long analysis times, and highly qualified personnel, which make them unsuitable for rapid in-field monitoring. Moreover, many of these methods rely on chemical reagents, thereby increasing both the cost of analysis and the associated environmental risks. In this context, optical sensors are of particular interest, as they combine high sensitivity with rapid response and remote measurement capabilities. The development of advanced water quality monitoring methods has become increasingly relevant in light of rising anthropogenic pressures on aquatic ecosystems. Conventional approaches, based on periodic sampling and laboratory analysis, suffer from several drawbacks, including high time costs, limited efficiency, and the inability to provide continuous real-time monitoring. Consequently, there is growing scientific and practical interest in developing sensor technologies capable of delivering high-precision measurements directly in the field. One promising direction is the use of fiber Bragg gratings (FBG), which offer high sensitivity, immunity to electromagnetic interference, and seamless integration into distributed measurement systems. Unlike conventional FBG sensors, which primarily respond to mechanical strain and temperature fluctuations, etched-FBG (e-FBG) sensors are sensitive to variations in the refractive index of the surrounding medium. This feature opens new opportunities for monitoring the chemical and biological composition of water. Other conventional methods of nitrate determination, such as potentiometry and its combination with sequential injection analysis [4]-[8], also provide high accuracy but remain expensive and impractical outside laboratory settings. Recent studies [9], [10] have proposed fiber optic sensors for in-situ nitrate monitoring based on colorimetric methods and evanescent wave absorption. Despite their broad dynamic range (ppb-ppm), the response time of such sensors typically spans several tens of minutes, which limits their efficiency for rapid detection. Research on e-FBG sensors with specialized coatings is actively evolving, with the choice of coating material depending on the target analyte (e.g., heavy metals, organic pollutants, biological agents). For example, coatings have been developed for heavy metal detection using Au nanoparticles with dithiothreitol (DTT) and polyvinyl chloride (PVC) with ionophore A23187; for organic pollutants using molecularly imprinted polymers (MIP) based on methacrylic acid; and for multifunctional sensing using graphene oxide combined with metal-organic frameworks such as ZIF-8 [13]-[16]. The optimal choice of coating is therefore determined by the specific monitoring task.

Kazakhstan is only beginning to develop research in this area. Several initiatives have already been undertaken by local universities: wastewater monitoring from industrial enterprises in East Kazakhstan [17]-[19]. Oil product adsorption studies based on refractive index changes [20], and acidity monitoring in the Balkhash-Alakol water system [20]-[23]. Due to their higher sensitivity, faster response, and broader versatility, partially-sheathed e-FBGs with full or partial removal of the protective cladding are generally preferred over modified e-FBGs for high-precision monitoring tasks.

This study examines the operating principles of e-FBG sensors based on refractive index measurements, their structural features, and their application in assessing key water quality parameters, including dissolved substance concentration, pollutant detection, and changes in the optical properties of water. Particular attention is devoted to evaluating the sensitivity and selectivity of these sensors, as well as to exploring their potential integration into environmental monitoring systems. The results highlight the potential of this technology to support early pollution detection and automated monitoring of aquatic ecosystems [24], [25]. This study contributes to the advancement of operational water quality monitoring methods by introducing an innovative approach for nitrate detection through advanced optical technologies. The practical significance of the research lies in the possibility of developing compact and cost-effective sensor systems suitable for widespread application in agriculture, industry, and water treatment systems.

2. Materials and methods

Traditional FBG sensors offer several notable advantages, including high sensitivity and accuracy, the capability for remote and distributed monitoring, resistance to electromagnetic interference, compact size, and suitability for integration into microsystems. An FBG is fabricated by irradiating a photosensitive single-mode optical fiber with an ultraviolet laser. The interference pattern produced by the laser induces periodic modifications of the refractive index in the fiber core. These periodic changes are formed along the fiber axis, with the period determined by the parameters of the interference beam. As a result, a structural region known as the Bragg grating is created. Each segment of this grating reflects a portion of the propagating light at a specific wavelength, corresponding to the Bragg condition, while the remaining light continues to transmit through the fiber.

Backscattering of specific wavelengths occurs only under the Bragg condition, and both the scattering parameters and the backscattering coefficients must remain stable throughout the operational lifetime of the fiber Bragg grating (FBG). These requirements must be carefully considered during the sensor design process. As a result, only light at the Bragg wavelength is reflected, while the fiber remains transparent to all other wavelengths. Nevertheless, the scattering characteristics and reflection coefficients are subject to variation under the influence of external environmental factors.

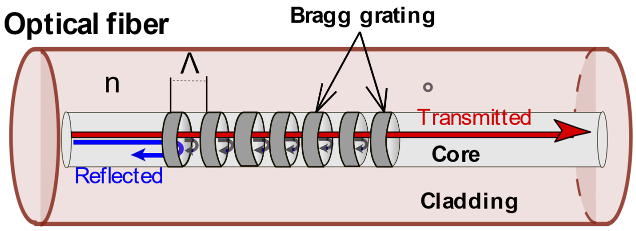

Figure 1 – Fiber Bragg gratings.

The reflection coefficient is primarily determined by the modulation depth of the refractive index and the physical length of the FBG, whereas the central reflection wavelength is governed by the Bragg condition:

$$\lambda_B = 2n_{eff}\Lambda, \quad (1)$$

where λ_B – is the wavelength of the Bragg resonance, n_{eff} – is the effective refractive index of the fiber core for the central wavelength, Λ – is the period of the Bragg grating.

While FBG is subject to physical variables such as temperature, strain, etc., e-FBG is an advanced version of the classic FBG, that can detect chemicals in water by combining optical and electrochemical methods. Etched-FBG is a periodic modulation of the refractive index in the core of an optical fiber. Such a structure reflects light only of a certain wavelength – the Bragg wavelength.

According to the paired mode optical fiber theory, the relationships between the effective refractive index of the e-FBG, the fiber diameter and the normalized frequency V_{ext} etched single-mode fiber looks like this:

$$n_{eff}^2 = n_{co}^2 - \left(\frac{U}{V_{ext}}\right)^2 \left(n_{co}^2 - n_{cl}^2\right) U =$$
$$= a\sqrt{k_0^2 n_{CO}^2 - \beta},\ V_{ext} = \frac{\pi d}{\lambda}\sqrt{n_{CO}^2 - n_{ext}^2} \quad (2)$$

where a and d – are the fiber core radius and the e-FBG diameter, respectively; β – is the propagation constant. The reflection wavelength shift e-FBG is related only to the effective refractive index. The simultaneous differential equation from equations (1) and (2) is as follows:

$$\frac{\Delta\lambda_\beta}{\lambda_\beta} = \frac{\Delta n_{eff}}{n_{eff}} = x = \frac{U^2\left(n_{CO}^2 - n_{Cl}^2\right)}{2V_{ext}^3\left[n_{CO}^2 - \left(\frac{U}{V_{ext}}\right)^2\left(n_{co}^2 - n_{ext}^2\right)\right]} \quad (3)$$

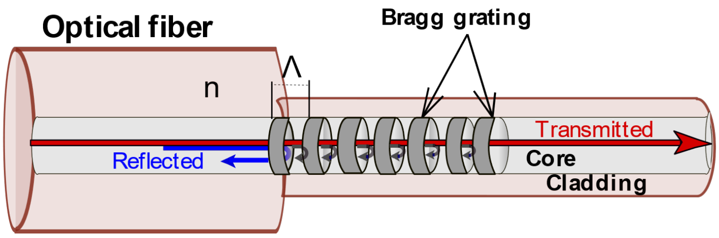

Figure 2 – Etched-FBG.

The refractive index of light in water n is a fundamental optical parameter characterizing the state of the medium. Physically, it is defined as the ratio between the velocity of light in vacuum C_0 and in the medium under investigation c, which depends on temperature T, concentration of dissolved substances (salinity, S), and hydrostatic pressure P_1 [26]. Variations in the refractive index determine the degree of light refraction during propagation. Consequently, measurements of this parameter form the basis of refractometry, a group of methods designed to determine the refractive index of diverse media. A change in the surrounding refractive index (e.g., the water medium around the FBG) alters the effective refractive index n_{eff} of the fiber, resulting in a Bragg wavelength shift λ_B that can be detected using a spectrometer. Certain FBG modifications allow direct sensitivity to the external refractive index, enabling detection of changes in salinity, pollutants, or chemical species. This sensitivity is typically achieved by removing part of the protective coating of the fiber, thereby ensuring direct contact between the grating and the medium. Approaches include using bare or etched fibers, D-shaped fibers, or tapered fibers to increase evanescent field penetration and enhance interaction with the surrounding medium.

In this study, e-FBG sensor was employed for the detection of nitrate concentrations in water. The e-FBG sensor provides a novel approach to high-precision, real-time measurements. Its advantages include high resolution for detecting wavelength shifts, a high optical signal-to-noise ratio (OSNR), and a narrow spectral bandwidth, which together improve the accuracy and reliability of peak wavelength detection and enhance remote sensing capabilities. Experimental results confirm the feasibility of using the e-FBG sensor for nitrate detection, demonstrating effective performance within the low concentration range of 0-80 ppm and achieving a detection limit of 3 ppm. These findings suggest that the proposed sensor can be applied for field-based water quality monitoring with strong potential for applications in agriculture, industrial processes, and the food industry. The sensitivity of FBG sensors is not uniform, as each grating possesses a unique structure resulting from its fabrication process. For e-FBGs, where part of the cladding is removed, as shown in Figure 1, the propagating light interacts with the external medium (e.g., water or aqueous solutions), thereby enabling the measurement of refractive index variations. Standard sensitivity values of e-FBG sensors range from 0.8-2 nm/RIU (nanometers per refractive index unit), increasing to 5-10 nm/RIU under extreme conditions. For example, a refractive index changes of $\Delta n = 0.001$ results in a reflected wavelength shift of approximately 1-2 pm (at 1-2 nm/RIU).

Etched FBG sensors are capable of measuring a wide range of parameters: refractive index of water (linked to the concentration of dissolved substances), total dissolved solids (TDS), salinity, heavy metal ions, organic contaminants, and temperature fluctuations. When combined with functional coatings, e-FBGs can also be used for pH monitoring and detection of specific analytes. When immersed in water, an e-FBG sensor records the shift in the reflected wavelength, which is directly correlated with the refractive index and, therefore, with the chemical composition of the medium. Arrays of e-FBG sensors can be fabricated, each tuned to a specific range of detection, thereby enabling real-time spectroscopic monitoring of multiple contaminants simultaneously.

During the experimental work and testing of the fiber-optic e-FBG sensor, designed to detect refractive index variations caused by changes in water composition (e.g., salinity, pollutants, or impurities) the components listed in Table 1 were employed.

Table 1 – Main components of the installation.

Component	Purpose
FBG sensor (etched)	Reflects light of a certain wavelength. When the refractive index of the environment (water) changes, the wavelength shifts.
Light source (broadband)	Irradiates the optical fiber – usually an LED or ASE (Amplified Spontaneous Emission) source.
Optical spectrometer (or reflectance spectrum analyzer)	Measures the wavelength reflected by the FBG and records its shift.
Cuvette/micro chamber with water	A container in which the FBG sensor is placed and the composition of the water is changed.
Temperature control (optional)	Maintains a stable temperature, or uses a second FBG sensor as temperature compensation.
PC or controller with software	Receives spectral data and calculates the change in wavelength.

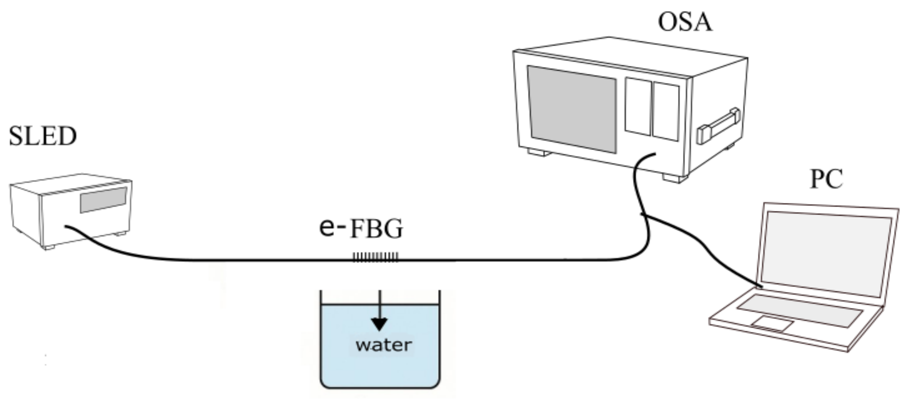

Figure 3 – Installation diagram:
[Light source] → [FBG sensor (in water cuvette)] → [Spectrometer] → [PC / Analysis software].

Below is a detailed experimental procedure to determine the sensitivity of e-FBG to changes in refractive index *n* and dissolved substance concentrations (using NaCl and pollutants as examples). The procedure includes calibration, measurements, temperature compensation, and data analysis. The cuvette is filled with distilled water. The FBG sensor is placed inside. The light source is started and the initial wavelength λ_0 is measured. Solutions with known concentration, for example, NaCl, $CuSO_4$, are added step by step. The change in wavelength $\Delta\lambda = \lambda - \lambda_0$ is recorded. The dependence of $\Delta\lambda$ on the concentration or refractive index is constructed.

Figure 4 shows the effect of substances on the Bragg wavelength: when determining NaCl in water, the wavelength shifts to the right, and when determining ethanol, to the left.

Table 2 – Example of substances for testing.

Substance	Change	Expected effect
NaCl	Increases *n*	Wavelength shift up
Ethanol	Lowers *n*	Downward shift of wavelength
Fe^{3+} / Cu^{2+}	Chemical reaction with coating (optional)	Change *n* shell

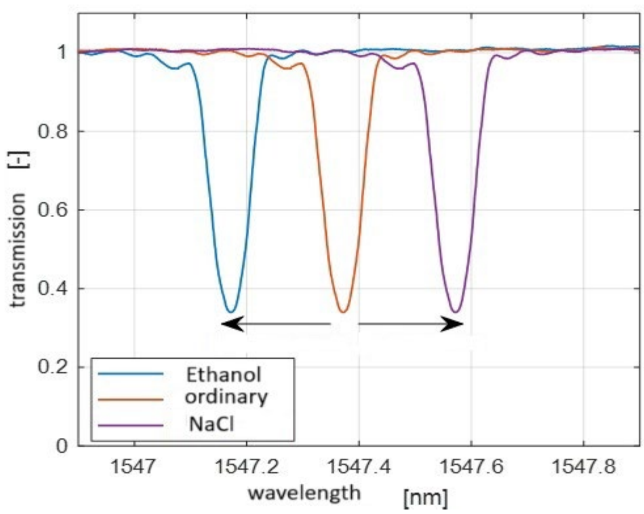

Figure 4 – Characteristics of the transfer of FBG for the determination of substances in water.

3. Results

Linear or nonlinear relationship is shown between Δλ and the concentration of the dissolved substance. Demonstration of high sensitivity of FBG to changes in water composition and the possibility assess water quality without direct electrochemical contact.

Table 3 – Calculations results.

Conc. NaCl (%)	Refractive index	Δn	Shift Δλ (pm)	λ_B (nm)
0	1.3330	0.0000	0.0	1550.00
1	1.3360	0.0030	900.0	1550.90
2	1.3395	0.0065	1950.0	1551.95
3	1.3428	0.0098	2940.0	1552.94
4	1.3460	0.0130	3900.0	1553.90
5	1.3492	0.0162	4860.0	1554.86

- $\boldsymbol{\lambda_B}$ – is the Bragg wavelength reflected by the e-FBG sensor.
- **Δλ** – is the shift of the reflected wavelength depending on the change in water composition.
- The calculation is based on an FBG sensitivity of about 300 pm/RIU (picometers per refractive index change).

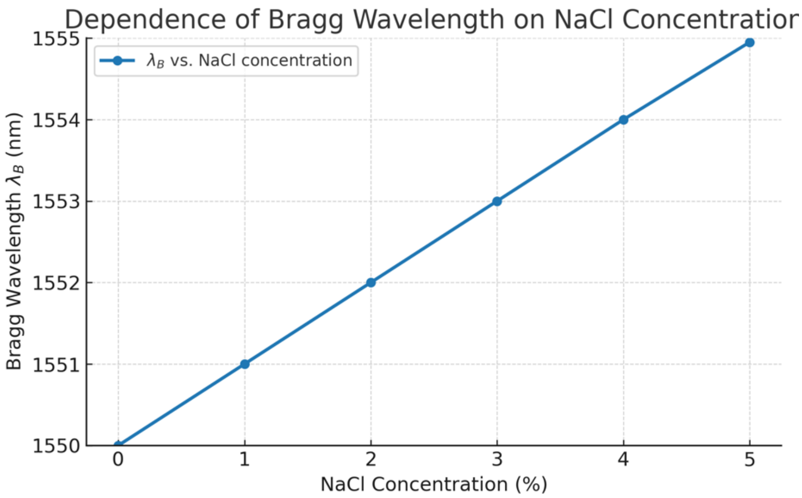

Figure 5 – Graph of the dependence of the Bragg wavelength on the concentration of NaCl.

As shown in Figure 5, an increase in salt concentration leads to a nearly linear shift in the reflected Bragg wavelength. This linear relationship demonstrates the potential of the e-FBG sensor to function as a high-precision tool for water quality assessment based on optical characteristics.

4. Discussion

The measurements demonstrated that the e-FBG sensor is capable of detecting variations in the refractive index of aqueous solutions within the range of 10^{-4}-10^{-3}. The obtained results reveal a linear dependence between NaCl concentration and the Bragg wavelength (λ_B) shift, confirming the applicability of this technology for assessing water quality through compositional changes. Since the refractive index of water undergoes significant variation upon the addition of salts, the characteristics of the FBG sensor are directly affected. The sensor exhibits a strong linear correlation between wavelength shift and solute concentration, which considerably simplifies the calibration procedure. Even a refractive index changes of 0.001 produces a wavelength shift of approximately 300 pm, which can be readily detected by a spectrometer with a resolution of 1 pm.

The proposed e-FBG sensor functions as a purely physical sensor and does not require functionalized coatings or chemical modifications. Its main advantages include rapid in situ refractive index measurement in aqueous environments, the possibility of repeated use due to simple surface cleaning, and high stability and reproducibility ensured by the corrosion resistance of quartz glass.

Furthermore, the sensor sensitivity, with a detection limit of 3 ppm, is considerably lower than the threshold set by current sanitary standards. Therefore, the e-FBG sensor, with its detection threshold of 3 ppm, fully satisfies the requirements for drinking water quality monitoring, offering a substantial sensitivity margin to ensure water safety.

5. Conclusions

This sensor introduces a novel approach for high-precision in-situ measurements in real time. The proposed system offers several important advantages, including high resolution for detecting wavelength shifts, a high optical signal-to-noise ratio, and a narrow bandwidth, all of which enhance the accuracy of peak wavelength determination and expand the potential for remote sensing applications. Experimental results confirm the feasibility of nitrate concentration detection in water using the e-FBG sensor. The system demonstrated good sensitivity within the low concentration range of 0-80 ppm and achieved a detection limit of 3 ppm, thereby validating its applicability for field-based water quality monitoring. These findings highlight the strong potential of the sensor for practical applications in agriculture, industrial liquid analysis, and the food industry.

The proposed technique enables effective detection of refractive index variations in water, which directly reflect its quality. Furthermore, e-FBG based sensors combine high accuracy with remote monitoring capability and are well suited for integration into automated environmental monitoring systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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