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Biosensors with tilted fiber Bragg gratings for virus detection

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Abstract

Optoelectronic technologies play a crucial role in medical diagnostics, especially in the detection of viruses. Infectious diseases caused by viruses pose a serious threat to humanity, as they can spread rapidly, leading to significant loss of life. Early diagnosis of viral diseases not only increases the chances of rapid recovery but also helps prevent the spread of infections. Significant efforts are currently being made to develop devices that enable rapid and accurate diagnosis of viruses and viral infections. For these purposes, fiber-optic biosensors based on Fiber Bragg Gratings (FBG) are used, which are essential tools for the simultaneous detection of multiple viruses. FBGs are becoming increasingly attractive for medical applications due to their unique properties, such as small size, biocompatibility, immunity to electromagnetic interference, high sensitivity, and multiplexing capabilities. Among the popular configurations of fiber-optic sensors are sensors based on Tilted Fiber Bragg Gratings (TFBG), which possess numerous unique features suitable for diagnostics and medical research. This article provides a brief overview of the principles of operation, manufacturing methods, characteristics, and practical implementations of TFBGs with a tilt angle of less than 100 degrees relative to the fiber axis. These sensors demonstrate high sensitivity and specificity in detecting viruses, making them promising tools for rapid and accurate diagnosis of viral infections. Particular attention is given to analyzing their capabilities and advantages in biomedical applications.

Keywords: Biosensors, Fiber optics, Tilted fiber Bragg gratings, Virus.

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1. Introduction

Fiber technologies occupy an important place in medicine. Modern medicine actively integrates biomedical tools and equipment based on these technologies to improve the quality of medical services. These technologies also include innovative auxiliary devices that facilitate the digitization of the medical field. Fiber technologies are used as effective tools for physiological monitoring, measuring heart rate, blood oxygen levels, blood composition analysis, various diagnostic tests, and air concentration control.

This study analyzes the application of fiber sensors for monitoring virus content in the air, which must meet strict standards to ensure safety, biocompatibility, reliability, stability, and compactness.

Indoor air quality is an important health risk factor. Indoor air can contain various chemical compounds and viruses that, at certain concentrations or combinations, can negatively affect health. Indoor air pollutants can be inorganic, organic, physical, microbial, and biological substances. Viruses pose a serious health threat. Their concentration indoors is determined by the interaction of factors such as indoor climate conditions, ventilation mode, air speed, temperature, humidity, and seasonal changes.

Viruses are microscopic parasites capable of rapidly multiplying and spreading, causing diseases and posing a significant health threat. They have the ability to mutate quickly and interact with various factors such as animal and human movements and environmental factors, contributing to the spread of infectious diseases [1-3].

Since viruses pose a significant threat, their rapid identification is crucial for saving lives, as even a slight delay can be dangerous for everyone. The human respiratory mucosa is most susceptible to respiratory viruses, including influenza and coronaviruses such as severe respiratory syndrome. These viruses typically spread through direct contact, airborne transmission, or contaminated food and water. Viral infections can be detected using various traditional laboratory methods. Classical methods such as polymerase chain reaction (PCR) and test kits help doctors identify pathogens [4, 5].

Therefore, for early diagnosis of viruses, more accurate, rapid, simple, and portable tests need to be developed, as sample preparation, high cost, labor intensity, and less precise dimensions limit their reliability. Fiber-optic biosensors meet these criteria: they are easy to use, provide fast and reliable results, are portable, convenient, capable of multiplexing, resistant to electromagnetic interference, miniaturize analyses, enable remote research, are inexpensive for diagnostics, and have high accuracy and sensitivity for virus detection.

Fiber-optic biosensors are devices that convert biological reactions into measurable signals. They consist of three key elements: a light source, optical fiber, and an analyzer. Optical fibers act as light guides, providing interaction of light with the surrounding environment. This interaction leads to changes in the light characteristics, which are monitored by the analyzer. Changes are used to monitor physical parameters such as temperature, pressure, and deformation [6, 7].

Recently, there has been increased interest in the use of optical fiber in optical sensors and biosensors. Among the popular configurations of fiber-optic sensors are sensors based on Tilted Fiber Bragg Gratings (TFBG), which have numerous unique features suitable for diagnostics and medical research.

2. Research Methodology

2.1. Fiber-Optic Biosensors for Virus Detection

In recent decades, Fiber Bragg Gratings (FBG) have gained significant popularity for medical applications. Numerous studies aim to develop biosensors that are easy to use, inexpensive, and economical to produce, provide real-time measurements, and allow simultaneous detection of various components, antibodies, and viruses. FBG is an optical device created by modulating the refractive index of the fiber core.

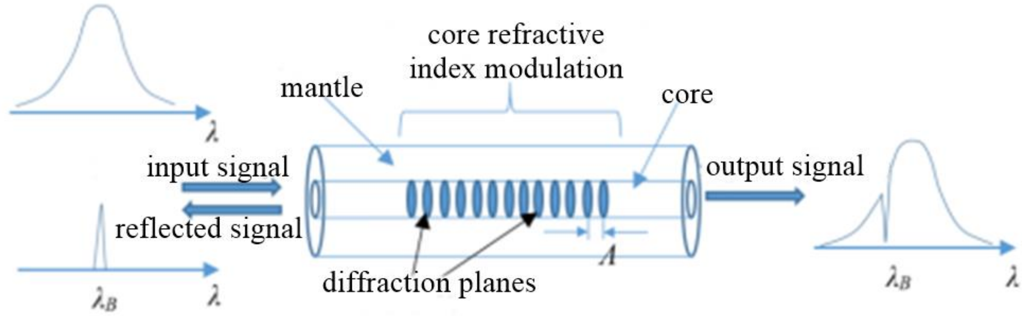

Figure 1.
FBG schematic.

There are many types of FBG, including gratings with a constant period and so-called apodized gratings, where the intensity of the refractive index modulation changes according to a specific law. Chirped gratings with a variable period along their length are also widely used. These gratings are used in dispersion compensators in telecommunications and laser physics. The dispersion provided by such a grating depends on the change in the grating period relative to its length.

In this work, we consider the structure of a type of fiber grating called Tilted Fiber Bragg Grating (TFBG). Introducing a tilt between the refractive index modulation planes and the fiber cross-section plane can change the internal structure of FBG, creating another type of grating—TFBG. In these structures, part of the light passing through the fiber core is transmitted to the cladding, which can be observed in the spectrum as a series of transmission dips associated with resonances at decreasing wavelengths. Conductivity through the optical fiber coating depends on changes in the coating parameters and their impact on spectral characteristics [8-12].

Next, we consider the structure, operating principle, and characteristics of fiber-optic sensors based on TFBG.

2.2. Fiber-Optic Sensors Based on TFBG

TFBG is a type of fiber grating made from standard single-mode fiber in which the gratings are inserted into the core at an oblique angle. Standard telecommunications optical fiber SMF-28 was used for recording and was previously subjected to photo sensitivity process in a hydrogen atmosphere at a pressure of 190 bar and temperature 20°C for 10 days, and the operating wavelength in the spectral range is 1510–1620 nm . TFBG recordings and experiments were carried out in the laboratories of the Technical University of Lublin.

These arrays provide single-point measurements in hard-to-reach locations with carefully controlled cross-sensitivity and allow both absolute and relative measurements of various parameters. The sensitivity of the TFBG is determined by the excitation of cladding modes that reach the region between the cladding and the surrounding environment. The resulting signal is generated based on the wavelength shift and amplitude change as the surrounding refractive index changes. In TFBG, there is coupling not only between modes conducted in the core, but also between modes propagated in the cladding [13]. Therefore, they are widely used in the creation of chemical and biological sensors. They can be used to determine the refractive index or concentration of substances [14]. Also, by applying a thin reference film to the outer part of the optical fiber, it is possible to observe the adsorption of materials on the surface of metals such as gold and silver due to the phenomenon of plasmon resonance [15, 16].

TFBGs are produced using the same technology as standard FBGs [17]. There are several recording methods, but this paper discusses the phase mask method. The phase mask method is one of the most effective methods for applying gratings. It consists of irradiating a phase mask, which is a diffraction structure made of quartz glass, with a monochrome beam in the UV range. Figure 2 shows a grating recording using the phase mask method.

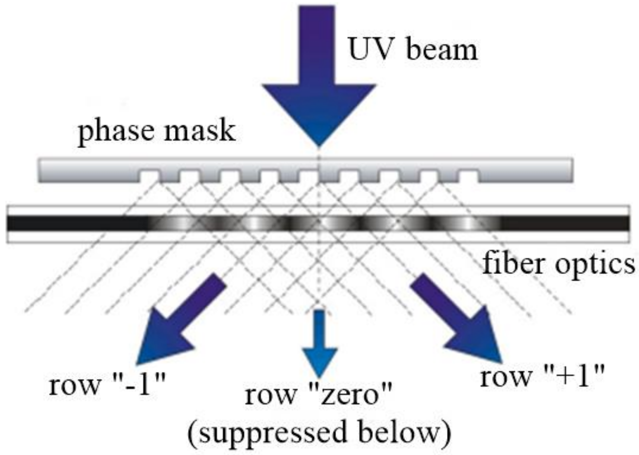

Figure 2.
Bragg lattice recording method using phase masking.

This method involves using a relief grating etched on a silica plate that is transparent to ultraviolet radiation. The depth of the grating grooves is calculated to minimize the diffracted intensity in the zero order and maximize the intensity in the ±1 order. The tilt in the phase mask method can be achieved in two ways: rotating the phase mask and optical fiber around an axis perpendicular to the laser beam (while they remain parallel) or holding the optical fiber and phase mask perpendicular to the incident laser beam and rotating the mask around the laser beam axis. For increased photosensitivity, the single-mode fiber is saturated with hydrogen. Figure 3 shows the diagram and operating principle of TFBG.

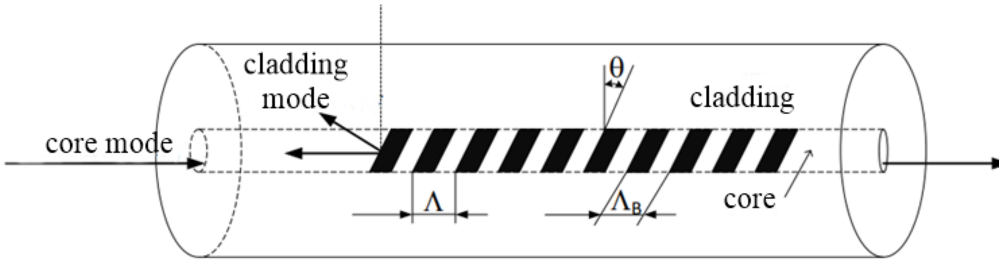

Figure 3.
TFBG schematic

The incident light directed through the core interacts with the grating with a constant refractive index embedded in the fiber using intense ultraviolet radiation through a diffraction phase mask. The tilt of the grating planes facilitates the redirection of light into modes propagating in the cladding rather than the core. Thanks to the large cladding diameter, many modes with a specific wavelength can be excited, creating a fine comb of resonances in the transmission spectrum of the grating. The grating tilt angle is an important parameter that allows selecting a set of cladding modes in the range from tens of nanometers to over a hundred nanometers, enabling sensor operating range adjustment and optimizing its response to various types of perturbations.
The first-order Bragg wavelength described by the equation [18]:

$$\lambda_B = 2n_{eff}^{r}\frac{\Lambda_B}{cos\theta} \quad (1)$$

where n_{eff}^{r} - is the effective core refractive index Λ_B - is the actual grating period, and θ - is the tilt angle of the grating planes.

For the second-order core-cladding coupling, the resonant wavelengths of cladding modes corresponding to backward-propagating core-to-cladding mode couplings are described by the equation:

$$\lambda_p^i = \left(n_{eff}^{p,i} + n_{eff}^{r}\right)\frac{\Lambda_B}{cos\theta} \quad (2)$$

where $n_{eff}^{p,i}$ - is the effective refractive index of the i-th cladding mode, where i=1….n and n is the total number of cladding modes.

The transmission spectrum of TFBG is significantly more complex compared to a conventional Bragg grating and contains spectral dips at wavelengths corresponding to the excited cladding modes. Figure 4 shows an example of a typical TFBG spectrum. The main Bragg reflection peak is visible on the right side of the spectrum, while all other peaks correspond to cladding modes.

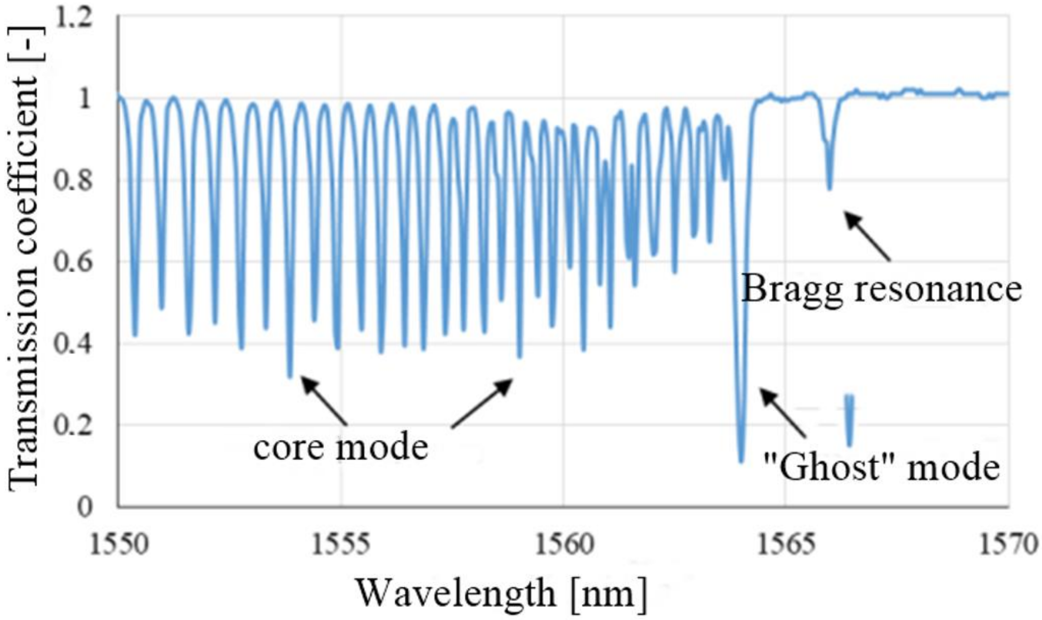

Figure 4.
Spectral characterization of TFBG

In TFBG operating as a sensor, the properties of the resonances of both the core and cladding modes are used, most often their positions or widths. Two types of mode couplings are distinguished in TFBG. The first type is the standard coupling of the forward-propagating core mode (from the light source to the other end of the fiber) with the backward-propagating core mode, similar to a uniform Bragg grating. The second type of resonance involves coupling the forward-propagating core mode with the backward-propagating cladding modes. The sensitivity of TFBG can be increased by applying a metal coating to excite surface plasmon resonance.

The most important parameter determining the spectral properties of tilted gratings is the tilt angle of TFBG between the refractive index modulation planes in the core and the fiber cross-section surface.

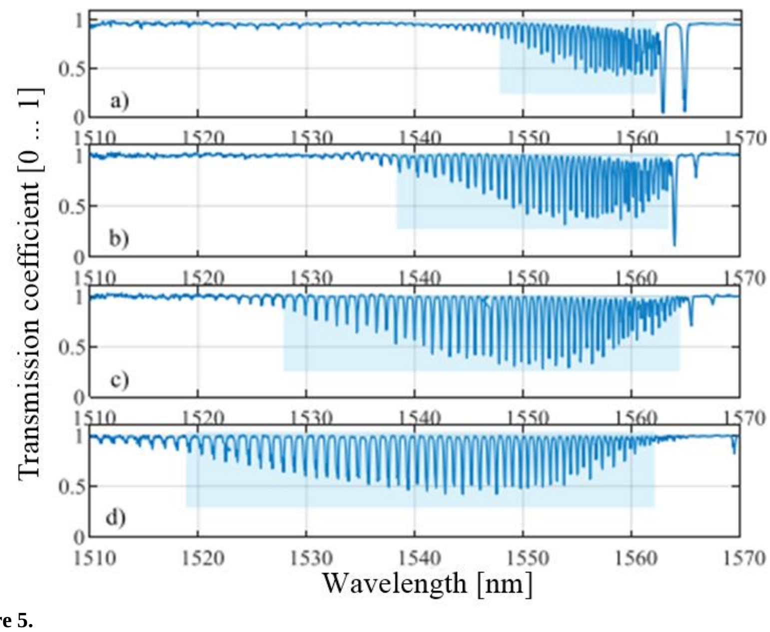

Figure 5.
The transmission spectra of TFBG were measured depending on the inclination angle a) 2°, b) 3°, c) 4°, d) 5°

Figure 6 demonstrates the transmission spectra of TFBG at various tilt angles of the internal zones with increased refractive index. The spectral range where transmission loss maxima occur due to cladding modes is marked in blue. As the tilt angle of the refractive index modulation planes relative to the fiber cross-section increases, the spectrum covered by the transmitted light power minima expands. It can also be noted that the wavelength associated with the core mode resonance shifts towards longer wavelengths, which is related to geometric dependencies arising from the increase in the tilt angle of the grating internal structure. At the same time, the power losses characteristic of ghost modes become less noticeable, as shown in Figure 6.

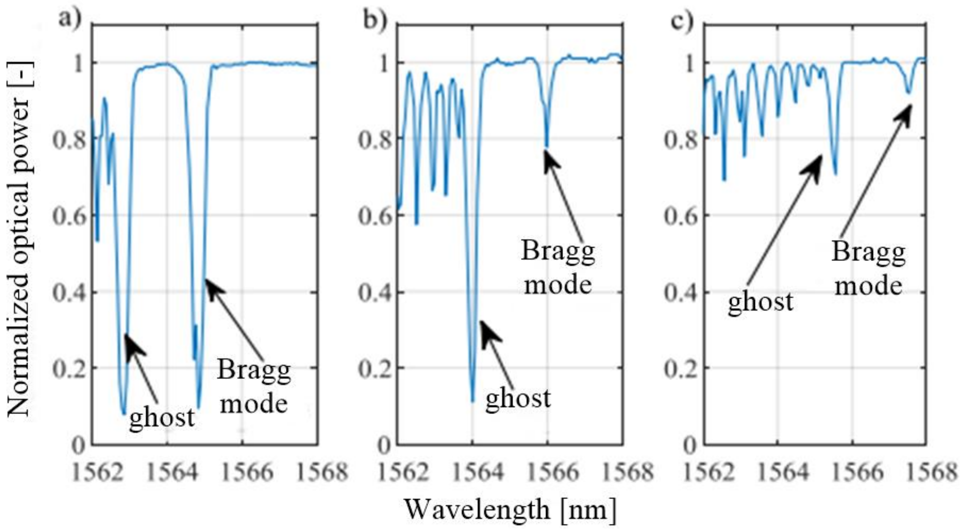

Figure 6.
Characteristics of TFBG spectral regions with angles, (a) 1°, (b) 2°, (c) 3°, showing the transmission spectra of Bragg resonance and mode ghosting

Another particularly important parameter affecting the spectral properties of periodic TFBG with an increased refractive index value is the modulation depth of this coefficient. This parameter is essentially related to the power of the recording radiation source and the duration of the recording process. In this work, an excimer laser with adjustable energy and pulse repetition frequency was used. The spectra of structures with increasing refractive index profile amplitude along the optical fiber longitudinal axis were measured during the manufacturing process at one-minute intervals. Figure 7 shows transmission spectra of TFBG with a 4° angle generated with recording radiation pulse energy of 90 mJ and repetition frequency of 50 Hz during recording: a) 1 minute b) 3 minutes c) 4 minutes.

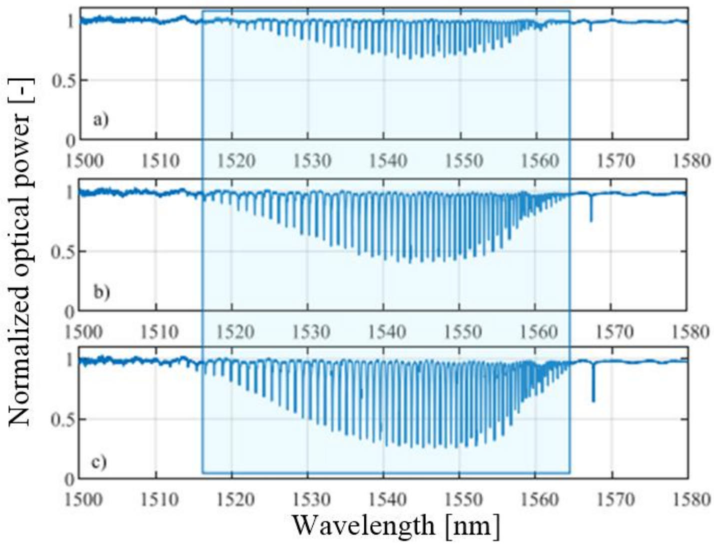

Figure 7.
Transmission spectra of TFBG with an angle of 4° depending on production time: a) 1 minute, b) 3 minutes, c) 4 minutes

It is noteworthy that increasing the amplitude of the refractive index profile modulation does not affect the expansion of the spectral range where the power minima characteristic of cladding modes are present. However, the degree of coupling of individual resonances is enhanced, which is manifested in the deepening of the power minima observed in the transmission spectrum. The use of TFBG with small tilt angles improves coupling efficiency and narrows the spectral range. This is advantageous for sensor operation in measurement systems, allowing simultaneous measurement of several parameters.

2.3. Biosensors for Virus Detection.

To prevent and combat future pandemics caused by respiratory viruses, it is necessary to have rapid and reliable detection methods. This can be achieved with inexpensive and sensitive sensors that provide quick and accurate results.

These sensors will help better control the diagnosis and treatment of existing and future respiratory viral infections. Three main aspects influence the sensor platform: the target analyte (bacteria, viruses) to be identified; the identification process (bioreceptor); and signal amplification generated during the identification process so that they can be quickly recorded [19]. The principle of biosensor operation is that the analyte interacts with the bioreceptor, and the detecting component specifically recognizes this substance through specific adsorption or another process such as physicochemical interaction. The transducer then converts molecular changes into a measurable signal that is recorded by the digital detector module [20].

Ideal sensors for detecting respiratory viruses should provide reproducible results, be autonomous, provide immediate results, have high sensitivity, detect multiple analytes simultaneously, have various measurement modes, be inexpensive, durable, easy to use, and easily disposable without harming the environment.

In recent years, four types of sensors have been used for virus detection: nanomaterial-based sensors, electrochemical sensors, optical sensors, and piezoelectric sensors. In this work, we consider the principle of optical sensors for virus detection.

3. Results

Virus detection methods that are efficient, fast, inexpensive, and easy to use are key to combating viruses during pandemics. In this regard, new optical technologies can become promising biosensors. In biosensing measurements using TFBG sensors, a base measurement in solution is used as a reference for all subsequent measurements in test analytes.

An optical biosensor can be defined as a transducer by which biological measured interact with light, which is either guided through an optical fiber or directed into an interaction region via an optical fiber [21] to produce a modulated optical signal with information related to the parameter being measured, which means, that the optical fiber interacts with an external parameter and transmits a modulated light signal from the source to the detector. Input measurement information can be extracted from this modulated optical signal (Figure 8).

There are various stages in the development of an optical biosensor for the detection of biomolecules (viruses). The first step is the identification of the target biomolecular species/ analyte for detection, followed by the determination of the biorecognition mechanism, which is key not only to achieving the desired selectivity, but also to the final selection of the specific photonic technology to use. The next step typically involves functionalizing the biorecognition element on a suitable platform based on the selection of the biotransduction mechanism to use. Figure 8 schematically shows the basic optical measurement setup, which represents the illumination of the biorecognition element before and after its interaction with the analyte, as well as the methodology for detecting changes in the light beam as a result of the interaction of the biorecognition element with the analyte.

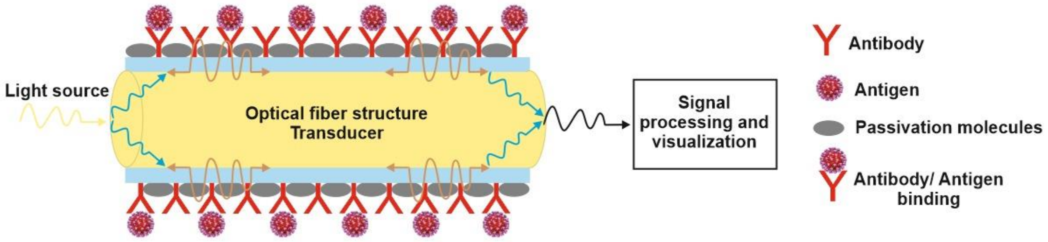

Figure 8.
Scheme of the process of converting a virus into an optical signal

In general, an optical biosensor typically consists of an optical source, a transduction platform, and an optical detector/receiver, as schematically shown in Figure 9. The transduction platform contains appropriate receptors designed to specifically bind to the target analytes (virus). Of the various transduction platforms, optical fiber-based platforms are particularly attractive as they are able to perform well in harsh environments and their array readout capabilities allow them to be used for multi-channel and multi-parameter detection [22].

The image shows the virus detection process using an optical sensor. In the foreground is an optical sensor connected to a light source and a photodetector. In the center are depicted viral particles that interact with antibodies applied to the surface of the sensor. When viruses bind to antibodies, the optical properties of the surface change, which is detected by a photodetector, demonstrating the presence of a virus.

a)

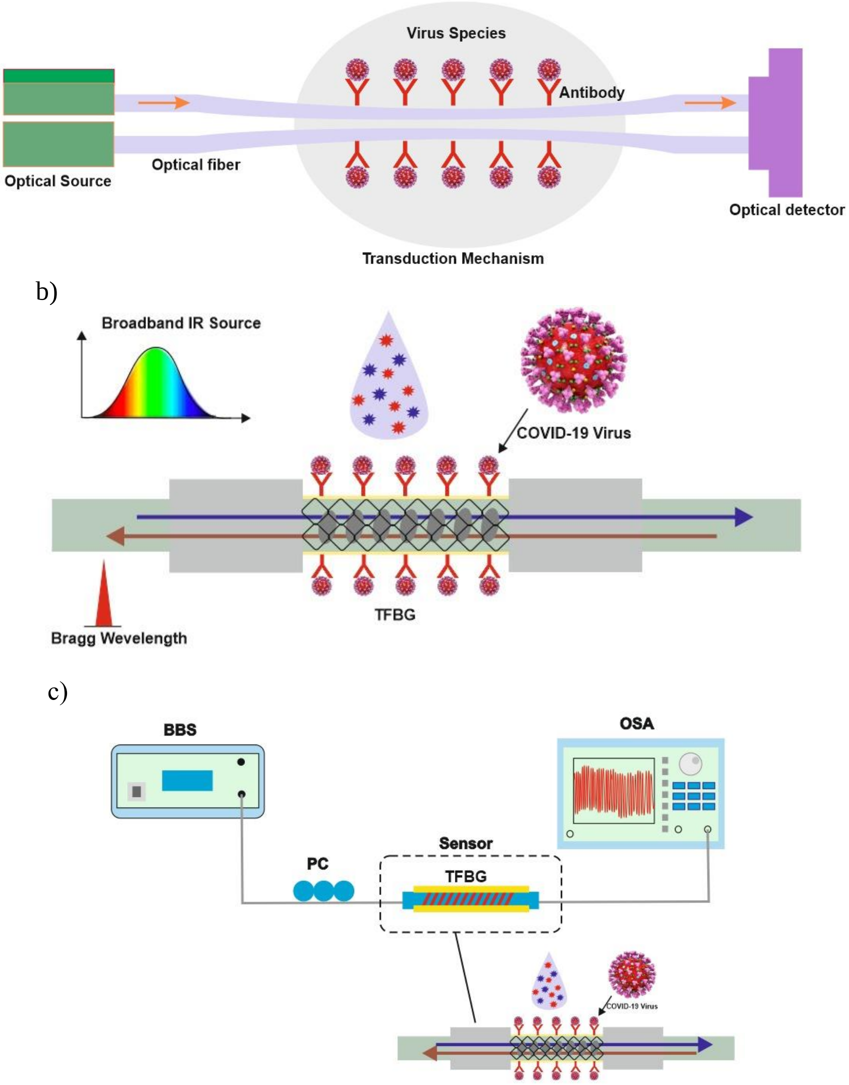

Figure 9.
Schematic representation of virus detection by a TFBG - based biosensor a) general diagram of the operating principle b) principle of virus detection by a TFBG-based biosensor c) experimental setup.

To detect the COVID-19 virus using a TFBG-based biosensor, several steps are used, including sensor preparation, sample interaction, change measurement, and data analysis.

Preparation of the biosensor. TFBG is integrated into an optical fiber that is highly sensitive to changes in the environment. The surface of the fiber is modified to allow binding of specific biomolecules , such as antibodies or nucleic acids, that will specifically interact with viral particles or their components (for example, the SARS-CoV-2 spike protein).

Interaction with the sample . The prepared biosensor is immersed in the test sample, which can be fluid from the nasopharynx or other biological material. If viral particles are present in the sample, they bind to biomolecules on the surface of the sensor.

Measuring change . When viral particles bind to biomolecules on the surface of the TFBG, the local environment around the optical fiber changes. These changes affect the propagation properties of light in the fiber, which is recorded as a shift in the spectrum of reflected light.

Data analysis . The spectral shift is analyzed using specialized equipment and software. The magnitude of the shift correlates with the amount of virus in the sample, which allows its presence and concentration to be determined. Based on the analysis of spectral data, a conclusion is made about the presence or absence of the COVID-19 virus in the sample under study. Results can be presented in an easy-to-interpret format, such as numerical data or visual graphs. Figure 10 plots the wavelength of detected light after passing through the fiber probe (TFBG) versus exposure time for various virus concentrations. Figure 8 shows the virus concentration increasing linearly over exposure time. Green light line graph showing low virus concentration. During the initial stages of exposure, the change in wavelength will be negligible. As exposure time increases, a linear increase in wavelength is observed as viral particles begin to interact with TFBG. The orange light line is the average concentration of the virus. At the initial stages of exposure, the change in wavelength is more noticeable compared to low concentrations. The linear increase in wavelength is more pronounced as more viral particles interact with TFBG. Blue light line high concentration of virus . A significant change in wavelength is observed already at the initial stages of exposure. The linear increase in wavelength reaches higher values as the high number of viral particles significantly affects TFBG.

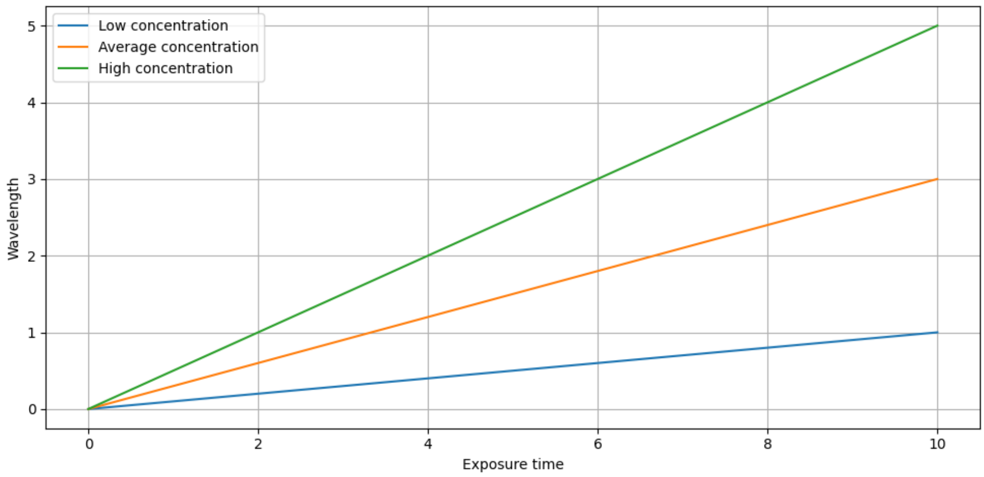

Figure 10.
Graph with linear increase in virus concentration

In the presence of a virus, a shift in the reflection peak is observed towards increasing or decreasing the wavelength. This shift indicates changes in the local environment around TFBG. The larger the shift value, the higher the concentration of virus in the sample. This process allows for rapid, sensitive and specific tests for the presence of the COVID-19 virus, which is essential for diagnosing and monitoring the pandemic. The use of TFBG-based biosensors for virus recognition allows rapid and accurate tests for COVID-19, which is especially important for effective management of the pandemic.

Early diagnosis of viral infections is of great importance for both individual and public health, as demonstrated by the COVID-19 pandemic. Fiber optic sensors, in particular TFBG, have shown great potential in the development of highly sensitive point-of-care testing devices.

4. Conclusions

In the modern world, where the speed and accuracy of virus and viral infection diagnosis are critically important, optical biosensors based on Tilted Fiber Bragg Gratings (TFBG) show significant potential and represent a promising direction in biomedical research and applications. TFBGs allow for eliminating cross-sensitivity and measuring multiple parameters simultaneously. TFBGs have high sensitivity and specificity, enabling effective detection of viral particles and biomarkers even at low concentrations, making them indispensable in situations requiring rapid and accurate diagnosis. Thanks to their characteristics, TFBG biosensors can provide diagnostic results in the shortest possible time, which is particularly important in situations requiring immediate response, such as viral infection outbreaks.

TFBG biosensors can be integrated into various diagnostic platforms, expanding their application possibilities in medical institutions, laboratories, and even field conditions. They can be part of compact portable devices, providing on-site diagnostics. Using optical methods allows for developing non-invasive diagnostic approaches, reducing patient discomfort and the risk of infection spread. The technologies underlying TFBG have the potential for large-scale production, making their widespread dissemination and accessibility possible, which is crucial for ensuring global health and combating epidemics. TFBG biosensors can be configured to detect various types of viruses and infections, making them versatile tools for medical diagnostics. The ability to adapt sensors to new viral threats increases their value in a dynamically changing epidemiological environment.

The TFBGs with a tilt angle of less than 100 degrees considered in the article have proven their effectiveness and high sensitivity in detecting viruses. Thanks to their unique characteristics, such as measurement accuracy and reusability, TFBGs are becoming an important tool in modern diagnostic methods. Continued research and development of these technologies open new horizons in biomedical diagnostics and enhance readiness for rapid response to viral threats.

Future work will focus on improving sensitivity and resolution by optimizing various fiber sensor structures and using them with artificial intelligence.

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