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Original article

Design of optical splitter using ion-exchange method for DNA bio-sensor

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ABSTRACT

A high-sensitivity y-splitter, based on thermal ion-exchange waveguide has been studied for biochemical sensing platform applications. Based on the analysis, the ion-exchange waveguide has been simulated and designed by using the finite difference time domain method (FDTD). To realize high-resolution, y-splitter read-out configuration is investigated based on the ion-exchange waveguide with a total height of 0.22 μm and width of 0.5 μm at the operating wavelength between 1500 and 1600 nm. The length of the sensitive window in the y-splitter configuration is 4 μm, where the total length of the y-splitter is 16 μm. In this context, the produced bio-sensor which can be made using the optical waveguide configurations, is providing a cost-effective method for sensing materials such as DNAs. The sensing arm which is covered by the DNA as upper cladding has 0.45 x 10^{-3} decreasing power in comparison to the reference arm. In this paper, the simulation of the y-splitter optical waveguide has been performed using the ion-exchange technique to detect the DNAs.

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1. Introduction

Like all transduction methods, the optical sensors have higher sensitivity and immunity to electromagnetic interference, which can offer many applications in photonics (Hong et al., 2006). The most valuable of in situ to perform real-time sensors are the optical waveguides among many other types, where they possess the miniaturization and integration with other devices. Surface plasmon resonance (SPR), Quantum-Dot and piezoelectric biosensors are the emerging area of molecular diagnosis. The Intelligent opto sensors interfacing based on universal frequency-to-digital converter has opened new opportunities for development of DNA biosensors (Sidek and Afzal, 2011). Some success has been achieved in the commercialization of optical fiber sensors. However, they still suffer from competition with other mature sensor technologies and new ideas are being continuously developed and tested not only for the traditional measurements but also for new applications (Lee, 2003; K'Owino et al., 2007). Efficient biosensors will not necessarily function as a stand-alone detector but will form an integral part of an analytical system. Compact and portable devices such as waveguides will constitute another future area of intensive multidisciplinary sensor research.

The waveguide based technology to biosensing applications is rapidly growing, where a higher sensitivity and stability still a demand to have high efficient sensor devices. These requirements are motivating researchers to use new materials in waveguide sensor fabrications, which have a high-refractive-index as promising component (Schmitt and Hoffmann, 2010). To achieve higher refractive index material in the case of optical waveguides fabrications, the use of practical techniques is very selective. The appropriate technique such as the ion-exchange should be selected. For the optical waveguide sensors, not only the sensitivity is desired but also the easy structuring process and their resistance against the chemicals are of concerns especially in the biosensing applications. The chemicals are used to bio-molecule immobilization and their regeneration. Deoxyribonucleic acid (DNA) is a polymer bio organic that resulting from natural sources such as salmon roe. This polymer has attractive properties for the photonics applications and known as unusual material possessing (Rau et al., 2012; Kwon et al., 2009; Grote et al., 2003; Yu et al., 2006;

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Krupka et al., 2008; Heckman et al., 2006; Gupta et al., 2006). As a photonic material, DNA can be applied for instance in optical waveguides application. It can be used on its own and as a host material accepting chromophores in photonics applications. Several fluorescent dyes can bind to the DNA to form stable complexes. By analyzing the critical parameters, this study can be applied to photonic device applications considering the DNA and the materials obtained from it. The used parameters can be functioned and altered according to the device requirements. These parameters can be oriented in parallel or perpendicular to the rod-like double helix axis, which can be associated with the external helical grooves, incorporated by intercalation or inclined to the major DNA axis. At $\lambda = 1300–530$ nm, the nonlinear refractive index of the DNA varies from $\approx 2 \times 10^{-15}$ to $1 \times 10^{-14} cm^2/W$ (Samoc et al., 2006). Here the maximum concentration of DNA was 3 wt%. For many years, the ion-exchange technique was used to change the color of the glass. By using this technique, the refractive index can be changed within the part of the glass. Ion-exchange is the cheap and appropriate method as well as easy for industrial purposes (Righini and Pelli, 2001). In the ion-exchange method, combining the salt form of silver nitrate and sodium nitrate and put them in high temperature would cause the silver ions (Ag+) to be replaced with the sodium (Na) that is available on the surface of the glass. Silver nitrate (AgNO3) and sodium Nitrate (NaNO3) will be melted in 400 degrees centigrade so that the ion exchange can be implemented (Kuhler and Griese, 2010).

The most common ion used is silver (Ag+) due to its significant variation in the refractive index compared to other ions, such as potassium (K+) and thallium (Tl+) (Ramaswamy and Srivastava, 1988; Amiri et al., 2017,2019; Ariannejad et al., 2015). Ag+ has high ion exchange capacity as well. The concentration of Ag+ ions can be a critical key to cause variation in the height and width of buried waveguide channel. In this study, we have chosen the Ag + concentration for the particular presented application.

The design structure of the optical waveguide in finite difference time domain method (FDTD) is a simple y-splitter which is the most considerable structure, because of its simplicity in fabrication, where the existence of the sensing arm helps to distinguish common-mode effects (Raghuwanshi et al., 2012). There are various applications of waveguide devices based on splitter (Amiri et al., 2018) configurations such as advanced applications, receivers in coherent optical communication (Amiri et al., 2017,2019) systems, wavelength demultiplexing and high resolution spectroscopy in telecommunication applications, polarization microscopes and sensors for biomedicine applications, radar displays in defense and security systems, saccharimeters for measuring glucose content in chemistry, and polariscopes for determining strain patterns in mechanical engineering (Tsutsumi et al., 2010). The simulation of the DNA biosensor based on the ion-exchange process has been studied on a glass substrate. Consequently, an optical waveguide of y-splitter has been designed using the glass as substrates and the critical parameters were analyzed. The sensor can be further optimized by choosing wavelength range from 1500 to1600 nm to show the power variations with respect to different wavelength range (Samoc et al., 2006).

2. Methodology

For making the DNA sensor, we should first do the ion-exchange process. Referring to Fig. 1, the thermal ion-exchange has been performed after it had an opening window on the sensing arm of the splitter, where the DNA can be detected. For simulation, the thermal ion-exchange in the glass is used and the IONEX software was utilized. To solve the differential diffusion equation, the Finite Difference Method (FDM) is utilized. In this method at the beginning the glass will be totally cleaned, then by using the sputtering machine 150 nm layer of aluminum will be sputtered on the glass substrate in a uniform and good quality condition. The waveguide design after designing will undergo a process to make a mask and then the desired pattern will be on the aluminum using the UV lithography technique. Using the wet etching which uses a fast and cheap method is recommended. In order to create the ion exchange channel, we use the melts that usually consist of nitrates, chlorides or sulfates. The glass substrate that modifies ion A+ for example, Na+ that could be dipped into a molten salt within the existence of the cation B+ such as Ag+ . The interface of the glass melt, both ions shortly could decrease to zero. To understand the equilibrium, the thermal will cause the interface or B+ -ions and opposite. Moreover, the diffusion of cations as a gradual spreading of particles can be taken place away from the interface. While the B + cations generate thin layer near the glass surface, the A+ cations move quickly missing from the interface. At glass surface, the exchanged B+ cations have the highest concentration, where it decreases in the glass. By using more Ag+ concentration we would have good quality, more uniformity, deep and wide channels. After the channels are made precisely, we can start to do the ion-exchange steps that should put the samples inside the molten salt (400 °C). After 40 min, the samples will bring out from the furnace and then they will cool down in the room temperature, after cleaning the sample the channel will be made as is illustrated in Fig. 1.

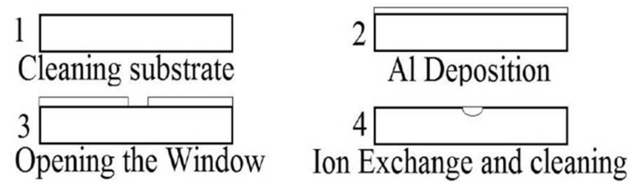

Fig. 1. Shows the processing configurations for ion-exchange, (1). Clean the glass substrate precisely (2). Al deposition with using the sputtering machine (3) using photoresist and within the usage of UV open the window that we want to open the channel and wet etching (4). Ion-exchange with using 400 °C in the molten salt after that clean the substrate precisely.

After completing the ion-exchange process regarding the proposed design, we have two arms; one arm is considered as a reference arm and another arm as sensing arm, for this matter the sensing arm should open one window for the purpose of detecting the DNA that would be on the top of it. In Fig. 2 the ion-exchange sample will be coated with photoresist by Spincoater, after that the proper mask will match to the sensing arm and then after exposing to UV the developer will open and clean the window as expected.

The sample would be ready, where the sensing arm can detect the DNA Fig. 3) on the top of the waveguide, the refractive index of sensing arm will be changed. By measuring the refractive index which will be different from the reference arm, we can consider about special comparing of the reference arm and sensing arm in case of recognizing of different material.

Fig. 4 shows the schematic of the splitter waveguide which can consist of 4 different parts (Tsutsumi et al., 2010). Single mode

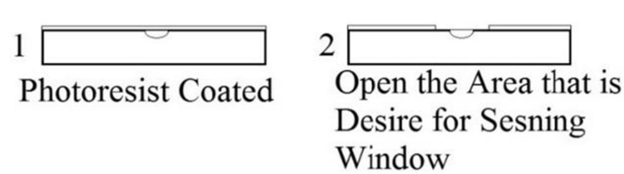

Fig. 2. The processing configurations for producing the sensor, (1). Coat the photoresist with a spin coater (2). Open the window by using mask and UV exposure with considering of developer.

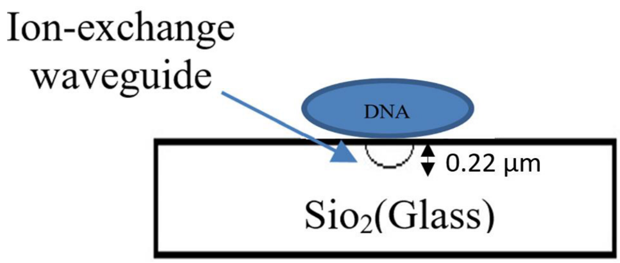

Fig. 3. Showing the DNA on top of the ion-exchange waveguide in case of sensing.

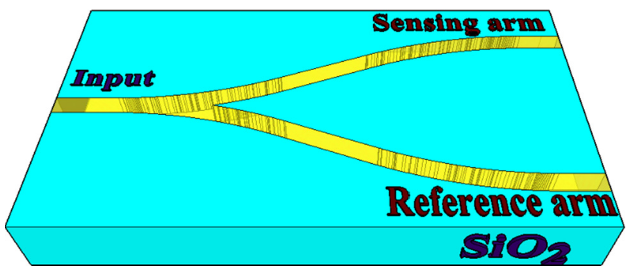

Fig. 4. The different regions structure of splitter waveguide.

splitter structure can be simulated by FDTD method. Ion-exchange can help to make such a buried waveguide. The coupling of light into the thin-film waveguides are critical and sensitive due to the small dimensions of the structures. The method used to couple the light into a waveguide structure can be selected with respect to the waveguide's dimension and its application as a sensor device. Either optical focusing lens utilized to collimate the light into the waveguide structure or the optical fibers can be used as different techniques to perform the front-face light coupling into the waveguides sensors. The front-face light coupling method has disadvantages of low robustness against vibrations in the sensor system, however a good and accurate alignment method can minimize the system vibration to improve the coupling efficiency. The well-polished and prepared waveguide's edge and the accurate alignment between the optical element utilized to focus the light and the waveguide structure are the essential conditions to accomplish the coupling method. A better coupling can be performed by maximizing the intensity distribution within the waveguides. In this simulation-based study we have not used optical fibers to couple the light into the structure and the ion-exchange technique has been performed through waveguide fabrication using the IONEX simulation software, Although, experimentally, there are several techniques which can be utilized to couple the light into the small waveguide structures as presented in reference (Barrios, 2018; Liu et al., 2018; Fain et al., 2017; Malka and Peled, 2017; Ishigure et al., 2017).

3. Simulation for Ion-exchange

Investigations of bioreactions within the evanescent field can be done by using high refractive index waveguide structures. High sensitivity and accurate measurements are benefits of using optical sensors. The principle behind the optical sensors can be determined by the label-free factor, where the effective refractive index within the waveguides is a pivotal parameter. Therefore, the study of the kinetic, and determination of the affinity contrasts can be performed by using appropriate sensor devices based on the refractive index changes monitoring. Table 1 illustrates the parameters that have been used in ion-exchange simulation (IONEX). The

Table 1
IONEX simulation parameters.

Glass Properties	
Na Concentration (moles/m^3)	5000
Ag diffusion coefficient (m^2/s)	2E−15
Ratio of diffusion coefficient of Ag/Na	0.7
Correlation factor	0.51
Substrate thickness (mm)	1
Process parameters	
Temperature (°C)	400
Step duration (min)	40
Ag surface concentration from melt	1
Calculations	
Grid period (m)	3.333333E−07
Time interval (s)	0.2

cross-sectional view of the optical waveguide device for different Ag^+ ionic surface concentrations illustrated in Fig. 3.

By using a soda lime glass substrate where $AgNO_3$ and $NaNO_3$ were melted within 400 °C for 40 min, the ion-exchange process occurred. The concentration of Ag^+ at the surface can be varied from 0.2 to 0.8moles/m^3. In Fig. 5 the following junction depth studied for different ionic concentrations. The junction became shallower and shorter when the Ag^+ ionic concentration was increased. The waveguide was less than 2 µm deep and near to 6 µm wide in the case when the Ag^+ surface concentration was 0.2 moles/m^3, however, waveguide was less than 1 µm deep and more than 4 µm wide if the Ag + surface concentration is 0.8.

The waveguide can support two lateral modes with considering for a long time, more than 20 min, in thermal ion-exchange duration. Within this condition, the low noise devices achieved even when the process time was shorter than 50 min and the performance of the waveguide device would not be changed. To have a high quality and uniformity of the channel the concentration of the Ag ions apparently, can be an important role to have a deep channel suitable for propagating the light. The sensing has been optimized through the simulation process so that the presented details and parameters such as the depth, length are consequences of the optimizations performed.

The thermal exchange from a molten salt, with or without the presence of an applied electric field, followed by field-assisted burial and thermal annealing, has been shown to produce waveguides

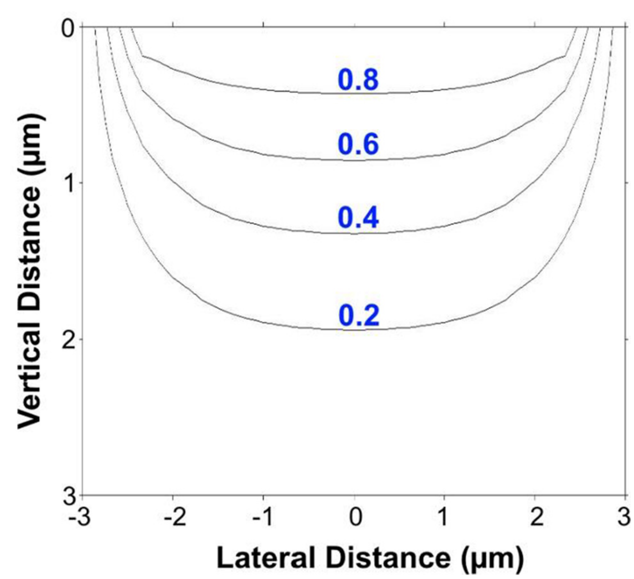

Fig. 5. Displays the calculation by FDM in IONEX for Silver ion concentration distribution.

with the aforementioned desirable properties (Honkanen et al., 2006). Thermal exchange may also be assisted by an waveguide applied electric field. Under the influence of the resulting electric field, the Ag+ migrate deeper into the glass. In this study we have not applied electric field.

4. Simulation of the splitter

Table 2 lists the parameters that were used in the simulated the splitter design by using FDTD method. L_w is length of the three individual straight waveguide sections at the input and output ports (4 μm), L_s is x span of the s-bend sections, base angle describes the sidewall angle of the waveguide (6 μm), base height is the height of waveguide, base width is the width of the waveguide base and y span can stand for the center-to-center distance between the two output ports. The total length of the proposed y-splitter silicon waveguide is 16 μm.

Base on the information given in the Table 2, the Fig. 6 illustrates the parameters. As it can be seen in this figure that the output-1 would be the sensing arm, where the output-2 is the reference arm. In order to demonstrate the splitter design, we have shown three sections which are the tapered, coupled separating and isolation separation sections (Honkanen et al., 2006).

The splitter is a very efficient structure design for the applications of sensing as we could have the sensing arm and reference arm to compare the results therefore the sensing of the material refractive index would be easier and more precise.

Table 2
Single mode splitter Parameters.

Parameter	Value
DNA Refractive index	2 (Samoc et al., 2006)
Substrate Refractive index	1.5126 (Veerasamy and Hatwar, 2014)
Ion-exchange channel Refractive index	3.444 (Ariannejad et al., 2014)
L_s	6 μm
L_w	4 μm
Tapered section	2 μm
Base angle	67°
Base height	0.22 μm
Base width	0.5 μm
Y_{span}	6 μm

4.1. Simulation results

In the photonics applications, if the high sensitivity of the sensor devices is required or the light must be well-defined polarized at the remote sensing point, single mode waveguides are utilized. The intrinsic sensors which are single mode waveguides are most preferred. The advantages of the high sensitivity of the single mode waveguides are significant due to ease of sensing the construction interferences built up directly from the waveguide itself. The measuring of the small phase changes due to the transmitted light through the sensing region can be performed. Fig. 7 shows the time in femtosecond versus the power. With the consideration of changing of the phase about $\pi/2$ it can be very sensitive waveguide to the DNA material and the reference arm follow the sensing arm and also the power won't be affected that much regarding this design. The phase of the light is comparable and distinguishable if the light traveling the sensing path and if it travels through to the reference arm.

The design can be a straight waveguide then the waveguide would split into two waveguides, therefore, light can travel and split within this design the inference of DNA can make $\pi/2$ shift which is significant in sensing. Fig. 8 shows the optical light power which has the same power in both arms. However, Fig. 9 can show the power of light has been changed due to interfering the light and DNA material. The simulated optical light propagation through the sensor with considering the opening window and putting the DNA on the waveguide and the interaction between them can influence the light propagation of that region and the real parts of the data in the optical light propagation.

By implementing the DNA material on the waveguide, it can change the refractive index of that region and by changing refractive index in one side of splitter arm the light power behavior can be influenced.

Fig. 10 discussed the wavelength changes due to the output power, as it can be seen the sensing arm has more power at 1.5 μm and due to the increasing the wavelength the power of reference arm would increase through the sensing arm would.

Fig. 10 shows the power changing due to the reference arm and sensing arm by the consideration of wavelength changes between 1.5 and 1.6 μm. In the light guiding structures, the contrast (difference between the refractive indices) of the core and cladding significantly affects the total internal reflection (TIR) of the input light within the core section (Yu et al., 2017; Chollet, 2016). High refractive index contrast is essential to confine and guide the light within the core section rather than the cladding, where lower

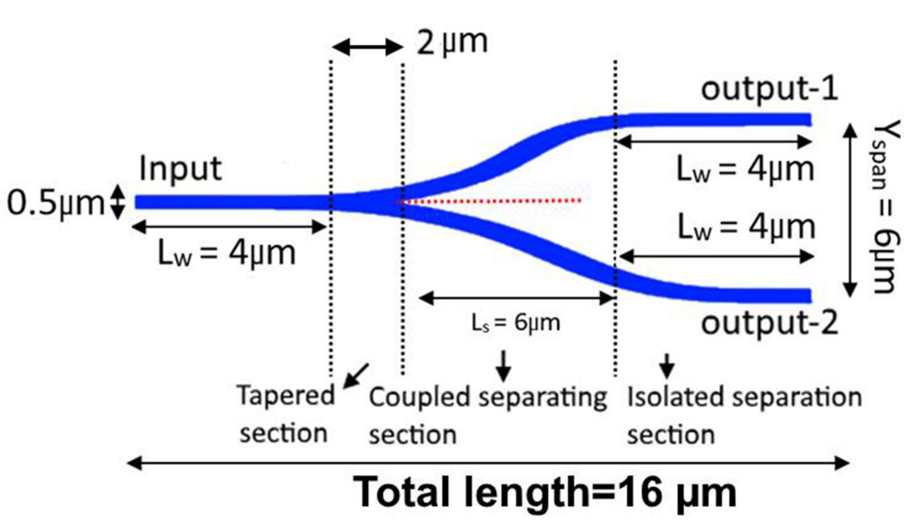

Fig. 6. Illustrates the three different sections of the splitter design according to the parameters presented in Table 2.

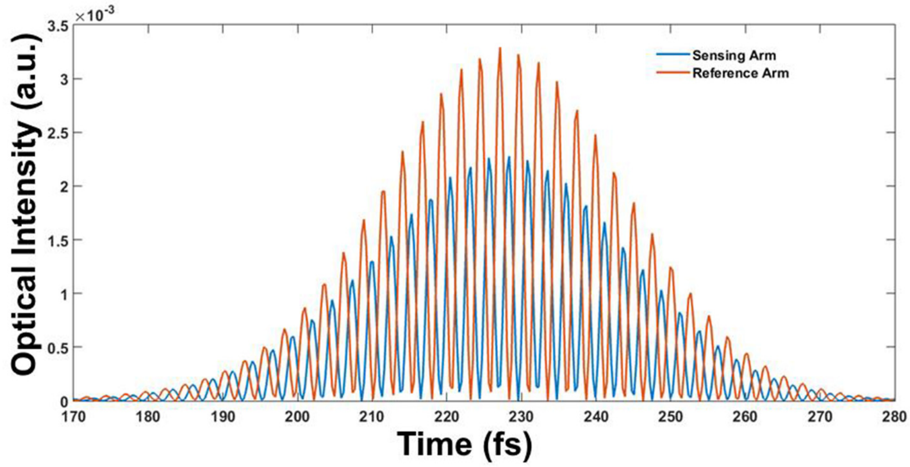

Fig. 7. Showing the model calculation with the software which is single mode. By designing the normal splitter in FDTD that we can see the power propagation through the splitter.

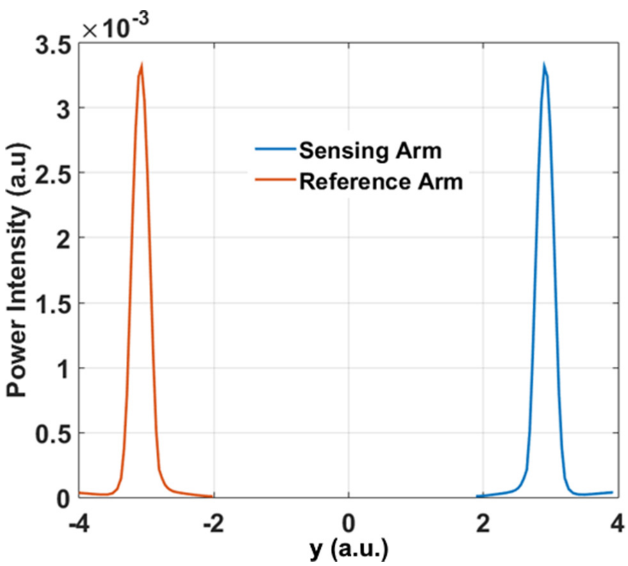

Fig. 8. Optical power output without DNA implementation.

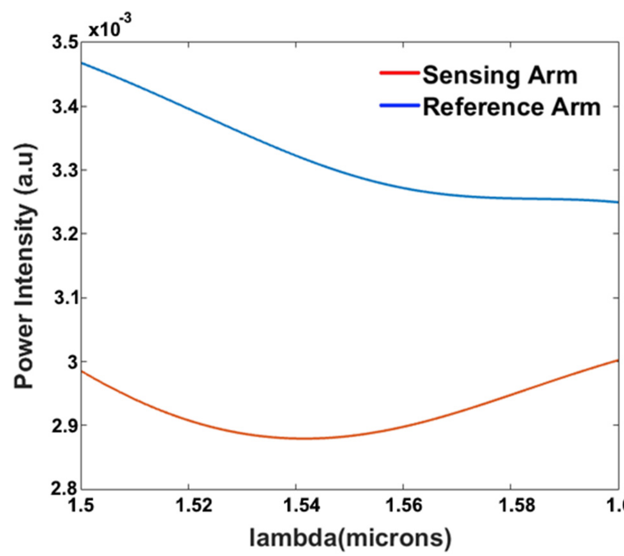

Fig. 10. Wavelength versus the output power.

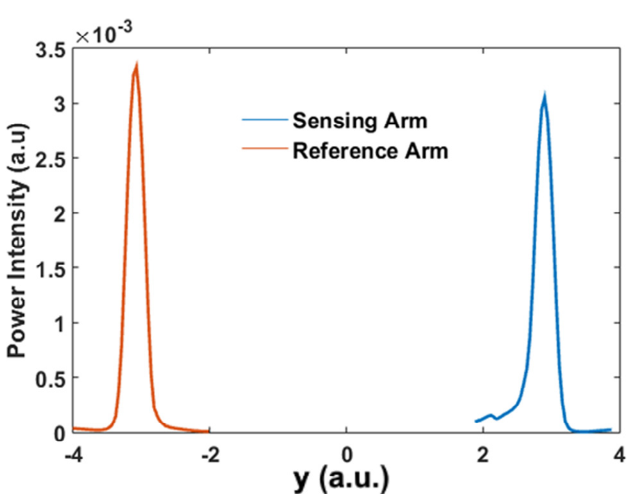

Fig. 9. Optical light propagation (simulation) through the single mode splitter with having the sensor designed to detect DNA.

refractive index contrast of the core and cladding causes portion of the input light travels in the cladding due to the light bending effects (Baets et al., 2017). Therefore, the power losses increase, and result a lower output power detection at the output port of the guiding structure which can be either fibers or waveguides. In this study if the input light propagates in the ion-exchange channel core (refractive index of 3.444), senses a higher refractive index of DNA (which is 2) compared to the air refractive index (which is 1), the lower refractive index contrast of the core and cladding induces a power loss within the core and consequently causes a lower power detection at the output port of the sensing arm in the splitter silicon waveguide.

The width of the channel in this design means to be 4 μm to have single mode waveguide. Output power can be changed by putting the DNA on the gold window that has been designed and it can be so sensitive in this case for sensing. In this study which is the refractive index sensing application, the output power of the waveguide varies with respect to any changes in the upper cladding refractive index. Here, the typical amplitude (arbitrary units (a.u.)) response of a resonant structure is considered as the sensing unit.

For most materials including DNAs, when the concentration of the materials changes, the refractive index changes accordingly,

Table 3
Optical power output in DNA sensor and ion-exchange channel.

Type of channel	Sensing arm (power in a.u)	Reference arm (power in a.u)
With having sensor window	3.0×10^{-3}	3.45×10^{-3}
Just ion-exchange channel	3.3×10^{-3}	3.3×10^{-3}

where increasing of the concentration causes an increase of the refractive index. In our study we have investigated the refractive index sensor device using the simulation method, where the sensing (power response) of the device was affected by any changes in the upper cladding refractive index. If the concentration of the DNA changes, the refractive index changes accordingly which affects the sensitivity results.

5. Discussion

The device design and optical light propagation through the device have been done by using the FDTD method. The optical power outputs of the Y junction on each arm were considered. The sensing arm as a sensing for the DNA is simulated for high performance, Figs. 8 and 9 show the optical light power in both arm that is simulated through the device. A well-confined light through device ensures a high output power at the output arms. The Y- junction is a splitter; therefore, the maximum power value for each arm of the device was almost same without any DNA material on sensing arm. The measured output powers were analyzed and processed using FDTD software to predict the optimal design. The completed responses for both arms to study the effect with sense arm and without sense arm is shown in Table 3. The device acts as a perfect splitter as the output powers in both arms in all experiments have almost equal values. Therefore, the analysis will consider the output power in only one of the arms. The sensing arm has 0.45×10^{-3} decreasing power in comparison to the reference arm regarding the Table 3.

In this design, we sense the changing the output power that can be suitable for this material as a good sensor. Therefore, the chemical and biological reactions can be transformed into the measurable signals, where the biochemical based sensors are widely applicable in chemical industry, medical diagnostic, and environmental monitoring.

6. Conclusion

The DNA sensor can be designed for more sensitivity as well as using a cheap method as ion-exchange can produce sensing purposes. With these properties, different Ag^{+} concentrations were deposited by using IONEX software, where on glass substrates defined the channel size and channel depth, which the results of it were used in the next step by using FDTD method. Further, it was shown that DNA can change the refractive index and it can make differences in output power in case of sensing this material. A splitter design with optimization of the parameters that can make more promising optical waveguides considered. The future work would be work on the fabrication and characterization other designs as well by using the ion-exchange on glass substrates.

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