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Computational analysis of core cavity Mach-Zehnder interferometer based optical sensor for various types of virus

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In this effort, the demonstration has been done for designing the new optical sensor for the detection of various viruses. In this design, we have revealed about Photonic crystal based CCMZIs (Core Cavity Mach-Zehnder interferometers) structures namely CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4. These structural designs are commonly referred here as CCMZI_X cavity sensors where X denotes the gradual decrement of scattering rods present in the cavity sensors. By selecting four types of viruses we are interested to detect these viruses in bio-sample using the device, CCMZI_X based sensor for light wave propagation. It has been found that, while removing the number of rods in the structure distinct transmission patterns are obtained. By the consideration of the sensitivity part, further simulation has been done by using the signature of the viruses. The analysis of virus existence is simulated in the FDTD tool. The optimization has been done to provide the higher amplitude spectrum with the range up to 0.8712 and the sensitivity can be calculated in the range of 200-250µm which are obtained by comparing the structures having corresponding analytes.

Keywords: Photonic crystal, FDTD, Mach-Zehnder, virus analysis, Optical sensor, HIV

1 Introduction

In past, optical sensors have got very strong scope not only to be very simple and cost-effective devices but also to let rather sophisticated multi sensor applications. Optical sensors are a range of devices that makes use of multiple forms of light–matter interactions, namely photon-atom to detect, quantify and interrogate molecules for various applications. An optical sensor consist of a light source that emulates electromagnetic waves, a sensing platform and a detector where the light–matter interactions befalls and the latter recognizes and computes spectral shifts in electromagnetic waves upon contact with directed analytes respectively.

A sensor is a device which implicit about the conversion of light into electronic signal. The prime function is to convert the incoming electronic signal into human readable format. It is a part of photonic integrated circuit where many applications can be defined. In light theory of physics, it is proved that light can be defined as an electromagnetic wave, which follows electromagnetic wave properties. By considering this principle, all the electromagnetic wave equations include Maxwell's equations, Schrodinger wave equations etc., can be applied to light signal behavioral study. Nowadays in various arenas of applications including food storage, testing, biomedical research and drugs production optical sensors are highly been involved[1]. The device holds a biological component and a physicochemical transducer collectively in order to sense the analyte[2, 3]. We can categorize the mechanism of sensing into two types i.e. label-free detection and fluorescence. Here we will looking about the label-free detection in more deep which is instigated by persuading fluctuations in the refractive index of the sensing area due to the existence of analyte[4].

Among most of the major environmental agents, viruses are the main cause of human disease and illness. This brings up the necessity of virus detection as a vital one which has been delayed by few technical phases such as the small scope of target viruses' interrogated, sophisticated laboratories for analysis and tests that require substantial time.

As per Selma souf, one of the serious dangers to human life is global pandemics. Even though the HIV (Human Immune deficiency Virus) and Herpes, which are well-established and known virus, still killing

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huge number of people, the emerging viruses are also problematic and have caused several serious outbreaks in the recent years[5]. In 2002–2003 SARS-CoV (Severe Acute Respiratory Syndrome-Coronavirus), In 2009 H1N1 A (Swine Influenza) and In 2014 multiple deaths happened in West Africa due to Ebola Hemorrhagic fever are some examples.

Mortality rates and Illness have been quite higher. In 2013, HIV have infected thirty-five million people and prolonged transporters of Hepatitis B virus are around 340–410 million. With respect toWHO the (World Health Organization) 2014 report (2014,WHO), around seven lakhs peoples have died every year by Hepatitis B and about five lakhs die of liver diseases caused by Hepatitis C. The raised occurrence of these diseases has increased the enlightening efforts in clinical research area.

Human virus infections cause many serious illnesses and chronic diseases with varying effects, ranging from no obvious symptoms to debilitating infections, chronic conditions, acute, and even lethal infections[6].

The symptoms of virus infections are diverse, including fever, diarrhea, encephalitis, immune deficiency, and tissue damage and organ failure. In many cases, the clinical features of virus infection overlap other human diseases, making them difficult to diagnose. Obtaining a rapid, exact detection of causative virus agent is an acute component of medical diagnostic, even if only to rule out other potential conditions. Furthermore, rapid detection of virus infection provides for disease surveillance and can help contain outbreaks. The range of human illnesses and disease associated with virus infection is vast, differential ability of viruses are due to the infection caused by selected organ systems and tissues. Notable examples of human viruses that cause significant health problems include HIV causing severe immunodeficiency. Other viruses targeting the digestive tract (rotavirus, astro viruses), nervous system (Zika virus; ZKV and West Nile virus; WNV) and lung (Influenza, respiratory syncytial virus; RSV) are associated with gastroenteritis, neurological and pulmonary symptoms, respectively. In addition, viruses such as HTLV-I (Human T-cell Lymph Tropic Virus), HPV, Merkel virus and other viruses are associated with different types of cancer[7].

The full spectrum of known viruses that infect human host cells (i.e., the human virome) and their impact on health remains largely incomplete[8]. The total number of human viruses is unknown but likely comprises over several hundred different viruses. Cataloging human viruses can be challenging, because while some virus agents only cause acute infection and then are completely cleared, other viruses produce chronic infections and, in some cases, remain dormant for long periods of time, showing reactivation on occasion. Despite the many clinically defined features associated with different virus infections, a major gap exists in determining whether viruses, which are not generally recognized to cause chronic illnesses, contribute to disease susceptibility or even show complex contributions to chronic diseases[9].

P Zhang et al.[10] report a novel ENIA which is nothing buteuropium nanoparticle-based immunoassay for rapid detection of Influenza A and B viruses. The confirmation of ENIA sensitivities are around 90.7 percentage (147/162) in terms of Influenza A viruses and 81.80 percentage (9/11) in terms of influenza B viruses associated with an in-house (RT)-PCR reverse transcription assay in analysis of clinical samples that are influenza-positive.

JB Mahony et al.[11] presented new respiratory viruses, in the past nine years counting with the swine-origin influenza A/H1N1 and SARS coronavirus in the had been tested and develop diagnostic tests to prove the ability of virology laboratories for the identification of these viruses. NATs are called as Nucleic acid based amplification tests which can be used for the detection of both conventional and emerging respiratory viruses, were first declared two decades before and utilized for further. Both of these tests are higher sensitive than other approaches in medical diagnostic, containing shell vial culture (SVC), antigen detection by direct fluorescent antibody (DFA) staining, rapid enzyme immunoassay (EIA) and virus isolation in cell culture and it remains the spine of testing in clinical virology laboratory throughout the world.

There are many research works available in this field of optical sensor for detecting viruses and still it is an emerging technology so here in this paper photonic sensor method have been used for the detection of several types of viruses using four types of waveguide structure. The simulation can be done in Finite Difference Time Domain (FDTD) method. The four waveguide structures for various types of viruses has been compared and tabulated.

2 Types of virus

Normally Viruses shows its transformation as in the part of habitual activities by the human being in terms of its symptoms and health issues. Different viruses have different behaviors when it is present in human serum. Some of those types have been studied:

2.1 M13 Bacteriophage

M13 Bacteriophages are commonly called as bacterial viruses and comprised of a single-stranded RNA or DNA encapsulated by a protein capsid. They can easily infect the bacteria by inserting their nucleic acids within the crowd (host). These viruses can proliferate and persuade lysis of the cell present in the host. Generally it is not so dangerous to humans but the phages of bacterial virus can actually transport virulence elements to bacterial inhabitants and causes diseases in human being.

2.2 HIV-1

HIV-1[12] is the common type virus of Human Immunodeficiency Virus. It directly assaults our immune system in the body. These viruses can extinguish CD4 cells and these cells make our body to fight against infections. HIV-1 can damage the immune system of the human body and leads to AIDS (Acquired Immune Deficiency Syndrome). The symptoms are as same as those of virus illnesses, and they're frequently compared to the virus disease, flu. Headache, aching muscles, swollen lymph nodes, Fatigue, Sore throat, and Fever are some of the early signs of HIV.

2.3 Herpes Simplex Virus type 1

Herpes Simplex Virus-1 (HSV-1)[13] is family member of the human Herpes viridae also acknowledged by its taxonomical name Human alpha herpes virus 1. It has a set of new viruses which leads tovirus infections in the majority population of humans. HSV-1 creates cold sores which is contagious and common. When an infected person begins shedding the virus it can be easily spread. Itching, pain during urination and blistering sores (in the mouth or on the genitals) are the basic symptoms related to the virus. It may also include the following symptoms such as fever, headaches, swollen lymph nodes, tiredness, lack of appetite.

2.4 Influenza A

Influenza A[14] virus commonly infects some mammals and birds. Uniquely, this virus is from the Orthomyxoviridae virus family and the only species of the genus Alpha influenza virus which belongs to same family. Fever over 38 C (100.4 F), Sore throat, Chills and sweats, Dry cough, Fatigue and weakness, Headache, Aching muscles and Nasal congestion are found to be the common symptoms of the flu.

3 Tools and Techniques

Finite Difference Time Domain Method (FDTD) is a mathematical scrutiny technique which is utilized for computational electrodynamics modeling. It is used for finding outcomes approximately to the differential equations systems. This method has been well-known as a prevailing engineering tool for diffractive optics and integrated device in terms of simulation part. Due to its distinctive mixture of properties that includes, scattering and diffraction and reflection, polarization effects and ability to model light propagation.

The unique and highly integrated application software which allows the simulation of advanced passive, CAD and non-linear photonic components is Opti FDTD. Analyzing, designing, test for wave propagation and the nonlinear phenomenon are enabled in the software. The UPML (Uniaxial Perfectly Matched Layer) and advanced boundary condition are used in Optiwave FDTD. The steps or algorithm aids us to solve both the fields (electric and magnetic) in spatial and temporal domain under Maxwell's coupled - curl equations in the full-vector differential format. It assists us in the places no restriction on the material properties of the devices and in arbitrary model geometries.

The Opti FDTD is a fundamental program which is based on the finite difference time domain algorithm having second order arithmetical accuracy and mainly associated with uniaxial perfectly matched layer (UPML) boundary condition and advanced boundary condition. This enables us to analyze design, and test passive, scattering, nonlinear photonic components for wave propagation, reflection, polarization, nonlinear phenomena and diffraction.

In 2D Opti wave, the photonic device is positioned out in the XZ plane here propagation is along Z. Since this is two dimensional, Y direction is said to be infinite (assumed). This removes all the y derivatives from Maxwell’s equations and makes it to divide them into two as TE and TM which are independent sets of equations.

In 2D TE mode, only Hx, Ey and Hz have non-zero elements. In lossless media, Maxwell's equations[15] take the following form:

$$\frac{\partial E_y}{\partial t} = \frac{1}{\in}\{\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial z}\} \quad \ldots(1)$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu_0}\{\frac{\partial E_y}{\partial t}\} \quad \ldots(2)$$

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_0}\{\frac{\partial E_y}{\partial t}\} \quad \ldots(3)$$

where,

The dielectric permittivity is $\in = \in_0 \in_r$ and the magnetic permeability of the vacuum is μ_0.

FDTD analysis makes use of the above given equations (1) (2) (3). The vital reason behind the usage of these equations is that the photonic crystal can be used as a sensor for various applications which is proven in these equations subsequently.

$$E_y^n(i,k) = E_y^{n-1}(i,k) + \frac{\Delta t}{\in \Delta z}\left[H_x^{n-\frac{1}{2}}\left(i,k+\frac{1}{2}\right) - \right.$$

Hxn−12i,k−12

$$\left. - \frac{\Delta t}{\in \Delta x}\left[H_z^{n-\frac{1}{2}}\left(i+\frac{1}{2},k\right) - H_z^{n-\frac{1}{2}}\left(i-\frac{1}{2},k\right)\right] \quad \ldots(4)$$

$$H_x^{n+\frac{1}{2}}\left(i,k+\frac{1}{2}\right) = H_x^{n-\frac{1}{2}}\left(i,k+\frac{1}{2}\right) + \frac{\Delta t}{\mu_0 \Delta z}\left[E_y^n(i,k+\right.$$

1−Eyni,k

…(5)

$$H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},k\right) = H_z^{n-\frac{1}{2}}\left(i+\frac{1}{2},k\right) - \frac{\Delta t}{\mu_0 \Delta x}\left[E_y^n(i+\right.$$

1,k−Eyni,k

…(6)

The above equations include (4), (5), and (6) can be derived from equations (1), (2), (3) using central difference approximation.

The representation of space step along x and z direction and time step respectively happens in relation with change of x, y and z. Master equations is obtained using above equations (4, 5 and 6) for different boundary. Photonic crystal has been designed using the master equation. Also, n, I and K represents discrete space step and discrete time step respectively.

Any change in dielectric function will reflect in resonance frequency simultaneously which itself gives a fair picture that a photonic crystal is well eligible to be used as sensor.

4 Analysis of optical sensor

Design specification

- Basic configuration used: Rod In Air configuration
- Lattice property types: 2D Hexagonal lattice
- Lattice Constant: 0.45µm
- Dimension of lattice: 15x20 µm
- Rod height: Infinite
- Radius of rod: 0.11 µm
- Material considered (dielectric constant): Silicon

In Bio medical and bio sensor applications, additional cavity sensor has been achieved and utilized in CCMZI sensors[16,17,18]. This can be attained by gradually removing the rods from the center and named as CCMZI_1, CCMZI_2, CCMZI_3 and CCMZI_4 cavity sensors. In other words, the cavity Sensor length is considered as X. For further illustration, an CCMZI_1 cavity sensor can produced by the way of removing two rods in the air in photonic forty eight signs of progress in chemical sensor crystal structure. The CCMZI_1sensor is formed as shown in Fig. 1.

The design parameters of photonic crystal structure can be noted as radius of rod, the lattice constant, and the thickness of the slab where the wavelength[19,20] achieved as 1550nm. For considering the properties of longer sensitivity, the analysis can be taken with the four types of cavity sensors. Here CCMZI_1 and CCMZI_2 structures have sensitivity higher than the other waveguides.

The rod in air configuration is used here. In Fig. 2 the structure can be modified by removing the alternate rods located in the center cavity of CCMZI_1 sensor. It can be analyzed and optimized.

In Fig. 3 the structure of CCMZI_3 sensor can be formed by gradually remove the neighborhood rods

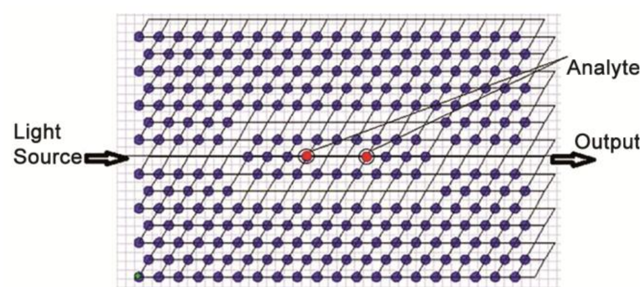

Fig. 1 — Structure of CCMZI_1 Sensor.

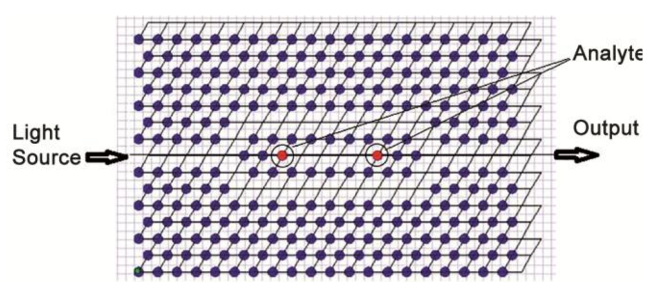

Fig. 2 — Structure of CCMZI_2 Sensor.

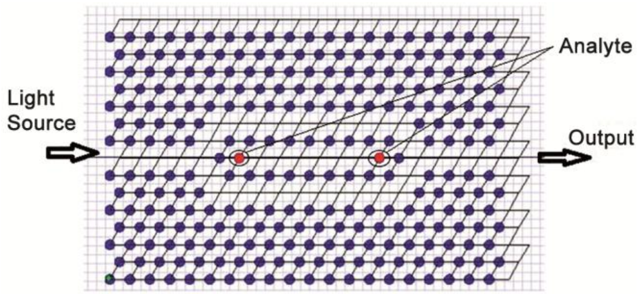

Fig. 3 — Structure of CCMZI_3 Sensor.

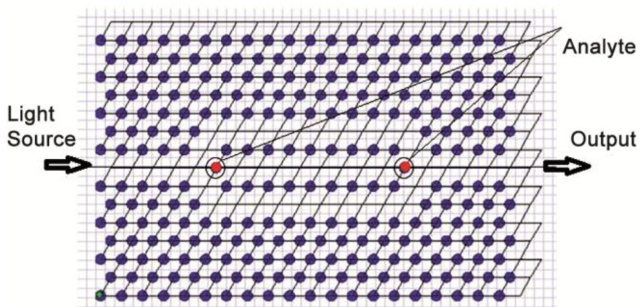

Fig. 4 — Structure of CCMZI_4 Sensor.

Table 1 — Refractive index values of the sample.

Name of the Sensing Parameters	Refractive Index
Normal	1.35
M13 Bacteriophage	1.57
HIV-1	1.50
Herpes Virus type-1	1.41
Influenza A	1.48

located in the cavity of CCMZI_2 sensor and optimized with the input parameters given. The CCMZI_4 sensor in Fig. 4 can also be formed in the same way as we followed in the earlier one.

Designing and Modeling can be achieved in crystal waveguide by using 2D hexagonal lattice structure with suitable lattice constant and the height of the rods are infinite.

Table 1 shows the refractive index values of various types of virus[21] and normal cell to be considered in the proposed waveguide design.

5 Results and Analysis

The distinct transmission spectrums are obtained as outcome of the simulation done in FDTD for different virus cells with respect to corresponding index values. The spectrum graph of all the virus cells with normal cell in human serum are shown in Figs 5 to 9.

Figure 5 explains the simulated waveform for normal or unaffected cell. The normal human serum of refractive index value as n=1.35. The input

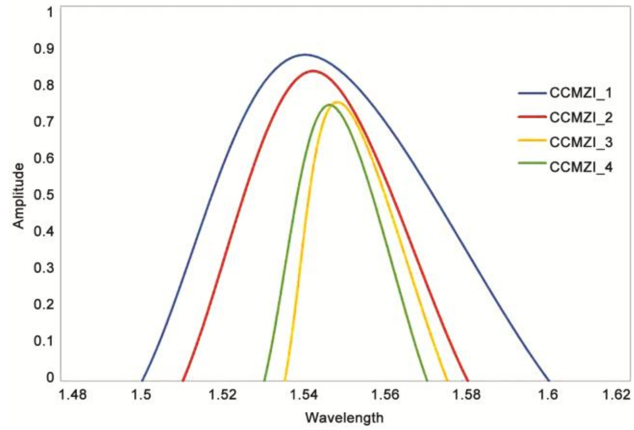

Fig. 5 — Simulated result of Normal cell.

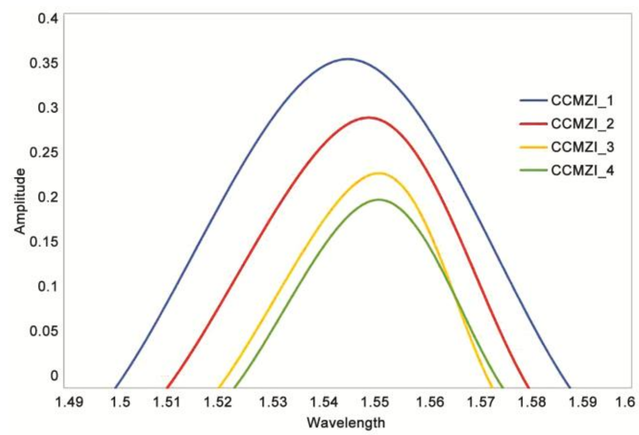

Fig. 6 — Simulated result of M13 Bacteriophage.

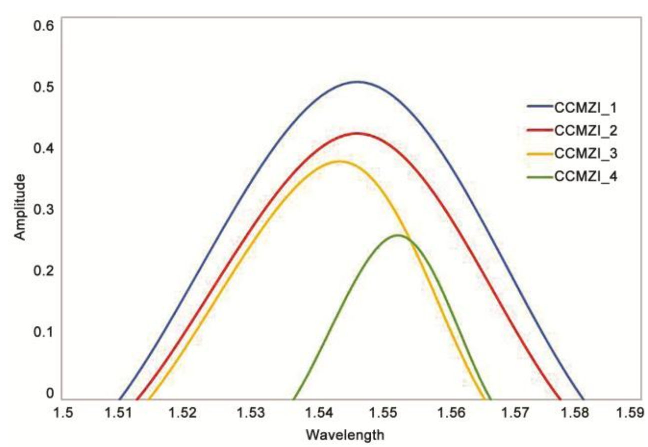

Fig. 7 — Simulated result of HIV-1.

wavelength of 1550 nm is compared among the considered cavity sensor structure. The amplitudes obtained are 0.8712 units, 0.8273 units, 0.7452 units and 0.7376 units for CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4 respectively. 0.01µm, 0.04µm and 0.03µm are the wavelength shift obtained here.

Table 2 — Comparative Analysis for various types of virus cells using CCMZI based sensor.

Cells considered	Amplitude of M3 sensor	Amplitude of M5 sensor	Amplitude of M7 sensor	Amplitude of M9 sensor
Normal	0.8712	0.8273	0.7452	0.7376
M13 Bacteriophage	0.3516	0.2891	0.2297	0.2013
HIV-1	0.5824	0.4879	0.4368	0.3011
Herpes Simplex Virus type1	0.5486	0.4853	0.4349	0.4194
Influenza A	0.5837	0.5695	0.5218	0.3759

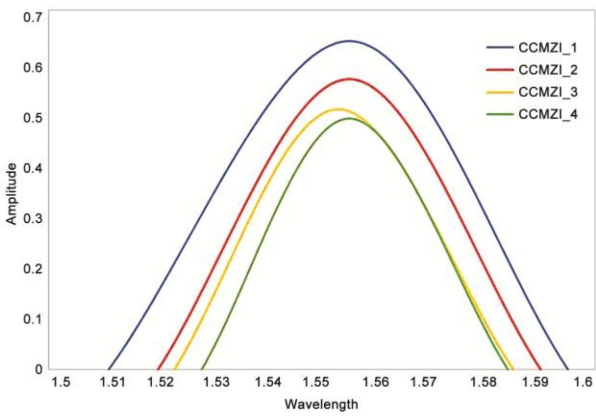

Fig. 8 — Simulated result of Herpes Simplex Virus type-1.

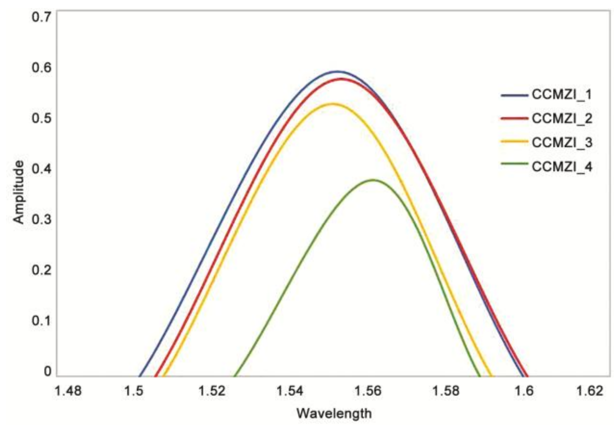

Fig. 9 — Simulated result of Influenza A.

The above graph in Fig. 6 describes about the performance of cavity waveguide sensor in M13 bacterio phage. The refractive index value is n=1.57 and it is used with the input plane wavelength of 1550nm. The comparison can be taken with the proposed structures. The amplitudes obtained are 0.3516 units, 0.2891 units, 0.2297 units and 0.2013 units for CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4 respectively. The wavelengths obtained are 0.01µm, 0.02µm, 0.023µm.

The graph in Fig. 7 labels simulated outcome of cavity sensor in HIV-1. The refractive index value is n=1.50 with the selected input wavelength of 1550nm.The comparison can be taken with the proposed structures. The amplitudes obtained are 0.5824 units, 0.4879 units, 0.4368 units and 0.3011 units for CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4 respectively. The wavelength shifts obtained are 0.003µm, 0.005µm, 0.03µm.

Figure 8 defines the simulated output of waveguide sensor in Herpes Simplex Virus type-1. The refractive index is 1.41. The input wavelength selected as 1550nm. The amplitudes obtained are 0.5486 units, 0.4853 units, 0.4349 units and 0.4194 units for CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4 respectively. The wavelength shifts obtained are 0.009µm, 0.012µm, 0.017µm.

The Fig. 9 illustrates the simulated outcome of waveguide sensor in Influenza A. The refractive index is 1.48. The input wavelength selected as 1550 nm. The amplitudes obtained are 0.5837 units, 0.5695 units, 0.5218 units and 0.3759 units for CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4 respectively. The wavelength shifts obtained are 0.004 µm, 0.006 µm, 0.024 µm.

All the simulated graphs explain about wavelength versus amplitude values among the used cavity sensor waveguides. The variation can be shown in colored figures.

From Table 2, we can observe that four type of virus are providing higher amplitudes for CCMZI_1 and CCMZI_2 sensors when compared to other sensors. The quality factor of CCMZI_1 and CCMZI_2 ranges from 1500-2000 while CCMZI_3 and CCMZI_4 are ranging from 700-900. Hence CCMZI_1 and CCMZI_2 sensor structure have been used further to attain the higher performance of the sensor.

6 Conclusion

In this paper, simulation of photonic crystal based on cavity sensor has been proposed for the detection of virus using Rod in air (RIA) photonic crystal configuration. The simulation has been carried out for the normal cell initially and then it is moving forward to virus cells namely M13 bacterio phage, HIV-1, Herpes and Influenza A. The designed structures are intended and analyzed using FDTD software. Changes occurred in amplitude values of the different refractive index have been calculated and measured. It has been shown that the observed values of CCMZI_1, CCMZI_2, CCMZI_3, and CCMZI_4 sensors can be used to provide the expected value for the detection of viruses. It has been done by considering transmission spectrum for distinct values of viruses with variety of diagnostic analysis. The waveguides are designed using easy and non-complicated structures to minimize the area. Therefore it has been used in Lab-on-chip biosensors applications. As it can be observed that transmission spectrum of CCMZI_1 and CCMZI_2 having higher amplitude values when compared to other two sensors.

So it is interpreted that CCMZI_1 and CCMZI_2 sensor will be taken as best choice for fabrication process. By analyzing the amplitude spectrum of the cavity sensors, it has been concluded that colossal difference in amplitude provides the simple way for the detection of virus diseases in human serum. It can also use in biochip application. The CCMZI_1 has high amplitudes such as 0.8712, 0.5486, 0.5824, 0.3516 and 0.5837 in comparison with others.

7 Future scope

The designed sensor has the future scope which includes real time usage of optical sensor for virus detection. The waveguide design of the proposed structure can also be varied or modified as different structure to enhance the performance of the device. These structures apply with the simple line defect, since it relies at micro level fabrication. It is mainly used for fabrication in photonic integrated circuits.

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