THz Metamaterial Sensor for Possible Influenza A Virus Detection

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Abstract Due to COVID-19 pandemic, there is a substantial need for high precision diagnostic test, which can be able to detect very small virus strain concentrations. The conventional methods are limited; due to these, the need for an alternative method such as THz metamaterials utilization based THz spectroscopy. In this paper, THz-time domain spectroscopy (TDS) has been used for detection of the AI viruses is presented. The square shape split ring metamaterial resonator is designed on the composition of VO_2 (Vanadium Dioxide), SiO_2 and gold layer (Au). The metamaterial resonator shows resonant peak at around 5 THz. The sensitivity analysis for three different types of Avian Influenza (AI) virus has been discussed based on the metamaterial absorber. The numerical analysis of sensor model has been carried-out using CST microwave studio. The general sensitivity of the proposed sensor is analyzed using graphical representation and shows 99.12/ 562.26/ 2197.53 (THz/nm), which makes a potential candidate for the application in THz sensing.

Keyword Avian Influenza (AI), Metamaterial, Sensors, Sensitivity, THz Spectroscopy, Absorber

1. INTRODUCTION

The COVID-19 pandemics plays much more pressure on medical sciences to provide the fastest possible results in order to stop the spread of the virus. Besides SARS-CoV-2, there are many different viruses, which are having significant potential to lead the future pandemics. The Avian Influenza (AI) virus or bird flu, is a disease caused by Type 'A' influenza viruses which is the most concerning group. The AI tends to spread not only by contact but also via droplets and aerosols, which makes difficult to control the transmission [1]. Based on these above, the need for high precision reliable diagnostic tests are required which can be able to detect extremely low virus concentrations instantaneously. There are many conventional methods such as molecular approach [1], chemi-luminescent immunoassay technology [2], and immuno-based detection [3] and these have certain limitations reflected in their high time consumption, difficulties during use and/or poor sensitivity [4]. In modern era, terahertz (THz) spectroscopy received a lot of attention for sensing applications. In THz spectroscopy, excitation of intra and intermolecular vibration is greater than absorption, which makes THz technology, is effective in sensing applications [5]. The THz technology suitable for level free sensing due to its non-ionizing nature. Apart from these, the wavelength is much larger than the size of particles in the sample. Therefore, there is need to maximize the interaction between the generated wave and particle which can be achieved by utilizing THz metamaterials. The metamaterial is a homogeneous material contains meta-atoms with magnetic and electric resonance [6]. The properties of metamaterials depends on the design of choice of geometry and materials. Many different THz metamaterials are investigate for various applications [7-10]. The THz metamaterial-based sensors are capable for detection of biomaterials [11]. The virus particle covers a wide range of dimensions i.e. 30 nm for bacteriophage to around 120 nm for SARS-CoV-2. These detectors can be realized using absorbers, reflectors, or antennas. The THz absorber for AI virus detection presented in [12] uses a I-shape metamaterial cell for resonance mode. Metamaterial reflector could be implemented using graphene H shapes at a semiconductor substrate, where the detection of AI viruses has been performed by observing the reflection response [13]. The slot antenna realization with silver nano-wires to improve virus detection is given in [14]. Plasmon sensors for detecting Zika viruses could use particles of gold in order to improve sensor quality [15]. A multi-resonance detecting chip presented in [16], was used to detect the AI virus concentration from the obtained transmittance. In general, the THz sensing methods are based on resonant peaks shift due to the change in sample thickness.

In this paper, THz-time domain spectroscopy (TDS) has been used for detection of the AI viruses is presented. The square shape split ring metamaterial resonator is designed on composition of VO_2 (Vanadium Dioxide), SiO_2 and gold layer (Au). The sensitivity analysis provides the detailed sensing characterization of proposed sensor. The proposed work is based on the numerical and graphical approach for detection of H1N1, H5N2 and H9N2 virus strain. This THz sensor is useful in the medical application such as cancer and different virus detection.

2. ABSORBER DESIGN AND ANALYSIS

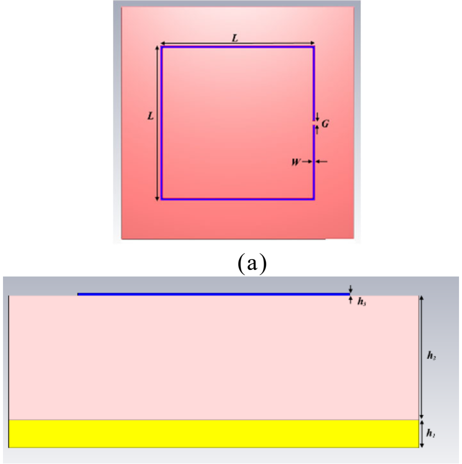
Fig. 1 shows the front and top view of the proposed THz absorber. It consist of VO_2 (Vanadium Dioxide), SiO_2 and gold layer (Au). The top layer of having thickness of consists of a square shape single split ring resonator as shown in Fig. 1. The middle dielectric layer is SiO_2 having thickness of $9\mu m$. The bottom layer consists of gold with a thickness of 0.2. The optical characteristics of VO_2 in the THz range can be described using Durde model [17], which can be expressed as:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{(\omega^2 - j\gamma\omega)} \tag{1}$$

where ε_∞=12 is the dielectric permittivity, $\gamma = 5.75 \times 10^{12}$ rad/s is the collision frequency. The relationship between the conductivity (σ) and plasma frequency (ω_p) can be expressed as [18]:

$$\omega_p^2(\sigma) = \frac{\sigma}{\sigma_0}\omega_p^2(\sigma_0) \tag{2}$$

In this work, $\sigma_0 = 3 \times 10^5 S/m$, $(\sigma_0) = 1.4 \times 10^{15}$ rad/s, and conductivity of VO2 changes from 200 S/m to $2 \times 10^5 S/m$ when it turns into insulator to metal phase. The VO_2 has been chosen due to its excellent transition behavior from an insulator phase to a metal phase at about 340 K in THz range.



(a)

(b)

Fig. 1. (a) Top view schematic and (b) side view schematic of absorber.

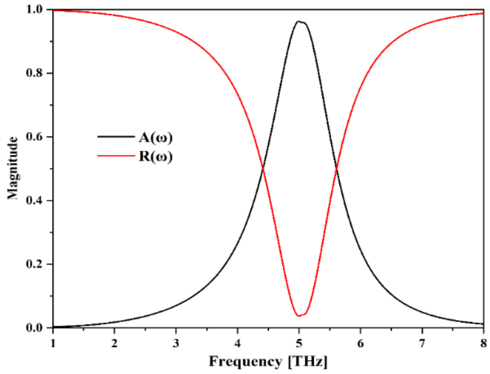


Fig. 2. The reflection spectrum and absorption spectrum of the absorber.

The boundary condition set as unit cell in x- and y-direction and perfect matching layer at Z-direction. Since the thickness of the metal ground plane is much greater than the skin depth, the transmittance will become $T(\omega) = 0$. Under these conditions, absorbed power can be defined through the absorptance $A(\omega)$ and calculated as [18]:

$$A(\omega) = 1 - R(\omega) = 1 - |S_{11}(\omega)|^2 \tag{3}$$

Where $R(\omega)$= reflectance and $S_{11}(\omega)$ = reflection coefficient in the S-parameters. When VO_2 layer having conductivity $2 \times 10^5 S/m$, the reflection and absorption spectrum are shown in Fig. 2. The Figure shows that, under normal incidence the absorption bandwidth is greater than 90% from 4.8 THz to 5.20 THz. The absorption peak is located at 5 THz. The absorption peaks of the proposed absorber can be tuned by varying its SiO_2 layer thickness. The parametric analysis of different SiO_2 layer thickness has been carried-out and is shown in Fig. 3. The figure reveals that as the length of the SiO_2 layer increase, peak frequency shifts at lower side.

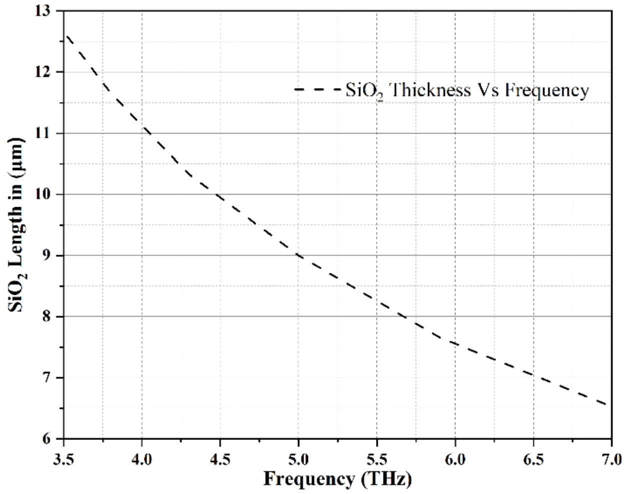


Fig. 3. Variation of SiO_2 layer with frequency.

3. VIRUS SAMPLE AND SENSING ANALYSIS

In this paper, three different subtype of IAV virus has been chosen for sensitivity analysis. These subtypes are: H1N1, H5N2 and H9N2. These are the major threat to human health as they causes highly at respiratory system. These three virus are modelled as a dielectric layer which completely covering the top of the sensor structure. The concentration of virus is prepared by varying its layer thickness. The optical properties of virus sample in THz spectroscopy are given in Table 1 [19]. The frequency dependent complex permittivity of the sample has been calculated for each frequency using [20]:

$$\tilde{n} = n + jK \tag{4}$$

The Drude-Lorentz model is used to obtain $\tilde{n}$:

$$\tilde{n} = \sqrt{\varepsilon} = \sqrt{1.5^2 - \frac{\omega_p^2}{\omega^2 - \omega_0^2 + j\omega\gamma}} \tag{5}$$

where $\varepsilon =$ complex permittivity, $\omega_p = 4 \times 10^{12} S^{-1}$ is plasma frequency, $\gamma = 4 \times 10^{12} S^{-1}$ is the damping coefficient and $\omega_0 = 2.8 \times \pi \times 10^{12} S^{-1}$ is the resonant frequency. The $\tilde{n}$ has been modified for H1N1, H5N2 and H9N2 strain according to the optical properties available on the Table 1.

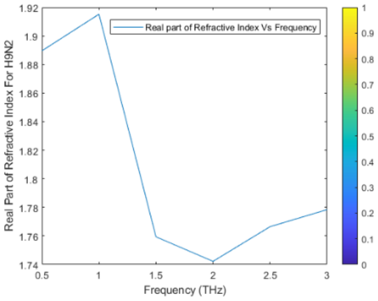


Fig. 4. Real (n) of the refractive index for H9N2.

The dependence of real part of refractive index on frequency is given for H9N2 in Figure 4. The absorption response for different strain i.e. H1N1, H5N2 and H9N2 with virus are given in Fig. 5. The figure reveals that resonant frequency moves at lower side when the virus strain are introduced into the sensor.

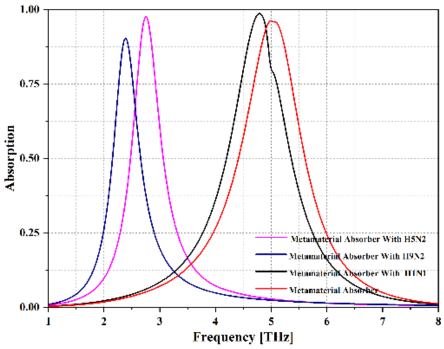


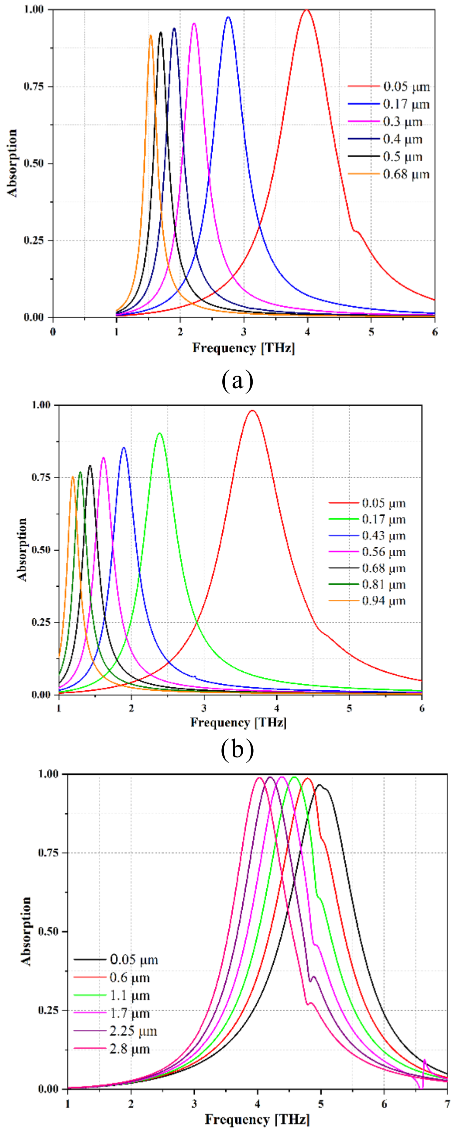
Fig. 5. Absorption response of different H1N1, H5N2 and H9N2 virus.

Therefore, the frequency shift peak can be used to detect the virus and quantify virus concentration. Apart from the frequency peak shift, the amplitude of the peak also varies when the virus strain dimensions are changes. This mechanism is the basic sensing principle; the amplitude of the peak is not used as the main parameter in the sensing application.

Table 1. Optical properties of three different strains of Influenza A for specific protein concentration:

Strain	**Protein concentration (mg/ml)**	**Refractive Index (A n + B j K)**	
		A	B
H1N1	0.54	1	1.4
H5N2	0.2	1	1
H9N2	0.28	1.2	1.4

The proposed sensitivity analysis method is based on graphical representation of peak frequency shift in terms of virus thickness layer. The presented absorber having single resonant peaks at 5 THz, which is used to determine the sensor behavior which enables the best use of the sensor for specific medical application.

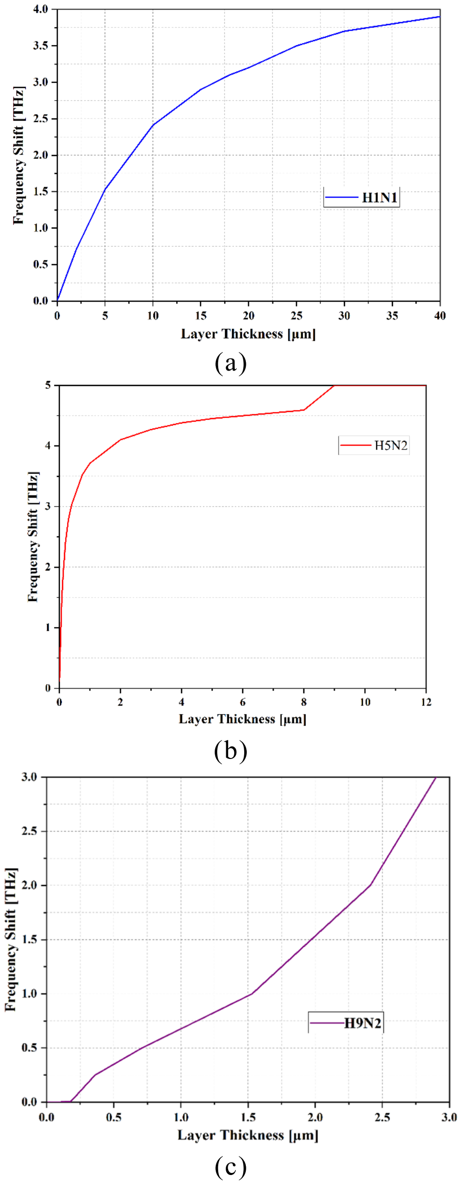


(c)

Fig. 6. Absorption response for resonant peak of the sensor with different virus layer thickness (a) for H5N2 (b) H9N2 and (c) H1N1.

The parametric analysis for three-virus strain are analyzed for different virus thickness layer as shown in Fig. 6. The figure reveals that for all the cases as the thickness of the virus layer increases resonant peaks are moving at lower side. As the thickness increases much more, resonant peaks completely disappear therefore the maximum thickness for which the resonant peaks are alive has a measurable absorption. Apart from the maximum thickness of the virus layer the minimum thickness can also bound. The no frequency shift corresponds to the case of sensor without the virus strain. Therefore the first non-zero virus thickness shifts the resonant peak is defined as the minimum thickness. Another consideration for the determination of the minimum thickness is the size of the particles in the sample. The average size of the IAV particles are defined as $0.1\,\mu m$ [21]. This sensitivity is differs from the commonly used sensitivity parameter i.e. $\Delta f/\Delta n$, where Δf is shift of resonant frequency per changes of the refractive index [22]. The general sensitivity of the sensor can be calculated [23]:

$$\text{Sensitivity} = \Delta f_{total}/(d_{maximum} - d_{minimum}) \qquad (6)$$



(a)

(b)

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Fig. 7. Detection curves for H1N1, H5N2 and H9N2.

Where Δf_{total}= difference between the frequency shift between $d_{maximum}$ and $d_{minimum}$. The detection curve for H1N1, H5N2 and H9N2 for different layer thickness is show in Fig. 7. The general sensitivity is represented by the linearized between $d_{maximum}$ and $d_{minimum}$. The sensitivity of the sensor is decreased, as the layer thickness is increases. At larger thickness the absorption peaks are below 50 %. The sensitivity of different virus strain are tabulated in Table 2.

Table 2. Numerical representation of sensitivity for H1N1, H5N2 and H9N2:

Virus Subtype	**H1N1**	**H5N2**	**H9N2**
$d_{minimum}$ (μm)	0.05	0.05	0.001
$d_{maximum}$ (μm)	40	8	2
$d_{minimum}$ - $d_{maximum}$ (μm)	39.95	7.95	1.99
Sensitivity [THz/nm]	99.1	562.2	2197.5

3. CONCLUSION

This paper presents, a method for sensitivity analysis using THz metamaterial absorbers for detection of possible H1N1, H5N2 and H9N2 virus strain. The square shape split ring metamaterial resonator has been designed on VO_2 (Vanadium Dioxide) and structure shows resonant peak at around 5 THz. The sensitivity of the proposed sensor is 99.12/ 562.26/ 2197.53 (THz/nm) which makes a potential candidate for the application in THz sensing. Apart from theses, proposed model is useful for detection of small concentration of other virus also. This analysis suggest that proposed method of sensing can be included into the medical diagnosis. The future work of the proposed analysis is towards the fabrication and experimental validation.

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