Investigation of the Negative Effect of the Surrounding Dielectric on the Antenna on the Spectral Response of the THz Antenna Detector

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ABSTRACT— **In this paper, the frequency response of a detector antenna is investigated when a layer of dielectric is placed on it. For this purpose, the surface wave theory has been used to explain the propagation of the current pulses in the antenna electrodes. Examinations are also performed of the propagation spectra of two types of terahertz antennas, bow-tie and dipole (with LT-GaAs substrates), on which the dielectrics of gallium arsenide and silica are located. These antennas are simulated through the CST software (FDTD method). The simulations show that the presence of a surrounding dielectric on the surface of an antenna affects the velocity of the current pulse propagation on the electrodes. It is also shown that the change in the thickness and position of the surrounding dielectric have a negative effect on quality of detector antenna by shift its spectral response to lower frequencies.**

KEYWORDS: CST software, Detector antenna, Plasmonic, Surface wave, Surrounding dielectric, Terahertz radiation.

I. INTRODUCTION

The frequency region of an electromagnetic spectrum between microwave and infrared frequencies is called the terahertz band, which typically refers to the frequency range from 0.1 to 10 terahertz. Due to the rotational levels of many molecules in the terahertz range, absorption spectroscopy in this region provides unique information about the structure and chemical composition of molecules. Terahertz waves are of wide applications, and their generators and detectors have been studied vastly from the perspectives of theories, modelling as well as modern structures [1]-[3]. There are different methods for generating and detecting terahertz radiation. A few of the methods to produce terahertz radiation are the use of photoconductive antennas, optical rectification in non-linear media, oscillation in semi-conductive structures, and quantum cascade lasers [4]. In this regard, photoconductive antennas, first proposed by Aston and Lee [5], are the most commonly used devices to generate and detect terahertz waves. The use of THz antennas is of lower cost and higher sensitivity than the other methods. These antennas usually consist of metal electrodes on low-temperature GaAs layers grown on SI-GaAs substrates, and they are used to generate and detect terahertz radiation [6].

Simple setup, better signal-to-noise ratio, continuous bandwidth and room temperature performance are the best features of terahertz photoconductive antennas. In contrast, low frequency peaks and the low efficiency of converting optics to terahertz are the weaknesses of these antennas; their frequency peak is usually below 1 THz, and the efficiency is less than 0.1%. Many efforts have been made to improve the responses and efficiency of antennas [7], such as numerical studies [8] using large aperture antennas [9] as well as the use of terahertz photoconductive antennas based on nano-structures, graphene and microlenses in antenna gaps [10]-[11]. Of them, microlenses are used in array antennas and fiber-coupled antennas to simplify their setup and enhance their efficiency. It has been observed that the presence of a dielectric layer on an antenna affects the propagation of plasmonic waves on the electrodes and, in turn, the frequency response of the generating antenna [12]-[13].

This study seeks to evaluate the surrounding dielectric effect of detector antennas on their frequency responses. This is specified as a negative effect on quality of a terahertz antenna. For this purpose, two detector antennas, bow-tie and dipole, are used, and simulations are performed on them to determine how the material and thickness of the dielectric affects the frequency response of the detector antenna.

II. THEORETICAL BASIS

When a femtosecond laser pulse is radiated at the antenna gap, electron-hole pairs are generated. If a DC voltage biases the electrodes, the generated photoelectrons are accelerated and a current pulse is propagated across the gap between the electrodes. Changes of the electric current in terahertz biased antennas induce electromagnetic radiation in the terahertz range (i.e., in emitters) [8]-[9].

The approximate frequency of the terahertz radiation produced in generating antennas is calculated by the following equation [14]:

$$\upsilon_r = \frac{c}{2l_e\sqrt{\varepsilon_e}} \quad (1)$$

where c is the speed of light in vacuum, l_e is the effective length of the antenna electrodes, and ε_e is the effective dielectric constant defined as $\varepsilon_e = \frac{1+\varepsilon_d}{2}$. This equation shows that, as the effective length of an antenna and the surrounding dielectric constant (ε_d) on it increase, the antenna frequency response peak tends to lower frequencies. This effect is expected to be seen on detector antenna as well. In a terahertz detector antenna where there is no external bias voltage, a simultaneously illuminated THz field accelerates the photoelectrons generated by the femtosecond optical pulse in the gap and creates a current that is proportional to the magnitude of the coupled terahertz field in the antenna [15]. The current density in the detector antenna is obtained based on the convolution of the optical time pulse pattern and the semiconductor properties. It is expressed by the following equation [15]:

$$j(t;\Delta t) = P_{opt}(t)\otimes\left\{\exp\left(\frac{-t}{\tau_{rec}}\right)qv(t;\Delta t)\right\} \quad (2)$$

where Δt is the time delay between the terahertz pulse and the optical pulse, P_{opt} is the optical pulse power, τ_{rec} is the recombination time of the carriers, and v is the average velocity of the carriers in the gap semiconductor [4]-[9]. The generated current pulse propagates through the electrodes as a surface plasmonic wave. The amplitude and the propagation velocity of this pulse depend on the shape and the material of the electrodes. An analysis of the surface plasmon can help to predict the specifications of the THz antenna, emitter and detector [12]. Thus, in this study, at first, the surface wave field propagation is analyzed at the boundary of two semi-infinite media, in which the lower surface is a metal electrode and the upper dielectric medium is often air (Fig. 1) [16]. Then, to more accurately investigate the frequency response of the detector antenna, a three-layer structure is explored. In this structure, a thin layer of metal is placed between two dielectrics, one as a substrate and the other as a surrounding dielectric (Fig. 2).

Fig. 1. Geometry of a metal-dielectric junction for the movement of surface plasmon polaritons. ($\varepsilon_1 = -877 + 610i$ and $\varepsilon_2 = 1$)

According to Fig. 1, to investigate the propagation of terahertz waves in the electrodes, it is assumed that the terahertz pulse is propagated as an electromagnetic wave with frequency ω in the **-x** direction to the boundary of the two media. This wave is eventually propagated as plasmonic waves at the separation boundary of the two media in the **z** direction. Maxwell equations can be used to find the longitudinal and transverse components of the field. In this structure, the surface waves are divided into TE and TM polarizations. Since there are surface plasmon polaritons for the TM mode, investigations are performed on this mode. Once the wave equation is solved and continuity is applied to the electric and magnetic fields at the boundaries, the following relations are achieved [17]:

$$\frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1} \tag{3}$$

$$k_i^2 = \beta^2 - k_0^2\varepsilon_i \tag{4}$$

where k_i $(k_i \equiv k_{xi}, i = 1, 2)$ is the wave vector component perpendicular to the separation boundary of the two media and β is the propagation constant. The value $\frac{1}{k_x}$ is defined as the length of the skin field perpendicular to the boundary of the two media. As a result, the dispersion relation for the surface plasmon polaritons propagated at the boundary of the two media is as follows, where β is obtained with the values of k_0, ε_1 and ε_2 for the metal and the air media:

$$\beta = k_0\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_2+\varepsilon_1}} \tag{5}$$

For a more accurate analysis of the detector antenna, the dielectric-metal-dielectric structure, which is the actual structure of the antenna, must be examined (Fig. 2). In this structure, a metal layer (electrode) is located between two dielectric layers.

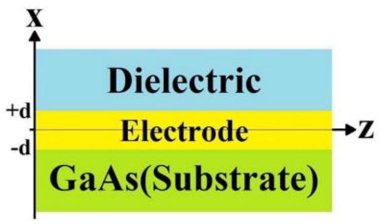


Fig. 2. Geometry of the electrode location between two dielectric layers in a multilayer structure. The thickness of the substrate is 200 μm, the thickness of the electrod is 100 nm and the thickness of the dielectric is variable.

Due to the thinness of the metal and the influence of the electric fields propagated on its surfaces, the equations for the terahertz wave propagation are expressed at the junction of the metal and the surrounding dielectric. By these equations, the dependence of the antenna frequency response on the surrounding dielectric can be investigated. In this regard, the terahertz wave penetration into the dielectric layer is also taken into account. The electric current of the wave propagation on the detector antenna electrodes, $J(r,t)$, and the electric field polarized in the z direction are calculated as follows [17]-[18]:

$$J(r,t) = E_z(x)e^{i(\omega t-\gamma_i z)} \tag{6}$$

$$E_z = \begin{cases} Ae^{-k_3(x-d)} & for\ x > d \\ Be^{k_1(x-d)} + Ce^{-k_1(x+d)} & for\ |x| < d \\ Fe^{k_2(x+d)} & for\ x < -d \end{cases} \tag{7}$$

where ω is the wave frequency and γ is the wave propagation constant. Coefficients A, B, C and F are determined with regard to the boundary conditions. In Eq. (7), k_i is defined as follows:

$$k_i = \pm\sqrt{\gamma^2 - \omega^2\mu_i\varepsilon_i} \tag{8}$$

After k_i, is calculated, the relation of γ and ω can be obtained through the following equation [17]:

$$e^{-4k_1d} = \frac{k_1/\varepsilon_1 + k_2/\varepsilon_2}{k_1/\varepsilon_1 - k_2/\varepsilon_2}\frac{k_1/\varepsilon_1 + k_3/\varepsilon_3}{k_1/\varepsilon_1 - k_3/\varepsilon_3} \tag{9}$$

In this equation, ε_1, ε_2 and ε_3 are the electrical permittivity of the metal layer, substrate and surrounding dielectric, respectively. The equations above suggest that γ and, consequently, the wave propagation velocity are a function of metal thickness (d), the substrate and the surrounding dielectric constants (ε_2, ε_3). Based on this factor, the penetration of an electric field into each of the dielectrics is affected by the constant of that dielectric. The depth of the penetration of the surface waves into the surrounding dielectric $\left(\frac{1}{k_3}\right)$ can play a decisive role in how the surrounding dielectric thickness affects the frequency response of the detector antenna. The analytical solution of this equation is very difficult to obtain k_i and γ. Therefore, Eq. (9) is approximated to get a simple and close answer.

After the solving Eq. (9), γ will have two values for even and odd modes (i.e., symmetric and antisymmetric modes) [19]. Since the loss of the symmetric mode is less during the surface wave propagation, the study of this mode is more important [18]-[19]. For this mode, the penetration depth of the surface wave (in case the dielectrics on the two sides of the electrode are the same) is calculated according to the following equation [19]:

$$\frac{1}{k_3} = \sqrt{\frac{\varepsilon^2 d^2}{{\varepsilon_d}^2}} \tag{10}$$

where *d* is the thickness of the metal thin layer, ε is the metal permittivity coefficient, and ε_d is the dielectric permittivity. Once the values of ε and *d* for the thin gold layer and ε_d for the dielectric are placed in Eq. (10), the depth of the penetration of the surface wave into the dielectric is obtained. The penetration depth denotes the thickness of the surrounding dielectric layer. If the dielectric thickness is greater than the penetration depth, the effect an increase in that thickness is reduced on the spectral properties of the antenna.

As Eq. (9) suggests, it is a complex task to solve surface wave problems and to investigate the frequency behavior of multilayer detector antennas with antisymmetric dielectrics on both sides of the metal layers. Indeed, there is no explicit analytical answer in this regard. Therefore, in the present study, for antisymmetric dielectrics on the sides of the electrodes in detector antennas, the surface wave propagation is investigated by numerical methods (approximation in Eq. (9)) and simulation through the CST software.

III. RESULTS AND DISCUSSION

Using the CST software, a terahertz pulse was produced and radiated as a planned wave to an antenna to investigate its response. This THz pulse had the frequency range of 0.1 to 5 terahertz and the frequency peak of 2.74 terahertz. The study of the detector antenna was conducted by the designing of a bow-tie antenna with a multilayer structure and a dipole antenna with 100-nm-thick gold electrodes on a gallium arsenide substrate. These antennas were designed and simulated in two sizes, small and large. The structure of this antenna was specified in a three-dimensional space. Since the propagation of the wave at the boundaries causes reflection from their surface, to eliminate these effects of wave reflection, the boundary conditions were considered as “open add space”. Figure 3 shows the designed bow-tie antenna with its parameters for small and large sizes.

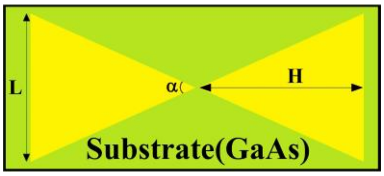


Fig. 3. Designed bow-tie detector antenna with a 2μm gap between the electrodes: small antenna (L=14μm, α=38˚, H=20μm) and large antenna (L=20μm, α=36˚, H=30μm)

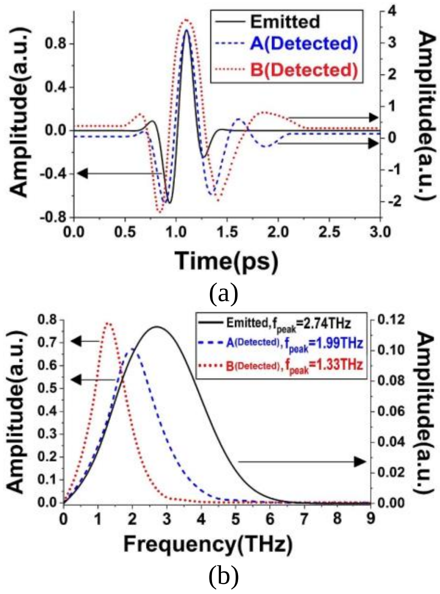


Fig. 4. The time response (a) and the frequency response (b) of the emitted (solid line) and the detected (dash line) terahertz pulses for small (A) and large (B) bow-tie antennas.

In the first stage, the accuracy of the numerical calculations was checked. To do this, the numerical results were compared with the analytical results. For validation, the terahertz pulse generated by the CST software was propagated onto the bow-tie antenna with two different sizes without a surrounding layer. As shown in Fig. 4 and as it was expected, due to the better sensitivity of bow-tie antennas at lower frequencies, the peak of the detected signal shifted to lower frequencies, and the time pattern of the detected pulse was wider. As already known, if the dimensions of an antenna become larger, the sensitivity peak move to lower frequencies, which is also evident in the comparison of the propagation spectra of the two antennas [19].

In the second stage of validating the numerical results, the effect of the upper electrode thickness on the antenna frequency response was investigated. For this purpose, a layer of dielectric with variable thickness was placed on the upper surface of the antenna.

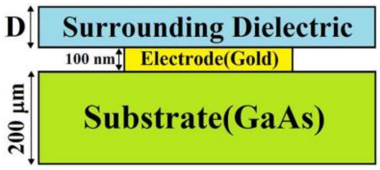
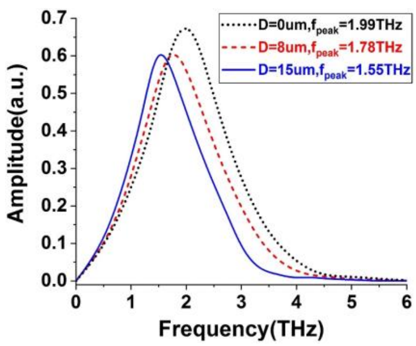


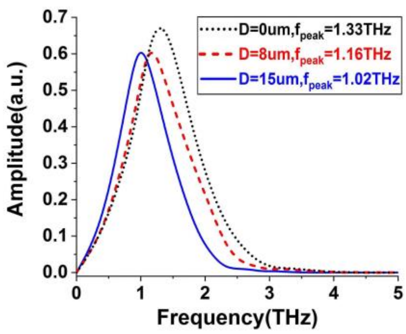
Fig. 5. Placement of the surrounding dielectric layer on the surface of the detector antenna. The surrounding dielectric layer was selected from GaAs and Silica with a thickness ranging, D, from 0 to 36 μm.

Equation (10) was used to calculate the depth of the penetration of the surface wave field into the dielectric in a symmetrically structured antenna. In addition, the CST software served to evaluate how a change in the dielectric layer thickness would affect the antenna behavior. As predicted, the thicker the surrounding dielectric for wave penetration in it, the weaker the effect of the dielectric on the frequency response of the antenna and the displacement of the frequency peak of the detected spectrum. In fact, according to Eq. (8), the presence of this surrounding dielectric layer increases the number of the propagating waves in the z direction and decreases the wave velocity in that direction; the effective length of the antenna finally increases, and the its resonance frequency changes [17]-[19].

To investigate the effect of the dielectric layer thickness on the frequency peak displacement, the depth of the field penetration into the dielectric was calculated. Eq. (10) was used to study an antenna with a symmetrical structure (Fig. 3), dielectric surrounding of gallium arsenide ($\varepsilon_{GaAs} = 12.9$), gold electrodes ($\varepsilon_{gold} = -877 + 610i$) and thickness of 100nm at the frequency of 2.3 terahertz [20]-[21]. In this case, the depth of the penetration of the surface wave into the dielectric layer was $\frac{\lambda}{19}$ or about $7\mu m$. This value did not make much difference for longer and shorter wavelengths [21]. As this experiment indicated, at thicknesses about twice the tested value or more, the amplitude of the field, which decreased exponentially in the dielectric at a distance from the electrode, would be close to zero. As a result, increasing the dielectric thickness more than that value would have no effect on the spectral peak displacement and the antenna response.



(a)



(b)

Fig. 6. Spectra of (a) a small and (b) a large bow-tie detector antenna affected by the changes in the thickness of the surrounding GaAs dielectric on it: There are three frequency response peaks for the antennas.

Figure 6 shows the results of the simulation performed with the CST software for large and small bow-tie antennas. As it can be seen, the spectral peak of these antennas reduced when the thickness of the gallium arsenide dielectric layer was increased. Also, due to the dielectric layer on the surface of the antennas, some of the incident wave was reflected and did not reach the electrodes. It is concluded that an antenna with a surrounding dielectric has a lower signal amplitude than that without a surrounding dielectric (D=0μm).

The figure also shows that, when the thickness of the gallium arsenide dielectric surrounding the small bow-tie antenna was increased from 0 to 15μm, the frequency response peak of the antenna decreased from 1.99 to 1.55 terahertz. Similarly, for the large bow-tie antenna, as the thickness of the gallium arsenide surrounding dielectric was increased from 0 to 15μm, the frequency response peak of the antenna decreases from 1.33 to 1.02 terahertz. An increase of more than 15μm in the dielectric thickness of the small bow-tie antenna had no effect on the velocity of the surface wave propagation across the antenna and, therefore, did not change the frequency peak (Fig. 7).

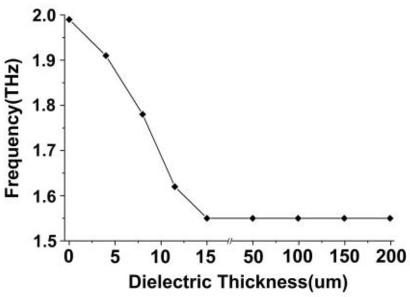


Fig. 7. Variations of the frequency response peaks based on the changes in the GaAs surrounding dielectric thickness for small bow-tie detector antenna

Through the comparison of the results of simulating an antenna with symmetric dielectrics with the expected analytical results, it was found that the simulation method provided valid results. Then, an antenna with a silica surrounding dielectric was simulated. In fact, the dielectric that may be present on an electrode is usually silica, and gallium arsenide is not used for surrounding. The previous antenna simulation was done only to compare the results of simulation with those of the analytical calculations and validation. Therefore, an investigation was performed to check the effect of a surrounding dielectric, such as micro lenses or fibers connected to terahertz antennas, on the detection spectrum. The antenna was the same as that in the previous section, i.e., a bow-tie antenna in two sizes, small and large, which consisted of a substrate of gallium arsenide, thin metal electrodes and a dielectric layer of silica surrounding the electrodes. The dielectric coefficient of silica in the terahertz region is 3.8 ($\varepsilon_{silica} = 3.8$), which is a value between the dielectric coefficient of air and that of gallium arsenide [22]. Although the structure of the antenna was antisymmetric with respect to the dielectrics used, the modes of the waves propagated at the electrodes were considered to be symmetric due to the lower dissipation as before. With regard to the equations of the symmetric modes for the multilayer structures described in the theory section, it is concluded that the penetration depth of the surface wave with the placement of silica is greater than the penetration depth of gallium arsenide but less than that of air.

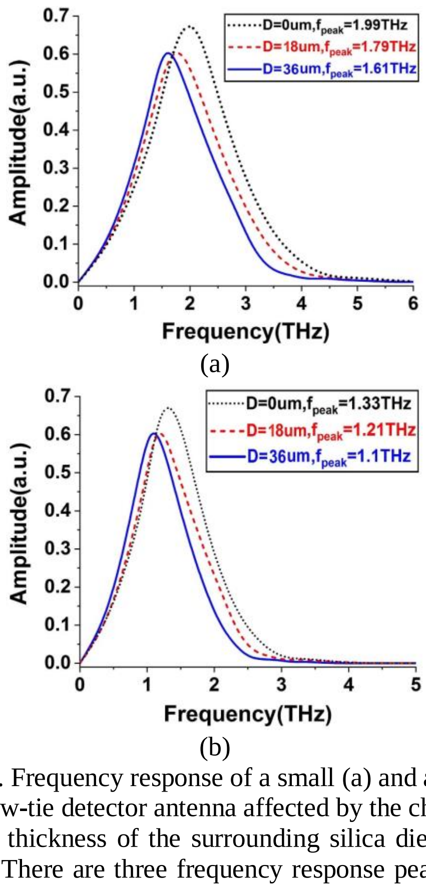


Fig. 8. Frequency response of a small (a) and a large (b) bow-tie detector antenna affected by the changes in the thickness of the surrounding silica dielectric on it: There are three frequency response peaks for this antenna.

The results of this part of the simulation also showed that, when a silica surrounding layer is placed on an antenna, not only is the penetration depth higher than that of the gallium arsenide surrounding layer, but also the frequency response of the antenna decreases less due to the change in the surface wave velocity. As the thickness of the silica on the small bow-tie antenna increased from 0 to 36μm, the frequency response peak of the detector antenna changed from 1.99 to 1.61 terahertz. Also, for the large bow-tie antenna, when the thickness of the silica surrounding layer was increased from 0 to 36μm, the peak of the frequency response of the antenna decreased from 1.33 to 1.1 terahertz (Fig. 8).

In the antenna with silica surrounding dielectric, due to its lower dielectric coefficient than gallium arsenide, it was predicted that the penetration depth would increase. Also, increasing the dielectric thickness to values greater than 15μm affected the peak frequency response. As the simulation of the antenna frequency response showed, if the silica thickness changed in the range of 0 to 36 microns, the antenna frequency response peak would shift to a lower frequency due to the reduction in the velocity of the surface wave propagation on the electrodes. However, at thicknesses higher than 36 micrometers, increasing the thickness did not affect the peak of the frequency response (Fig. 9).

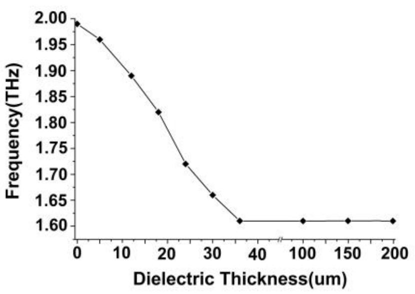


Fig. 9. Variations of the frequency response peaks based on the changes in the thickness of the silica surrounding dielectric for small bow-tie detector antenna.

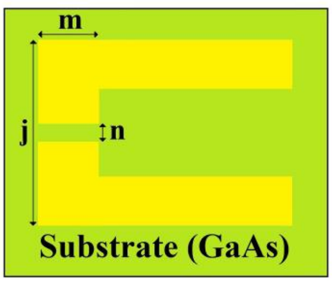
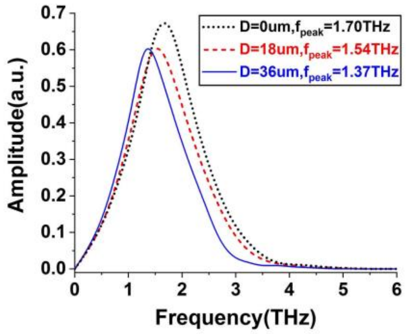


Fig. 10. Designed dipole antenna detector small antenna: m=18μm, n=3μm, j=51μm and large antenna: m=27μm, n=3μm, j=77μm.

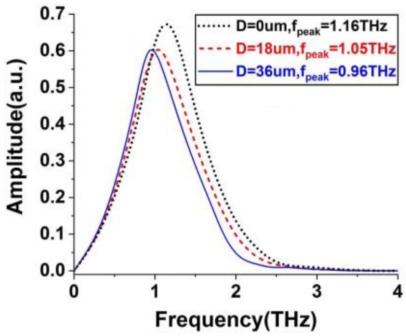
To complete this study, a dipole antenna with two different sizes was simulated. It was found that these antennas had similar behavior in the presence of a surrounding dielectric (Fig. 10 and Fig. 11).

At First, a pulse generated by the CST software was radiated to these antennas when there was no dielectric surrounding layer. The pulse had a frequency peak of 2.74 terahertz in the spectrum range of 0.1 to 5 terahertz. Then, the time and the frequency pattern detected by the antennas were recorded. Based on the simulation results, the frequency peak detected by the small dipole antenna was 1.7 terahertz and that by the large dipole antenna was 1.16 terahertz. These results were also predictable based on Eq. (1). Since the effective length of a small dipole antenna is larger than that of a small bow-tie antenna, the frequency response peak must be less. The same is true of large dipole and large bow-tie antennas. The antennas were then coated with various thicknesses of silica dielectric, the same pulse was propagated on the antennas at a frequency peak of 2.74 terahertz, and the frequency responses of the antennas were investigated. According to Eq. (1), due to the longer effective length of the large dipole antenna, its frequency response peak was lower. These results are illustrated in Fig. 11. As the figure suggests, the frequency response peak of the small dipole antenna decreased from 1.7 to 1.37 terahertz when the thickness of the silica surrounding layer was increased from 0 to 36μm. Similarly, for the large dipole antenna, the frequency response peak decreased from 1.16 to 0.96 terahertz when the thickness of the silica was increased from 0 to 36μm.

As a result, according to the simulations performed for the two types of antennas with different sizes and two different types of surrounding dielectric, an increase in the surrounding dielectric thickness on the antennas would reduce their frequency response peaks.

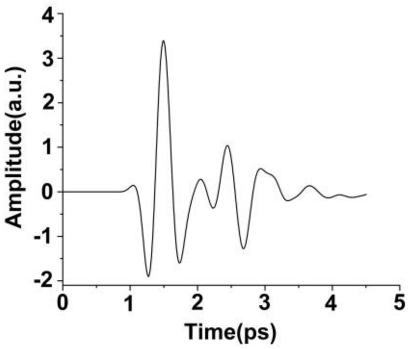


(a)

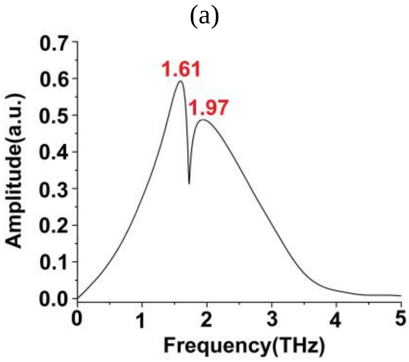


(b)

Fig. 11. Spectra of (a) a small and (b) a large dipole detector antenna affected by the changes in the thickness of the surrounding silica dielectric: There are three frequency response peaks for this antenna.



(a)



(b)

Fig. 12. Appearance of a new peak in the output signal: time signal detected (a) and frequency signal detected (b) in the small bow-tie antenna due to the resonance echo effect when the dielectric (silica) thickness is 39μm.

The surrounding dielectric layer not only affected the surface wave propagation velocity but also caused the pulse to travel round trip between the electrode and the dielectric and air. According to Eq. (11), if the thickness of this layer is such that the resonance wavelength is within the spectral detection range of the antenna (i.e., less than 100μm) [23], the spectral response curve of the detector is greatly affected. This causes the atypical appearance of two peaks in the spectral response curve.

$$D = \frac{\lambda}{2n} \tag{11}$$

where D and n are the thickness and the refractive index of the dielectric layer, respectively.

As shown in Fig. 12, when the thickness of the dielectric surrounding the small bow-tie antenna was increased up to 39μm, in addition to the main frequency peak, another peak with a frequency of 1.97 terahertz was observed in the frequency curve of the antenna. The appearance of this peak was justified given the values of $n_{Silica} = 1.95$ and D=39μm for silica. This also happens as the terahertz pulse moves round trip at the substrate of a detector antenna [23]. The thickness of the gallium arsenide substrate is high, the duration of the round trip of the pulse is increased and the echo effect on the detector response can be eliminated by the removal of the return pulse from the time data. This can be done when the dielectric thickness is greater than 100μm or when the reflection effect is removed from the gallium arsenide substrate.

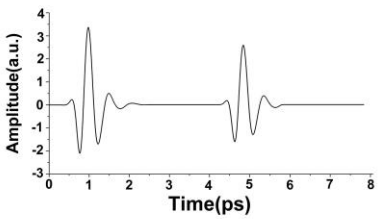


Fig. 13. A round trip detected pulse propagated through a 200μm GaAs substrate.

IV. CONCLUSION

In this study, the thickness the dielectric surrounding a terahertz detector antenna was changed to check its effect on the frequency response of the antenna. In this research, antennas with bow-tie and dipole structure were studied by CST software, in which a layer of dielectric was placed as a cover layer on these antennas. Then, a layer of dielectric (gallium arsenide and silica) was placed on these antennas to serve as a surrounding layer. To investigate the effect of the surrounding dielectric layer on the frequency response of the antennas, a pulse in the frequency range of 0.1 to 5 terahertz was generated by the CST software and radiated to the antennas. The waves that the pulse created on the surface of the antenna electrodes penetrated into the surrounding dielectrics. It was found that the amount of this penetration depends on the thickness and material of the surrounding dielectric. As a result, by changing the thickness and material of the surrounding dielectric, the pulse propagation velocity of terahertz current in the electrodes and finally the frequency response of the antenna changed. According to the simulation results, when gallium arsenide or silica dielectric is used as a surrounding layer on an antenna, an increase in the thickness of this layer leads to the shift of the antenna frequency response peak to lower frequencies. As the thickness of this dielectric layer increases, the resonant effects of the echo may cause unusual behavior in the antenna frequency response curve. The results of this study showed that the use of dielectric layers, which are usually applied as microlenses on some terahertz antennas, reduces the responsibility in higher frequency and cause a negative effects on the spectral response of terahertz detector antennas. To reduce these negative effects, materials that have both a lower dielectric coefficient and a lower thickness can be used.

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