Design of a Photoconductive Antenna for Pulsed-Terahertz Spectroscopy with Polarization Diversity

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Abstract— **In the present paper, a photoconductive antenna is designed to work as both pulse-terahertz emitter and receiver. The proposed two-port antenna benefits from polarization diversity with high sensitivity of polarization detection. The antenna electrodes consist of three arms and two gaps that can be excited by laser illumination. An 800 nm wavelength laser beam with output power of 80 mW, 100 MHz repetition rate, and 100 fs laser pulse duration is considered as optical excitation. Each port stimulates a pulse that its polarization is orthogonal to that of the other one according to their arrangement. Along with GaAs as photoconductive substrate beneath the antenna electrodes, an anti-reflection coating of Taconic RF-35 is used for depreciating unwanted terahertz echoes. The simulated results clarify that the proposed antenna shows polarization diversity and also, proper broadband behavior.**

Keywords—photoconductive antenna; pulsed terahertz; spectroscopy; polarization diversity;

I. Introduction

Terahertz frequency band includes the region between microwave and infrared frequency which have been the topic of a number of researches in recent decades due to some specific characteristics of this part of spectrum: lower photon energy made it safer than infrared and lower wavelength can cause higher resolution than microwave [1]. On the other hand, some molecules have their inter- and intra-vibrational movements in the terahertz region, such characteristic is known as their spectral fingerprint [2]. On the other hand, there have been challenges and limitations with terahertz technology, i.e. sources, detectors and terahertz wave generation [3, 4]. One of the most desired and efficient techniques for terahertz generation and detection is photoconductive technology in which terahertz pulses can be generated using femtosecond laser excitation [5].

In recent decade, many applications in medicine, security, chemistry and NDT (Nondestructive Testing) have emerged for terahertz imaging and spectroscopy [2, 6, 7]. Due to the nature of Terahertz radiation, terahertz waves can propagate more easily in some biological tissues with lower scattering [1]. This is because of higher sensitivity of terahertz wave to some molecules such as water molecules which turned the light on for spectroscopy applications. There are several spectroscopy and imaging techniques relying on reflectance and transmission mode of terahertz waves [8]. Terahertz time-domain spectroscopy (TDS) is one of the spectroscopy techniques that uses transient electric field to obtaining optical and electrical properties of a sample. A great dominancy of this technique is that one can measure the amplitude and phase of pulse in broadband manner not only the intensity of the wave and consequently much more information from the measured electric field.

In THz TDS ellipsometry, the goal is to analyze polarization behavior of a target. Hence, the emitter should be able to emit and detect two orthogonal polarization component [9, 10, 11]. For these purposes, polarization sensitivity in a terahertz source and detector is of great interest. Such antenna can be used for time-domain spectroscopy, particularly for materials which have different reactions in front of electromagnetic waves with different polarizations such as birefringence materials. In fact, some optical materials have the property of being birefringence that can cause their refractive index depends on the polarization of electromagnetic wave passing through [12]. The ability of discriminating between different polarizations in spectroscopy techniques makes it possible to measure different polarization at the same time without any antenna rotation which can cause misalignment. Also, one of the main advantages of such terahertz antennas can be seen in circular dichroism [13]. This phenomena can cause different amount of absorption of light according to their left- or right-handed circular polarization. Vibrational Circular Dichroism (VCD) is one of the spectroscopy techniques that consider the attenuation of circularly polarized light when passing a sample around infrared and terahertz frequencies [9]. It is worth mentioning that, many vibrational and intermolecular dynamics of water molecules are in the terahertz region of spectrum [14, 15].

Diversity technique has long been used in microwave systems to enhance the performance of link, especially in terms of channel capacity [16]. However, it is not attracted a considerable attention in THz band till now and is limited to mathematical analysis and discussions [17]. From the antenna points of view, diversity can be categorized in three approaches: spatial, pattern, and polarization diversity. Among these three, the first one is achieved simply by placing a number of antennas close to each other in a way that the corresponding correlation coefficient remains as low as required. But the second and third approaches are not that simple: an antenna with pattern diversity is the one that

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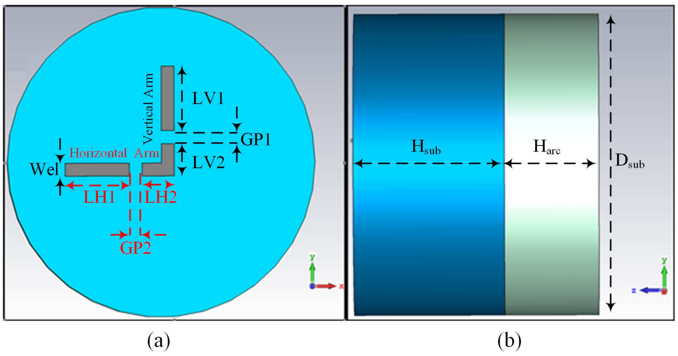

Fig. 1. Proposed photoconductive antenna and its physical parameters (a) front view and (b) side view.

benefits from two (or more) orthogonal radiation patterns to make low-correlated channel links; corresponding to each radiation pattern, a port should be considered in the antenna structure. The thing that is also true when we are talking about polarization diversity; i.e. an antenna with two (or more) orthogonal polarizations.

Considering all discussed terahertz applications that are sensitive to polarization properties of waves, beside the eye-catching advantages of benefiting from the diversity techniques, make the design of terahertz antennas with polarization diversity a valuable field of study which is not payed attention by this time.

The main purpose of this work is to propose a novel design of a photoconductive antenna with polarization diversity for spectroscopy applications. The details about antenna design is presented in Section II while Section III is dedicated to results and discussions. Finally in Section IV, we are going through the conclusion.

II. Antenna Design

The proposed photoconductive antenna consists of a GaAs substrate covered with an L-shaped two-port dipole electrodes as depicted in Fig. 1. A quarter wavelength anti-reflection (AR) coating along with the GaAs layer is applied to depreciate unwanted terahertz echoes. The Au and Taconic RF-35 are chosen as materials for the electrode and AR coating respectively.

The substrate layers have the shape of cylinder and are optimized with 120 µm radius (D_{Sub}= 240 µm) in order to raise directivity and also suppressing unwanted echoes. The GaAs layer has thickness of H_{Sub}=120 µm and also, the anti-reflection coating with $\varepsilon_r = 3.5$ and thickness of H_{arc}= 75 µm, forms a quarter wavelength layer for matching the GaAs-air connection at 1 THz.

As shown in Fig. 1, the antenna has two orthogonal electrodes which are named as Vertical and Horizontal arms. The dimensions of these arms are optimized in a way that meet the best performance at 1 THz (LH_1= LV_1= 50 µm, LH_2= LV_2= 25 µm, and W_{el}= 10µm). The length of excitation gaps are GP_1= GP_2= 10 µm which make the area for optical excitation and can influence directly on laser intensity and consequently on excitation photocurrent [18]. The designed antenna can act in two scenarios as follows;

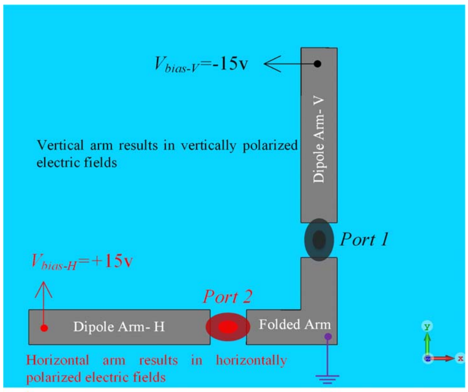

Fig. 2. The elliptical laser illumination is used on each port for delaying screening effect and also biasing arms with reversed voltage for possible two ports excitation as emitter or detector.

- *Scenario I- Polarization Diversity:* According to the orthogonal angle between these two arms, and due to the fact that currents in each arm is generated through the arm's physical direction, it is expected that two orthogonal currents could be generated in the proposed antenna. Under this circumstance, the mentioned currents result in two orthogonally polarized electrical fields which leads to polarization diversity. Corresponding to each arm (and each polarization), there is a gap that the laser could illuminate on. To put it in a more clear presentation, the proposed antenna has two ports, each port is a gap (GP_1 and GP_2 in Fig. 1) that will be illuminated by two separate lasers beams.
- *Scenario II- Dual-Polarized Spectroscopy:* One of the expected working mode for this antenna is spectroscopy mode. As mentioned in the previous section, in some terahertz spectroscopy techniques, it is critical that the emitter or detector can radiate or receive two orthogonal component simultaneously such as afore-mentioned issues that happens in THz ellipsometry and VCD. In this mode, we need to excite (emitting mode) or measure (receiving mode) both of the ports. For this purpose, i.e. working with two ports at the same time, biasing approach is proposed as presented in Fig. 2. Otherwise, this scenario will not be achieved due to reverse current direction in arms relative to each other.

Putting in mind the above mentioned scenarios, an 800 nm wavelength laser beam with output power of 80 mW and 100 MHz repetition rate and 100 fs laser pulse duration is considered as optical excitation. Such laser illumination on the gap can cause generation of photocurrent between the electrode tips which is due to displacement and drift current in semiconductor substrate. To decrease the screening effect in proposed photoconductive antenna, laser beam spot assumed to be elliptical [19] as depicted in Fig. 2.

Using the equivalent circuit of photoconductive antenna, the photocurrent generated in gaps and between the electrodes can be calculated [18] by (1):

$$I_{photocurrent} = \frac{V_{bias}}{Z_{ant} + \dfrac{1}{G_s}} \qquad (1)$$

Where, V_{bias} is the DC voltage between dipole arms and folded arm (Fig. 2), Z_{ant} and G_s are antenna electrode impedance and equivalent conductivity of photoconductive antenna respectively. To avoid the breakdown voltage of substrate and air, the bias voltage is considered V_{bias}= 15 v. It is necessary to bias the horizontal and vertical arms reversely ($V_{bias\text{-}H}$ = -$V_{bias\text{-}V}$ = 15 volts) and the folded arm must be grounded. Otherwise, generated currents from each excitation will attenuate other excited current when both ports are activated. On the other hand, the dipole impedance for each port is obtained Z_{ant}= 40 ohms which is the impedance of antenna electrodes at 1 THz. In addition, the equivalent conductivity of the photoconductive antenna can be calculated using (2) [18]:

$$G_s(t)=\frac{W}{L}e\mu_e L_{\text{intensity}}\exp(-2)(1-R)(1-\exp(\alpha T_{GaAs}))$$
$$\times\frac{\sqrt{2\pi}}{4h\nu_{opt}}\tau_{Laser}\exp\left(-\frac{\tau_{Laser}^2}{8\tau_c^2}-\frac{t}{\tau_c}\right) \tag{2}$$
$$\times\left(\operatorname{erf}\left(\frac{\sqrt{2}t}{\tau_{Laser}}-\frac{\sqrt{2}\tau_{Laser}}{4\tau_c}\right)+1\right)$$

Importing the physical parameters into (1) and (2), the expected photocurrent can be calculated as illustrated in Fig. 3-a. So the photocurrent generated by laser illumination is obtained and used for excitation signal in CST MWS software as excitation current in each defined ports. The photoconductive antenna can emit terahertz pulse in two orthogonal polarization by different excitation ports due to perpendicular angle of dipole's arms. In fact, the proposed terahertz emitter can be excited with two ports according desired polarization. Each port can generate terahertz pulse compliant with the direction of the arm of the dipole.

III. Results and Discussions

The designed antenna can be analyzed for previously-defined scenarios and also for various applications. At the first step, it is necessary to consider the isolation parameter between the ports. One of the challenges in multi-port antennas is to keep the ports isolated from each other. Otherwise, the induction effect of the excited port will generate unwanted induced current on the other port. Such phenomena can excite other polarization components and therefore can cause to decrease the sensitivity of polarization detection of the system. Apart from that, the term "diversity" will be achieved whenever the correlation coefficient between ports remains as low as possible. The higher isolation between ports, the less correlation coefficient between ports. Considering Fig. 2, to calculate this issue, the excited *Port 1* photocurrent (Fig. 3-b) is compared to the induced current at *Port 2* (Fig. 3-c). As shown in this figure, current's amplitude at *Port 1* is larger than the unwanted induced current at *Port 2* for more than 12 times. This difference has great positive impact on the polarization sensitivity and also the correlation coefficient between ports of the antenna. Fig. 4 shows the 3D radiation pattern of the designed antenna at 1 THz for both ports (antenna gain is 9.4 dBi). As it is clear from this figure, the antenna radiation pattern for both ports is to highly resemble each other which is a direct consequence of cylindrical shape of substrate. This

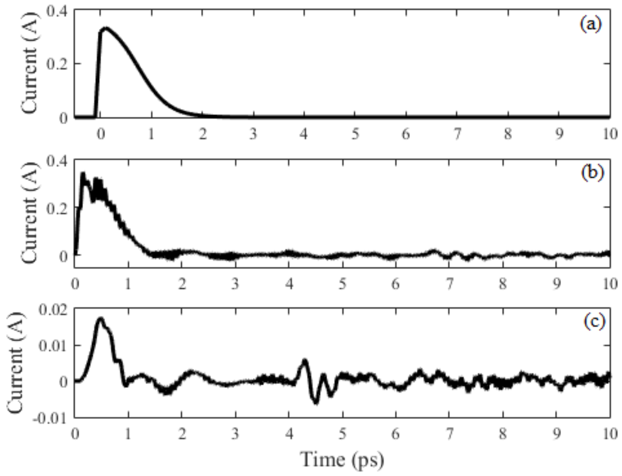

Fig. 3. Photocurrent generated by laser illumination. (a) Expected photocurrent calculated by equivalent circuit. (b) Photocurrent modeled and simulated in CST- MWS as excitation current for *Port 1*. (c) Unwanted current induced in *Port 2*.

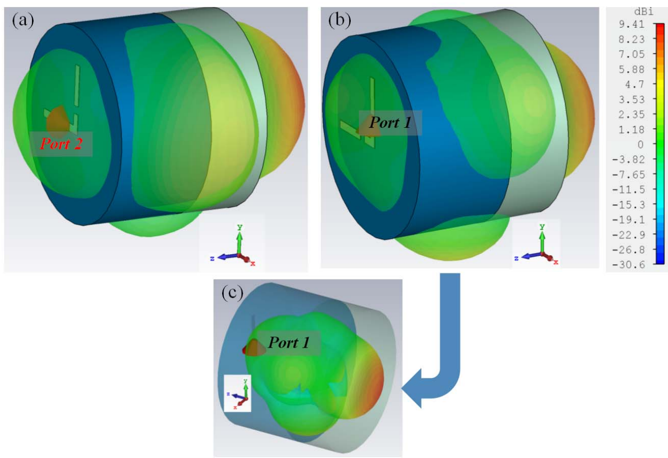

Fig. 4. Radiation pattern of photoconductive antenna simulated by CST-MWS at 1 THz which has the same shape and direction for both excitation port.

resemblance provides a unique characteristic for the proposed antenna: generally, pattern diversity and polarization diversity are latched together whenever we are talking about each one. In other word, most of the times, orthogonal currents in an arbitrary antenna result in orthogonal polarizations and also orthogonal radiation patterns. Under this circumstance, the provided diversity is called pattern diversity [20] and polarization orthogonality is considered as usual consequence of currents direction. However, the proposed antenna benefits from almost same radiation pattern for two orthogonal polarizations, the thing that makes a pure polarization diversity.

From the perspective of *Scenario I*, the terahertz pulse generated from the antenna must be measured in the time domain for two orthogonal polarization. A probe in the farfield of emitter is used for calculating the electric field of pulse in vertical and horizontal polarization. Consider *Port 2* as the excited port by laser illumination. So it is expected that the antenna will have a stronger component through horizontal polarization than vertical one. In Fig. 5, the horizontal (E_x) and vertical (E_y) components of the generated electric field pulse

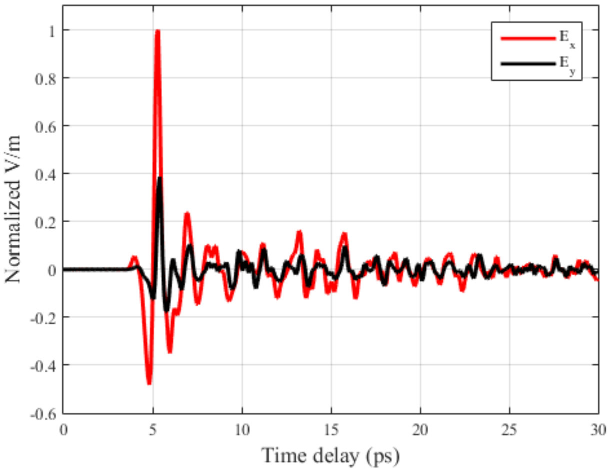

Fig. 5. Comparison of vertical (E_y) and horizontal (E_x) components of the time-domain electric field. The stronger pulse corresponds to the excited port and the weaker pulse shows the orthogonal component of electric field.

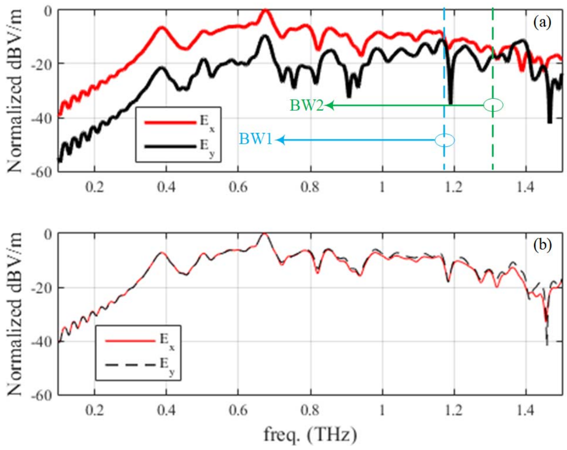

Fig 6. (a) Comparison of Fourier transform of vertical and horizontal polarization component of THz pulse generated in range between 0.1-1.5 THz whenever the *Port 2* is excited, (b) whenever both ports are excited simultaneously.

can be seen. The stronger pulse component corresponds to the excited port (here is the x-polarized) and the weaker one is for the orthogonal component (here is the y-polarized) of electric field. As it is clear from this figure, maximum amplitude of E_x is about 2.5 times (7.95 dB) larger than that of E_y. This difference between these two orthogonal fields could make the diversity in polarization for the proposed antenna. It is also worth mentioning that the E_x and E_y difference versus frequency is presented in Fig. 6- a. According to this figure, from the beginning of THz band, i.e. 0.1 THz, the magnitude of E_x is always higher than that of E_y up to the frequency of 1.17 THz – this interval is defined as *Bandwidth 1* (BW1) – and is higher or equal than that of E_y up to 1.31 THz, i.e. *Bandwidth 2* (BW2).

The above mentioned conditions is also true whenever the *Port 1* is excited.

In *Scenario II*, due to ultrafast picosecond THz pulse, it is possible to use such antenna in time-domain terahertz spectroscopy (TDS). As we know, TDS is very sensitive and powerful tool around 1 THz (particularly below 4 THz for some biomedical applications) because of molecular dynamics of some materials that have vibrational and translational molecular movements in this part of spectrum [21, 22]. So the picosecond output pulses can satisfy this in frequency domain. Analyzing the Fourier transform of time-domain pulses (Fig. 6) can reveal valuable information by pulsed-terahertz TDS. According to Fig. 6, the BW1 or BW2 are broadband enough for THz time-domain spectroscopy.

The scenario can be furthur elaborated by looking at the antenna while two ports are excited simultaneously. As previously mentioned, in some applications, particularly spectroscopy applications, using two polarizations can reveals more information about a sample. In such condition, one needs to measure two transiet electric fields passing through the sample at the same time. To identify this feature, the corresponding electric field, arising from exciting of both ports simultaneously, is reported in Fig. 6- b. According to this figure, the proposed antenna has good functionality in this regard. Therefore, the antenna can be used as emitter or detector whether both ports are stimulated as terahertz pulse source or measured as terahertz detector.

IV. Conclusion

A photoconductive antenna is proposed that has prominent features for working in terahertz regime. One of the main advantages of the proposed photoconductive antenna is its proper polarization diversity which enables the antenna to transmit and receive more information with high sensitivity in two orthogonal polarizations. The diversity is calculated for the antenna for each polarization and the results show great polarization sensitivity. Such characteristics can be very effective and necessary for polarization sensitive applications such as ellipsometry and vibrational circular spectroscopy. Apart from that, some materials such as birefringence has different responds in interaction with different polarizations. Therefore, the designed antenna can effectively be useful in such conditions. In addition to this feature, its broadband behavior makes it a very suitable choice for spectroscopy applications especially, pulsed-terahertz TDS. Spectral lines of different materials spreads in broad part of spectrum, in this way, a terahertz emitter or receiver with broadband characteristics can reveal more information lied in the spectrum.

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