Cross-polarization Response of a Two-contact Photoconductive Terahertz Detector

Yandong Gong *, Hui Dong and Zhining Chen
Institute for Infocomm Research, 1 Fusionopolis Way, # 21-01 Connexis South, Singapore 138632
* Email: gongyd@i2r.a-star.edu.sg

Abstract: The cross-polarization response of a two-contact photoconductive terahertz (THz) detector, is experimentally found in the polarization state measurement of THz radiation in THz time-domain spectroscopy (THz-TDS). It means that this detector responded to a mixture of the two polarization components of THz radiation and such a response is frequency dependent. To evaluate this response quantitatively, three parameters are presented and measured. In the measurement of THz-TDS, such a detector response will result in the distortion of the measured THz spectrum. As a consequence, it will reduce the dynamic range of the system in some frequency bands. In some special cases, it may even lead to a fake "absorption peak" in the THz spectrum. Furthermore, when such a detector is used to measure the polarization state of THz radiation with the assistance of THz polarizers, it will be impossible to decide the optimum orientations of the polarizers as its cross-polarized response is frequency dependent. Finally, we experimentally demonstrated that this effect could be partially eliminated by adjusting the focusing condition of the probe laser beam on the antenna.

Keywords: Terahertz time-domain spectroscopy, Photoconductivity, Polarization

doi: 10.11906/TST.137-148.2011.09.21

1. Introduction

Terahertz time-domain spectroscopy (THz-TDS) is a powerful technique for the measurement of spectrally-resolved properties of a material in the frequency range of hundreds of GHz to a few THz. A typical THz-TDS system is usually used to measure two optical parameters: attenuation coefficient and refractive index [1]. In the recent years, modified THz-TDS setups have been used to measure polarization parameters of materials, such as birefringence, polarization-dependent loss (PDL) and Mueller matrix [2-4].

In some THz-TDS systems, photoconductive (PC) antennas are used as the THz detector. For the measurement of attenuation coefficient and refractive index, a two-contact PC detector is usually utilized. In principle, this detector should only respond to the THz radiation which is polarized along the direction orthogonal to the gap between the two contacts of the antenna [5]. For the measurement of polarization parameters, multi-contact PC detectors have been designed to detect the two polarization components of THz radiation simultaneously [5-8]. On the other hand, a two-contact PC detector can also measure the polarization state of THz radiation with the assistance of one or two THz polarizers [2, 3].

In principle, the aforementioned PC detectors should only respond to the THz electric fields that are polarized along the desired directions and such responses should be frequency-independent. However, Hiroyuki Makabe *et al* have reported that a three-contact PC detector has indeed a frequency-dependent and cross-polarization response [7]. They explained that such a response may be induced due to several reasons, including 1) inhomogeneity of probe beam intensity and electrical property of the PC substrate, 2) imperfect shapes of the contacts and gap, 3) misalignment of the antenna orientation, and 4) polarization-dependent resonances or reflections of THz radiation in the antenna structure [7]. Under such circumstance, calibration measurements are necessary before it can be used for the polarization state measurement [7].

It is easy to keep in mind that the preceding factors, which affect the response of a three-contact PC detector, may also impact a two-contact PC detector. If so, a two-contact PC detector may respond to a mixture of the two polarization components of a THz electric field and the response may be frequency-dependent. For the measurement of attenuation coefficient and refractive index of an isotropic material using a two-contact PC detector, this effect may be hidden if the signal is divided by the reference [1]. However, it will be demonstrated that such an effect may cut down the dynamic range of the system in some frequency ranges; and in some special cases, it may even result in a fake “absorption peak”. More importantly, this effect will seriously affect the polarization measurement in THz-TDS and it can be clearly observed in such measurements.

This paper is organized as follows: in Section 2, the result of the polarization state measurement of THz radiation is presented to show the experimental evidence of the frequency-dependent and cross-polarization response of a two-contact PC detector. In Section 3, three parameters are proposed to phenomenally evaluate how serious this effect is in a two-contact PC detector. Please note that, we are not trying to investigate the reasons of this effect in this paper. In Section 4, the influence of such an effect on the measured THz spectrum is presented and explained. In Section 5, the influence of this effect on polarization state measurement in THz-TDS is analyzed. In Section 6, experimental results show that this effect highly depends on the focusing condition of the probe laser beam on the PC antenna.

2. Frequency-dependent and Cross-polarization Response of a Two-contact PC Detector

The frequency-dependent and cross-polarization response of a two-contact PC detector can be clearly observed in the polarization state measurement in THz-TDS. As shown in Fig. 1, a THz-TDS system is set up to measure the spectrally-resolved polarization state of the THz radiation. In this system, a Ti: Sapphire femtosecond laser provides 10 fs optical pulses at 80 MHz repetition rate with a central wavelength of 800 nm. The PC THz emitter is biased with a 40V square wave at a frequency of 65 kHz. A beam splitter splits the laser beam into the pump beam and the probe beam with average powers of 46 mW and 56 mW, respectively. The time delay line and the lock-in amplifier are controlled by a computer. The purging box is filled with nitrogen gas to avoid the absorption of the THz energy by water vapour. The two-contact PC THz detector, used in the experiments, is a product of EKSPLA. It consists of a micro strip antenna integrated with photoconductor and silicon lens mounted on the back of PC antenna. Low temperature grown GaAs of 400μm thickness is used as photoconductor. The antenna, consisting of two micro strips, each of 5mm length and 20μm width, is formed using Ti/Au metallization. The gap between the two strips is 50μm. Based on its design, this detector should only respond to the electric field polarized along the direction orthogonal to the gap between two contacts of the antenna.

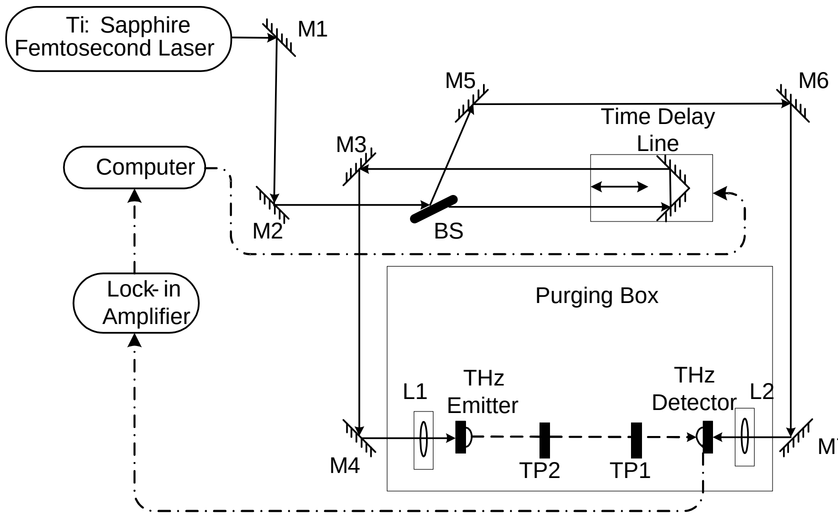

Fig. 1 Experimental configuration for polarization state measurement in THz-TDS. M: Mirror; L: Lens; BS: Beam Splitter; TP: THz Polarizer.

With such an ideal THz detector, for the measurement of polarization state of THz radiation, only one rotatable THz polarizer is required to be placed in front of this detector as we have demonstrated in [3] and [9]. We take the direction orthogonal to the gap between two contacts of the antenna as the x-axis. By rotating the THz polarizer to two angles -45º and 45º with respect to x-axis and taking two temporal scans respectively, two time-domain THz electric fields $\tilde{E}_{-45^\circ}(t)$ and $\tilde{E}_{45^\circ}(t)$ are measured. By doing Fourier transformation, corresponding frequency domain electric fields $E_{-45^\circ}(\omega) = A_{-45^\circ}\cos\Theta_{-45^\circ}$ and $E_{45^\circ}(\omega) = A_{45^\circ}\cos\Theta_{45^\circ}$ can be obtained. Then, at frequency ω, four Stokes parameters, which quantitatively depict the polarization state of THz radiation, can be calculated using the following equations [9]

$$\begin{cases} S_0 = 2\left(A_{45^\circ}^2 + A_{-45^\circ}^2\right) \\ S_1 = 4A_{45^\circ}A_{-45^\circ}\cos\left(\Theta_{-45^\circ} - \Theta_{45^\circ}\right) \\ S_2 = 2\left(A_{45^\circ}^2 - A_{-45^\circ}^2\right) \\ S_3 = 4A_{45^\circ}A_{-45^\circ}\sin\left(\Theta_{-45^\circ} - \Theta_{45^\circ}\right) \end{cases} \tag{1}$$

In the experiment, two wire-grid THz polarizers TP1 and TP2 are used as shown in Fig. 1. Their polarization extinction ratios are larger than 320 in the frequency range of 0.2 to 2.5 THz. The THz polarizer TP2 is fixed at the angle 0° to guarantee that the THz electric fields of all frequencies are linearly polarized along x-axis. The second rotatable polarizer TP1 is used for the polarization state measurement as we have discussed above. Then, if the two-contact THz detector is ideal, the measured normalized Stokes vector $\vec{s} = \left(S_1, S_2, S_3\right)^{\mathrm{T}} / S_0$ should be of constant linear polarization state $(1,0,0)^{\mathrm{T}}$ ("T" denotes the matrix transpose) in the frequency range of 0.2 to 2.5 THz. However, the measurement result, shown in Fig. 2, is inconsistent with this prediction. From 0.2 to 1 THz, the polarization state of THz radiation is close to be $(1,0,0)^{\mathrm{T}}$;

but from 1 to 2.5 THz, the polarization state of THz radiation is actually elliptical. Based on the measurement result, we can conclude that the response of this two-contact PC detector is cross-polarization and frequency dependent.

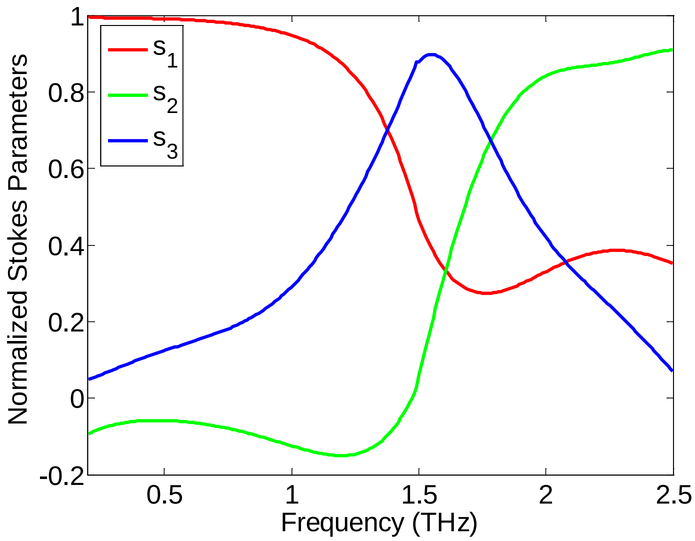

Fig. 2 The measurement result of polarization state of THz radiation in the frequency range of 0.2 to 2.5 THz. The normalized Stokes vector should be $(1, 0, 0)^T$; but has been measured as frequency-dependent elliptical polarization state by using a two-contact PC THz detector.

3. Mathematical Model

An ideal two-contact PC detector should behave like a linear polarizer followed by a polarization-insensitive detector. In Stokes space, a linear polarizer can be represented by the vector $(1, 1, 0, 0)^T$ if its polarizing axis is parallel to the x-axis; equivalently, it can be depicted as $(1, 0)^T$ in Jones space. From the measurement result in Section 2, the two-contact PC detector can actually be treated as an elliptical polarizer followed by a polarization-insensitive detector. An elliptical polarizer can be depicted as $1, D_1(\omega), D_2(\omega), D_3(\omega)^T$ in Stokes space. Here, $(D_1, D_2, D_3)^T = \vec{D}$ is the PDL vector; for a polarizer, $|\vec{D}| = 1$[10]. In Jones space, this vector can be converted as [11]

$$\hat{\rho}(\omega) = \left(\sqrt{1+D_1}, \sqrt{1-D_1}e^{j\delta}\right)^T / \sqrt{2} \tag{2}$$

where

$$\cos\delta = \frac{D_2}{\sqrt{1-D_1^2}}, \sin\delta = \frac{D_3}{\sqrt{1-D_1^2}} \tag{3}$$

As a consequence, at frequency ω, the THz field, detected by such a detector, will be

$$E(w) = \sqrt{\frac{1+D_1}{2}} E_x(w) + \sqrt{\frac{1-D_1}{2}} e^{jd} E_y(w) \tag{4}$$

Equation (4) shows that if $-1 < D_1 < 1$, the two-contact PC detector will have a cross-polarization response, viz., respond to a mixture of the two polarization components $E_x(\omega)$ and $E_y(\omega)$ of THz radiation. Further, the existence of D_2 and D_3 will induce an extra phase difference δ between $E_x(\omega)$ and $E_y(\omega)$.

It is clear that the response of the two-contact PC detector is determined by the three parameters D_1, D_2 and D_3. In the following, we explain how to measure these parameters. This can be performed utilizing the same setup shown in Fig. 1. When the THz radiation passes though THz polarizer TP2, the THz electric field at frequency ω will be $\vec{E}(\omega) = A(\omega)(1, 0)^{\mathrm{T}}$. Then, when TP1 is rotated to the angles ±45º respectively, the detected THz electric field in frequency domain, by the two-contact PC detector, should be

$$E_{\pm 45^\circ}(\omega) = \frac{A(\omega)}{2\sqrt{2}}\left(\sqrt{1+D_1} \pm \sqrt{1-D_1} e^{j\delta}\right) \tag{5}$$

Then, we can easily obtain

$$\begin{cases} \sqrt{1+D_1} = \dfrac{\sqrt{2}}{A}\left(E_{45^\circ} + E_{-45^\circ}\right) \\ \sqrt{1-D_1} e^{j\delta} = \dfrac{\sqrt{2}}{A}\left(E_{45^\circ} - E_{-45^\circ}\right) \end{cases} \tag{6}$$

Therefore,

$$\frac{E_{45^\circ} - E_{-45^\circ}}{E_{45^\circ} + E_{-45^\circ}} = \sqrt{\frac{1-D_1}{1+D_1}} e^{j\delta} = k \tag{7}$$

From Eq. (7), it can be derived that

$$\begin{cases} \sqrt{\dfrac{1-D_1}{1+D_1}} = |k| \\ \delta = \arg(k) \end{cases} \tag{8}$$

where, $\arg(k)$ is the argument of the complex number k. Finally, we have

$$\begin{cases} D_1 = \left(1-|k|^2\right) / \left(1+|k|^2\right) \\ D_2 = \sqrt{1-D_1^2} \cos\left[\arg(k)\right] \\ D_3 = \sqrt{1-D_1^2} \sin\left[\arg(k)\right] \end{cases} \tag{9}$$

In Fig. 3, the measured parameters D_1, D_2 and D_3, of the two-contact PC detector, are plotted. Comparing curves in Fig. 2 and Fig. 3, it is easy to notice that $(D_1, D_2, D_3)^T$ and $(s_1, s_2, s_3)^T$ are the same. This means $(D_1, D_2, D_3)^T$ is just the response of the two-contact detector to the constant polarization state $(1, 0, 0)^T$.

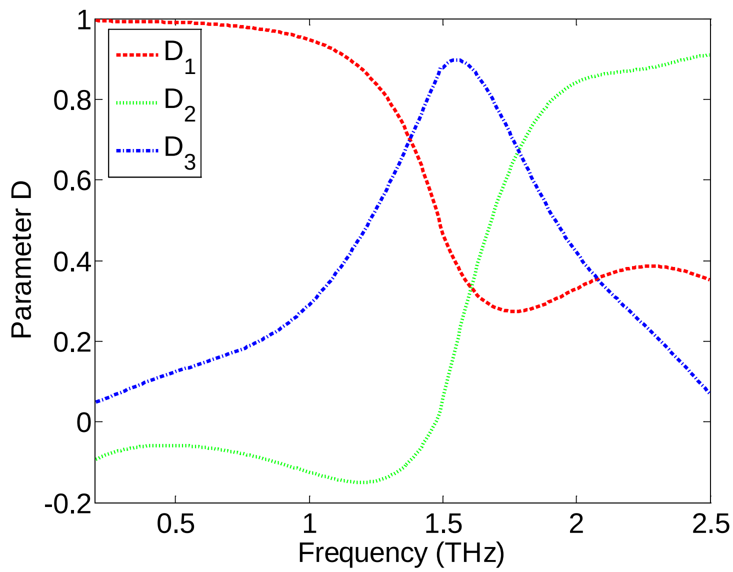

Fig. 3 The three parameters D_1, D_2 and D_3 of the two-contact PC detector measured in the frequency range of 0.2 to 2.5 THz.

4. Influence on THz Spectrum

Usually, a THz PC emitter launches THz pulses that are approximately polarized along $(1, 0)^T$. According to Eq. (4), the detected THz electric field, by a two-contact PC detector, should be

$$E(w) = \sqrt{\frac{1+D_1}{2}} E_x(w) \tag{10}$$

In the frequency ranges where $D_1 < 1$, $|E|$ will be less than $|E_x|$. Then, the cross-polarization response of the detector reduces the dynamic range of the system at these frequencies.

In the experiment, when the THz polarizer TP1 is removed, the measured amplitude of THz electric field $|E|$ is plotted as the red curve in Fig. 4. Since D_1 changes with respect to the frequency as shown in Fig. 3, based on Eq. (10), the true amplitude of THz electric field $|E_x|$ should be plotted as the blue curve in Fig. 4. The discrepancy between two curves from 1 to 2.5 THz can be clearly observed. The signal strength is reduced resulting in the reduction of the dynamic range of this THz-TDS system in this frequency range.

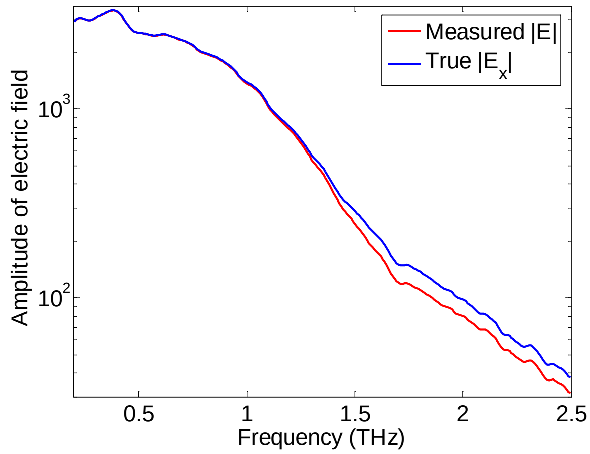

Fig. 4 The red curve shows the measured amplitude of the THz electric field by the two-contact PC detector and the blue curve shows the true amplitude.

If the THz emitter launches the THz pulses with an elliptical polarization state [12] or the THz pulses pass through a birefringent material [13] or a broadband THz waveplate [2], the cross-polarization response of the THz detector will make the measured amplitude and phase of the THz electric field very complicated. From Eq. (4), we can calculate the amplitude and phase of the electric field $E(\omega)$ as

$$\begin{cases} |E| = \sqrt{\dfrac{(1+D_1)|E_x|^2 + (1-D_1)|E_y|^2}{2} + \sqrt{1-D_1^2}\,|E_x||E_y|\cos(\delta+\delta_y-\delta_x)} \\ \arg(E) = \arctan\left[\dfrac{\sqrt{\dfrac{1+D_1}{2}}|E_x|\cos\delta_x + \sqrt{\dfrac{1-D_1}{2}}|E_y|\cos(\delta+\delta_y)}{\sqrt{\dfrac{1+D_1}{2}}|E_x|\sin\delta_x + \sqrt{\dfrac{1-D_1}{2}}|E_y|\sin(\delta+\delta_y)}\right] \end{cases} \tag{11}$$

where δ_x and δ_y are the phases of $E_x(\omega)$ and $E_y(\omega)$, respectively.

From the first equation in Eq. (11), when $\cos(\delta+\delta_y-\delta_x) = -1$ and $|E_x / E_y| = \sqrt{(1-D_1)/(1+D_1)}$, it can be easily calculated that $|E| = 0$. If the THz radiation is polarized as an elliptical polarization state $(0.4846, 0.8747j)^{\mathrm{T}}$ ($j = \sqrt{-1}$), the THz spectrum, measured by the detector with parameters shown in Fig. 3, can be calculated and plotted as the curve in Fig. 5. At 1.474 THz, a fake "absorption peak" will be induced by such a response. Please note, the THz spectrum in Fig. 5 is a theoretical result based on Eq. (11) because we do not have broadband quarter-wave and half-wave plates to really generate the required elliptical polarization state in the experiment. Then, on one hand, the dynamic range of the system will be seriously reduced around 1.474 THz; on the other hand, if a material is measured without a reference, the peak at 1.474 THz may be erroneously assumed to be an absorption peak of this material.

Further, when the material under test has polarization effects, $|E_x|$, $|E_y|$ and $\delta_y - \delta_x$ may vary with respect to the frequency [3]. Hence, such a detector response may introduce more fake "absorption peaks" than those reported in [13]. The signal interpretation will require the knowledge of the full Mueller matrix [3, 13].

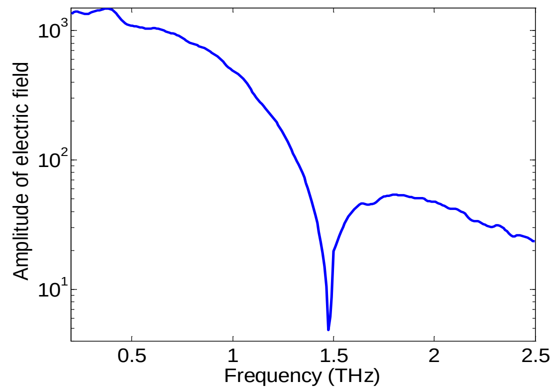

Fig. 5 This calculated curve shows the "measured" amplitude of the THz electric field by the two-contact PC detector will have a fake "absorption peak" at 1.474 THz when the THz pulses have a polarization state of $(0.4846, 0.8747j)^{\mathrm{T}}$.

5. Influence on Polarization State Measurement

As we have presented in Section 2, the cross-polarization response of a two-contact PC detector makes the polarization state measurement result wrong when one rotatable THz polarizer is utilized. In this section, we will study in detail how such a response affects the polarization measurement in a polarimetric THz-TDS using a two-contact PC detector and THz polarizers.

Generally, we assume N THz polarizers are used in the measurement, which are oriented at angles $\theta_i, i=1,\cdots,N$ respectively (the polarizer of $i=1$ is close to the detector). If the incident THz electric field is $(E_x, E_y)^{\mathrm{T}}$, then at frequency ω, the detected electric field, by the two-contact PC detector, can be derived as

$$E=\left[\prod_{i=1}^{N-1}\cos(\theta_i-\theta_{i+1})\right]\left(\cos\theta_1\sqrt{\frac{1+D_1}{2}}+\sin\theta_1\sqrt{\frac{1-D_1}{2}}e^{j\delta}\right)(\cos\theta_N E_x+\sin\theta_N E_y) \tag{12}$$

It is obvious that only the first ($i=1$, close to the THz detector) and the last polarizers are really functioning in the measurement. The use of more polarizers will only reduce the strength of the measured THz electric field.

If only one polarizer is used, based on Eq. (12), we have

$$E=\cos^2\theta\sqrt{\frac{1+D_1}{2}}E_x+\cos\theta\sin\theta\sqrt{\frac{1-D_1}{2}}e^{j\delta}E_x+\cos\theta\sin\theta\sqrt{\frac{1+D_1}{2}}E_y+\sin^2\theta\sqrt{\frac{1-D_1}{2}}e^{j\delta}E_y \tag{13}$$

If parameters D_1, D_2 and D_3 are known, then $(E_x, E_y)^{\mathrm{T}}$ can be obtained by rotating the polarizer to two different angles, such as 45º and -45º. If D_1, D_2 and D_3 are unknown, there are actually four variables $\sqrt{\frac{1+D_1}{2}}E_x$, $\sqrt{\frac{1-D_1}{2}}e^{j\delta}E_x$, $\sqrt{\frac{1+D_1}{2}}E_y$ and $\sqrt{\frac{1-D_1}{2}}e^{j\delta}E_y$ in Eq. (13). When the polarizer is rotated to M angles one by one, we have

$$\begin{pmatrix} E_1 \\ E_2 \\ \vdots \\ E_M \end{pmatrix} = \begin{pmatrix} \cos^2\theta_1 & \cos\theta_1\sin\theta_1 & \cos\theta_1\sin\theta_1 & \sin^2\theta_1 \\ \cos^2\theta_2 & \cos\theta_2\sin\theta_2 & \cos\theta_2\sin\theta_2 & \sin^2\theta_2 \\ \vdots & & & \\ \cos^2\theta_M & \cos\theta_M\sin\theta_M & \cos\theta_M\sin\theta_M & \sin^2\theta_M \end{pmatrix} \begin{pmatrix} \sqrt{1+D_1}E_x \\ \sqrt{1-D_1}e^{j\delta}E_x \\ \sqrt{1+D_1}E_y \\ \sqrt{1-D_1}e^{j\delta}E_y \end{pmatrix} / \sqrt{2} \tag{14}$$

Therefore, $(E_x, E_y)^{\mathrm{T}}$ can not be uniquely obtained no matter how many angles the polarizer is rotated to because the rank of the coefficient matrix in Eq. (14) is 3 and hence four variables can not be uniquely solved [14].

If two polarizers are used: the first one is fixed at angle q_1 and the second one is rotated to two angles, such as $q_2 = 45^\circ$, then at frequency ω, we have

$$\begin{cases} E_x = \left(E_{45^o} + E_{-45^o}\right) / \left(\cos q_1\sqrt{1+D_1} + \sin q_1\sqrt{1-D_1}e^{jd}\right) \\ E_y = \left(E_{45^o} - E_{-45^o}\right) / \left(\cos q_1\sqrt{1+D_1} + \sin q_1\sqrt{1-D_1}e^{jd}\right) \end{cases} \tag{15}$$

If D_1, D_2 and D_3 are unknown, $(E_x, E_y)^{\mathrm{T}}$ still can not be obtained. However, E_y / E_x can be uniquely achieved as

$$\frac{E_y}{E_x} = \frac{E_{45^o} - E_{-45^o}}{E_{45^o} + E_{-45^o}} \tag{16}$$

Equivalently, the normalized Stokes parameters can also be achieved. Obviously, the use of a fixed THz polarizer can partially eliminate the close-polarized response of the two-contact PC detector. Usually, this fixed polarizer is oriented at $\theta_1 = 0^\circ$ [2]. However, when D_1 is close to -1, such measurement will have a bad signal-to-noise ratio (SNR). Even if this fixed polarizer is oriented at another angle, according to the discussion in the Section 4, it is always possible that at some frequencies, the SNR is very low. Therefore, we can not generally decide the optimum orientation of the fixed polarizer. Consequently, two angles of the rotatable polarizer can not be optimized as we have done in [9].

6. Adjustment

As we have mentioned in Section 1, the frequency-dependent and cross-polarization response of a two-contact PC detector is introduced due to many reasons. It is possible to partially eliminate this effect by changing certain conditions in the setup. If we change the focusing condition of the probe laser beam by adjusting the mirrors M5, M6 and M7 as well as the lens L2 in the setup, the first and third reasons mentioned in Section 1 will be affected and the values of $(D_1, D_2, D_3)^{\mathrm{T}}$ can be changed. In the experiments, $(D_1, D_2, D_3)^{\mathrm{T}}$ can be changed to different values by adjusting the components mentioned above. Figure 6 shows a worse state of the detector; the measured D_1 at 2.1 THz is close to -0.4.

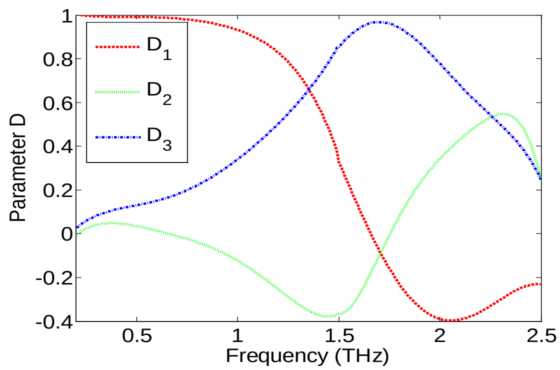

Fig. 6 The measured $(D_1, D_2, D_3)^{\mathrm{T}}$ in a worse state by adjusting the optical components

On the contrary, we can also change the response of the two-contact detector to better states as shown in Fig. 7. Particularly, in Fig. 7 (d), $(D_1, D_2, D_3)^{\mathrm{T}}$ is close to be $(1, 0, 0)^{\mathrm{T}}$ in the frequency range of 0.2 to 1.5 THz. In fact, the polarization state measurement results presented in [3] and [9] were obtained when the two-contact detector is in this state. Hence, one rotatable THz polarizer can lead to the correct measurement result and the two angles of the polarizer can be optimized as ±45º [9].

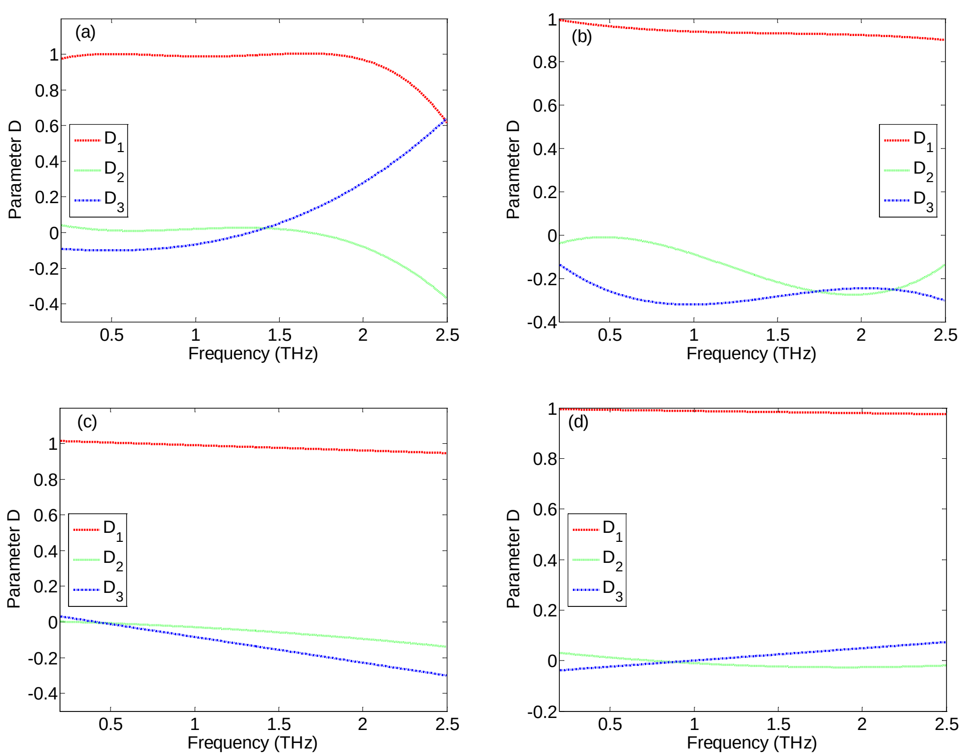

Fig. 7 The measured $(D_1, D_2, D_3)^{\mathrm{T}}$ in different states by adjusting the optical components

7. Conclusion

In this paper, we reported the frequency-dependent and cross-polarization response of a two-contact PC THz detector. Such a response is experimentally observed in the polarization state measurement of THz radiation in THz-TDS. It makes the PC detector behave like an elliptical polarizer and hence three PDL parameters have been used to evaluate it quantitively. Such an effect can make the measured THz spectrum distorted in THz-TDS. It will reduce the dynamic range of the system in some frequency bands. We theoretically demonstrated that, in some special cases, it may even lead to a fake “absorption peak”. During the measurement of the polarization state using such a detector and THz polarizers, such an effect will make the decision of the optimum orientations of polarizers impossible as this cross-polarization response is frequency dependent. Finally, we experimentally illustrate that this effect could be partially eliminated by adjusting the focusing condition of the probe laser beam on the antenna.

Acknowledgement

This work is supported by the international joint project between A-STAR of Singapore and JST of Japan with A-STAR/SERC/SICP grant No. 1021630069.

References

[1] L. Duvillaret, F. Garet and J. L. Coutaz, “A reliable method for extraction of material parameters in terahertz time-domain spectroscopy”, *IEEE J. Sel. Top. Quant. Elec*. 2, 739-746, (1996).

[2] J. B. Masson and G. Gallot, “Terahertz achromatic quarter-wave plate”, *Opt. Lett.* 31, 265-267, (2006).

[3] H. Dong, Y. D. Gong, Varghese Paulose and M. H. Hong, “Polarization state and Mueller matrix measurements in terahertz-time domain spectroscopy”, *Opt. Commun.* 282, 3671-3675, (2009).

[4] H. Dong, Y. D. Gong, Patricia S. P. Thong, Ramaswamy Bhuvaneswart and Malini Olivo, “Measurement of polarization dependent loss in terahertz time domain spectroscopy”, presented at *the 34th International Conference on Infrared, Millimeter, and Terahertz Waves*, 21-25 Sept, (2009).

[5] E. Castro-Camus, J. Lloyd-Hughes, M. D. Fraser, H, H, Tan, C, Jagadish and M. B. Johnston, “Detecting the full polarization state of terahertz transients”, *Proc. SPIE* 6120**,** 61200Q, (2005).

[6] E. Castro-Camus, J. Lloyd-Hughes and M. B. Johnston, “Polarization-sensitive terahertz detection by multicontact photoconductive receivers”, *Appl. Phys. Lett.* 86, 254102, (2005).

[7] Hiroyuki Makabe, Yuichi Hirota, Masahiko Tani e, “Polarization state measurement of terahertz electromagnetic radiation by three-contact photoconductive antenna”, *Opt. Express.* 15, 11650-11657, (2007).

[8] E. Castro-Camus, J. Lloyd-Hughes, L. Fu, H. H. Tan, C. Jagadish and M. B. Johnston, “An ion-implanted InP receiver for polarization resolved terahertz spectroscopy”, *Opt. Express*. 15, 7047-7057, (2007).

[9] H. Dong, Y. D. Gong and Malini Olivo, “Measurement of Stokes parameters of terahertz radiation in terahertz time domain spectroscopy”, *Microw. Opt. Techn. Let.* 52, 2319-2324, (2010).

[10] Shih-Yau Lu and Russell A.Chipman, “Interpretation of Mueller matrices based on polar decomposition”, *J. Opt. Soc. Am. A* 13, 1106-1113, (1996).

[11] A. Gerrard and J. M. Burch, *Introduction to matrix methods in optics* (Dover Publications, 1994).

[12] J. V. Rudd, J. L. Johnson and D. M. Mittleman, “Cross-polarized angular emission patterns from lens-coupled terahertz antennas”, *J. Opt. Soc. Am. B* 18, 1524-1533, (2001).

[13] L. Zhang, H. Zhong, C. Deng, C. Zhang and Y. Zhao, “Polarization sensitive terahertz time-domain spectroscopy for birefringent materials”, *Appl. Phys. Lett*. 94, 211106, (2009).

[14] Michael T. Heath, *Scientific Computing: An Introductory Survey* , McGraw-Hill, (1996).