Physical Parametric Analysis of Terahertz Photoconductive Bow-Tie Dipole Antenna on Frequency and Radiation Pattern Using Electromagnetic Simulation Tools

Nor Baini Alias[1], Dr Aziati Husna Awang[2]
Faculty of Electrical Engineering
Universiti Teknologi MARA Malaysia
40450 Shah Alam,Selangor, Malaysia
Email: baini_alias@yahoo.com

Abstract **— this paper presents the investigation of Terahertz (THz) Photoconductive Antenna (PCA) parameters on the frequency, bandwidth and radiation pattern. Nowadays, studies on PC antenna still don't provide a comprehensive solution in designing a good THz PCA for short distance applications. Most of the recent researchers focused on the GaAs as substrate material. Bow-tie antenna has been used in this investigation due to the frequency independent characteristics, bandwidth and high THz radiation power. Basically, the observation is focus on the performance of the antenna in terms of the resonant frequency, bandwidth and radiation pattern with respect to the change of substrate materials, substrate length, substrate thickness, gap width, gap length and the angle of the tapered flare by varies to a few dimensions and the result is illustrated in graph. Gallium Arsenide (GaAs) with 12.94 dielectric constant ($\varepsilon r = 12.94$) was set as the substrate reference with the resonate frequency of 1 THz. Through this research finding, the parametric study of the substrate gives significant effect to the frequency whilst the parametric study on the dipole patch antenna gives significant effect to the bandwidth. The simulation is done using CST Studio Suite.**

Keywords-THz, PCA, Bowtie antenna, GaAs

A. INTRODUCTION

Terahertz (THz) is a set of frequencies located in between microwave and optical. It has some advantages over microwave frequencies such as in the application of imaging system, in which it can provide higher resolution image compared with microwave imaging system [1]. The range of THz radiation is loosely defined between 100 GHz (3 mm) to 10 THz (30 µm) in the electromagnetic spectrum [2]. In recent years, Terahertz (THz) is one of the fastest growing research field and the most popular devices in THz system is photoconduction technique. Photoconductive antenna (PCA) is one of the most promising devices to radiate THz for various applications such as medical, medicine and security [3] in which distance is not a priority. However, the radiated power and the efficiency of this antenna are very low. So, many researchers in recent years focused on photoconductive antenna enhancement to overcome the weaknesses [4].

A typical photoconductive antenna consist of two metal electrodes on a photoconductive substrate for biasing the device and act as an antenna. Photoconductive gap is the distance between the two electrodes. Photoconductive gap is the place where the laser pulses illuminate and the electron hole pairs are produced. A gap at the center of the antenna works as a feeding point when compared to a common microwave antenna. By illuminating the gap with femtosecond laser, an electron hole will be created in this area [5]. This typical PCA can be illustrated in Fig. 1 [6].

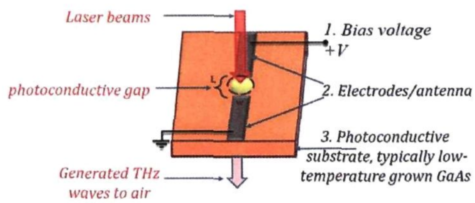


Fig. 1 : Typical Photoconductive Antenna (PCA)

There are various shapes and structures of the THz antenna such as Bow-tie antenna, Four-leaf-clover-shaped antenna and Spiral-type antenna. Due to the frequency independent characteristics as claimed, larger bandwidth and high THz radiation power, most of the researchers used bow-tie antenna as the most favorable antenna type in THz pulsed system [2] [7-8].

A bow-tie antenna has been chosen as the shape and structure of the antenna. Bow-tie antenna has two triangles with the edge facing each other and there is a gap to represent a dipole antenna.

Nowadays, studies on PCA antenna design still don't provide a comprehensive solution in designing a good THz PCA. Theoretically, the structure of the antenna won't give much effect to the frequency of the THz. However, one of the papers shows that the performances of the PCA are sensitive to the dimensions of the substrate [9]. So this is one of the motivations to do the parametric study of the THz PCA.

The limitation of the study is not only on the dipole patch antenna but also on the material. So, the objective of this research is to focus on the parametric study such as the substrate length, substrate thickness, gap width, gap length and the angle of tapered flare by varies to a few dimensions. The comparison for each of the parameters is also been carried out.

Besides that, most of the recent researchers focused on the GaAs as substrate material. So, in this research, the investigation on the different type of substrates such as GaAs, GaN, GaP, GaInAs, and GaSb is also one of the objectives. The performance of each substrate is observed in terms of the frequency, bandwidth and radiation pattern. The simulation is done by using CST Studio Suite to design the THz PCA bow-tie antenna.

The research study could provide information on the systematic parametric study in order to get the best performance of the THz PCA. This study would be beneficial to the theoretician so that they can resolve the theoretical questions, develop a theoretical model and can stimulate new research. This parametric study can provide baseline information on the recent status of the parametric study of THz PCA.

B. METHODOLOGY

A bow-tie antenna was chosen due to the frequency independent characteristics as claimed, bandwidth and high THz radiation power. Bow-tie antennas have two triangles with the edge facing each other and there is a gap to represent a dipole antenna. Plus, the sharp end of the antenna will lead to high electric field, so the radiation will be enhanced.

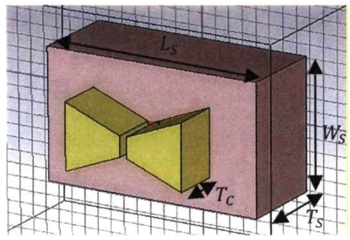
In designing the bow-tie PCA antenna, the most important is the resonant frequency. For this research, 1 THz was chosen as the resonant frequency for PCA. There is an equation involved to calculate the resonant frequency:

$$f_r = \frac{c}{\lambda_r} = \frac{c}{l_e\sqrt{(1+\varepsilon_r)/2}} \qquad \text{(Equation 1.0)}$$

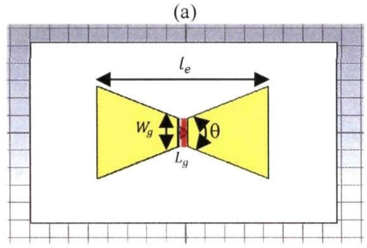
Where c is the speed of light with the value of 3 x 10^8 m/s, l_e is the length of the effective dipole antenna and ε_r is dielectric constant. Since this PCA used the most popular substrate which is Gallium Arsenide (GaAs) as photoconductive material, then the value of dielectric constant, ε_r are about 12.94. Gallium Arsenide (GaAs) was chosen as the reference substrate since it is the most popular substrate material in designing the THz antenna due to its desirable characteristics namely ultra-short carrier lifetime, high intrinsic resistivity, high electron mobility and high breakdown voltage [10].

Theoretically, with the resonant frequency of 1 THz, by using Equation 1.0, the dipole length for bow-tie antenna is calculated about 114 μm. However, the value of the effective dipole length is 86 μm. The angle of the tapered flare is set to 45^0. It is because, the lower limit of the resonant frequency occurs here [11].

Fig. 2(a) shows the perspective view of the antenna physical parameters while Fig. 2(b) shows the front view of the bow-tie antenna simulated by CST 2015.



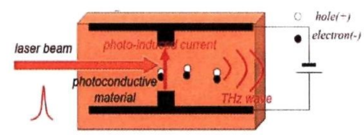
(a)



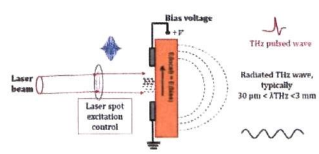
(b)

Fig. 2 (a) Perspective view of antenna physical parameters (b) Front view of bow-tie antenna

When the laser beam illuminated on the photoconductive gap of the photoconductive antenna, then electron and holes were generated in the photoconductive substrate. With the bias voltage, electron and holes produced the photo-induced currents. This time varying currents radiate THz waves. Detail process can be seen in Fig. 3(a) and (b) [6].



(a)



(b)

Fig. 3 : Laser beam induced the photo-current (a) top view (b) side view

For simulation process, a discrete port is a feeding port. The discrete port was placed at the center of the gap length of the bow-tie PCA. And the dimension of the discrete port must be suited with the gap length and the width of the bow-tie PCA. The reference impedance of the discrete port was already set to be 50 so that there will be no issues in the simulation process.

The PCA is optimized at 1 THz. The final dimensions obtained from the optimization process are as TABLE 1.

TABLE 1 : DIMENSION FROM THE OPTIMIZATION PROCESS

Parameters	Dimensions
Type of substrate	Gallium Arsenide (GaAs)
Substrate length, Ls	155 μm
Substrate width, Ws	102 μm
Substrate thickness, Ts	64 μm
Copper thickness, Tc	35 μm
Effective dipole length, le	86 μm
Gap length, Lg	5 μm
Gap width, Wg	16 μm
Angle of tapered flare, θ^0	65.4^0

C. RESULT AND DISCUSSION

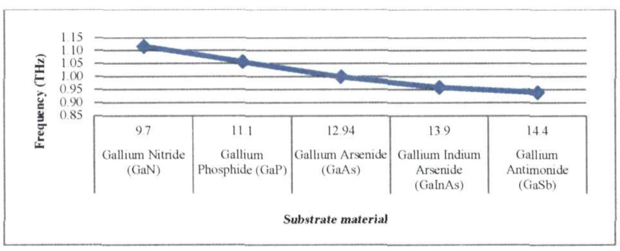
I. SUBSTRATE MATERIAL EFFECT

Substrate material is one of the key element in determine the performance of the THz PCA. Recently, an investigation of the effect of the substrate on the performance of the antenna has attracted many researchers. In THz antenna, the substrate is a photoconductive material which is basically a semiconductor [12]. So, a few optical semiconductor materials has been investigated with Gallium Arsenide has been chosen as the reference substrate.

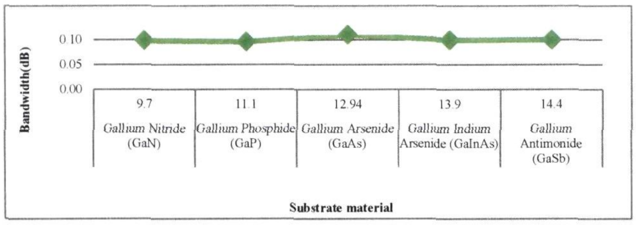
Five (5) optical semiconductor materials have been chosen as the substrate from the group of Gallium. The substrates are Gallium Nitride (GaN) with dielectric constant of 9.7, Gallium Phosphide (GaP) with dielectric constant of 11.1, Gallium Arsenide (GaAs) with dielectric constant of 12.94, Gallium Indium Arsenide with dielectric constant of 13.9 and Gallium Antimonide (GaSb) with dielectric constant of 14.4.

TABLE 2 : PERFORMANCE OF THE ANTENNA WITH RESPECT TO THE CHANGE OF THE SUBSTRATE MATERIALS

Substrate Material	ε_r	Frequency (THz)	(S_{11}) (dB)	Bandwidth (dB)
Gallium Nitride (GaN)	9.7	1.12	-25.28	0.09
Gallium Phosphide (GaP)	11.1	1.06	-52.34	0.10
Gallium Arsenide (GaAs)	12.94	1.00	-39.37	0.11
Gallium Indium Arsenide (GaInAs)	13.9	0.96	-24.77	0.10
Gallium Antimonide (GaSb)	14.4	0.94	-24.45	0.10



(a)



(b)

Fig. 4 : Effect of the substrate materials to (a) frequency and (b) bandwidth

As it can be analysed from Fig. 4(a) which shows that as the dielectric constant of the material increase, then the frequency will decreased. A decrease in the dielectric constant with the increase of the frequency is expected in most dielectric material due to the dielectric relaxation, as the speed of dipole rotation at high frequency is insufficient to match the shift in the applied AC bias [13].

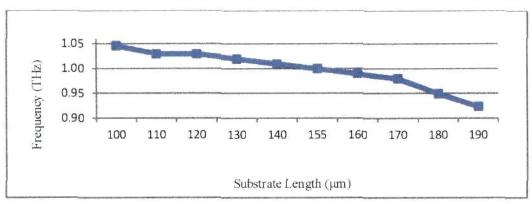
From Fig. 4(b), we can see that GaN, GaP, GaInAs and GaSb have similar trend of bandwidth while GaAs has the highest bandwidth. Based on this result, it is found that GaAs maintains as the most popular substrate due to the characteristics mentioned in [9] and with the additional finding in this result that this material also has a wider bandwidth compared to other materials.

II. SUBSTRATE LENGTH EFFECT

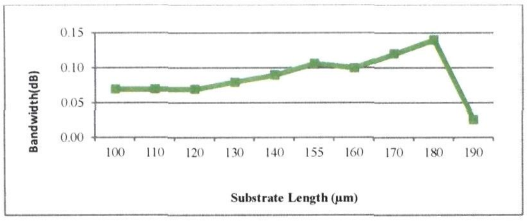
Second parameter has been investigated is the length of the substrate. TABLE 3 shows the performance of the antenna in terms of the frequency and the bandwidth has been observed. There are 10 dimensions have been varies starting from 100 μm to 190 μm.

TABLE 3 : PERFORMANCE OF THE ANTENNA WITH RESPECT TO THE CHANGE IN THE SUBSTRATE LENGTH

Ls (μm)	Frequency (THz)	(S_{11}) (dB)	Bandwidth (dB)
100	1.05	-22.63	0.07
110	1.03	-24.19	0.07
120	1.03	-27.69	0.07
130	1.02	-29.11	0.08
140	1.01	-32.81	0.09
155	1.00	-39.37	0.11
160	0.99	-39.09	0.10
170	0.98	-20.24	0.12
180	0.95	-13.88	0.14
190	0.92	-11.49	0.03



(a)



(b)

Fig. 5 : Effect of the substrate length to (a) frequency and (b) bandwidth

Fig. 5(a) shows that when increasing the substrate length, the frequency will decrease proportionally. It can be concluded that the substrate length does affect the performance of the THz PCA. Therefore, this parameter should be taken into account on designing the antenna. This parameter was also discussed in [8] where they found that the substrate length in a typical THz coplanar strip line dipole antenna has an effect on the input impedance and resonance frequency. The result meets their expectation when the periodic fluctuation of the antenna impedance in the low frequency region was clearer with respect to the increasing of the bias line length.

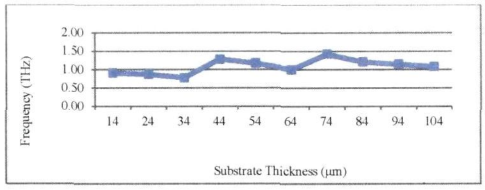
From Fig. 5(b), the trend shows that the substrate length is proportionate with the bandwidth. It is proven that when increasing the substrate length, the bandwidth also increased marginally. After it reaches the maximum dimension i.e 180 µm, the bandwidth dramatically drop.

III. SUBSTRATE THICKNESS EFFECT

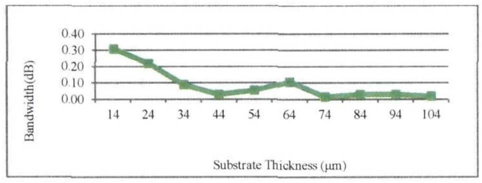
The effect of the substrate thickness also been investigated. The substrate thickness is varied from 14 µm to 104 µm. From TABLE 4 shows the effect of the substrate thickness to the performance of the antenna in terms of the frequency and bandwidth.

TABLE 4 : PERFORMANCE OF THE ANTENNA WITH RESPECT TO THE CHANGE IN THE SUBSTRATE THICKNESS

Ts (µm)	Frequency (THz)	(S_{11}) (dB)	Bandwidth (dB)
14	0.91	-11.64	0.31
24	0.88	-28.39	0.22
34	0.78	-11.90	0.09
44	1.28	-12.42	0.03
54	1.18	-14.24	0.06
64	1.00	-39.37	0.11
74	1.42	-11.45	0.02
84	1.21	-20.26	0.03
94	1.15	-16.77	0.03
104	1.08	-12.49	0.02



(a)



(b)

Fig.6 : Effect of the substrate thickness to (a) frequency and (b) bandwidth

Fig. 6(a) shows that the trend is quite similar with the frequency will decrease after reach the optimum dimension. As can be seen from the graph, 44 µm and 74 µm has the highest frequency and after that optimum value, the frequency decreased from 20 µm to 30 µm before it increased back. It is found that the thickness of the substrate do affect the performance of the photoconductive antenna. So this observation can be taken into consideration in designing the THz PCA.

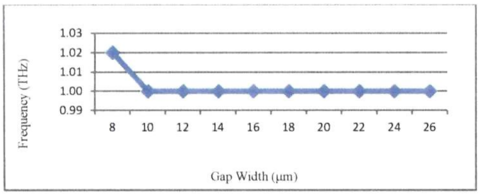
Fig. 6(b) shows the effect of the bandwidth with the change of the substrate thickness. As we can see, 14 µm has the highest bandwidth compared with the other dimensions. From here, it is found that in order to get the wider bandwidth; we need to print the antenna on a thinner substrate since in [14] stated that the thicker substrates tend to trap surface wave modes.

IV. GAP WIDTH EFFECT

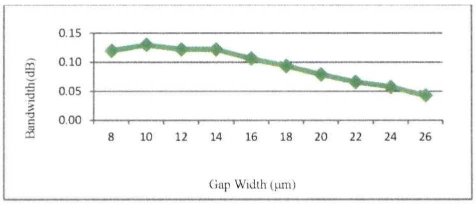
The next parameter is the width of the gap. 10 dimensions varied from 8 µm to 26 µm. TABLE 5 shows the effect of the gap width to the performance of the antenna in terms of frequency and bandwidth.

TABLE 5 : PERFORMANCE OF THE ANTENNA WITH RESPECT TO THE CHANGE IN THE GAP WIDTH

Wg (µm)	Frequency (THz)	(S_{11}) (dB)	Bandwidth (dB)
8	1.02	-12.86	0.12
10	1.00	-15.27	0.13
12	1.00	-18.46	0.12
14	1.00	-22.70	0.12
16	1.00	-39.37	0.11
18	1.00	-26.80	0.09
20	1.00	-19.72	0.08
22	1.00	-16.89	0.07
24	1.00	-14.34	0.06
26	1.00	-12.57	0.04



(a)



(b)

Fig.7 : Effect of the gap width to (a) frequency and (b) bandwidth

From Fig. 7(a), it shows that all the width of the gap resonates at the same frequency except for the starting width i.e 8 µm. The dimension of the gap width from 10 µm to 26 µm resonates at 1 THz. This results shows that the width of the gap doesn't affect the frequency of the antenna when it reaches the stable dimension. It is because the femtosecond laser beam is spotted at the centre of the gap.

Fig. 7(b) shows the effect of the bandwidth with respect to the change of the gap width. The widest bandwidth occurs at the width of 10 µm. The results show that while increasing the width of the gap, the bandwidth will decreased. So it is found that the bandwidths of the antenna are significantly affected by the gap width. Therefore, this is met the theoretical with an equation from parallel plate capacitor and bandwidth.

$$C = \frac{\varepsilon A}{d} \qquad \text{(Equation 2.0)}$$

$$BW = \frac{1}{2}\frac{1}{2\pi R_F C_F} \qquad \text{(Equation 3.0)}$$

It seems that when the area A is increased, the capacitance C will increase. The increased of the capacitor will reduce the bandwidth BW. For this case, gap width represents the area A. The relationship is illustrated in Fig. 8.

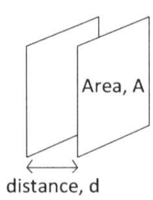


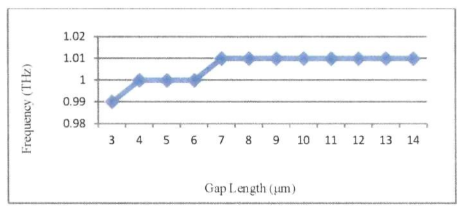
Fig. 8 : Parallel plate capacitor

V. Gap Length Effect

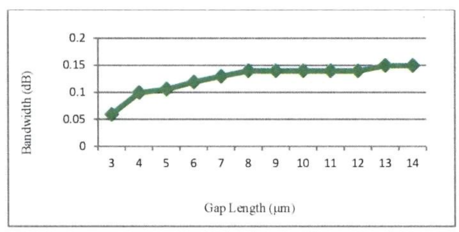
Another parameter involved in this investigation is the length of the gap. TABLE 6 shows the effect of the performance of the antenna in terms of frequency and bandwidth. They are 12 varied dimensions starting from 3 µm to 14 µm.

TABLE 6 : PERFORMANCE OF THE ANTENNA WITH RESPECT TO THE CHANGE IN THE GAP LENGTH

Lg (µm)	Frequency (THz)	(S11) (dB)	Bandwidth (dB)
3	0.99	-19.26	0.06
4	1.00	-32.45	0.1
5	1.00	-39.37	0.11
6	1.00	-25.55	0.12
7	1.01	-21.33	0.13
8	1.01	-18.78	0.14
9	1.01	-17.26	0.14
10	1.01	-15.89	0.14
11	1.01	-14.76	0.14
12	1.01	-14.00	0.14
13	1.01	-13.26	0.15
14	1.01	-12.63	0.15



(a)



(b)

Fig.9 : Effect of the gap length to (a) frequency and (b) bandwidth

Fig. 9(a) clearly shows the upward trend of the frequency whereas the frequency has increased marginally upon the increment of the gap length up to 7 µm. However, the result remains unchanged thereafter. It is found that for the smaller dimension of the gap length; do affect the frequency while the bigger dimension doesn't affect the resonant frequency of the photoconductive antenna. It is also agreed in [15] that the gap size of the dipole does not affect the characteristics of the antenna as long as it is smaller than the wavelength. It is because, the femtosecond laser spots at the area of the gap length.

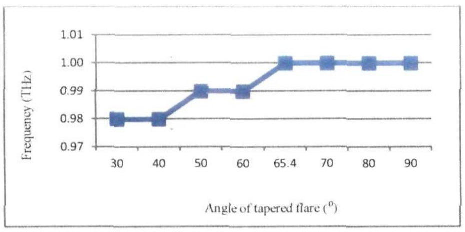
Fig. 9(b) shows the bandwidth of the antenna with the change of the gap length. It can be seen that the bandwidth has an upward trend since the bandwidth becomes wider with the increasing of the gap length. This can be explained with Equation 2.0 and Equation 3.0 that shows when the separation distance, d is increased, capacitor C will decrease. And the reducing of the capacitor C will increase the bandwidth. Gap length represents separation distance, d for this research.

VI. ANGLE OF TAPERED FLARE EFFECT

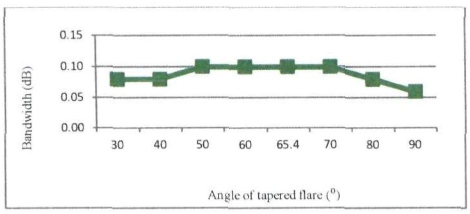
The last parameter has been analysed is the angle of tapered flare. Here, 8 varied angles have been chosen starting from 30° to 90°. TABLE 7 shows all the performances involved in this investigation.

TABLE 7 : PERFORMANCE OF THE ANTENNA WITH RESPECT TO THE CHANGE IN THE ANGLE OF TAPERED FLARE

Angle of tapered flare	Frequency (THz)	(S11) (dB)	Bandwidth (dB)
30	0.98	-37.65	0.08
40	0.98	-39.75	0.08
50	0.99	-39.70	0.10
60	0.99	-50.59	0.10
65.4	1.00	-39.37	0.10
70	1.00	-33.43	0.10
80	1.00	-22.11	0.08
90	1.00	-14.51	0.06



(a)



(b)

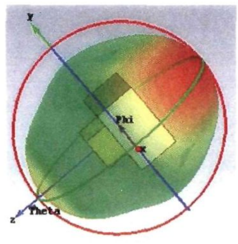
Fig. 10 : Effect of the angle of the tapered flare to (a) frequency and (b) bandwidth

Fig. 10(a) clearly shows the upward trend of the frequency whereby the frequency has increased more gradually upon the increment of the angle of the tapered flare up to 65.4° which is this is the optimization dimension. However, the result remains unchanged thereafter. It is found that the frequency doesn't affected by the angle of the tapered flare when it reach the maximum value.

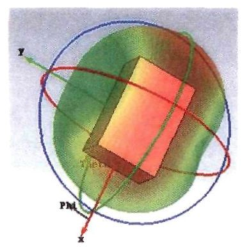
Fig. 10(b) shows that the best bandwidth is at the angle of 50^0 to 70^0. However, for the angle less than 50^0 and greater than 70^0, the bandwidth has slightly dropped. This result also meets the Equation 2.0 and Equation 3.0 where the bandwidth will decrease with the increasing of the area i.e the angle. Unfortunately, the graph seems more or less same because the different between each angle is so small i.e 5 µm.

D. RADIATION PATTERN

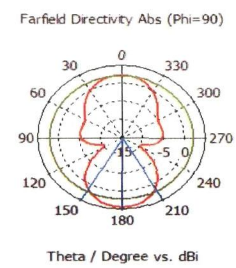
The radiation pattern of the antenna in 3D and polar plot is shown in Fig. 11. It is clearly shows that more power radiated towards the substrate (i.e -z-direction). These results agree with the study in [16]. It was found that most power is normally radiated towards the substrate.



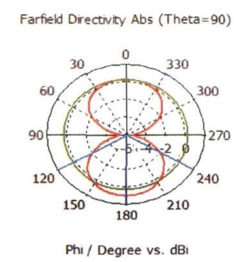
(a)



(b)



(c)



(d)

Fig. 11 : Radiation patterns of photoconductive bow-tie antenna

Fig. 11(c) shows the polar plot for vary theta while phi constant at 90^0 and 270^0. From here, we can see the directivity is at 180° (at –z direction). It is understandable based on the behaviour of the antenna that the directivity will going out from the substrate.

Fig. 11(d) shows the polar plot for vary phi and constant theta at 90^0 and 270^0. ^{0}. It is shows that the main lobe direction is at 180^0. It is understandable that the radiation pattern directivity is at –z direction and the shape is compatible with the dipole patch antenna.

E. CONCLUSION

Through this research finding, the parametric study of the substrate gives significant effect to the frequency whilst for the parametric study on the dipole patch antenna gives significant effect to the bandwidth. The radiation pattern is unchanged for all the parametric study conducted due to the dipole patch antenna.

Further modeling technique and numerical analysis of this finding can be obtained in the future.

F. References

[1] Ning Zhu, and Richard W. Ziolkowski, "Photoconductive THz Antenna Designs With High Radiation Efficiency, High Directivity, and High Aperture Efficiency," IEEE Transaction on TeraHertz Science and Technology, Vol. 3, No. 6, November 2013.

[2] Neda Khiabani, "Modelling, Design and Characterisation of Terahertz Photoconductive Antennas", September 2013.

[3] Neda Khiabani, Yi Huang, and Yao-chun Shen, "Discussions on the Main Parameters of THz Photoconductive Antennas as Emitters", Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), 2011

[4] Yi Huang, Neda Khiabani, Yaochun Shen and Di Li, "A Further Study of THz Photoconductive Antennas", 2012 IEEE.

[5] Lei Hou and Wei Shi, "An LT-GaAs Terahertz Photoconductive Antenna With High Emission Power, Low Noise, and Good Stability", IEEE Transactions On Electron Devices, Vol. 60, No. 5, May 2013.

[6] Prof Yi Huang and Dr Neda Khiabani, "Terahertz Photoconductive Antennas", Forum for Electromagnetic Research Methods and Application Technologies (FERMAT), 2016

[7] Ameerul Faisal bin Asmari, "Investigation On The Effects Of Physical Parameters Of Terahertz Bow-Tie Photoconductive Antennas To Their Performance", UiTM, July 2014

[8] Neda Khiabani, Yi Huang, Yao-chun Shen, Stephen Boyes and Qian Xu, "A Novel Simulation Method for THz Photoconductive Antenna Characterization", 7th European Conference on Antennas and Propagation (EUCAP 2013).

[9] Truong Khang Nguyen and Ikmo Park, "Effects of Antenna Design Parameters On The Characteristics Of A Terahertz Coplanar Stripline Dipole Antenna", Progress in Electromagnetics Research M, Vol. 28, 129-143, 2013

[10] Aznida Abu Bakar Sajak, Yao-chun Shen, Yi Huang, Neda Khiabani and Rula Alrawashdeh, "An Investigation on THz Antennas Using Graphene as a Substrate",

[11] D. Li, Y. Huang, Y. Shen, A. Boland-Thoms and A. Vickers, "Development of a THz Photoconductive Horn Antenna", European Conference on Antennas and Propagation (EUCAP), 2010.

[12] Aznida Abu Bakar Sajak, Yao-Chun Shen, Rula Alrawashdeh, Lei Xing and Saqer Al Ja'Afreh, "A Comparison of the Effect of Substrate on the Performance of THz Antenna", 4th International Conference on Engineering Technology and Technopreneuship (ICE2T), 2014

[13] Hua-Min Li, Chang-Ho Ra, Gang Zhang and Won Jong Yoo, "Frequency and Temperature Dependence of the Dielectric Properties of a PCB Substrate for Advanced Packaging Applications", Journal of the Korean Physical Society, Vol. 54, No. 3, 2009

[14] Arvind Yadav, Dr. Kuldip Pahwa, "Design & Parametric Study of Rectangular Slow Microstrip Patch Antenna for UWB Applications", IJEEE, Vol. 1, Issue 3, 2014

[15] Ramesh Garg, Prakash Bhartia, Inder Bahl and Apisak Ittipiboon, "Microstrip Antenna Design Handbook", 2000, British Library Cataloguing in Publication Data

[16] Di Li, Yi Huang, Yao-Chun Shen and Neda Khiabani, "Effects of Substrate on the Performance of Photoconductive THz Antenna", IEEE, 2010