Investigation on the Effects of Physical Parameters of Terahertz Bow-Tie Photoconductive Antennas to Their Performance

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***Abstract*— The physical parameters of bow-tie photoconductive antenna is investigated, their effects and relationship with resonant frequency have been reviewed and discussed. The reference dimensions for 1 terahertz (THz) resonant frequency bow-tie photoconductive antenna has been used. Analysis has been done using data from the parameter sweep simulation result. The parameter chosen is dipole length, angles of tapered flare, gap length, gap width, substrate length, substrate width, substrate thickness and copper thickness. 10 dimension is taken for each parameter and their relationship to the resonant frequency is illustrated in graph. The simulation is done by using CST Studio Suite and plotted by Matlab software. From the analysis studied, the dipole length and gap length affect the resonant frequency but with uncertain characteristics. Other parameters also affect the resonant frequency but with predictable characteristics. Angle of tapered flare, gap width and copper thickness share almost the same pattern which is the resonant frequency gets higher as their dimension increased. Substrate width, substrate thickness and substrate length however gives difference characteristics which is the resonant frequency gets lower as their dimension increased. This study conclude that all the investigated parameter affect the resonant frequency of bow-tie photoconductive antenna.**

Keywords-Terahertz, bow-tie, photoconductive antenna, resonant

I. INTRODUCTION

Terahertz (THz) radiation is electromagnetic radiation which frequency falls between microwaves and infrared regions[1]. The terahertz frequency range is mostly defined around 100 GHz to 30 THz even though some other sources might define it in other frequency range[2]. Terahertz radiation is non-ionizing submillimeter microwave radiation that shares the characteristics of microwaves. Non-ionizing radiation refers to the electromagnetic radiation that does not carry enough energy per quantum to ionize atoms or molecules[3]. In other words, the electromagnetic radiation does not have enough energy to completely remove an electron from an atom or molecules. The energy terahertz radiation carry are not enough to knock electron off atoms and molecules in human tissue which could trigger harmful reactions [1][3]. This is one of the reason why Terahertz is now being developed mostly for imaging and medical applications as it not causes harmful to the human cells[4].

Nowadays, THz technology has attracted a lot of attention because of its radiation characteristics. For example of it unique features, it can produce high resolution images and can move a lot of data quickly[3]. THz emitters especially, has undergone many research and development in order to produce better emitter for terahertz applications.

There are two basic technique in generating THz radiation known as solid-state electronics and optical generation. Solid state electronics method anyway proves difficult to be produced[5]. One of the examples of solid state generation technique is quantum cascade laser. Here, the transition between semiconductors layers is used to emit light. However, it is impossible to produce THz radiation at room temperature using this technique [5-7]. The second method which is by optical generation is the most chosen technique for almost research in the recent years. By using optical generation technique, high speed lasers pulsed on certain semi-conductor surfaces, thus generating terahertz signal. This laser with 100 fs then pointed to the semi-conductor material such as GaAs[8]. All the semi-conductors material or known as photoconductive material are the mostly used in recent research and industrial applications.

One of the most popular emitter for terahertz applications is photoconductive antenna. With its ability to radiate at terahertz region, it has become more popular for terahertz applications[9]. Many research and development recent years had focused on photoconductive antenna in order to overcome its weakness[10]. A typical photoconductive antenna consists of a planar antenna, substrate made from photoconductive material and a bias voltage attach to the antenna [11, 12]. The most common substrate used for photoconductive antenna is GaAs[13]. A photoconductive antenna should have a gap at the center of the antenna. By illuminating the gap with femtosecond laser, electron-hole pairs are created in this area[1]. The applied bias will then accelerates the electron-hole pairs producing ultra-short current pulse which decays with carrier lifetime of the photoconductive substrate[14].

A dipole and bow-tie antenna is the most frequently used antenna shape for photoconductive antenna[15]. The bow-tie shape has been chosen for this study because of its larger bandwidth and high THz radiation power [16-18]. Various parameter will be study in this paper such as dipole length, angle of tapered flare, substrate length and width, substrate thickness, copper thickness, gap length and gap width. Therefore their relationship to the resonant frequency is the aimed of this study.

II. METHODOLOGY

A. *Project's flowchart*

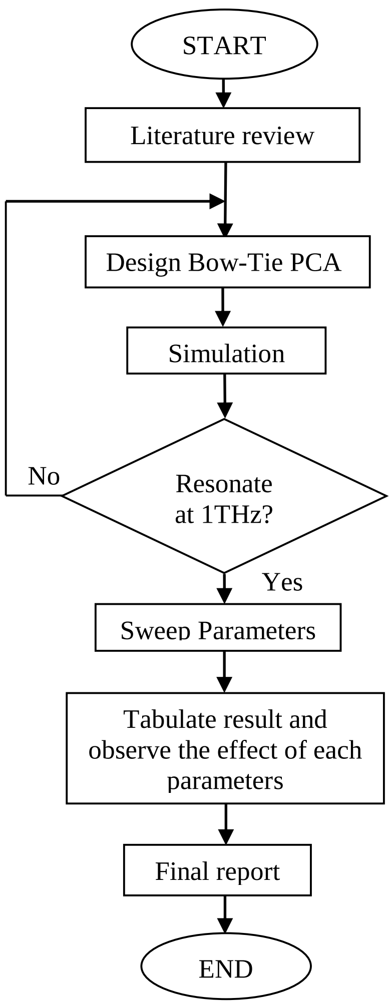

Fig. 1 Project Flowchart

Figure 1 shows the flowchart for this study. This study starts by doing literature review on related articles. At the same time, all theoretical and principles study about photoconductive antenna is done. The next step is to design the bow-tie antenna based on 1 THz resonant frequency. All the calculation for dimension are done by using theory and formula study before. The dimension are then transferred to the simulation tools which is the CST Studio Suite 2013. The design has undergone several simulation and optimization process. After 1 THz resonant frequency is achieved, all the parameter that need to be investigated are varied. The parameters effect to the resonant frequency for this design are tabulated.

B. *Design of the bow-tie photoconductive antenna*

The resonant frequency of bow-tie photoconductive antenna on a semiconductor substrate[17] is calculated by

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

where c is the free space speed, ε_r is the dielectric constant, and l_e is the total effective length of the dipole. The substrate used is the most popular material for photoconductive antenna which is LT-GaAs whose dielectric constant is about 12.9. Theoretically, the length of electrode is about 57 um for center frequency of 1 THz[19]. In practice, the width of electrodes and the bias line will extend the total effective length of the bow-tie antenna. So, the actual length that should be used in practice is shorter than the theoretical length. The bow-tie antenna is an evolution from the dipole antenna that resulting in wider bandwidth. The angle for tapered flare is set to 45° because the lower limit of the resonant frequency occurs here[20]. Figure below shows the dimension of the bow-tie photoconductive antenna that resonates at 1 THz.

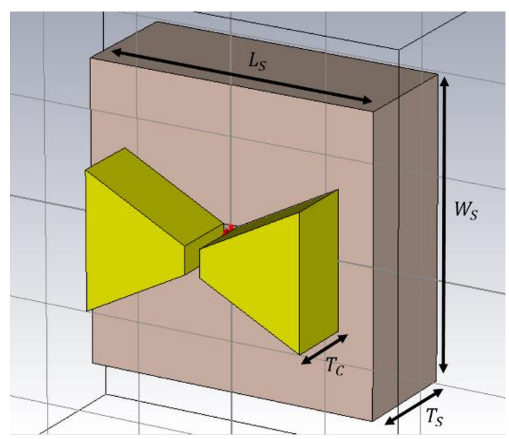

Fig. 2 The structure of bow-tie photoconductive antenna

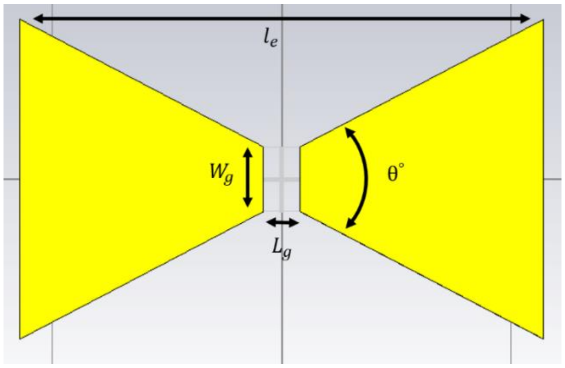

Fig. 3 Front view of bow-tie photoconductive antenna

C. Simulation technique

The bow-tie photoconductive antenna then simulated using TDS solver on CST Studio Suite. Here, the input element use to replace the femtosecond laser is by using discrete port instead of waveguide port as illustrated in Figure. Optimization process has been done to get the resonant frequency at 1 THz. The final dimension is collected after the optimization and tabulated in Table 1.

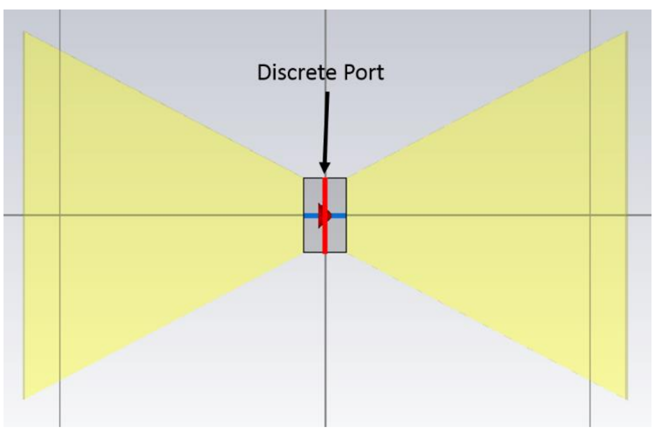

Fig. 4 Discrete port as the input element replacing the laser excitation

Tab. 1 Dimension obtain after the optimization process

Parameters	**Dimensions**
Substrate length, L_s	150 µm
Substrate width, W_s	150 µm
Substrate thickness, T_s	60 µm
Copper thickness, T_c	35 µm
Effective dipole length, l_e	113.2 µm
Gap length, L_g	8 µm
Gap width, W_g	14 µm
Angle of tapered flare, θ°	55.2°

D. Parametric Sweep analysis

The parametric sweep analysis is the method of analysis the parameters relationship to the antenna design by doing several iteration or samples. The result then is tabulated and analyse.

For this study, the parameter sweep has been done by varying 10 samples from the reference dimension. The simulation result then analyse to get the relationship between that parameter and the resonant frequency for bow-tie antenna design. The parameter sweep analysis is done on substrate length, substrate width, substrate thickness, and dipole length, angle of tapered flare, gap width, gap length and copper thickness.

III. Results and Discussions

A. Dipole Length

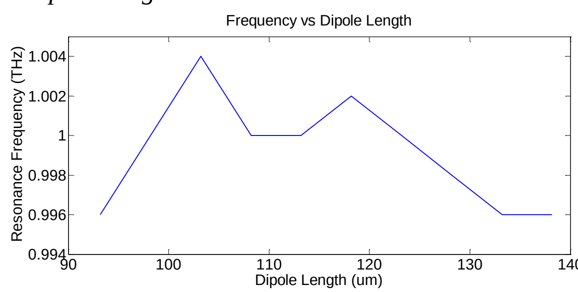

Fig. 5 Dipole length variation effect on resonance frequency

Here the dipole length is varies from 93.2 µm to 138.2 µm resulting in 10 samples. This parameter affects the resonant frequency of this design but not consistent as shown in Figure 5. As illustrated above, the resonant frequency value increase as the dipole length increase from 93.2 µm to 103.2 µm dipole length. From 103.2 µm to 138.2 µm, the graph shows decrease pattern in resonant frequency. From equation (1), the effective length is one of the function for resonant frequency. The effective length of the antenna is different for every dipole length dimension because it is related to fringing effects that could come from substrate as well. The effective length at 93.2 µm to 103.2 µm maybe shorter at this point thus resulting in higher resonant frequency. From 103.2 µm to 138.2 µm, the fringing effects increase due to increasing in effective length. As the effective length gets longer, the resonant frequency will decrease depending on the effective length of the antenna[21]. This implies that for lower resonance frequency, longer dipole length is required. This simulation result match well with the real photoconductive antenna design[20].

According to Table 2, the return loss value is the best at 113.2 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 103.2 µm dipole length which is 0.12 THz. For gain performance, the best dipole dimension is on 108.2 µm with 6.509 dB magnitude. The best dimension for directivity is on 113.2 µm dipole dimension with value 6.64 dBi. However, for power pattern, the higher is at 108.2 µm with value -4.488 dbW.

Tab. 2 Dipole length variation effect on performance parameters

Dipole Length(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
93.2	-15.26	0.11	6.379	6.395	-4.744
98.2	-17.53	0.0963	6.423	6.46	-4.646
103.2	-21.27	0.12	6.454	6.517	-4.578
108.2	-28.99	0.0974	6.509	6.6	-4.488
113.2	-49.61	0.08	6.471	6.64	-4.522
118.2	-33.2	0.063	6.438	6.564	-4.556
123.2	-28.91	0.05	6.374	6.445	-4.623
128.2	-27.09	0.0537	6.257	6.303	-4.743
133.2	-25.66	0.05	6.091	6.13	4.913
138.2	-24.84	0.0548	5.987	6.002	-5.019

B. *Angles of Tapered Flare*

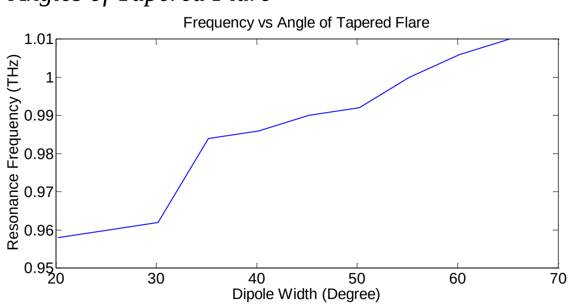

Fig. 6 Angles of tapered flare variation effect on resonant frequency

Next, the effect of tapered flare angles of the photoconductive antenna is investigated. The angle chosen for this simulation is from 20.2° to 65.2°. From Figure 6, by increasing the angle of tapered flare, the resonant frequency also increased. Due to bow tie antenna shape that has triangle like shape, the distribution of fringing effects on bow tie antenna is not same with the normal dipole antenna. The fringing effects has extend the effective length of the dipole because the width of the antenna has increase. The width of the antenna is a function of effective length which is a function of resonant frequency[21].

According to Table 3, the return loss value is the best at 55.2° degrees with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 60.2° and 45.2° degrees which is 0.09 THz. For gain performance, the best angle dimension is on 30.2° angle with 7.381 dB magnitude. The best dimension for directivity is also on 30.2° angle with value 7.434 dBi. However, for power pattern, the higher is at 35.2° with value -3.651 dbW.

Tab. 3 Angles of tapered flare variation effect on performance parameters

Angle of Tapered Flare(deg)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
20.2	-23.3061	0.07599	5.005	5.063	-6.008
25.2	-22.5708	0.0774	5.253	5.299	-5.763
30.2	-20.8046	0.08217	7.381	7.434	-3.69
35.2	-21.7288	0.0849	7.371	7.422	-3.651
40.2	-27.1644	0.0879	7.244	7.262	-3.756
45.2	-34.5402	0.09	7.019	7.007	-3.974
50.2	-38.1272	0.08	6.78	6.772	-4.213
55.2	-49.6067	0.08	6.471	6.64	-4.522
60.2	-28.3324	0.09	6.45	6.526	-4.548
65.2	-29.5463	0.08	6.39	6.276	-4.607

C. *Gap Length*

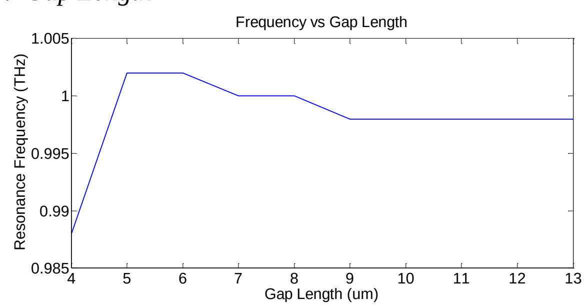

Fig. 7 Gap length variation effect on resonant frequency

The effect of the antenna gap length now is investigated. From Figure 7, by increasing the antenna gap length, the resonant frequency change for 4 µm until 9 µm gap length and start to remain unchanged until 13 µm. This shows that smaller dimension gap length do affect the resonant frequency whereas the bigger dimension gap length does not affect the resonant frequency of a photoconductive antenna design. Due to the fringing effects, electrical field is produced around the gap. Shorter gap length will lead to the coupling phenomenon between the two dipole[22]. Thus, it affect the effective length of the antenna which is the function of the resonant frequency[21].

According to Table 4, the return loss value is the best at 8 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 13 µm gap length which is 0.1307 THz. For gain performance, the best gap dimension is on 13 µm with 6.556 dB magnitude. The best dimension for directivity is on 13 µm gap dimension with value 6.687 dBi. However, for power pattern, the higher is at 12 µm with value -4.485 dbW.

Tab. 4 Gap length variation effect on performance parameters

Gap Length(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
4	-15.9076	0.0502	6.455	6.456	-4.651
5	-19.0874	0.0565	6.398	6.577	-4.648
6	-24.1754	0.06	6.428	6.604	-4.581
7	-29.3708	0.07	6.451	6.62	-4.546
8	-49.6067	0.07	6.471	6.64	-4.522
9	-33.289	0.1	6.496	6.637	-4.498
10	-29.3064	0.11	6.514	6.653	-4.488
11	-22.7494	0.1165	6.518	6.657	-4.497
12	-20.5969	0.1192	6.545	6.678	-4.485
13	-18.7949	0.1307	6.556	6.687	-4.493

Tab. 5 Gap width variation effect on performance parameters

Gap Width(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
10	-18.6379	0.1219	6.53	6.699	-4.521
11	-21.2878	0.1144	6.514	6.683	-4.51
12	-25.0223	0.11	6.525	6.663	-4.481
13	-31.2322	0.097	6.487	6.656	-4.509
14	-49.6067	0.077	6.471	6.64	-4.522
15	-32.1003	0.068	6.45	6.624	-4.545
16	-26.214	0.065	6.44	6.595	-4.562
17	-22.2497	0.0597	6.413	6.561	-4.606
18	-19.8799	0.0507	6.393	6.534	-4.644
19	-18.0356	0.048	6.393	6.485	-4.669

D. Gap Width

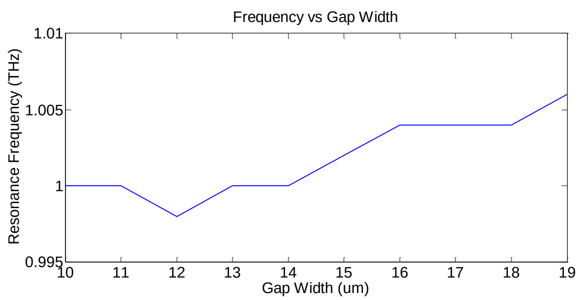

Fig. 8 Gap width variation effect on resonant frequency

Next, the effect of gap width on resonant frequency is investigated. According to Figure 8, overall pattern shows as the width of the gap gets bigger, the resonant frequency increase. By increasing the gap width, the width of the antenna increase thus affecting the effective length of the antenna. From [21], the width of the antenna is the function of effective length. Based on equation (1), the effective length is the function of resonant frequency. This shows that gap width dimension need to be consider in order to design a bow tie photoconductive antenna with desire resonant frequency.

According to Table 5, the return loss value is the best at 14 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 10 µm gap width which is 0.1219 THz. For gain performance, the best gap dimension is on 10 µm with 6.53 dB magnitude. The best dimension for directivity is also on 10 µm gap width dimension with value 6.699 dBi. However, for power pattern, the higher is at 12 µm with value -4.481 dbW.

E. Substrate Length

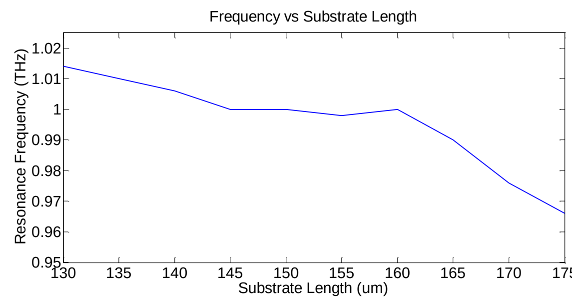

Fig. 9 Substrate length variation effect on resonant frequency

Here the substrate length effect on resonant frequency is investigated. From Figure 9, the pattern shows as the length of substrate gets bigger, the resonant frequency decrease. In order to design a bow tie photoconductive antenna that has low resonant frequency, the length of substrate needs to be considered as well.

According to Table 6, the return loss value is the best at 150 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 130 µm substrate length which is 0.996 THz. For gain performance, the best substrate length dimension is on 130 µm with 7.449 dB magnitude. The best dimension for directivity is also on 130 µm substrate length dimension with value 7.493 dBi. For power pattern, the higher is also at 130 µm with value -3.551 dbW.

Tab. 6 Substrate length variation effect on performance parameters

Substrate Length(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
130	-27.2797	0.996	7.449	7.493	-3.551
135	-34.043	0.0992	7.147	7.229	-3.847
140	-41.3133	0.096	6.953	6.98	-4.039
145	-39.1851	0.0923	6.728	6.733	-4.265
150	-49.6067	0.082	6.471	6.64	-4.522
155	-27.2819	0.0902	6.178	6.147	-4.929
160	-32.8099	0.088	6.417	6.285	-4.578
165	-23.6805	0.0783	6.303	6.815	-5.101
170	-18.6182	0.075	6.08	6.023	-4.972
175	-17.0005	0.0727	5.775	5.724	-5.304

F. Substrate Width

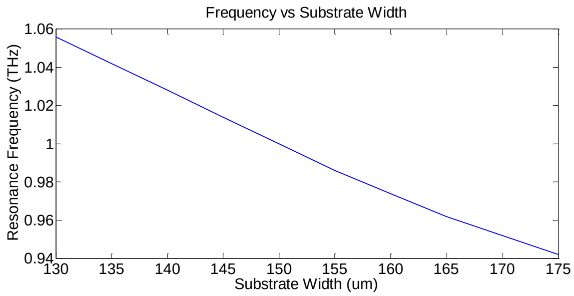

Fig. 10 Substrate width variation effect on resonant frequency

Next, the width of substrate effect on resonant frequency is investigated. The substrate width is varied from 130 µm to 175 µm. According to Figure 10, the resonant frequency decrease as the width of substrate get higher.

According to Table 7, the return loss value is the best at 150 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 145 µm substrate width which is 0.886 THz. For gain performance, the best substrate width dimension is on 135 µm with 6.797 dB magnitude. The best dimension for directivity is on 145 µm substrate width dimension with value 6.745 dBi. For power pattern, the higher is at 135 µm with value -4.201 dbW.

Tab. 7 Substrate width variation effect on performance parameters

Substrate Width(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
130	-34.9751	0.079	6.77	6.63	-4.223
135	-29.236	0.0832	6.797	6.599	-4.201
140	-26.2027	0.085	6.757	6.681	-4.246
145	-30.2256	0.0886	6.615	6.745	-4.381
150	-49.6067	0.08	6.471	6.64	-4.522
155	-40.0446	0.0874	6.5	6.537	-4.493
160	-37.4766	0.086	6.504	6.495	-4.489
165	-42.6408	0.0829	6.145	6.218	-4.91
170	-40.0073	0.077	6.404	6.435	-4.588
175	-34.755	0.0773	6.288	6.327	-4.706

G. Substrate Thickness

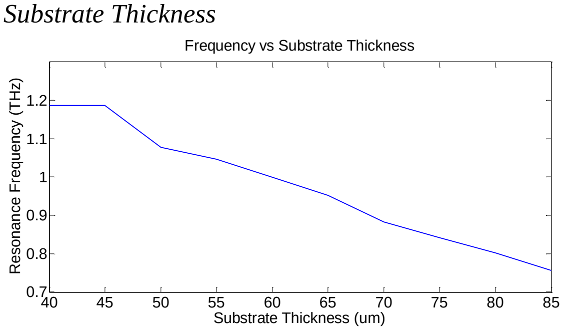

Fig. 11 Substrate thickness variation effect on resonant frequency

The effect of substrate thickness towards resonant frequency now is investigated. Here the substrate thickness is varied from 40 µm to 85 µm. From 40 µm to 45 µm substrate thickness on Figure 11, this antenna resonate at the same frequency which is 1.186 THz. However, from 45 µm to 85 µm, the resonant frequency decrease gradually as the substrate thickness gets higher. From [21], it is state that the substrate thickness is a function of relative dielectric constant. In microstrip antenna theory, the relative dielectric constant is a function of resonant frequency.

According to Table 8, the return loss value is the best at 60 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 80 µm substrate thickness which is 0.1195 THz. For gain performance, the best substrate thickness dimension is on 65 µm with 7.448 dB magnitude. The best dimension for directivity is also on 65 µm substrate thickness dimension with value 7.487 dBi. For power pattern, the higher is also at 65 µm with value -3.55 dbW.

Tab. 8 Substrate thickness variation effect on performance parameters

Substrate Thickness(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dB W)
40	-26.6745	0.04	4.374	4.764	-6.627
45	-21.1501	0.1021	3.613	3.799	-7.412
50	-10.6377	0.018	4.149	4.281	-7.234
55	-20.3216	0.0574	5.875	5.772	-5.158
60	-49.6067	0.076	6.471	6.64	-4.522
65	-28.3994	0.0984	7.448	7.487	-3.55
70	-26.5299	0.10048	4.941	4.979	-6.061
75	-21.1414	0.11585	4.94	5.008	-6.085
80	-21.0663	0.11953	5.344	5.414	-5.682
85	-23.1635	0.10696	5.568	5.636	-5.444

H. Copper Thickness

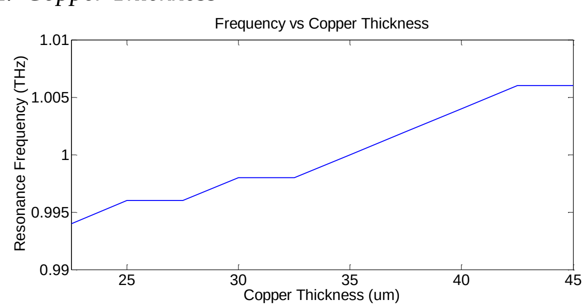

Fig. 12 Copper thickness variation effect on resonant frequency

Now the effect of copper thickness on resonant frequency is investigated. The copper thickness dimension is varied from 22.5 µm to 45 µm and the result is represent in Figure 12. From Figure 12, the overall pattern shows that as the copper thickness gets higher, the resonant frequency also increase.

According to Table 9, the return loss value is the best at 35 µm with -49.61 dB magnitude which is the dimension for 1 THz resonant frequency. The bandwidth is very good at 22.5 µm copper thickness which is 0.0949 THz. For gain performance, the best copper thickness dimension is on 22.5 µm with 6.593 dB magnitude. The best dimension for directivity is on 25 µm copper thickness dimension with value 6.691 dBi. For power pattern, the higher is also at 25 µm with value -4.435 dbW.

Tab. 9 Copper thickness variation effect on performance parameters

Copper Thickness(um)	Return Loss (S11) dB	Bandwidth (THz)	Gain (dB)	Directivity (dBi)	Power(dBW)
22.5	-26.289	0.0949	6.593	6.686	-4.409
25	-28.3412	0.093665	6.564	6.691	-4.435
27.5	-31.1811	0.092486	6.559	6.681	-4.436
30	-34.7404	0.0837	6.523	6.674	-4.471
32.5	-40.3977	0.07955	6.531	6.644	-4.463
35	-49.6067	0.0795	6.471	6.64	-4.522
37.5	-42.0952	0.07499	6.475	6.583	-4.523
40	-36.5801	0.0739	6.409	6.58	-4.584
42.5	-32.2901	0.0711	6.372	6.515	-4.623
45	-29.4881	0.0704	6.315	6.457	-4.682

IV. CONCLUSIONS

In this paper, a complete bow-tie photoconductive antenna has been designed and simulated. The dimension has undergone several optimization in order to have the resonant frequency at 1 THz. Then, the obtained dimensions was set as the reference point for parameter sweep analysis. 10 samples were taken from each parameter and simulated. The parameter sweep analysis was done on substrate length, substrate width, substrate thickness, gap width, gap length, copper thickness, and angle of tapered flare. All the data were collected and the relationship between those parameters and resonant frequency were analyse and discussed. It is found that all the parameters listed has relationship with the resonant frequency. In order to design a bow-tie photoconductive antenna, those parameters cannot be ignored and need to be consider to get the desired resonant frequency.

V. FUTURE DEVELOPMENT

Future research should focus on others range of dimension as the dimension chosen in this paper only contribute a small part of the main objectives. Others research should focus on different shape of the antenna such as fractal antenna because the only popular shape for photoconductive antenna is dipole and bow-tie. It is also recommended to research on the photoconductive antenna performance parameter to investigate the advantages of this bow-tie antenna.

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