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T-ray Photoconductive Antenna Design for Biomedical Imaging Applications

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Abstract**—— Photoconductive antennas are promising sources of terahertz (THz) radiation, which is frequently used to investigate and analyze biological organisms. These compact antennas make it possible to generate ultra-broadband pulses and continuously tunable THz transmissions at room temperature without the need for high-power laser sources. Here, a high efficiency spiral THz photoconductive antenna (PCA) is proposed. The design consists of a gallium arsenide (GaAs) substrate and a silicon (Si) hyper hemispherical lens. The proposed design has a radiation efficiency of up to 92.4% between 2.5 and 3.4 THz, with a directivity up to 17.6 dBi. With several current PCA designs as references, comparisons and analyses are made, indicating that the proposed work shows higher efficiency and radiation directivity at a wider band. The design of electrodes and hyper hemispherical lens are demonstrated in the paper. Simulations of contrast designs are shown as well, illustrating a 25%-40% efficiency and 12.8 dB gain increase by this design. Due to its performance and small structure, this antenna is ideal for T-ray medical imaging.**

Index Terms**—Terahertz, Spiral antenna, Photoconductive antenna, Antenna lens.**

I. INTRODUCTION

The use of terahertz (THz) technology is gaining traction in diversified communication technologies over the past several years [1]. Meanwhile, it is an urgent requirement to promote higher frequency band of communication system [2]. The THz band is the unit of wave frequency that refers to the range of 0.1 THz ~ 3 THz (100 GHz ~ 3000 GHz), which is located between microwave and infrared region of electromagnetic spectrum [1]. Waves of this frequency are narrower and more directional, and the THz spectrum is wide, thus a great number of new potentialities can be developed in various areas considering the advantages of THz communication, such as new sensing technology 'miniaturized radars for gesture detection' and new imaging technology called Light Detection and Ranging (LIDAR) [1]. Besides, THz waves have important properties such as non-ionization and non-invasion due to its weak photons. Also, the phase sensitivity to water, spectral footprint, penetrating capabilities, and good resolution makes it an excellent tool for spectroscopy and medical imaging [3].

T-ray imaging is a new concept that uses THz waves to detect potential threats beneath human skin [4]. With the THz waves of around 100 μm to 1 mm in length, T-ray imaging penetrates outer layers of non-conducting materials such as human skin using set angles to generate images of skin which is more meticulous than current methods such as X-ray [4]. T-ray imaging uses two prisms to focus THz waves with different angles on one specific area of the skin. Information can be obtained by comparing the different properties of THz waves before and after they enter the skin [4]. By deploying elliptically polarized focused T-ray at right angles to each other at four different locations, T-ray imaging yields more information than the standard reflection methods used in spectroscopy [4]. This technology could help detect skin cancer progression by revealing the extent of tumors under the skin. It could also allow doctors to discover and develop treatments for skin conditions such as psoriasis and eczema [5].

Over the past few years, the combination of optical and radio frequency (RF) technology to achieve high performance THz radiation sources has become an essential theory in the field of terahertz antenna development [5]. Photoconductive antenna (PCA) is one of these advanced technologies. A PCA consists of two direct current (DC) biased metal electrodes and a photoconductive substrate. This type of antenna is fed by a femtosecond laser that is spotted at the gap at the antenna center [6]. To gain a wide waveband, the antenna is backed by the absorber where only half of the power would be radiated [6], therefore low power level and low optical-to-THz conversion efficiency are the two main limitations in the development of PCA area.

In this paper, a spiral THz PCA is developed based on the requirements and purposes of T-ray imaging for skin cancer deduction with high efficiency and high gain within a wide THz bandwidth from 2.5 THz to 3.4 THz. The radiation efficiency keeps over 89% on this wide band, with peak efficiency reaching 92.4%. The realized gain and directivity over this band are over 14.9 dBi and 15.6 dBi, with the highest directivity up to 17.6 dBi. Comparison with conventional PCA and several enhanced PCA are made, manifesting that the proposed PCA efficiency and gain are increasing prominently. The proposed gap designs, electrodes geometry designs and silicon lens are the key solutions to gain a high performance in this simulation, and illustrations of improving efficiency and gain with hyper hemispherical lens design is provided.

II. ANTENNA DESIGN

In improving the efficiency and the gain, relative materials and designs are applied. The proposed antenna design in Fig. 1 consists of two gold electrodes, a gallium arsenide (GaAs) substrate and a hyper hemispherical silicon lens. The laser pulse photons have much higher energy than the semiconductor substrate's energy gap, hence they are absorbed by the GaAs substrate. Then, the absorbed photons form free electrons and holes that become electrically conductible. The excited photocurrent will flow in the electrodes and substrate, emitting THz waves at the bottom side of the antenna [7]. In choosing a suitable substrate material, good thermal conductivity which described by relative dielectric constant ϵ_r is essential [8]. GaAs is used as the material for substrate because of its sub-picosecond lifetime and considerable mobility ($200cm^2/V_s$).

CST Studio Suite 2020 is used to operate the simulations, and the running system is Windows 10. In the simulation, the geometry of the electrodes is designed by using (1) and (2). The constant b is the starting radius and a is the growth rate, and t is the incremental angle which relates to the number of turns. The maximum t is 8π, which means this spiral antenna has four complete turns.

$$X(t) = b + atcos(t) \tag{1}$$

$$Y(t) = b + atsin(t) \tag{2}$$

$$t = 0\sim8\pi, \qquad a = \pi, \qquad b = 0$$

The feeding gap G is labelled in Fig. 1 (b). The length of G is the distance between the center point at each side of the edge angle. According to the requirements of T-ray imaging [4], the wavelength selection is drawn up as 100 µm. The estimated frequency is calculated by $f = \frac{c}{\lambda}$, which gives 3 THz. Then, with the equation [8]:

$$D = n\lambda\text{ , n=1.1~3.5} \tag{3}$$

The wavelength could be defined with the help of D, which is the outer circumference of the spiral electrodes. The ratio of arm-gap G_a and arm-width W_a is tested in several simulations. According to comprehensive comparisons, the ratio of 3:1 is the most reasonable design. The dimensions of the proposed antenna electrodes and substrate are summarized in TABLE I. D=160.64 µm is calculated by the following equation:

$$D = 2 * (\pi * 8\pi * cos8\pi + \frac{W_a}{2}) \tag{4}$$

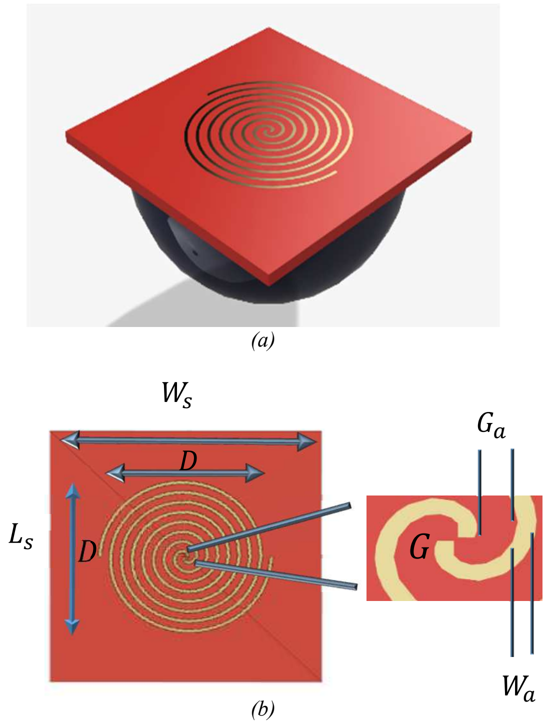
which is derived by combining (1), (2) and (3). With n of (4) is 1.5, the working frequency is 2.9 THz. T_a and T_s are the thickness of antenna electrodes and substrate.

TABLE I. CORRESPONDING VALUES OF ANTENNA ELECTRODES AND SUBSTRATE

Dimensions	$W_s = L_s$	D	G	G_a	W_a	T_a	T_s
Length/µm	250	160.64	0.86	7.15	2.72	0.12	10

TABLE II. CORRESPONDING VALUES OF LENS DESIGN

Dimensions	T_c	R_c	R_l
Length/ µm	26.25	125	125



(a)

(b)

Fig. 1: (a)Proposed spiral PCA made of two gold electrodes on a GaAs substrate and a silicon hyper hemispherical lens; (b)Dimensions of the proposed design

The parameters of the lens are shown in TABLE II, where T_c, R_c and R_l are the thickness of Si cylinder connection and the common radius of Si cylinder and hemispherical lens. This lens is designed on account of the dimensions of the proposed PCA to improve the efficiency and radiation directivity. The choice of silicon lens is due to its high refractive index and transparency to THz waves. The refractive index of Si n~3.4 is almost the same as GaAs. Silicon lens increases the escape one angle and decreases the divergence of emitted waves. The parameters of hyper hemispherical [9] are calculated by

$$d = R(1 + \frac{1}{n}) \tag{5}$$

while $d = T_c + R$ is the total length of hyper hemispherical lens, n is the refractive index of Si and R is the radius of the lens. Due to space limitations, the detailed theory of silicon lens will not be covered, but related research principle of how silicon lens improve PCA efficiency is provided by [9].
The photo current of the antenna could be calculated by [10]:

$$I_{dc}(t_d) = \frac{2}{\sqrt{\epsilon_r}+1}\frac{l_a w_g}{l_g \alpha}\frac{1}{T}, \int_0^T E_{THz}(t + t_d)\sigma_s(t)dt \tag{6}$$

Where t_d is the time delay before the optical pulses arrive at the gap. E_{THz} is the incident THz electric field that emitted from the substrate, and σ_s is the sheet conductivity at the antenna gap. It is defined as [10]:

$$\sigma_s(t) = \frac{e\mu(1-R)}{h\upsilon}\int_{-\infty}^{t} I(t')\, exp\left(-\frac{t-t'}{\tau}\right) dt' \tag{7}$$

III. RESULTS

In order to assess the performance of the proposed antenna, the efficiency results and the radiation patterns are compared and analyzed, for PCA measurement mostly detects the power of emitted pulses instead of measuring S_{11}. The efficiency is shown in Fig.2, and the radiation patterns are shown in Fig.3~6. As seen in Fig.2, the peak value of antenna radiation efficiency reaches up to 92.4%. On all band from 2.5 to 3.4 THz band, the total efficiency remains over 85.5%, while the radiation efficiency is over 89%. At the best performed frequency bands of 2.8-3 and 3.1-3.3 THz, the radiation efficiency is over 91% and the total efficiency is 87.7%. To probe the effect of the lens, the same PCA without lens is simulated and analyzed. By comparisons, it turns out that the efficiency and directivity have been improved by 25-40% and 12.79 dB in this waveband.

The performance of radiation directivity and gain of the proposed PCA are both high. The far field patterns are shown in Fig. 3. At 2.8 THz, the main lobe magnitude is 16.3 dBi, and the realized gain is 15.7 dBi, indicating the high gain of this design. The front-to-back ratio at this frequency is 21.1 dB. The angular width is 24.3° on E plane and 21.5° on H plane. The side lobe level is -16.5 dB on E plane and -14.6 dB on H plane. Fig.5 depicts the 3D radiation pattern of the antenna, in which the directivity is noted to be contended.

At 3.2 THz, the directivity main lobe magnitude is 17.6 dBi, while the realized gain is 17.1 dBi. The front-to-back ratio becomes 13.5 dB. On E plane, the angular width is 22.4°. On H plane, the angular width is 20.7°, the side lobe levels are both -13.6 dB. The 3D radiation pattern is shown in Fig.6.

The hemispherical silicon lens improves the efficiency and directivity because nearly all the forward directed THz intensity can escape the PCA [9].

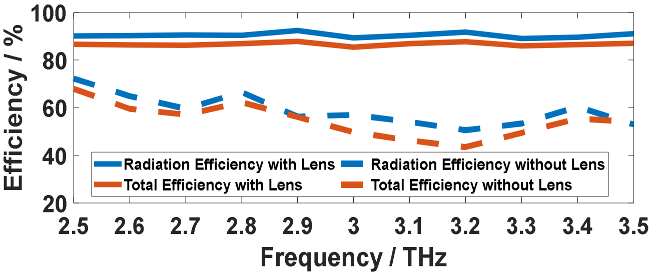
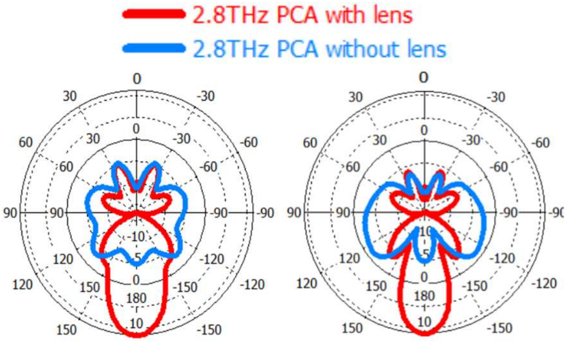
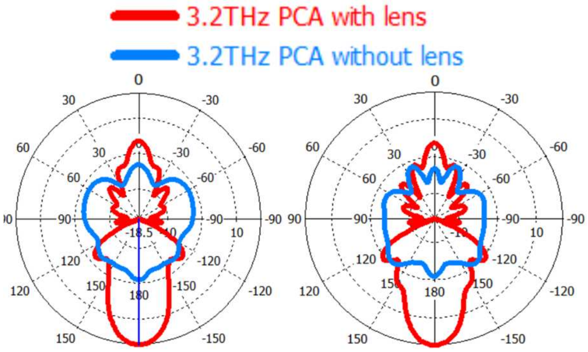


Fig. 2: Radiation and total efficiency of the proposed antenna with and without lens at 2.5-3.5 THz



(a) (b)

Fig. 3: (a) E and (b) H plane radiation pattern of the proposed antenna at 2.8 THz with and without lens



(a) (b)

Fig. 4: (a) E and (b) H plane radiation pattern of the proposed antenna at 3.2 THz with and without lens

Fig.5 and 6 also indicate the directivity is satisfying as the radiation intensity shown along the z-axis. The THz waves are emitted with a highly focusing trend, as shown in Fig.7, the realized gain and directivity magnitude both reach high level at all band from 2.5 THz to 3.4 THz.

Comparing to the performance on H plane, the performance is better on E plane at 2.8 THz. The side lobe level is lower, while the angular width is similar, revealing that the radiation is more directive. At 3.2 THz, the angular width is smaller on H plane. Due to the different features of angular width, more potentiality is provided in realizing more precise T-ray imaging skin cancer detection. The main lobe directions are all 180° at all band, expressing a very stable radiation along the z-axis of the antenna.

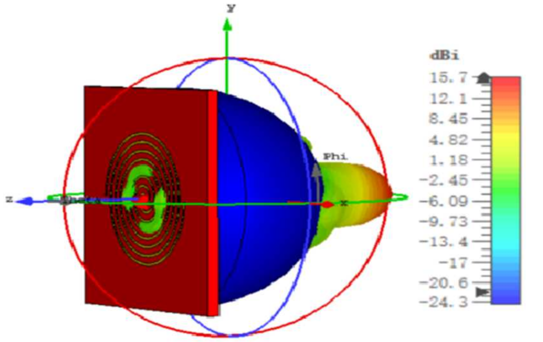


Fig. 5: 3D far-field radiation pattern of proposed antenna at 2.8 THz

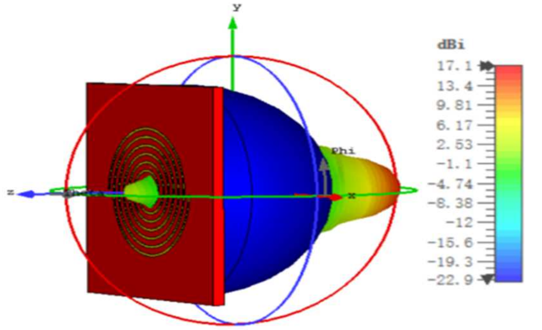


Fig. 6: 3D far-field radiation pattern of purposed antenna at 3.2 THz

Comparisons with several current research of THz PCAs which are based on lens design are made and shown below in TABLE III, after which analysis of the proposed PCA is provided. All parameters used in the comparisons are the best performance data in corresponding research.

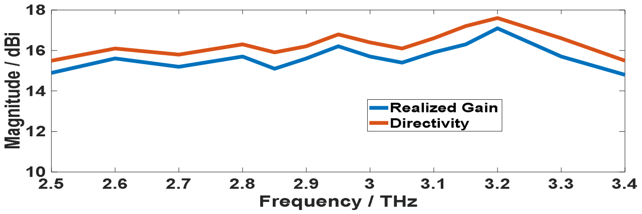


Fig. 7: Realized gain and directivity at all band from 2.5 THz to 3.4 THz

TABLE III. COMPARISONS OF THE PROPOSED ANTENNA AND OTHER THZ PCA DESIGNS

THz PCA designs	Efficiency/%	Directivity /dBi	F-to-B ratio/dB	Side lobe/dB	Bandwidth/THz
Proposed PCA	92.4	17.6	21.1	-16.5	0.9
Ref 1 [11]	96	13.3	10.6	-11.2	0.18
Ref 2 [12]	78	10.85	NP	NP	0.2
Ref 3 [13]	NP	7	17	NP	0.2
Ref 4 [14]	16.3	7.8	NP	NP	5.3

By comparisons, it is noted that the proposed PCA with designed lens has satisfying performance in both efficiency and radiation, and wider bandwidth than current lens based PCAs. Contrast to conventional lens PCAs, the efficiency, frequency and bandwidth of the proposed design are up to a very high standard. Such radiation pattern appears that this antenna is possessing very high radiation efficiency over 89% on a wide high frequency band, showing desirable potentiality in future T-ray imaging technology due to its preciseness, penetrability, and radiation intensity.

IV. CONCLUSION

Due to the prospect of THz technology, THz antennas, especially THz PCAs, are attracting the attention in the academic world. The design of a spiral PCA which operates at 3 THz is investigated in this paper. The proposed spiral nanoantenna shows satisfactory performance in 2.5-3.4 THz with high performance, which is difficult for conventional terahertz photoconductive antenna to realize. By comparing to several current PCA designs, it is showing that the proposed work has taken gain, efficiency, and bandwidth into account and achieves better results. In the 2.5-3.4 THz band, the radiation efficiency remains over 89%, while the top efficiency reaches 92.4%. The directivity in this band is higher than 15.8 dBi, with the peak magnitude of 17.6 dBi shows up at 3.2 THz. The analysis of how hyper hemispherical lens improves PCA performance is also discussed. This terahertz photoconductive antenna has a good prospect in THz applications such as T-ray imaging due to its eligible features. The geometry of the antenna can be fabricated using well-established techniques, which is crucial for the application phase. THz Time-Domain Spectroscopy (TDS) system will be used in measurement.

REFERENCES

[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Mdanayake, S. Mandal, A. Alkhateeb and G. C. Trichopoulos, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," *IEEE Access,* pp. 78729-78757, 06 June 2019.

[2] "6G will see convergence of terrestrial and satellite communication networks: DoT Secy," 03 Dec 2021. [Online]. Available: https://economictimes.indiatimes.com/industry/telecom/telecom-news/6g-will-see-convergence-of-terrestrial-and-satellite-communication-networks-dot-secy/articleshow/88078341.cms?from=mdr. [Accessed 19 Apr 2022].

[3] K. HUANG and Z. WANG, "Terahertz terabit wireless communication," *IEEE Microwave Magazine,* vol. 12, no. 4, pp. 108-116, 2011.

[4] H. Pozniak, "T-ray imaging gets under the skin: A method for analysing the structure of skin using a type of radiation known as T-rays could help improve the diagnosis and treatment of skin conditions," *Engineering & Technology,* vol. 16, no. 2, pp. 48-49, 2021.

[5] M. Tonouchi, "Cutting-edge terahertz technology," *Nature Photonics,* vol. 1, pp. 97-105, 2007.

[6] R. C. Johnson and H. Jasik, Antenna Engineering Handbook, New York: McGraw-Hill, 1984.

[7] A. Garufo, P. M. Sberna, G. Carluccio, J. R. Freeman, D. R. Bacon, L. Li, J. Bueno, J. J. Baselmans, E. H. Linfield, A. G. Davies, N. Llombart and A. Neto, "A connected array of coherent photoconductive pulsed sources to generate mW average power in the submillimeter wavelength band," *IEEE Transactions on Terahertz Science and Technology,* vol. 9, no. 3, pp. 221-236, 2019.

[8] H. Nakano, K. Nogami, S. Arai, H. Mimaki and J. Yamauchi, "A spiral antenna backed by a conducting plane reflector," *IEEE Transactions on Antennas and Prropagation,* pp. 791-796, June 1986.

[9] "PCA-Hyperhemispherical silicon lens," BATOP Optoelectronics, [Online]. Available: https://www.batop.de/information/PCA_infos.html. [Accessed 8 Sep 2022].

[10] D. Saeedkia, "Terahertz photoconductive antennas: Principles and applications," in *Proceedings of the 5th European Conference on Antennas and Propagation*, Rome, Italy, 2011.

[11] N. Zhu and R. W. Ziolkowski, "Photoconductive THz antenna designs with high radiation efficiency, high directivity and high aperture efficiency," *IEEE Transactions on Terahertz Science and Technology,* vol. 3, no. 6, pp. 721-730, Nov 2013.

[12] A. Jyothi, C. Saha, B. Ghosh, R. Kini and C. Vaisakh, "Design of a gain enhanced THz bow-tie photoconductive antenna," in *2016 International Symposium on Antennas and Propagation*, Cochin, 2016.

[13] A. Mingardi, W. D. Zhang, E. R. Brown, L. E. Garcia-Munoz, G. Carpintero del Barrio and D. Segovia-Vargas, "THz and Microwave Dual-Band Ultrafast Photoconductive Antenna," in *48th European Microwave Conference*, Madrid, 2018.

[14] A. Dhiflaoui, H. Rmili, O. Boularess, A. Yahyaoui, T. Aguili and R. Mittra, "Design of an ultra-wideband and highly-directive photoconductive THz Vivaldi antenna," in *2017 10th Global Symposium on Millimeter-Waves*, HongKong, 2017.