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A terahertz photoconductive antenna design for gain enhancement based on the Chinese Totem Tai-Chi

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***Abstract*—As a promising terahertz (THz) radiation source, the photoconductive antenna (PCA) is often used in investigating and analyzing THz applications. In this paper, a novel geometric structure of THz PCA is proposed. The design is composed of a gallium arsenide (GaAs) substrate and a silicon (Si) hyper hemispherical lens. Several existing PCA designs are compared and analyzed, showing that the directivity and gain of the proposed work are significantly improved in 1.5 ~ 3.5 THz, up to 15.45 dBi and 15.06 dBi. The design of electrodes and silicon hyper hemispherical lens are demonstrated in this paper. The proposed PCA is ideal for future THz wireless communication due to its great performance and simple structure.**

I. INTRODUCTION

In the past few years, terahertz (THz) technology has been widely used in various communication technologies. The combination of optical and radio frequency (RF) technology to achieve high performance THz radiation sources has become an essential theory in the development of THz antennas, among which photoconductive antenna (PCA) is one of the advanced research directions [1]. PCA consists of a photoconductive substrate and two direct current (DC) bias metal electrodes. In order to obtain a wide waveband, there is an absorber at the back of the antenna, where only half of the power will be radiated [2]. Hence, the main challenge of the PCA field is the low gain results from limited optical-to-THz conversion efficiency.

In this paper, a THz PCA with a novel dipole geometry design and a hyper hemispherical lens is developed with a high gain over 1.5 ~ 3.5 THz band. The geometry structure is similar to a traditional Chinese totem, Tai-Chi. The directivity and gain are over 16.1 dBi and 15.6 dBi, with the highest performance up to 22.3 dBi and 19.8 dBi on the broadband. Several previously published PCAs are compared to the proposed work, and the results show that the suggested structure significantly improves the antenna gain.

II. ANTENNA DESIGN

Fig.1 shows the proposed PCA, which is composed of a low-temperature grown gallium arsenide (LT-GaAs) substrate, two gold electrodes, and a silicon (Si) hyper hemispherical lens. The novel geometric structure of Tai-Chi is designed because THz pulses will be radiated more using inter-combined structures, for photo-carriers are easily attracted towards the electrodes [3]. As the photons of laser pulses have much higher energy than GaAs energy gap, they will be absorbed by the photoconductive substrate, hence the absorbed photons form free electrons and holes that become electrically conductible. Meanwhile, the photocurrent on the substrate will flow in the electrodes and drive the antenna to emit THz waves at the bottom side [4]. GaAs is used because this semiconductor has proper thermal conductivity, which is described by relative dielectric constant ϵ_r (approximately 13.18). Additionally, its sub-picosecond lifetime and high mobility (200 $cm^2 \cdot V^{-1} \cdot s^{-1}$) adapt to the requirements of the PCA field [5]. CST Studio Suite 2020 is used to operate simulations.

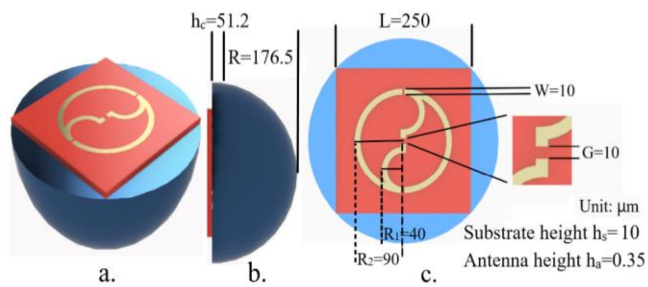

Fig.1. (a) Proposed novel dipole PCA made of two gold electrodes based on a GaAs substrate and a Si hyper hemispherical lens; (b)(c) Side view and front view of the proposed PCA and the dimensions of PCA design.

The overall structure is shown in Fig.1 (a). The electrodes are two circles with the width of 10 μm. The design of the Si lens and PCA is shown in Fig.1 (b) and (c) with dimensions labelled. According to (1) [6]:

$$D = n\lambda, n = 1.1{\sim}3.5 \quad (1)$$

The outer circumstance $D=2R_2=180\mu m$ indicates that the frequency band of the proposed antenna is 1.5 ~ 3.5 THz. The design of the hyper hemispherical lens is determined by [7]:

$$d = R(1 + \frac{1}{n}) \quad (2)$$

In (2), d represents the total height of the PCA, and in this design $d=h_a+h_s+h_c+R$; n represents the refractive index of Si.

III. RESULT AND DISCUSSION

The broadband directivity radiation patterns on 1.5 ~ 3.5 THz of the proposed PCA with and without the lens on E and H planes are shown in Fig.2 (a) and (b). On all operating bandwidth, the directivity and realized gain of the proposed design without lens are over 6.02 dBi and 3.52 dBi, with the highest results observed of 10.1 dBi and 8.27 dBi at 2.2 THz. Meanwhile, the radiation efficiency is over 80.5%, while its highest radiation and total efficiency are up to 95.1% and 78.5% at 2.2 THz. The front-to-back ratio, angular width, and side lobe level of this antenna are 10.4 dB, 24.2°, and -6.3 dB on E plane and 10.4 dB, 39.6°, and -7.5 dB, respectively. On the contrary, when applying the Si hyper hemispherical lens, the broadband directivity and gain are increased to 22.3 dBi and 19.8 dBi. Besides, the radiation and total efficiency jump to 97% and 87.6%. The front-to-back ratio is 11.2 dB, and the angular width and side lobe level on E and H planes are 10.3°, 9.9°, and -11.9 dB. -9.8 dB, respectively. Fig.3 (a) shows the 3D radiation pattern of the realized gain. The E-field distribution inside the PCA is shown in Fig.3 (b), illustrating the propagation of THz pulses in the gap and the Si lens. The directivity, realized gain, and efficiency are all enhanced by Si hyper hemispherical lens because almost all the forward directed THz intensity can escape the PCA. With this, the emitted THz pulses are more focused and can reach further distance and save energy due to it having very low radiation on the side lobe.

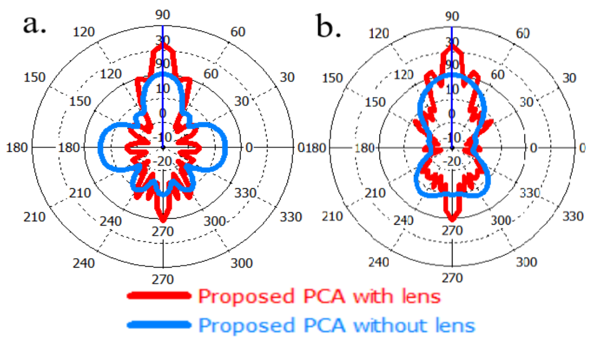

Fig.2. (a) E and (b) H plane radiation patterns of the proposed PCA directivity on the broadband from 1.5 THz to 3.5 THz

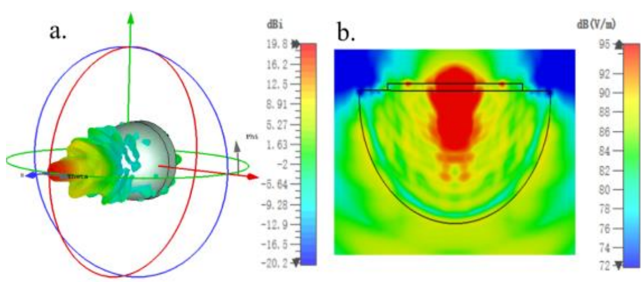

Fig.3. 3D radiation pattern of (a) realized gain (b) E-field distribution inside the proposed PCA.

In addition to the Si lens, the novel geometry of the PCA also plays a role in boosting the directivity and gain. The simulation results of the proposed PCA are illustrated in Table I. Moreover, several published PCA designs are reviewed for analogy. All data used in the comparisons are the best-observed results in corresponding research. Both the novel geometry structure and the hyper hemispherical lens make the proposed work obtain better performance.

TABLE I. COMPARISONS AMONG THE PROPOSED PCA WITH LENS, WITHOUT LENS, BOW-TIE, AND OTHER PUBLISHED PCAS

THz PCA geometric design	Directivity/dBi	Radiation (total) efficiency/%	Angular width/°	Frequency band/THz
Tai-Chi (lens)	22.3	97 (87.6)	10.3	1.5 ~ 3.5
Tai-Chi (no lens)	10.1	95.1 (78.5)	24.2	1.5 ~ 3.5
Tilting cross [8]	7.79	97.22	48.8	0.12-0.15
Bow-tie [9]	3.38	80	63.4	1.4 ~ 1.9
Patch [10]	8.29	NULL	NULL	0.345 ~ 0.48

IV. CONCLUSION

The proposed PCA is anticipated in future THz applications due to its high directivity and efficiency. A novel geometry design and a Si hyper hemispherical lens are developed to achieve high directivity. The results show that the proposed work covers a wide THz band from 1.5 to 3.5 THz and the directivity and realized gain are up to 22.3 and 19.8 dBi. The radiation and total efficiency are up to 97% and 87.6% in overall operating bandwidth. Figures of radiation and E-field distribution are provided to illustrate the high gain of the suggested structure. Compared to several recently published PCA designs, the proposed PCA has wider bandwidth and higher performance. Besides, the novel geometry structure of cultural content is also a significative feature that worths development. This PCA is regarded as a prospective candidate for future THz communications.

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