A circularly polarized wideband high gain antenna for THz wireless applications

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Abstract
For several years, the fields of new technologies have been experiencing a real boom. The use of the terahertz band is an appropriate solution to meet the requirements of these technology. However, this technology has special requirements among which its antennas must have high bandwidth of few THz and achieve high gain for high productivity. In this paper, we will focus on the design and analysis of an antenna for THz technology. The antenna structure proposed in this work has better performance in terms of bandwidth and gain. In fact, multiples slots were added to the antenna to enhance the antenna’s bandwidth. In addition, to enhance the antenna performance in terms of gain and protect the antenna feed line against environmental jeopardies a thin layer as superstrate is used. The suggested antenna covers a wide −10 dB bandwidth from 0.9 to 17.3 THz with a peak gain of 12.8 dBi. Moreover, a VSWR less than 2 at the operating band is obtained. Furthermore, the suggested antenna has circular polarized radiations with an axial ration (AR) less than 3 dB over a wide band 13.6–17.3 THz which mean that the proposed antenna is well suited for application where the transmitter and receiver are moving which is the most case for wireless system. Thus, the suggested THz antenna could be a successful choice for terahertz application like future high-speed short-range indoor wireless communication, explosive detections, arms detection, medical imaging, pharmaceutical analysis, and material characterization in the THz regime industrial inspections.

Keywords Terahertz antenna · Circular polarized antenna · Axial ratio · Right hand circular polarized antenna · Lift hand circular polarized antenna · Gain · Bandwidth · Front to back ration

1 Introduction

Wireless communications have undergone a significant evolution over the past decade through the development of a multitude of consumer standards and applications. Among these applications we can mention the use of THz bands (Lee et al. 2018; Lu et al. 2020). This technology opens up prospects to meet the current needs, but also those of the future,
when we will have several hundred billion connected objects, autonomous cars that we will use regularly and that we will consume even more videos of much better definition. This frequency range also has properties such as the ability to penetrate non-ionizing photons through optically opaque materials such as clothing, paper, cardboard, and many plastics or ceramics. For THz imaging, it is possible to detect hidden objects such as firearms and knives inside packages, clothes or mattresses. The purpose of THz technology is not only to meet the shortfalls related to bandwidth or increased throughput, but to obtain ultra-short latency, reduce energy consumption with ubiquitous quality service (Jeyakumar et al. 2022; Aghoutane et al. 2021). This frequency band has several advantages and makes it possible to target several applications such as "imaging, security, biomedical. For this, several research teams have focused on the realization of transceivers and antennas in this band in order to generate a signal and electronically control the radiation beam in order to dynamically orient it in a well-defined direction of space. In this work, we will focus on THz antennas.

Future generations of equipment will use increasingly high-performance antennas operating in the THz band (Tabatabaeian 2021; Torabi et al. 2022). Due to the short wavelengths of mmWave, large capacity antennas can be designed. The reasons why the scientific community is intensifying research in the development of antennas that can work effectively in the THz band (Shamim et al. 2021; Varshney 2021; Davoudabadifar and Ghalamkari 2019; Khan et al. 2020a, 2020b; Vijayalakshmi et al. 2021; Nissanov et al. 2021; Krishna et al. 2021; Singh and Singh 2021). In (Shamim et al. 2021) a microstrip patch antenna for wireless communication at terahertz bands is presented. The presented antenna shows a return loss $-59.97$ dB $0.72$ THz with an impedance bandwidth of $0.34$ THz. Varshney et al. have implemented numerically in Varshney (2021) a tunable DRA antenna for THz applications. The implemented antenna shows a $-10$ dB Impedance bandwidth of $0.067$ THz with a gain and radiation efficiency of $3.81$ dBi and $75\%$ respectively. In (Davoudabadifar and Ghalamkari 2019) a microstrip patch antenna is presented for terahertz applications. The presented antenna shows bandwidth of $1.24$ THz with a maximum gain of $5.72$ dBi. Khan et al. have proposed in Khan et al. 2020a a high-gain and ultrawide-band graphene-based patch antenna for the photonic crystal and dielectric grating application at terahertz frequency. The simulated antenna offers a $-10$ dB impedance bandwidth of $9.552$ THz along with a maximum gain of $21.22$ dB and a maximum radiation efficiency of $93.23\%$. In (Vijayalakshmi et al. 2021) a tri-band series fed microstrip two-element array multiple-input multiple-output antenna is implemented for Terahertz communications. The implemented antenna operates at $2.3$ THz, $3.2$ THz and $4.5$ THz with a bandwidth of $38$ GHz, $43$ GHz and $60$ GHz respectively. The presented antenna offers a gain around $5$ dBi in all the operating frequencies. Nissanov et al. (Nissanov et al. 2021) have presented in a THz microstrip array antennas. The presented antenna offers a maximum gain of $19.6$ dB with a $-10$ impedance bandwidth of $22$ GHz. In (Krishna et al. 2021) a compact wideband patch THz antenna is simulated. The simulated antenna shows a $-10$ dB impedance bandwidth ranging from $0.445$ to $0.714$ THz with a peak radiation efficiency of $97.3\%$, a peak gain of $5.7$ dBi, a maximum directivity of $6$ dB and a minimal VSWR of $1.1$. Singh et al. have proposed in Singh and Singh (2021) a 4 ports MIMO pentagonal terahertz patch antenna for multiple terahertz (THz) applications. The presented antenna is suggested to be used in high speed indoor communications, medical imaging, pharmaceutical analysis. The simulated antenna shows a maximum gain of $13.92$ dB and radiation efficiency of $85.77\%$. In (Khan et al. 2020b), a Graphene Patch Antenna for Terahertz Band Application is implemented. The presented antenna operates around $7$ THz with VSWR of $1.0003n$ a maximum gain of $7.286$ dB and radiation efficiency of $97.21\%$. 
Circular polarized antenna is also carried out for terahertz applications. These types of antenna are very attractive for wireless communications systems (Ran et al. 2022; Bagh-erii 2021; Guthi and Damera 2022; Thakur et al. 2022). For this reason, many researches have been conducted to design circular polarized antenna. In Shalini and Ganesh Mad-han (2021) circular polarized graphene-based patch antenna is presented and analyzed over terahertz frequencies. The presented antenna was analyzed in terms of axial ration (AR) bandwidth, returns loss, VSWR and gain. The presented antenna shows an axial ratio bandwidth of 0.5 THz, a maximum return loss of −22 dB, a VSWR less than 1.5 and again of 5.02 dBi. Vishwanath et al. (Vishwanath et al. 2021) have presented in a Circularly Polarized Antenna with the Higher Order Modes for Terahertz applications. The proposed antenna shows an impedance ranging from 3.3688 to 3.7232 THz with a 3 dB AR ranging from 3.6707 to 3.7379 THz. The simulated antenna provides a maximum gain of 8dBi and a maximum radiation efficiency of 80%.

In this work, a circularly polarized wideband high gain antenna for THz applications is proposed. The suggested antenna is designed on a 4-μm-thick silicon substrate mate-rial having a dimension of 29×50×4 μm³. To increase the total gain of the antenna and have a wider bandwidth and taking advantage of the functionality of circular polarization, we engraved several U-shaped, circular and square slots on a rectangular patch as well as we added T-shaped and semicircular slots on the ground plan. Moreover, to protect the antenna patch against environmental risks and enhancement of antenna gain, a thin layer of Copper (εr = 1) as superstrate is used. Apart from the thickness, the superstrate layer has the same dimensions as the feed line. The proposed antenna shows a wide bandwidth of 16.4 THz ranging from 0.9 to 17.3 THz with a peak gain of 12.8dBi. The VSWR of the proposed antenna is less than 2 in the operating band which mean that the proposed antenna achieved good adaptation. Besides, the proposed antenna is a Lift Hand Circular Polarized (LHCP). The advantage of circular polarized antenna is the emitting of the RF energy in a corkscrew fashion while a linear-polarized antenna concentrates RF energy in a narrow plane. For circular polarization, the corkscrew becomes larger when the distance between transmitter and receiver increase. The simulated results indicate a 3 dB axial ratio bandwidth (AR) of 3.7 THz which indicate that the proposed antenna is circular polarized over a wide band. Thanks to its high performance and to its exceptional properties, the suggested THz could be a successful choice for terahertz application.

2 Antenna design

As can be seen from Fig. 1, the designed circular patch antenna consists of a thin substrate layer mounted over a ground plane. The radiating circular patch is placed upon the sub-strate, and microstrip line is used for feeding. Figure 1a shows a thin superstrate layer is placed upon the microstrip line to protect the feed line against environmental jeopardies and enhancement of antenna gain. Apart from the thickness, the superstrate layer has the same dimensions as the feed line. Figure 1b, c shows the top view and the bottom view of the antenna without superstrate layer.

The design development of the required configuration initially starts with the modeling of a single element patch antenna. Then, the basic patch antenna was modified by incor-portation multiples slots on the resonator element as well as on the ground plan. A thin layer is added as superstrate as shown in Fig. 1a. The side view of the proposed structure is depicted in Fig. 1a. The antenna parameters are shown in Table 1.
3 Results and analysis

In this section, the performance of the suggested antenna is analyzed. The geometry of the proposed antenna is shown in Fig. 1. The top plane of the proposed antenna contains multiples circular, square and U-shaped slots loaded resonator elements. The back plane consists of T-shaped ground plane with semicircular shaped slots to enhance the performance of the proposed antenna. The antenna is integrated on a $29 \times 50 \times 4\,\mu m^3$ Silicon substrate. A superstrate of copper is used to protect the feed line. The final structural parameters are shown in Table 1. The performance of the development design is presented and discussed in the subsequent sections.

3.1 Parametric study

In this section, a parametric study on the radius of circle will be performed in order to get the optimal parameters. Firstly, the reflection coefficient of the antenna will be simulated.

![Antenna geometry, a side view, b top view, c back view](image)

**Table 1** Antenna dimensions

| Dimensions                  | Values (µm) | Dimensions                  | Values (µm) |
|-----------------------------|-------------|-----------------------------|-------------|
| Substrate length (L)        | 50          | r = D/2                     | 2.3, 2.5, 2.7|
| Superstrate length (Lu)     | 15          | W1                          | 4.75        |
| Substrate width (W)         | 29          | W2                          | 14          |
| Superstrate width (Wu)      | 3           | W3                          | 3.5         |
| Substrate height (h)        | 4           | W4                          | 7.5         |
| Superstrate height (hu)     | 4.5         | W5                          | 5           |
| Microscript feed lineht (Lf)| 15          | L1                          | 4.5         |
| Microscript feed width (Wf) | 3           | L2                          | 26          |
| Patch length (Lp)           | 25          | L3                          | 4           |
| Patch width (Wp)            | 21          | L4                          | 3           |
| Ground plan width (Wg)      | 21          | L5                          | 5           |
| Ground plan length (Lg)     | 37.5        | L6                          | 22          |
Figure 2a shows the S11 for three values of radius $r = 0.3, 0.5, 2.7 \, \mu m$. From this figure, it can be observed that when $r = 2.7 \, \mu m$ and $2.5 \, \mu m$ the antenna performs better, in terms of bandwidth and return loss, than the other cases. When $r = 2.7 \, \mu m$, the antenna covers the band ranging from 0.7 to 17.1 THz (16.4 THz) while the antenna with $r = 2.5$ covers the band ranging from 0.9 to 17.3 (16.4 THz). For $r = 2.3$, the antenna offers a bandwidth of 15.4 THz ranging from 2.1 to 17.5. Besides, the VSWR of the antenna is depicted in Fig. 2b. We can notice from Fig. 2 that when $r$ equal to 2.5 $\mu m$ and 2.7 $\mu m$ the antenna performs better than the case where $r = 2.3 \, \mu m$. The VSWR of the antenna is less than 2 over the whole band for $r = 2.5 \, \mu m$ and 2.7 $\mu m$ while the VSWR less than one over the band [2.1–17.5 THz]. We notice also there is a slight difference between $r = 2.5 \, \mu m$ and $r = 2.7 \, \mu m$.

In order to get the optimal value of $r$ we will simulate the antenna gain versus frequency. Figure 3a shows the gain of the antenna versus frequency for different values of $r$ and Fig. 3b is its zoom. We can divide Fig. 3b in three bands. First band when
frequency is less than 11 THz. In this band, $r = 2.7$ gives the best result among the others cases with a peak gain of 12.4dBi. The second band is the band when frequency is between 11 and 14.8 THz. In this second band, $r = 2.5 \, \mu m$ shows the best result with a peak gain of 12.8dBi. in the third band, i.e., when frequency more than 14.8 the antenna performs better when $r = 2.3 \, \mu m$ and the worst case is $r = 2.7 \, \mu m$. From the above discussion we can notice that when $r = 2.5 \, \mu m$ the antenna performs better in term of gain because it present high gain over a large range of frequencies. In addition the S11 of $r = 2.5 \, \mu m$ and $r = 2.7 \, \mu m$ are slightly the same. Table 2 summarize the antenna performance on terms of return loss, bandwidth, gain and VSWR. From this analysis we can conclude that the optimal value is $r = 2.5 \, \mu m$. In the next, the performance of the proposed antenna when $r = 2.5 \, \mu m$ will be analyzed in term of radiation, axial ration, front to back ration and nature of polarization.

Fig. 3 Gain versus frequency of the antenna for different value of $r$, gain over the whole band a and its zoom b
3.2 Performance of the proposed CP antenna

Figure 4 shows the front to back ration of the proposed antenna. Indeed, the FBR gives information about the privilege direction of the antenna. From Fig. 4, we notice that the value FBR depends strongly on the frequency, this value is about 20 at 4 THz and it is of about 2.5 at 8.2 THz. This result indicate that the proposed antenna performs better in some frequencies in terms of radiation.

To characterize and analyze the proposed antenna, we will simulate the axial ration. Because the value of AR determines the nature of the polarization. If the AR value less than 3 dB, then the polarization will be circular, if the AR finite value the polarization will elliptical if the AR value equal to infinite the polarization will be linear. We depicted in Fig. 5 the AR versus frequency.

It can be seen clearly that the proposed antenna is circular polarized over a wide band. According to 3 dB bandwidth the antenna is circular polarized over the band 13.4–18 THz. This later will be greater if we adopt 6 dB bandwidth (12.5–18 THz) for AR. So, Fig. 5 confirms the circular nature of polarization of the proposed antenna. This property is very interesting in wireless communication, because the advantage of circular polarized antenna is the emitting of the RF energy in a corkscrew fashion which allow to signal to be transmitted effectively to the receiver. But, a linear-polarized antenna concentrates RF energy in a narrow plane. For circular polarization, the corkscrew becomes larger when the distance between transmitter and receiver increase.

| Proposed antenna | S11 (dB) | −10 dB bandwidth (THz) | Peak gains (dBi) | VSWR |
|------------------|---------|------------------------|-----------------|------|
| r=2.3            | −13     | [2.1, 17.5] = 15.4     | 9.2             | <2   |
| r=2.5            | −21.9   | [0.9, 17.3] = 16.4     | 12.8            | <2   |
| r=2.7            | −26.2   | [0.7, 17.1] = 16.4     | 12.4            | <2   |

Table 2 Simulation results of the designed antennas

Fig. 4 Front to Back Ration versus frequency
Another parameter will be studied in this work which is the direction of rotation of the emissions. Indeed, if the antenna is left-hand circular polarization (LHCP) the truncated edge will be on the right side of the feeding point and if the truncated edge is on the left side of the feeding point, right hand circular polarization (RHCP) emission is obtained. We depicted in Fig. 6 the RHCP and LHCP as function of frequency. It is clear from this figure that the proposed antenna is LHCP over a wide band from 10 to 17.5 THz. The difference between LHCP and RHCP attains 30 dB at 16 THz but in some cases is about 7 dB like the case at 12 THz.

Figure 7 shows the LHCP and RHCP as a function of theta. It can be observed from Fig. 7 that the antenna has LHCP emission which confirm the results obtained in Fig. 6.

The circular polarization wave has obvious advantages. Indeed, its symmetrical structure, which has no privileged plane, adapts very rationally to devices of revolution, which
makes it possible to effectively use their entire surface, and to obtain a better directional power. If the traversed medium or the reflecting surfaces have a structure that disadvantages one of the components of the wave, the other component will always be received regardless of the orientation of its polarization plane, an interesting property in radiodetection, and which also makes it possible to use such devices for studying the analyzing properties of the traversed media.

Furthermore, a device emitting a wave rotating in a certain direction cannot receive the wave rotating in the opposite direction, a property that can be taken advantage of in certain particular cases. In short, the circular polarized antennas have this advantage in spite of the linear polarized antennas which have as drawback the difficulty of alignment between the linear polarized signals because of the characteristics of the THz channel which disturb the polarization due to multiple reflections, diffractions and diffusion. On the other hand, in order to detect objects independently of their orientations, the antenna must have circular polarization. Thus, the radiation of a wave with circular polarization is often of interest in order to remedy the depolarization phenomena that may appear during propagation. The radiation of a circular polarization is also often requested and particularly in the space field. For these reasons, the proposed antenna is more suitable for THz application for application where transmitter and receiver are moving.

### 3.3 Electric field distributions

Figure 8 investigate and display the surface current distribution of the proposed circular polarized antenna at 1.2, 3, 5 and 12 THz. It can be noted from Fig. 8 that the circulations of the distributed currents are much intensified near to the feed line for the four considered frequencies. Besides, for 1.2 THz the electric field is intensified in feed line but not in the patch. Also, the current distribution at 3 THz which is the resonance frequency and at 12 THz which is the frequency of the highest gain is very strengthened than the other frequencies. In the next section, the performance of the proposed antenna will be compared with other work in literature.
Fig. 8  Surface current distribution of the suggested circular polarized antenna at
(a) 1.2 THz, (b) 3 THz, (c) 5 THz, (d) 12 THz
4 Comparison

The suggested antenna is compared with some recently developed THz antennas in Table 3. The proposed CP antenna is designed for THz applications and there is a lack of such work because there is few work which deal with CP antennas. For this reason, the performance of the suggested antenna is compared with both linear and CP THz antennas. In this paper, a very wide bandwidth along with high gain is achieved as compared to the previous works. Besides, the circular polarization property of the proposed antenna will moderate the polarization mismatch losses that occur during the transmission between transmitter and receiver. In Table 2, a comparison between this work and some recent work is carried out.

5 Conclusion

In this paper, we proposed a CP antenna for THz applications. The proposed antenna has very wide bandwidth along with high gain. Besides, the suggested antenna has circular polarized radiations with an AR value less than 3 dB over the band 13.6 –17.3 THz. So that, the antenna take profit from its circular polarization property which allow the antenna to be suitable for wireless THz application where the transmitter and receiver are moving. The antenna, having a total dimension of 29×50×4 µm³, is designed by using two substrates material. The low profile, compact size, very wide bandwidth, high gain, circular polarization and desired directional radiation patterns confirm the applicability of the proposed antenna for the THz wireless system.

| Refs. | Bandwidth (THz) | Gain (dBi) | AR bandwidth | Operating band |
|-------|----------------|-----------|--------------|---------------|
| Shamim et al. (2021) | 0.34 | – | – | [0.535–0.84] |
| Varshney (2021) | 0.067 | 3.81 | – | [4.0629–4.1299] |
| Davoudabadifarahani and Ghamalakami (2019) | 1.24 | 5.72 | – | [0.434–1.684] |
| Khan et al. (2020a) | 9.552 | 21.22 | – | [0.448 THz–10] |
| Vijayalakshmi et al. (2021) | 0.06 | 5 | – | – |
| Nissanov et al. (2021) | 0.022 | 19.6 | – | – |
| Krishna et al. (2021) | 0.269 | 5.7 | – | [0.445–0.714] |
| Singh and Singh (2021) | 2 | 13.92 | – | Lu et al. (2020), Jeyakumar et al. (2022) and Aghoutane et al. (2021) |
| Khan et al. (2020b) | 0.386 | 7.286 | – | [6.8–7.186] |
| Shalini and Ganesh Madhan (2021) | 3.5 | 5.02 | 0.5 | [1.5–5] |
| Vishwanath et al. (2021) | 0.35 | 8 | 0.067 | [3.3688–3.723] |
| This work | **16.4** | **12.8** | **3.7** | **[0.9–17.3]** |

Bold to indicate that these values are for the presented work
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Data availability All the data generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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