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Research Article

Sub-THz Antenna for High-Speed Wireless Communication Systems

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Terahertz (THz) links will play a major role in high data rate communication over a distance of few meters. In order to achieve this task, antenna designs with high gain and wideband characteristics will spearhead these links. In this contribution, we present different antenna designs that offer characteristics better suited to THz communication over short distances. Firstly, a single-element antenna having a dipole and reflector is designed to operate at 300 GHz, which is considered as a sub-terahertz band. That antenna achieves a wide impedance bandwidth of 38.6% from 294 GHz to 410 GHz with a gain of 5.14 dBi. Secondly, two designs based on the same dipole structure but with added directors are introduced to increase the gain while maintaining almost the same bandwidth. The gains achieved are 8.01 dBi and 9.6 dBi, respectively. Finally, an array of 1×4 elements is used to achieve the highest possible gain of 13.6 dBi with good efficiency about 89% and with limited director elements for a planar compact structure to state-of-the-art literature. All the results achieved make the proposed designs viable candidates for high-speed and short-distance wireless communication systems.

1. Introduction

Over the last few years, wireless data traffic has been drastically increasing due to a change in the way today's society creates, shares, and consumes information. This change has been accompanied by an increasing demand for much higher speed wireless communication anywhere at any time. In particular, wireless data rates have doubled every eighteen months over the last three decades and are quickly approaching the capacity of wired communication systems. Following this trend, wireless terabit-per-second (Tbps) links are expected to become a reality within the next five to ten years [1]. Advanced physical layer solutions and, more importantly, new spectral bands will be required to support these extremely high data rates [2].

Terahertz (THz) and sub-THz communication refers to the use of the band that covers region from (0.1–10) THz and sub-THz region is covered from (0.1–0.3) THz [1].

THz communication links will play a major role in which very high data rates are required over short distances. Terahertz band can be used for high-speed data transmission within a range of 10 m. This coverage area consists of small cells of cellular networks. Terahertz communication is applicable in the indoor as well as outdoor environments with stationary and mobile users. Terabit wireless local area networks (T-WLAN) can provide flawless communication between high-speed fiber optical links and personal laptops and tablets. Wired and wireless links enjoy the same speed in terahertz communication [2]. Very high path loss is imposed as one of the main challenges at THz band frequencies, which poses a major constraint on communication distances. Additional challenges range from the implementation of compact high-power THz band transceivers, the development of efficient ultra-broadband antennas at THz Band frequencies, and characterization of the frequency-selective path loss of the THz band channel to the development of novel

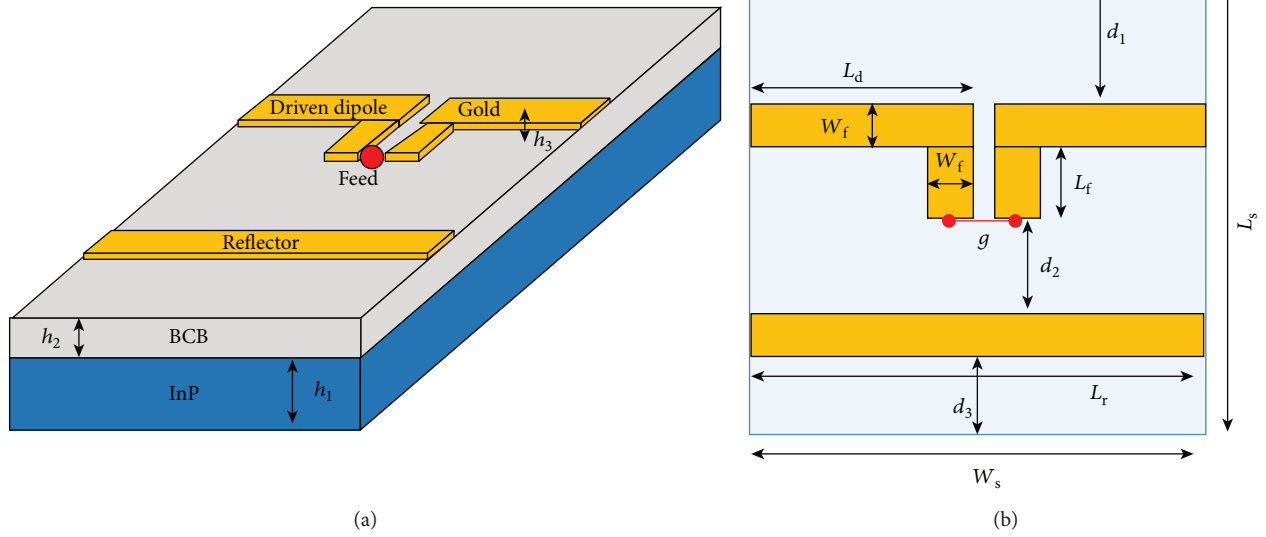


FIGURE 1: Geometric design of single-element dipole antenna: (a) perspective view and (b) front view.

TABLE 1: Optimized dimensions of single-element dipole antenna.

| Dimensions | Value (μm) |
|------------|-------------------------|
| d_1 | 78 |
| d_2 | 116 |
| d_3 | 82 |
| h_1 | 50 |
| h_2 | 6 |
| h_3 | 2 |
| g | 4 |
| L_f | 35 |
| L_r | 280 |
| L_d | 115 |
| W_f | 10 |

modulations, transmission schemes, and communication protocols tailored to the peculiarities of this paradigm. Many of these challenges are common to mm-wave communication systems, and as a result, the THz band is not yet regulated [3].

One of the major advantages of THz and sub-THz frequencies is the antenna size, which reduces to about sub-millimeter [4]. The implementation of these systems is now possible due to the advancements in the realization of the photonic and semiconductor devices with an operating frequency in the terahertz band. A common approach is to design the antenna in a low loss substrate and then integrate it to the active devices. On-chip antennas are easily integrated to the rest of the system but they have lower efficiencies due to the lossy substrate [5–7]. The substrate integration technology, one of the technologies used in THz, converts nonplanar antenna structures into their planar forms. Advanced microfabrication techniques are adopted for the design of terahertz antennas. Some of the substrate-

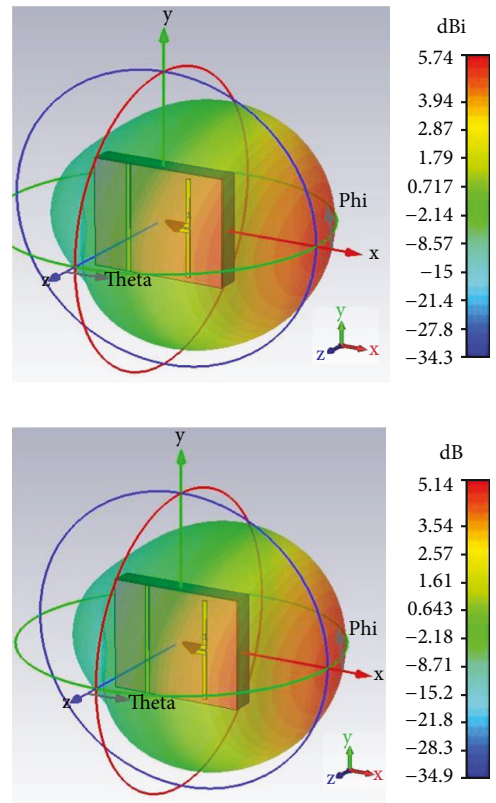


FIGURE 2: Reflection coefficient (S_{11}) and gain (dB) of single-element dipole antenna.

integrated antenna structures used in THz technology are slot array, dipole, reflector, horn, and leaky wave antennas [8]. For the sub-THz designs, high gain with compact size and wide bandwidth is preferred. Some antennas have been presented in literature such as in [9] where authors presented three antenna designs (rectangular horn, Cassegrain,

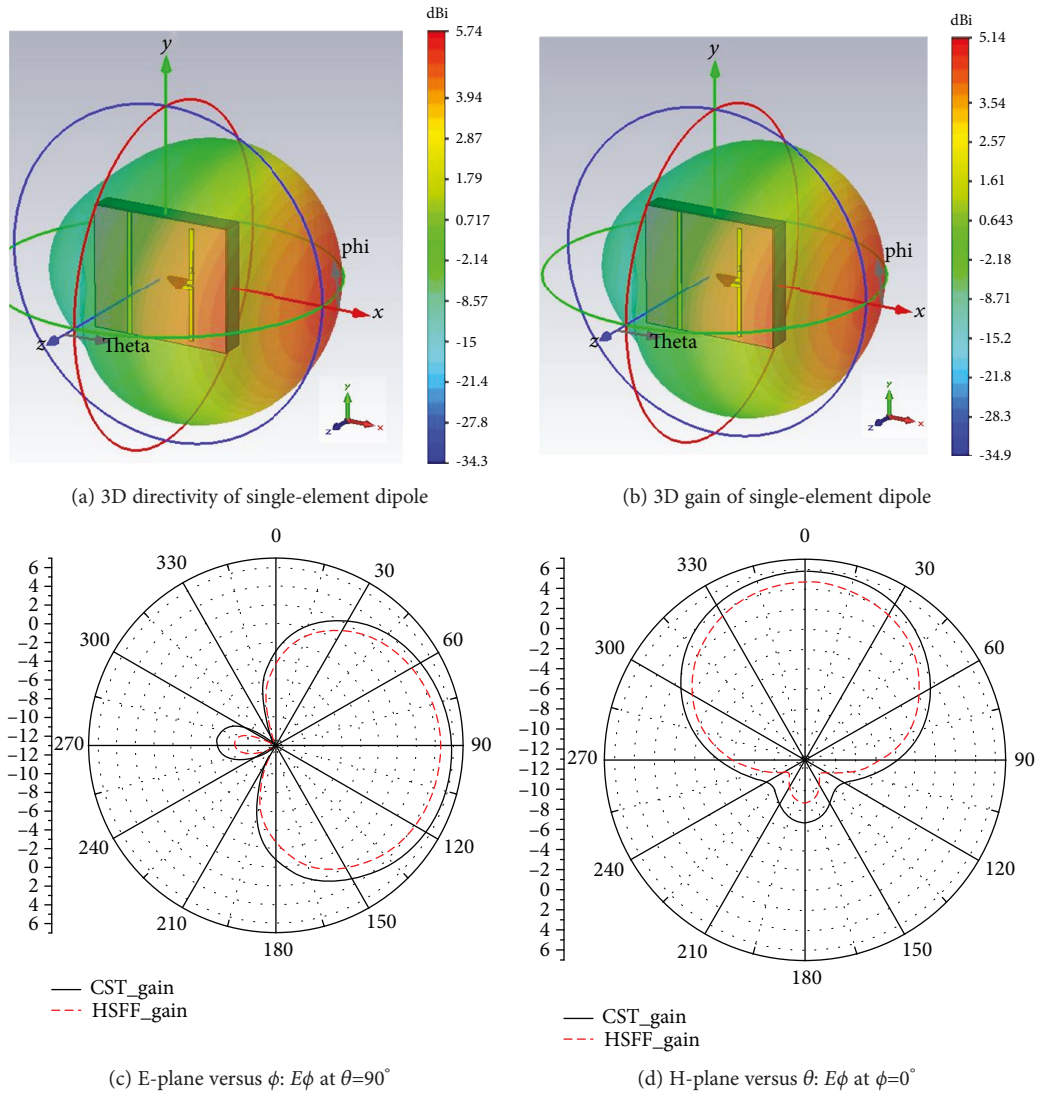


FIGURE 3: Radiation pattern of the single-element dipole antenna at 300 GHz: (a) 3D directivity, (b) 3D gain, (c) E-plane, and (d) H-plane.

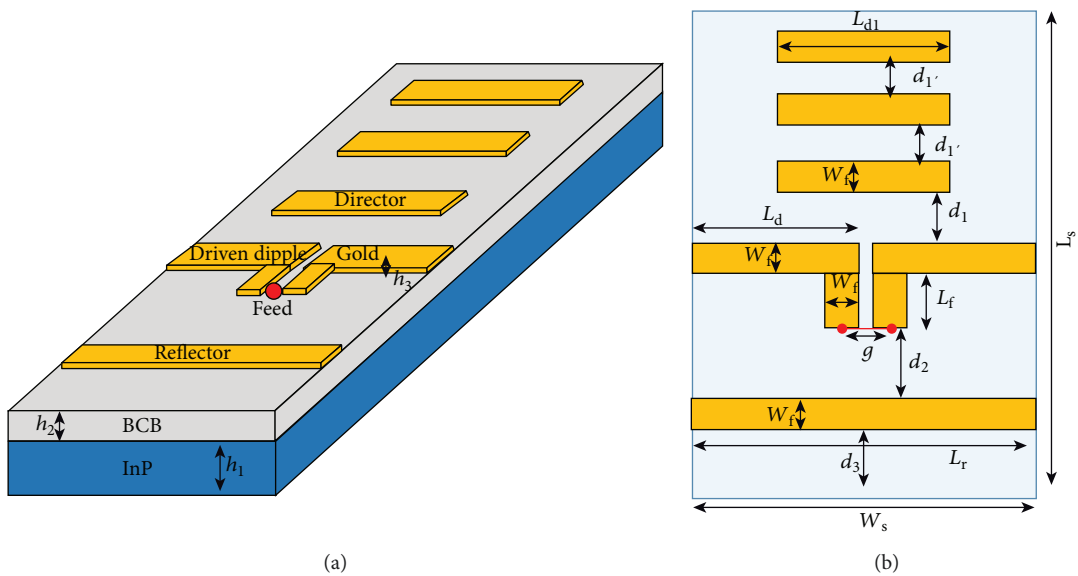


FIGURE 4: Geometric design of single-element dipole antenna with 3 directors: (a) perspective view and (b) front view.

TABLE 2: Optimized dimensions of single-element dipole antenna with 3 directors.

| Dimensions | Value (μm) |
|------------|-------------------------|
| d_1 | 135 |
| d_2 | 164 |
| d_3 | 116 |
| d_4 | 125 |
| L_{d1} | 150 |
| L_s | 822 |

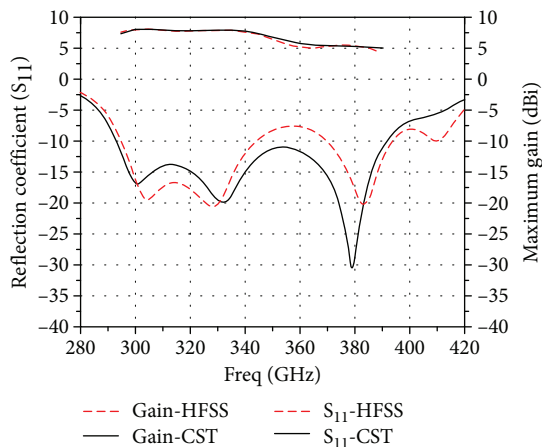


FIGURE 5: Reflection coefficient (S_{11}) and gain (dB) of single-element dipole antenna with 3 directors.

and off-set parabolic type) for achieving high gain characteristics at 300 GHz. They were able to achieve gains of around 25 dBi for alleviating link noises, but the size was not compact enough. Similarly, authors in [10] presented a rectangular cavity design based on InP substrate having multilayers. They achieved a wide impedance bandwidth of 38 GHz around the center frequency of 300 GHz with limited gain of 4 dBi. In [11], authors used CMOS on-chip technology to design a broadband sub-THz antenna. Four resonators were placed in top of a microstrip patch antenna. The authors were able to achieve a fractional bandwidth of 10% with radiation efficiency of 15% at the center frequency. The complications were in the manufacturing and measuring capability as every step is needed to be as precise as possible.

With the above literature review discussion, it can be seen that possibilities of designing sub-THz antenna at 300 GHz are a lot but limitations are presented in terms of trade-off between acquiring wide bandwidths, high gain, and complex structures. In this paper, we propose a simple antenna design solution that presents better results in terms of wide bandwidth and high gains at the sub-THz band. We propose a single-element design based on dipole technology that offers a much wider bandwidth and acceptable gain. Next, we introduce different radiating directors and array design to increase the gain of the structure while maintaining a compact size and wide bandwidth.

2. Antenna Designs and Results

The following sections will discuss the antenna design geometry and its simulation results performed in electromagnetic simulator CST Microwave Studio [12] with verifications done on commercially available simulator HFSS [13]. For all the designs, i.e., single element, enhanced gain with 3 directors, enhanced gain with 5 directors, and the array, the substrate materials used were indium phosphide (InP) and benzocyclobutene (BCB).

2.1. Single-Element Dipole with a Reflector. The geometry of the proposed single-element design is depicted in Figure 1. The perspective and front views are presented. The single-element design is based on a dipole antenna resonating at the center frequency of 300 GHz. A reflector element is placed behind the dipole. Both of the elements are made with gold as a conducting material with conductivity $\sigma = 4.561 \times 10^7$ S/m. The placement of reflector is for the purpose of increasing the directivity and gain of the single-element antenna. Its distance is approximately $\lambda/4$ from the dipole element at the center frequency. All the conducting elements, starting from the bottom layer to top, are placed on InP and BCB substrates. BCB has electrical properties of permittivity (2.5) and loss tangent (0.005) while InP has permittivity (12.5) and loss tangent (0.003) [11], respectively. The whole antenna occupies a small footprint of $L_s \times W_s = 322 \times 280 \times 58 \mu\text{m}^3$. The remaining optimized dimensions of the single-element design are listed in Table 1.

Figure 2 shows the simulated results in terms of reflection coefficient (S_{11}) and gain (dBi) of the proposed single-element dipole antenna. The results have been verified with another simulator HFSS. The similarity between them confirms the design scenario and its output results. The antenna covers a wide impedance bandwidth of 116 GHz (294-410 GHz) with the gain of 5.14 dBi at the center frequency of 300 GHz. Since the antenna is placed parallel to the y -axis, it should radiate in the end-fire direction (x -axis) as per E -field excitation and it is also evident by the placement of reflector.

The antenna radiation pattern in terms of directivity and gain is depicted in Figures 3(a)–3(b). The 3D pattern confirms its radiation in the end-fire direction with the directivity and gain of 5.74 dBi and 5.14 dBi, respectively, while the polar plots in both the E -plane and H -plane are depicted as well in Figures 3(c)–3(d). The E -plane (xy or $\theta = 90^\circ$) presents the antennas side lobe levels at -12.4 dB and angular beam width of 123.37° . Similarly the H -plane (xz or $\theta = 0^\circ$) has a side lobe levels of -12.4 dB and angular beam width of 97.9° . Here again, HFSS was used to confirm the simulation results. Good efficiency is obtained and it is about 87%.

Although the proposed single-element dipole antenna produced a wide bandwidth response, but the gain was not enough for sub-THz design. In order to increase the gain of the antenna while maintaining the same wider bandwidth, the next subsections will discuss the effects of adding conducting radiators or directors to the design especially in front of the main driven element.

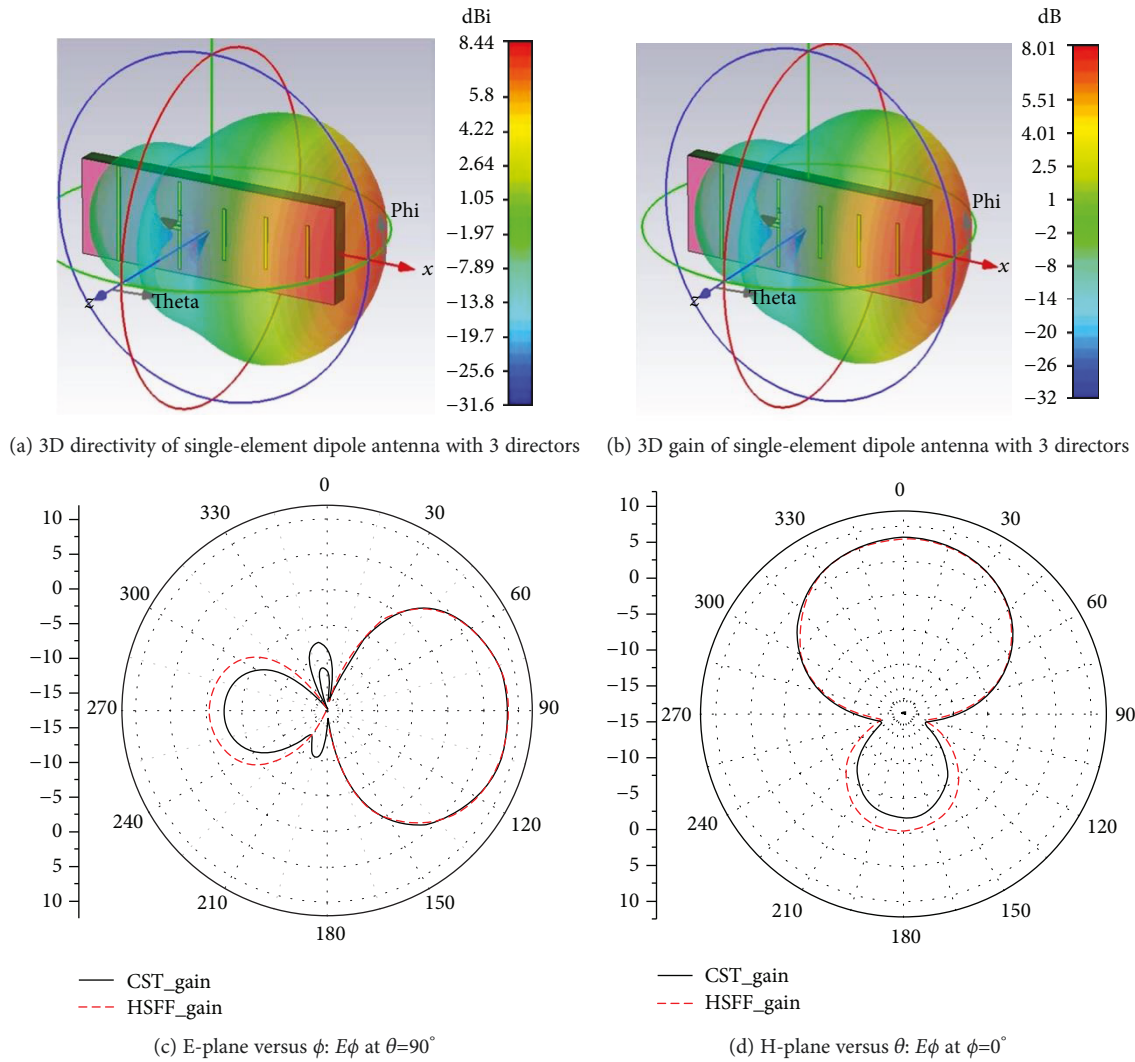


FIGURE 6: Radiation pattern of the single-element dipole antenna with 3 directors at 300 GHz: (a) 3D directivity, (b) 3D gain, (c) E-plane, and (d) H-plane.

2.2. Single-Element Dipole with 3 Directors. The geometric design of the single-element dipole with three directors made of the same conducting material, i.e., gold, is depicted in Figure 4. The same substrate materials InP and BCB have been utilized. Most of the dimensions are the same as was for the single-element design. The addition in terms of dimensions is listed in Table 2.

With these optimized dimensions, the antenna provides an impedance bandwidth of 98 GHz (293-391 GHz) with a gain of 8.01 dBi which can be seen in Figure 5. Optimization was done in such a way that almost wide bandwidth is maintained. The introduction of three directors placed at certain distances proved to be worthy in terms of achieving better gain.

This achievement can be seen from the radiation pattern results in the 3D and 2D polar plots depicted in Figures 6(a)–6(d). At the center frequency of 300 GHz, the antenna radiates with the directivity and gain of 8.44 dBi and 8.01 dBi, respectively. In this case, the efficiency is much better to the last dipole and it is about 90%. From the polar plots, the E-plane has a side lobe levels of -10.8 dB and angular beam width of 77.9°. The H-plane on the other hand offers

a side lobe levels of -10.8 dB and angular beam width of 76.7°.

2.3. Single-Element Dipole with 5 Directors. In order to further increase the gain of the antenna while keeping the size compact and bandwidth wider, two more directors were added to the previous design thus forming the 5-director single-element dipole antenna. Its geometric design with optimized dimensions is presented in Figure 7 and Table 3, respectively.

The antenna was able to maintain a wide bandwidth around 82 GHz (294-376 GHz) and gain of 10.2 dBi which can be seen in Figure 8.

With 5 directors in place, the antenna further enhanced the performance with better gain results. Figures 9(a)–9(d) show the radiation pattern of the antenna in 3D and 2D plots at the center frequency of 300 GHz. The antenna radiates with the directivity and gain of 10.2 dBi and 9.61 dBi, respectively. Due to a number of metallic element, the efficiency is reduced compared to the 3 directors but it remains good and it is about 87.3%.

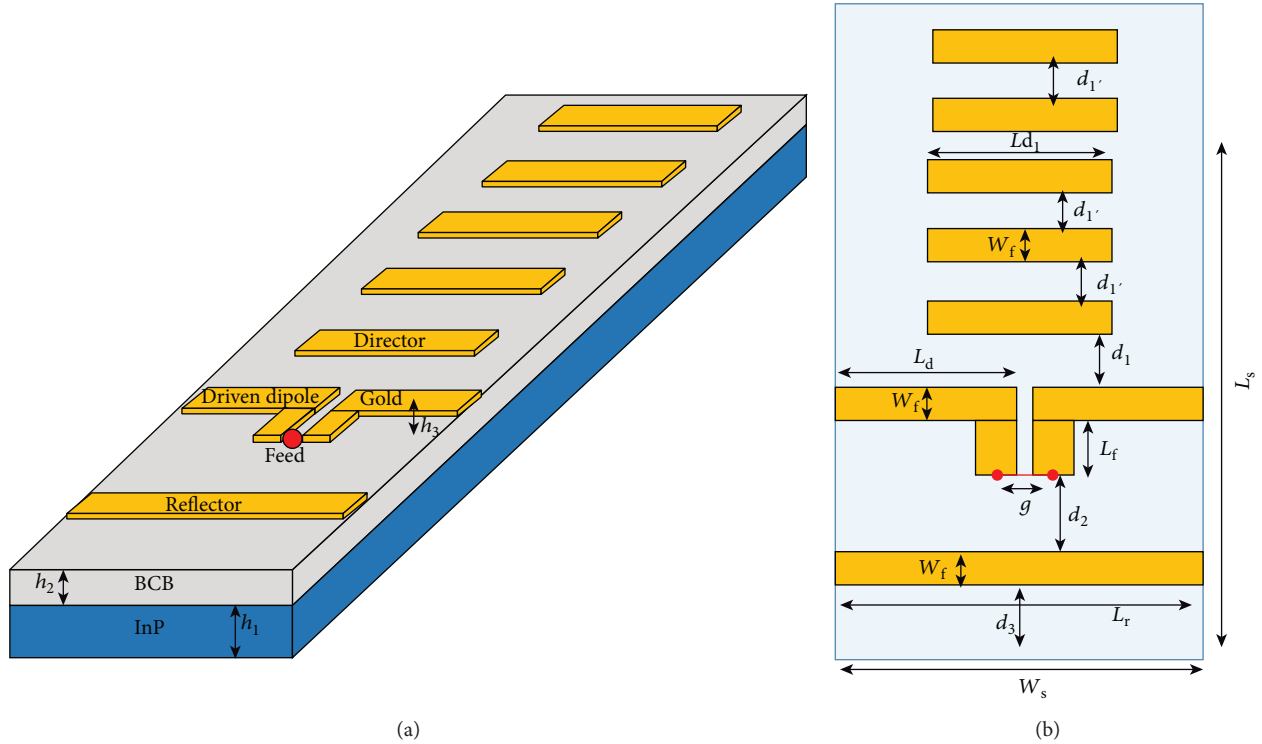


FIGURE 7: Geometric design of single-element dipole antenna with 5 directors: (a) perspective view and (b) front view.

TABLE 3: Optimized dimensions of single-element dipole antenna with 5 directors.

| Dimensions | Value (μm) |
|------------|-------------------------|
| d_2 | 188 |
| d_3 | 92 |
| L_s | 1122 |

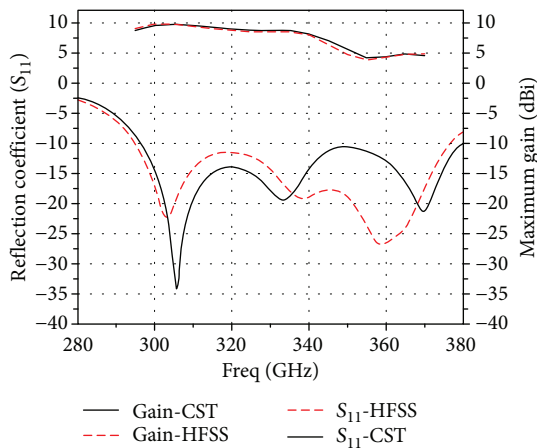


FIGURE 8: Reflection coefficient (S_{11}) and gain (dB) of dipole antenna with 5 directors.

From the polar plots, the E-plane has a side lobe levels of -13.3 dB and angular beam width of 63° . The H-plane on the other hand offers a side lobe levels of -13.9 dB and angular beam width of 62.7° .

3. Array Design and Results

Final design improvement was done to the single element with 5 directors in terms of presenting a linear array structure. Figure 10 presents the geometric dimensions of the 1×4 linear array with individual excitation. The geometric dimensions were the same as the single-element dipole with 5 directors provided earlier in Table 3. The distance between the array elements ($m = 220 \mu\text{m}$) was less than $\lambda/2$ which gave good isolation among the radiators.

The array provided with a wide impedance bandwidth of 82 GHz (294-376 GHz), better mutual coupling of -20 dB and increased gain of 13.6 dBi. Figure 11 presents the reflection coefficient and mutual coupling coefficient results along with achieved gain at the center frequency of 300 GHz.

Figure 12 shows the gain improvements by depicting the radiation patterns of the 1×4 array at the center frequency of 300 GHz. The array achieves directivity and gain of 14.1 dB and 13.6 dB, respectively. The efficiency remains good and it is about 89%. Of course, the final efficiency will depend to feeding array losses. From polar plots, the E-plane has side lobe levels of -10.2 dB and angular beam widths of 55° while the H-plane has side lobe levels of -11.3 dB with angular beam widths of 23.3° .

4. Conclusion

For sub-THz applications working at 300 GHz, we have proposed a single element and an array design based on the dipole technology. The single-element dipole achieved a wide impedance bandwidth of 38% (294-410 GHz) with a gain of 5.14 dBi as compared to other similar works

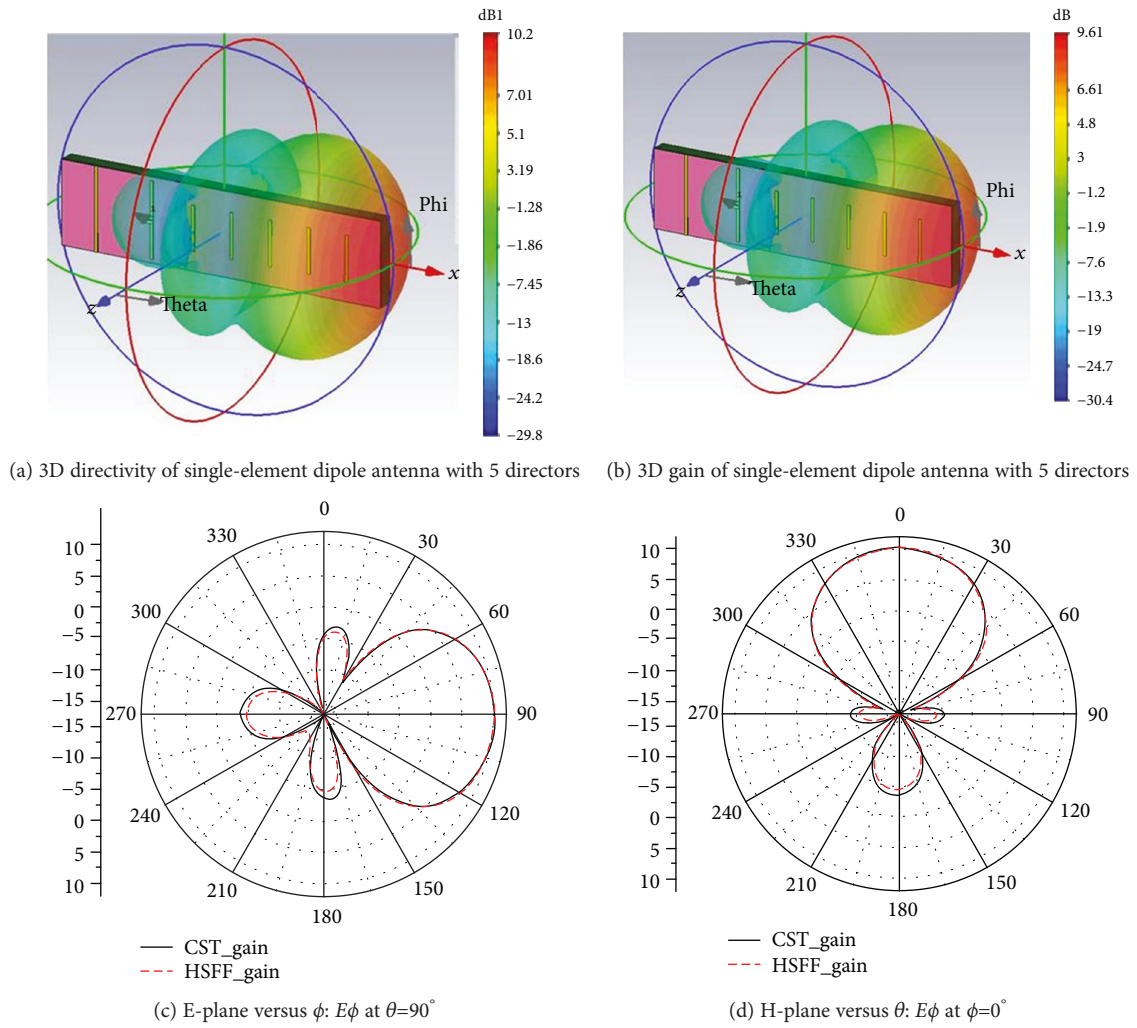


FIGURE 9: Radiation pattern of the single-element dipole antenna with 5 directors at 300 GHz: (a) 3D directivity, (b) 3D gain, (c) E-plane, and (d) H-plane.

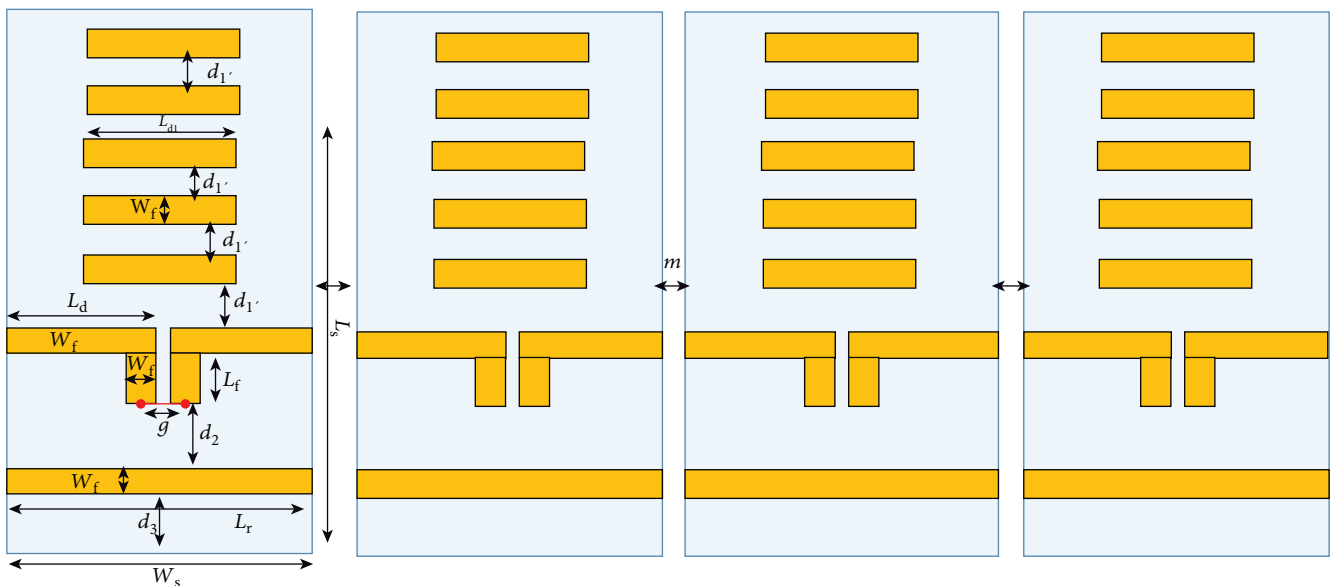


FIGURE 10: Geometric design of 1×4 array having single-element dipole antenna with 5 directors.

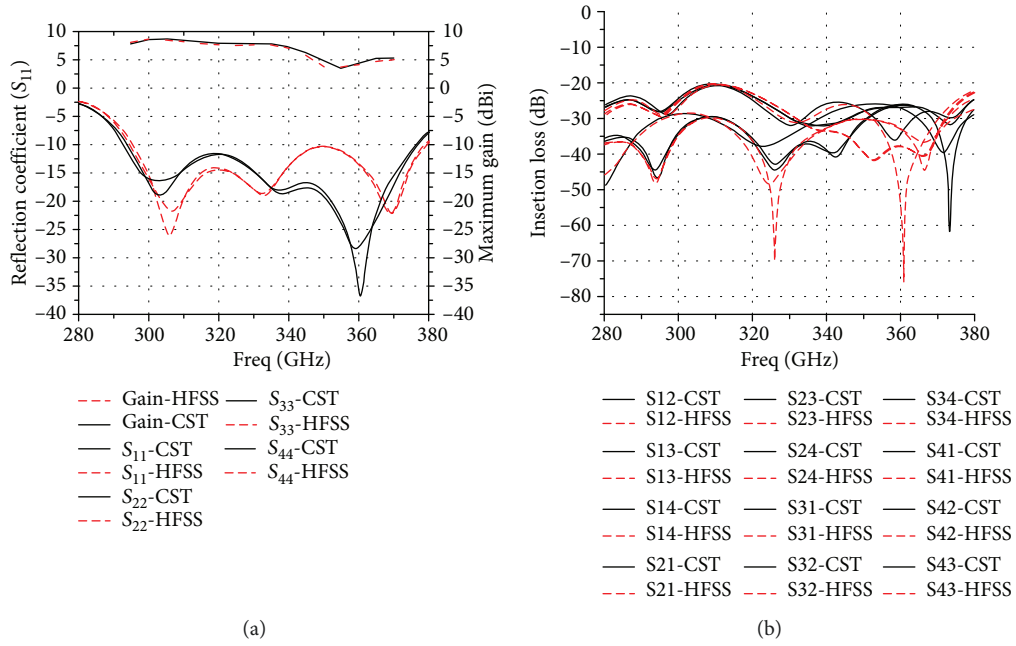


FIGURE 11: 1×4 array dipole antenna with 5 directors: (a) reflection coefficient (S_{nn}) and gain (b) mutual coupling coefficient (S_{mn}).

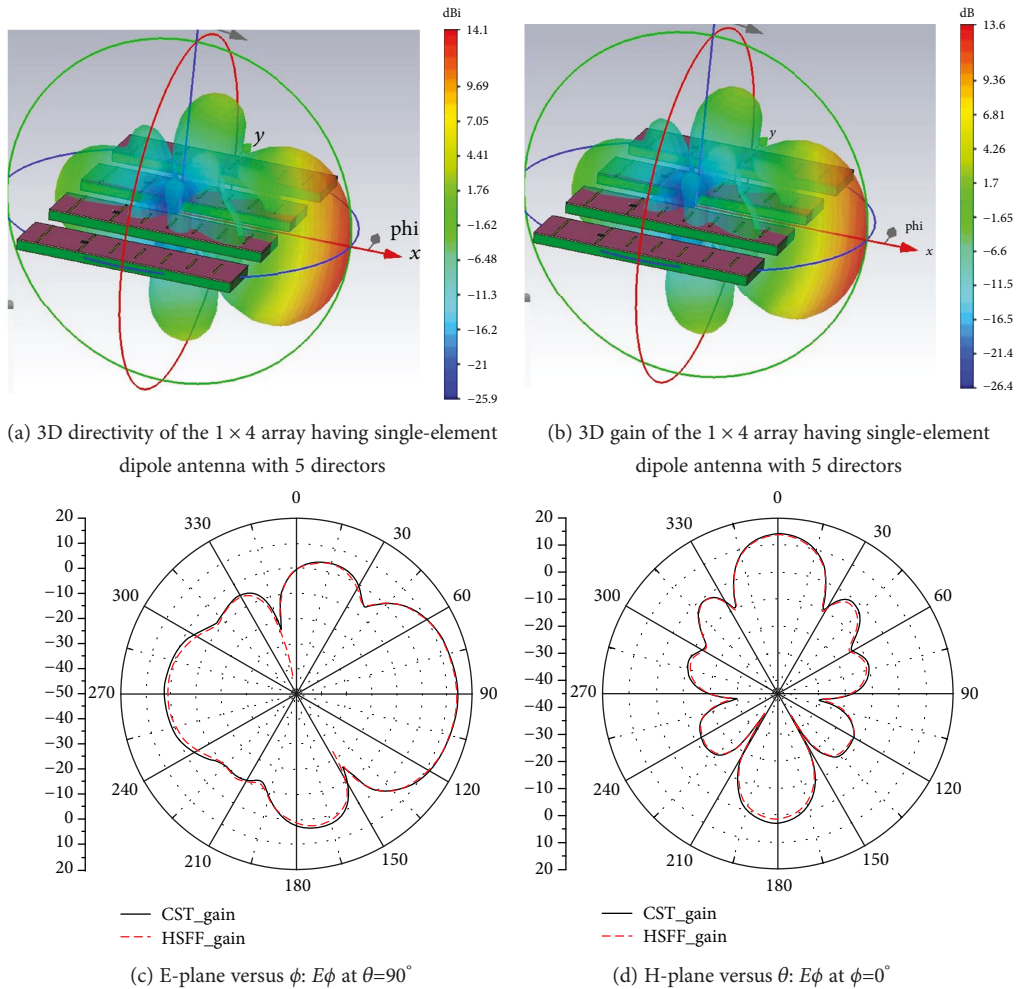


FIGURE 12: Radiation pattern of the 1×4 array having single-element dipole antenna with 5 directors at 300 GHz: (a) 3D directivity, (b) 3D gain, (c) E-plane, and (d) H-plane.

TABLE 4: Comparison of the single-element design with similar state-of-the-art work on sub-THz designs at 300 GHz.

| Ref. | B.W. (GHz) | Max gain (dBi) | Layers | Dimensions (μm^3) |
|-----------|------------|----------------|------------|--------------------------------|
| [14] | 270-330 | 4 | Multi | $1130 \times 1130 \times 610$ |
| [15] | 270-320 | 7.35 | Multiarray | $2550 \times 1217 \times 18$ |
| [16] | 220-325 | 8.8 | Multi | $2000 \times 2000 \times 100$ |
| This work | 293-410 | 5.14 | Single | $322 \times 280 \times 58$ |
| | 294-376 | 13.9 | Array | $1122 \times 1780 \times 58$ |

presented in Table 4. The gain of the single-element design was further investigated and increased by adding conducting directors (3 and 5) in front of the dipole driven element. A maximum gain of 9.6 dBi and a compact size of $1122 \times 280 \times 58 \mu\text{m}^3$ were achieved. To reach even better gain values for sub-THz communication, a 1×4 array structure was proposed. This array offered a bandwidth of 27.3% (294-376 GHz) with maximum gain of 13.9 dBi with 89% efficiency. With these merits, the proposed antenna designs are suitable candidates for high-speed and short-distance wireless communication in the sub-THz frequency range. All measurements of input impedance and radiation patterns will be published later and will include all details of waveguide to Yagi antenna transition.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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