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Design and Analysis of High-Gain Series fed Antenna Array Systems for Advanced Spaceborne Terahertz Applications

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Abstract*:* This paper presents an innovative high-gain terahertz (THz) antenna array designed for operation at a frequency of 0.867 THz. The array employs microstrip patch antennas (MPAs) and is crafted through a straightforward laboratory-based printed circuit board (PCB) etching process on a substrate made of Liquid Crystalline Polymer (LCP). The LCP substrate, with a thickness of 25 µm and a relative permittivity of 2.91, exhibits overall dimensions of 660 µm × 2800 µm × 25 µm. The potential applications of this antenna array span THz band space communication and extend into medical domains, including cancer detection via THz spectroscopy and vital sign detection through Doppler radar and on-body methodologies. The proposed antenna design is meticulously crafted and simulated using CST Microwave Studio, resulting in an antenna resonating at 0.867 THz with an impressive return loss of -25.3 dB. A 1×3 series-fed antenna array achieves a gain of 13.6dB with an operating bandwidth of 3.5 GHz, while a 1×5 series-fed antenna array achieves gain of 15dB with a broader 5 GHz operating bandwidth.

Keywords: *THz antenna, series fed antenna array, space research services, LCP*

1. Introduction

The Terahertz (THz) frequency spans from 0.1-10 THz, with corresponding wavelengths ranging from 3 mm to 30 µm in the electromagnetic spectrum. Possessing intriguing properties like non-ionizing behaviour and transparency to a wide range of dry materials, as well as molecular fingerprinting capabilities, THz imaging and diagnostics showcase significant potential for applications in non-destructive testing and imaging [1-4], medical diagnosis [5-6], health monitoring [7] and chemical and biological identification [8-10]. Nevertheless, the technology for constructing sources and detectors in the Terahertz (THz) range is still in its early stages compared to well-established microwave and optical counterparts. The direct scaling of microwave and optical technologies to THz frequencies is not feasible due to various reasons. Despite these challenges, THz technologies have found applications in diverse fields, including biomedical science and engineering. [11], [12], imaging schemes [13], [14], military [15], calibration systems for microwave sensors [16], space instrumentation [17], and environmental monitoring systems [18]. Many of the previously mentioned applications notably capitalize on the distinctive interactions between water molecules and THz waves [19]. The THz spectrum, often referred to as the THz gap, spans from 0.1 to 10 THz. Notably, this frequency range experiences less interference from adverse climatic conditions such as rain and fog [20]. In the context of implementing THz wireless systems, a persistent challenge exists in developing an ultrawideband (UWB), cost-effective antenna that is both scalable and readily integrated on-chip [21]. In the realm of Terahertz (THz) technology, recent proposals have introduced a diverse range of nanoantenna designs, serving as scaled versions of their microwave frequency counterparts. Notable examples in this category encompass printed dipoles [22]–[24], and simple patch antennas [25]. Recently, there have been reports of on-chip THz beam-forming array systems fabricated on silicon [26], [27].

While planar antennas may exhibit low gain and directivity, they remain widely utilized across various fields. High directivity can be achieved through multiple methods, including antenna arrays, photonic bandgap (PBG)-based antennas, and the reflector method [28,29]. Nevertheless, the array technique stands out as a suitable candidate, offering maximum gain and directivity when compared to other techniques [30]. The utilization of an antenna array offers numerous advantages in various operational scenarios, including the management of electromagnetic radiations and the provision of high directivity [31]. Numerous publications in the literature have explored wireless communication in the THz frequency band, as evidenced by works like [32], In a previous study, the authors introduced a Cassegrain-based horn antenna with a notable gain of 25 dB at 0.3 GHz; however, the antenna size was not compact. Additionally, in another work [33] a 15-element antenna array was reported, demonstrating directivity and radiation efficiency of 11.71 dBi and 70.8%, respectively, operating at 0.3 THz. This is consistent with findings by the authors in [34] a microstrip patch array antenna operating at 0.6 THz, utilizing a Photonic Band Gap (PBG) structure, was previously introduced, achieving a gain of 16.88 dBi, directivity of 17.19 dBi, and radiation efficiency of 89.72%. This study extends the exploration by developing 1×3 and 1×5 series-fed antenna arrays with the aim of achieving high gain in the terahertz (THz) range. The substrate material employed is

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Liquid Crystalline Polymer (LCP), featuring a thickness of 25 µm, a relative permittivity of 2.91, and overall dimensions of 660 µm × 2800 µm × 25 µm. The antenna design process is detailed in Section II, while Section III presents the results and discussion. Concluding remarks on the research findings are provided in Section IV, followed by references.

2. Geometry of Array Design

The two configurations mentioned: 1×3 and 1×5 series fed antenna arrays. The "1×3" indicates a one-dimensional array with three elements, and "1×5" indicates a one-dimensional array with five elements. Series feeding means that the elements are connected in series, one after the other. Geometry of the proposed 1×3 and 1×5 series fed antenna array is shown in Figure 1. & Figure 2 respectively. The patch width 'W' and length 'L' are calculated from the following expressions.

$$W = \frac{(2M+1)}{\sqrt{\frac{\varepsilon_r+1}{2}}} \times \frac{\lambda_0}{2} \quad (1)$$

$$L = \frac{(2N+1)}{\sqrt{\varepsilon_{eff}}} \times \left(\frac{\lambda}{2}\right) - 2 \times \Delta L \quad (2)$$

Where M and N are non-negative integers (in our present design M=N=1).

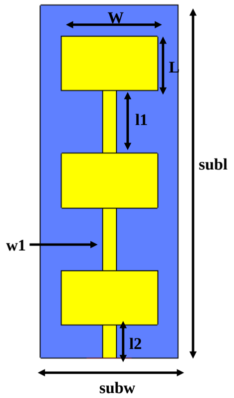

Fig. 1. Construction of Series fed antenna array, subl=2800µm, subw=660µm, W=430µm, L=230µm, l1=280µm, l2=158µm, w1=62µm.

The examined array is comprised of a 1×3 square linear array antenna with a single excitation port, designed to operate at a frequency of 0.867 THz. The configuration entails the organization of three-square patches in a sequential pattern, employing either series coupling or microstrip line feeding. A systematic approach was followed, involving the careful incorporation of a slot within each square of the linear array. This results in a 1×3 square array featuring a slot patch linear arrangement. Positioned as the topmost layer of the substrate, the antenna is surrounded by the substrate's lower copper cladding, serving as the grounding element. Mitigating antenna losses is achieved through the use of square-shaped patch elements interconnected in a series configuration, incorporating slots. The integration of an SMA connector facilitates input provision to the microstrip transmission line. The CST Microwave Studio software is utilized for simulations to achieve desired outcomes in a systematic manner.

Facilitating the effective transmission or reception of signals across considerable distances, often reaching several kilometres, necessitates the deployment of high-gain antennas. To attain a significant boost in antenna gain, it is common practice to construct an array of elements. The magnitude of the antenna's gain is directly influenced by the number of elements within the array. The proposed configuration involves the extension of the series-fed antenna array to comprise a series of 5 square patches, as illustrated in Figure 2.

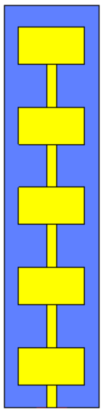

Fig. 2. 1×5 Series fed antenna array

3. Results and Discussions

Two series-fed antenna arrays have been meticulously designed using the proposed methodology, operating at a frequency of 0.867 THz. These arrays are implemented on LCP substrates with a relative permittivity (ε_r) of 2.91 and a loss tangent (tan(δ)) of 0.0025. The performance evaluation of the antennas includes a comprehensive analysis of parameters such as Return Loss (S11), impedance bandwidth (GHz), directivity (dBi), and gain (dB).

3.1 Return Loss

Figures 3 depict the S11 parameters, representing the reflection coefficient, for two distinct patch antenna arrays: a 1×3 array and a 1×5 array. The Series-fed 1×3 patch antenna array exhibits resonance at a specific frequency of 0.867 THz, with the reflection coefficient measured at -27 dB. Furthermore, this antenna array demonstrates a bandwidth of 3.5 GHz, indicating the effective operational range of frequencies. Similarly, the Series-fed 1×5 patch antenna array also resonates at the frequency of 0.867 THz, with a reflection coefficient of -27 dB at this resonant point. However, the 1×5 array boasts a larger bandwidth of 5 GHz, indicating a broader frequency range over which it maintains a low reflection coefficient. Both the 1×3 and 1×5 patch antenna arrays share the same resonant frequency (0.867 THz and -27 dB, respectively). The significant distinction lies in the bandwidth, where the 1×5 array offers a broader frequency spectrum for efficient operation compared to the 1×3 array.

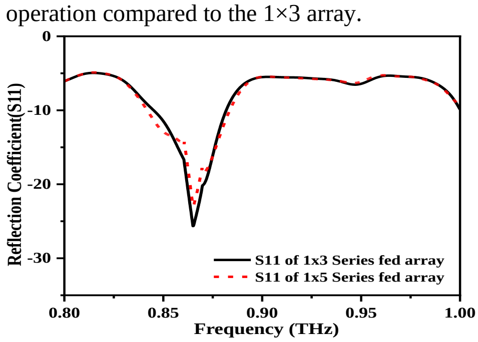

Fig .3. Return loss comparison between the proposed series fed 1×3 & 1×5 antenna arrays

3.2 Gain

The antenna's gain, a metric assessing its capability to focus transmitted or received signals in a specific direction relative to an isotropic radiator, is a crucial parameter. The configurations under consideration are denoted as 1×3 and 1×5 series-fed antenna arrays. The term "1×3" signifies a one-dimensional array with three elements, while "1×5" denotes a one-dimensional array with five elements. In series feeding, the elements are connected sequentially. In Figure 4, the Gain plot of 1×3 and 1×5 series-fed antenna arrays operating at a frequency of 0.867THz is depicted. Notably, the 1×3 and 1×5 series-fed antenna array configurations have achieved gains of 13.5dB and 15dB, respectively.

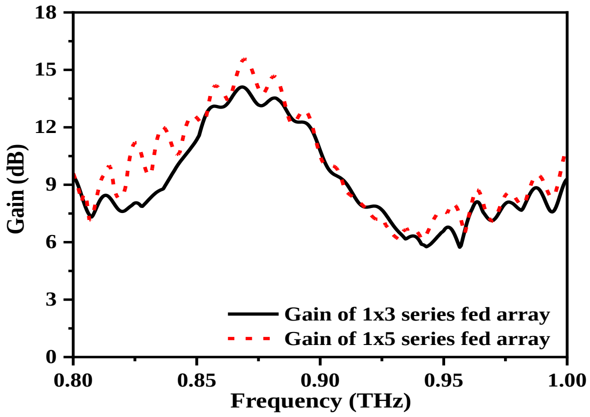

Fig. 4. Gain Comparison between the Proposed 1×3 & 1×5 Series fed Arrays

3.3 3D Radiation Pattern

The gain pattern illustrates how the antenna's radiation strength fluctuates in different directions. In a three-dimensional context, this pattern provides insights into how the gain varies not only in azimuth (horizontal) and elevation (vertical) planes but also at different angles around the antenna. Figures 5.a and 5.b present the 3D gain patterns of series-fed 1×3 and 1×5 antenna arrays operating at 0.867THz. Specifically, the 1×3 antenna array achieves a gain of 13.6dB, while the 1×5 array attains a higher gain of 15dB. The superior gain of the 1×5 array indicates its enhanced ability to concentrate radiated energy in the desired direction compared to the 1×3 array.

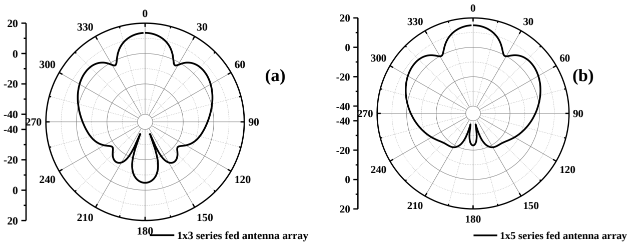

Fig. 5. Radiation pattern of a) 1×3 b) 1×5 series fed antenna arrays

The performance parameter 1×3, and 1×5 series fed Microstrip patch antenna array compared results are listed in Table 1.

Parameter	1×3 series fed array	1×5 series fed array
Bandwidth	3.5GHZ	5GHz
Gain	13.6dB	15dB
Directivity	14dB	16dB
FTBR	17.6	25.6
Resonant Frequency	0.867THz	0.867Thz

4. Conclusion

The 1×3 and 1×5 series-fed square patch linear arrays, tailored for THz frequency operation, have undergone intricate engineering to meet the specific requirements of THz applications. Computational analysis using CST Microwave Studio software was employed to obtain quantitative results for various array parameters, including reflection coefficient, bandwidth, directivity, gain, and front-to-back ratio. Through a comprehensive evaluation, it has been determined that the 1×5 array exhibits a 5GHz bandwidth, enabling it to handle a wide range of frequencies for transmission and reception. With a gain of 15dB, the array showcases its capability to amplify and enhance the received signal, improving both its strength and quality.

Author contributions

T. P. S. Kumar Kusumanchi **:** Conceptualization, Methodology, Software, Field study, Lakshman Pappula**:** Data curation, Writing-Original draft preparation, Software, Validation., Field study

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