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Design, Simulation, and Implementation of a Dual-Layer Perforated Partially Reflective Surface for Gain and Bandwidth Enhancement of Dielectric Patch Antenna Arrays

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تصميم ومحاكاة وتنفيذ سطح عاكس جزئي مزدوج الطبقة مثقّب لتحسين الكسب وعرض النطاق الترددي لمصفوفة هوائيات الشرائح العازلة

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Abstract:
The proposal, simulation, and experimental validation of a partially reflected surface applied over a high-density dielectric patch antenna array are presented. In order to improve the antenna bandwidth and gain, a partially reflective surface (PRS) is designed. By creating a positive reflection phase gradient with high reflectivity, these holey dielectric substrates are designed to enhance the antenna system's electromagnetic performance. A partially reflective surface (PRS) made up of two thin, perforated dielectric substrates is used as a superstrate in the suggested design to increase the antenna's gain and bandwidth. The effective permittivity of the dielectric superstrate is considerably altered by the addition of regularly spaced circular holes inside the PRS layers. The suggested arrangement makes use of smaller substrates, which helps to increase the operational bandwidth, in contrast to traditional designs, where the superstrate thickness usually equal to a quarter dielectric wavelength. A 3 dB gain bandwidth of 22% over the frequency range of 24.5 to 30.7 GHz was achieved. The antenna has a high simulated radiation efficiency of 92% along with a measured flat gain of roughly 16 dBi across this spectrum. Furthermore, the side lobe levels continue to be below -11 dB in the E-plane and -17 dB in the H-plane, demonstrating that unwanted radiation is effectively suppressed.

Keywords: Dense dielectric (DD) patch, high gain, wideband, PRS Superstrate, fifth-generation (5G) applications, millimeter-wave (MMW) antenna.

الملخص
تصميم سطح عاكس جزئياً مكون من طبقتين عازلتين مثقبتين تطبق فوق مصفوفة الهوائي بمسافة محددة لتحقيق الكسب العالي والنطاق الترددي العريض، ومحاكاتهما واختبارهما. هذا الهوائي تم تغذيته بتقنية اقتران الفتحة. تم تصميم سطح عاكس جزئيًا مكون من طبقتين رقيقتين من الركيزة العازلة لإنشاء تدرج موجب في طور الانعكاس مع انعكاس عالي من أجل تحسين عرض نطاق الهوائي وكسبه أيضًا. علاوة على ذلك، فإن حفر مجموعة من الثقوب الدائرية المتماثلة في طبقات للسطح العاكس المكون من ركيزتين عازلتين يلعب دورًا مهمًا في تغيير سماحية الركيزة العازلة. حسب الدراسات السابقة، يجب أن يساوي سمك الركيزة التقليدية ربع طول موجة. ومع ذلك، في التصميم المقترح، يتم استخدام نظام مكون من ركيزتين عازلتين رقيقتين ومثقبتين كطبقة علوية لتوسيع عرض النطاق الترددي ولتعزيز كسب الهوائي أيضًا. النتيجة عرض نطاق ترددي بنسبة 22% من 24.5 إلى 30.7 جيجا هرتز. يُظهر الهوائي المقترح كسبًا مسطحًا مُقاسًا يبلغ حوالي 16 ديسيبل على كامل عرض النطاق الترددي مع كفاءة إشعاع عالية تبلغ 92%. علاوة على ذلك، تكون مستويات الفص الجانبي للهوائي أقل من 11– و17 – ديسيبل في المستوى الكهربائي E و المستوى المغناطيسي H، على التوالي.

الكلمات المفتاحية: شريحة عالية النفاذية، كسب عالي، نطاق ترددي عريض، سطح عاكس جزئيًا، تطبيقات الجيل الخامس، هوائي الموجات الميلليمترية.

I. Introduction

For upcoming fifth generation (5G) wireless communication, wideband and high gain antennas have been increasingly popular over the past few decades [1]. To meet 5G criteria, a variety of antenna types have been deployed to deliver good performance. The Fabry-Perot cavity (FPC) antenna has been used extensively because of its wide bandwidth and strong directivity [2], [3]. When compared to traditional antenna arrays, its primary benefits are low complexity and great radiation efficiency [4], [5]. The radiating element used to excite the antenna in the majority of designs found in the literature can be a slit in the ground plane, a printed metallic patch, or a printed dipole [6]. The dense dielectric (DD) patch antenna, a novel type of antenna element, was recently introduced in [7], [8]. The metallic patch is replaced by a thin dielectric substrate with a high permittivity, as described in [9]. In [10] indicates that compared to a microstrip antenna the radiation efficiency of dielectric resonator antennas (DRAs) is typically better. With proper design of the air gap distance between the ground plane and superstrate which is around a half wavelength, multiple reflections between the ground plane and the superstrate layer occurred to create an electromagnetic (EM) field distribution over the antenna aperture which lead to a high directivity. However, the numerous reflections may induce a pronounced resonant characteristic, resulting in a limited impedance bandwidth [11]. In order to improve the antenna performance in terms of bandwidth and gain, various methods have been discussed. A high dense dielectric patch antenna array with perforated superstrate was implemented to improve the characteristics of the antenna [12]. In the literature, several kinds of partially reflective surfaces (PRS) are widely used. A metallic patch antenna used to excite two identical dielectric substrates, each measuring one-quarter of the dielectric wavelength to augment both the antenna gain and bandwidth Nevertheless, the bandwidth is a quiet narrow, but the gain is rather high [13]. To enhance the antenna's bandwidth, two dielectric superstrates are employed on the top of a waveguide antenna. Nevertheless, the thickness of the two dielectric superstrate was thick resulting in a 17.9% gain bandwidth [14]. In [15] employed three dielectric slaps to improve the gain and bandwidth of the antenna. The peak gain is 18.2 dBi and the 3 dB gain bandwidth is 22 %. Moreover, the antenna bandwidth may be enhanced through the utilization of frequency selective surface superstrates (FSS), which are not constrained by the thickness of the superstrate which is a quarter dielectric wavelengths. Three periodic partly reflecting surfaces (PRSs) created a three open cavities and positioned on the top of a slot fed by a waveguide to increase the bandwidth. The 3 dB increase bandwidth is approximately 15%, as seen in [16]. In [17], frequency selective surface superstrate (FSS) of two layers, constructed from periodic structures (PRS). This PRS placed above a single slot antenna excited by a ridge gap waveguide to increase the bandwidth. A constructive reflection phase at a specific frequency was achieved by designing a composite unit cell. As a result, 3 dB gain bandwidth is approximately 12 %.In the literature, Thicker substrates have been extensively utilized as PRS surfaces to attain a positive reflection phase. However, certain thicknesses are unavailable at specific frequencies.

In this article, a thin dual layer PRS is designed and simulated at 28 GHz, placed over high dense dielectric patch antenna array to enhance the gain and to broaden the 3 dB gain bandwidth. The dense patches have a high permittivity of 82 and fed by four slots etched in the ground plane. The slots are excited by microstrip line feeding network. This kind of patch is chosen to replace the metallic patch for attractive features such as low profile, broad bandwidth, and good radiation efficiency. As known as the reflection phase of the superstrate is rises with frequency, the antenna bandwidth increased, and the phase resembles the optimal phase. to generate a positive phase gradient across a specific frequency band, a unit cell composed of two thin dielectric substrate layers is employed. This unit cell layers are with different permittivities and thicknesses. As a result, the thickness of each superstrate layer could be less than $\lambda d/4$ as will be demonstrated later in this work. The PRS superstrate is applied above the DD patch antenna array.

This work is organized as follows. The unit cell design, performance, and some parametric study are discussed in section II. An antenna design is discussed in section III. In section IV, experimental and simulation results of the proposed antenna are presented. Finally, the conclusion is stated in section V.

II. Design of PRS with positive phase gradient

In this section, the design of the unit cell of the PRS to be used as a superstrate of the DD patch antenna array is presented. The unit cell is made out of two unprinted perforated thin dialectic slabs as illustrated in Figure 1. They are perforated to control the effective permittivity of the two substrates. As known, a conventional dielectric superstrate should have a $\lambda_d/4$ thickness, and should put at $\lambda_o/2$ above the antenna to achieve the target either to enhance the gain or to broaden the bandwidth. However, in this proposed design two thin dielectric substrates are used to build the PRS superstrate. Therefore, to compensate the thickness, the height h_{c1} is added to $\lambda_0/2$ between the two layers of the Partially Reflective Surface. In addition to the $\lambda_0/2$ distance between the antenna elements and the PRS superstrate, a certain air gap thickness is added.

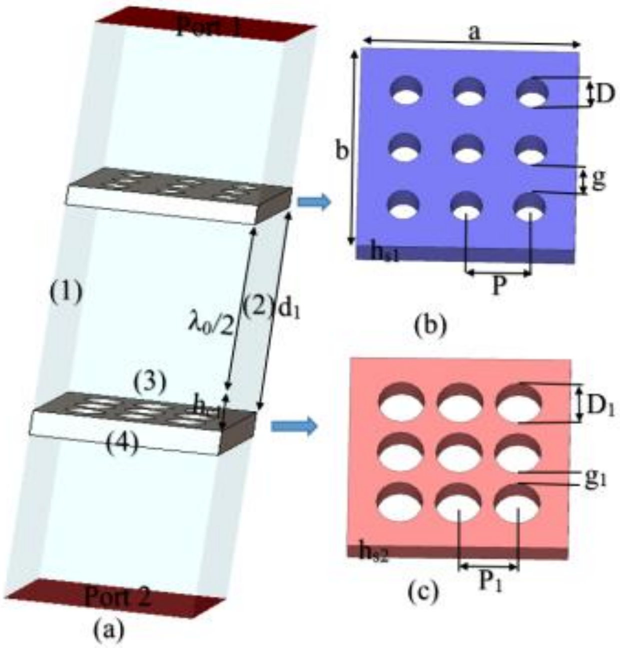


Figure 1: The proposed unit cell.

TABLE I
UNIT CELL PARAMETERS

Parameters	Value (mm)
a	4.7
b	4.7
P	1.36
D	0.7
g	0.66
P_1	1.25
D_1	1
g_1	0.25
h_{c1}	0.85
h_{s1}	0.64

Periodic boundary conditions can be applied to the four side walls of a unit cell, as shown in Figure 1(a). Boundaries 1 and 3 are set as perfect electric conductors (PEC) and boundaries 2 and 4 are set as perfect magnetic conductors (PMCs). Drilling holes on the dielectric layer can change the effective permittivity of the material. The effective relative permittivity of the two thin substrate layers is calculated as [12], [18].

$$\varepsilon_{eff} = \varepsilon_r \left(1 - \frac{\pi}{2}\left(\frac{D_1}{D_1 + g_1}\right)^2\right) + \frac{\pi}{2}\left(\frac{D_1}{D_1 + g_1}\right)^2 \qquad (1)$$

The effective permittivity of the top and bottom substrates are 6.7 and 2 respectively [12]. Figure 2 illustrates how the hole's diameter (D_1) can affect the calculation of the effective permittivity.

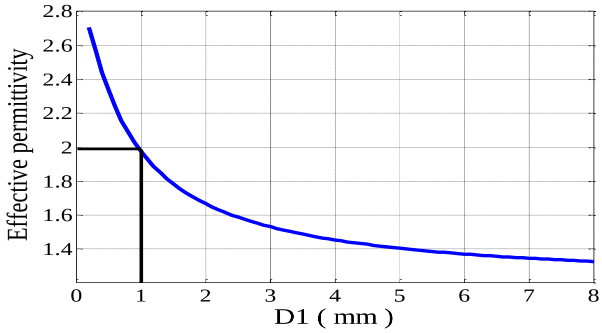


Figure 2: Effect of the hole's diameter (D_1) on the Calculation of effective permittivity of the underneath substrate layer of the PRS.

When a Partially Reflective Surface (PRS) is positioned at the optimal resonant distance d from the radiating antenna, a significant enhancement in antenna gain can be achieved [17]. The electromagnetic waves emitted by the antenna undergo multiple reflections between the PRS and the ground plane, with their amplitudes progressively attenuating. These multiple reflections lead to constructive interference, which in turn improves the antenna's directivity. This constructive interference occurs when the air gap d satisfies the resonance condition, typically expressed as:

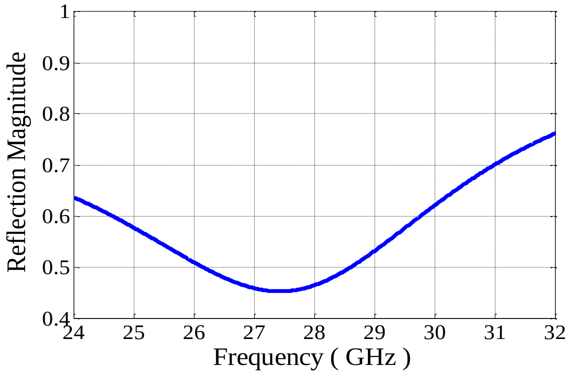
$$d = \frac{\lambda}{2}\left(\frac{\Phi}{2\pi} + 0.5\right) + N\frac{\lambda}{2} \qquad (2)$$

Here, Φ signifies the phase of the reflection coefficient associated with the Partially Reflective Surface (PRS), λ indicates the free-space wavelength, and N refers to the resonant mode order. It is assumed that both the ground plane and the PRS are of infinite extent to facilitate the analytical model. Given these assumptions, Equation (2) can be restructured as:

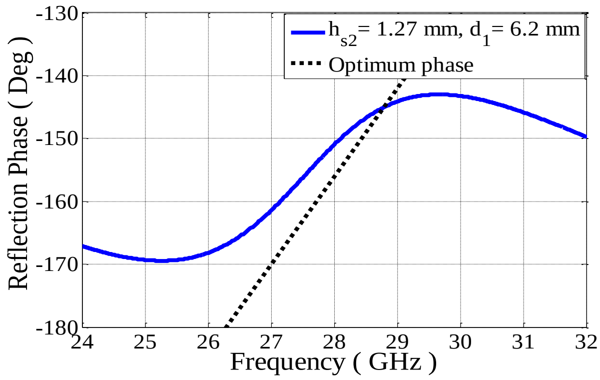
$$\Phi = \frac{4\pi d}{c} f - (2N-1)\pi \qquad (3)$$

In this context, f represents the operating frequency, and c denotes the speed of light in a vacuum. Using Equation (3), the optimal phase of the Partially Reflective Surface (PRS) can be determined. As a result the performance of the antenna can be improved by employing a PRS whose reflection phase increases with frequency.

Two thin dielectric slabs characterized by different permittivities designed as an implemented unit cell. Rogers RO 3010 is the upper substrate, which has a relative permittivity of ϵr = 10.2 and a loss tangent of $\tan\delta$ = 0.0023, resulting in an effective permittivity of roughly 6.7. The thickness of the substrate is h_{s1} of 25mil. Rogers RO 6002, exhibiting a relative permittivity of ϵr = 2.94 and a loss tangent of tanδ = 0.0009 is the bottom slab. This configuration yields an effective permittivity of approximately 2.0 and a thickness of $hs2$ = 50 mil. Table I presents the dimensional parameters of the unit cell. The phase and magnitude of the reflection coefficient for the unit cell are depicted in Figure 3.



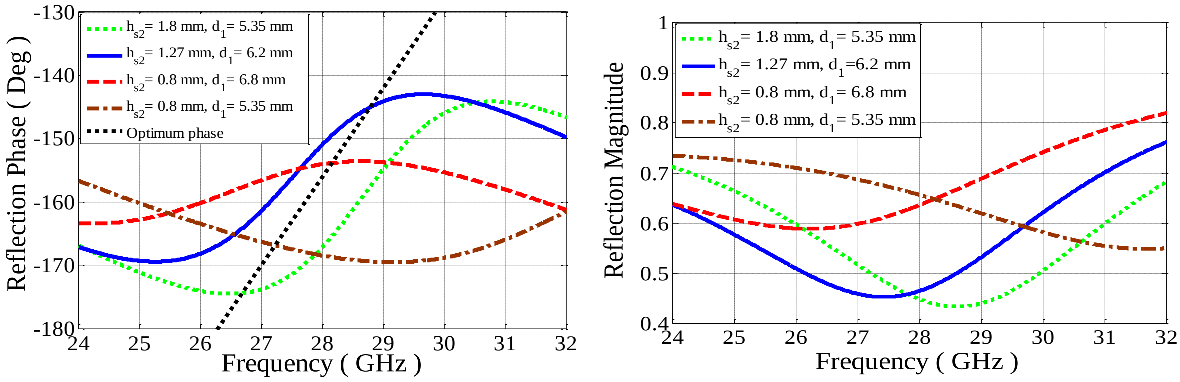
(a): magnitude



(b): reflection phase

Figure 3: The performance of the implemented unit cell.

A parametric analysis is conducted to investigate the influence of the bottom substrate thickness h_{s2} on the performance of the proposed unit cell. Figure 4 illustrates the impact of varying h_{s2}, ranging from a quarter-wavelength dielectric thickness to comparatively thinner values, on the performance of the partially reflecting surface (PRS). Both graphs highlight the importance of optimizing the PRS parameters for achieving enhanced performance in terms of both reflection phase and magnitude. The phase graph shows how the unit cell's phase response can be tuned for optimal constructive interference, while the magnitude graph illustrates how substrate thickness affects the reflection coefficient and impedance matching. Overall, these graphs provide valuable insights into how the design parameters of the PRS impact the unit cell's performance across different frequencies, and they underline the significance of optimizing substrate thickness and geometry to achieve the desired frequency response, bandwidth, and impedance matching.



(a) (b)

Figure 4: Impact of varying the underneath substrate thickness of the implemented unit cell on the PRS performance: reflection phase (a), and reflection magnitude (b).

III. Antenna design

Figure 5 presents the configuration and fabricated prototype of the proposed antenna, intended for millimeter-wave (MMW) applications. The antenna design is based on the same principles outlined in [12]. The dielectric-loaded dipole (DD) patches exhibit an ultra-low-profile structure, with a Lp = 4.1 mm and a height Hp = 0.15 mm with relative permittivity of 82. The DD patches are designed on a Rogers Duroid 6002 substrate (top layer) with thickness h1 = 20 mil, (εr = 2.94 and tanδ = 0.0009). Rogers RT 3010 is the bottom substrate. The two substrates are identical in dimensions of length and width (L = W = 20 mm). A 50-Ω power divider is designed to feed the patch antenna array. The excitation slot has a length Ls = 2.55 mm and width Ws = 0.25 mm. the distance d= 5.7 mm is from the proposed PRS superstrate to the DD patch antenna array. The entire structure is mechanically secured using plastic screws with a 1 mm diameter.

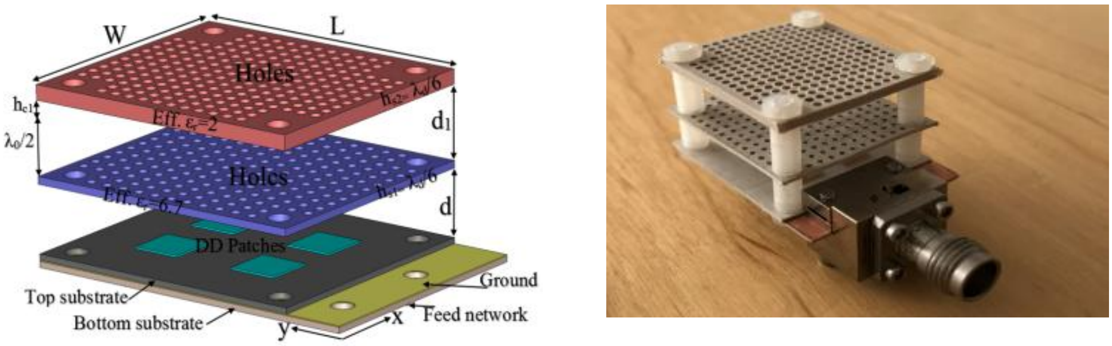


Figure 5: Geometry of the proposed antenna and the prototype.

IV. Antenna results

To validate the simulated results, a proposed PRS superstrate that placed on DD patch array was fabricated and experimentally evaluated. The measured and simulated reflection coefficients of the designed antenna are shown in Figure 6. The measured data indicate good impedance matching, with the antenna achieving a 3 dB gain bandwidth of approximately 22%. A minor discrepancy between the simulated and measured results is observed, which may be attributed to variations in the dielectric properties of the materials at millimeter-wave frequencies. According to the manufacturer's datasheet, the specified relative permittivity values are rated at 10 GHz; however, these values can vary at higher frequencies, potentially contributing to the observed shift in resonance frequency [19]. Additionally, slight deviations in the spacing between the PRS superstrate and the DD patch array may also result in resonance shifts

Figure 7 illustrates the simulated and measured gain, as well as the simulated radiation efficiency of the proposed array. The results show that the antenna maintains a consistent gain of approximately 16 dBi across the entire operational bandwidth.

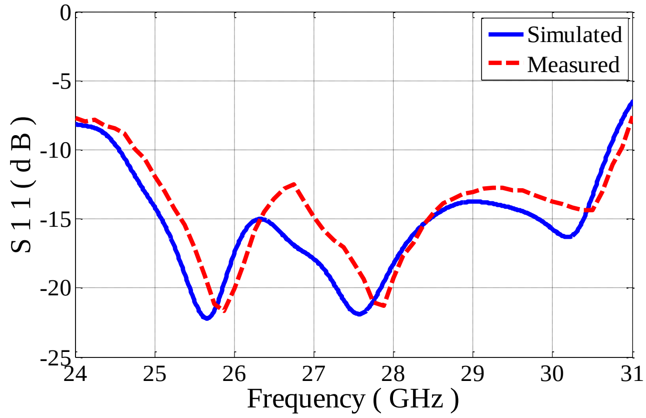
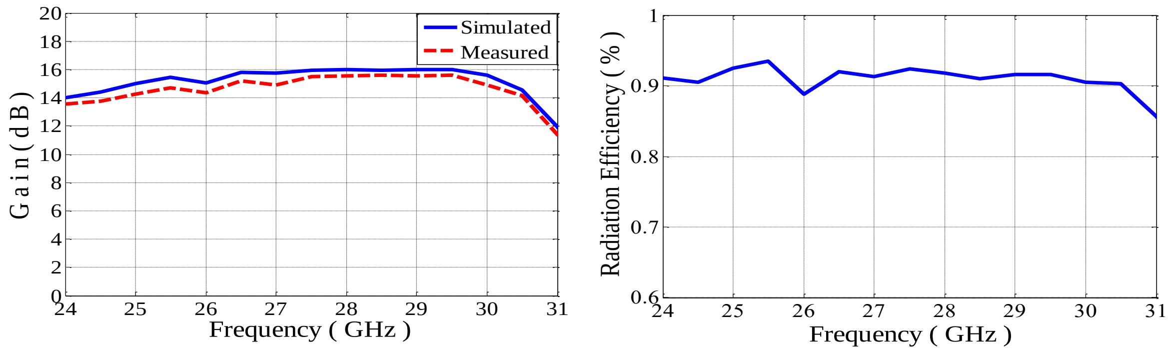


Figure 6: Simulated and measured reflection coefficient of the proposed antenna.



(a) (b)

Figure 7: Measured and simulated gain (a), and simulated radiation efficiency (b) of the proposed antenna.

The measured and simulated radiation patterns of the proposed partially reflecting surface (PRS) superstrate positioned above the (DD) patch array across multiple frequencies are depicted in Figure 8. The antenna demonstrates stable radiation characteristics, with a strong correlation observed between the simulated and experimental results. In the E-plane, the measured side lobe levels (SLLs) are approximately −12.6 dB, −15.4 dB, −14 dB, and −9.9 dB at 24.5 GHz, 26 GHz, 28 GHz, and 30 GHz, respectively. Similarly, in the H-plane, the SLLs are observed to be around −12.6 dB, −17.8 dB, −21 dB, and −19.5 dB at the corresponding frequencies. These results indicate effective side lobe suppression and consistent performance across the operating bandwidth.

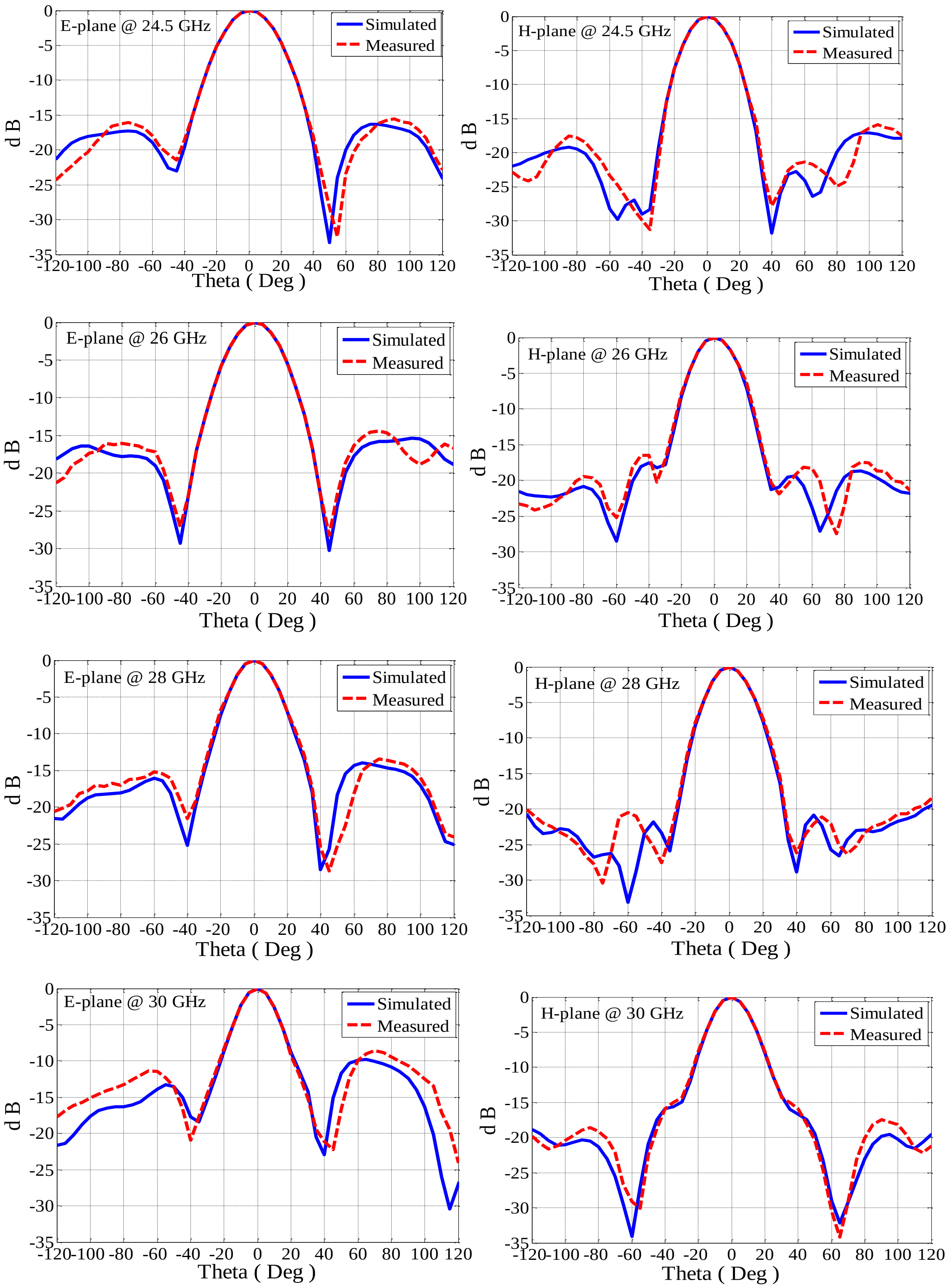


Figure 8: E and H-planes radiation pattern of the proposed antenna at different frequencies.

V. Conclusions

This work presents a millimeter-wave antenna designed to operate at 28 GHz, featuring high gain stability and a wide 3 dB gain bandwidth. Two thin perforated dielectric superstrates placed on the top of high-density dielectric patch antenna array has been designed, fabricated, and experimentally validated. The antenna is excited using a simple power divider feeding network. a positive reflection phase gradient with high reflectivity at specific frequencies created employing the PRS of two slim perforated dielectric layers. Unlike conventional superstrate designs that require a thickness of approximately one-quarter of the dielectric wavelength ($\lambda d/4$), the proposed structure utilizes thinner perforated superstrate layers to achieve broader bandwidth and improved gain. A 3 dB gain bandwidth of approximately 22% was achieved based on the measured reflection coefficient. Additionally, the antenna results showed a high measured gain of 16 dBi, and a simulated radiation efficiency of about 92%, both of which remain nearly constant across the operational bandwidth. The antenna also exhibits stable radiation patterns with well-suppressed side lobe levels (SLLs) in both the E-plane and H-plane throughout the frequency range. These characteristics make the proposed antenna a strong candidate for high-gain, wideband short-range communication applications in the millimeter-wave spectrum.

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