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Low Loss Anisotropic Circular Near-Zero Flexible Metasurface for Gain Enhancement

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ABSTRACT: This paper proposes a new low loss high dielectric substrate made of $CaTiO_3$ incorporated butyl rubber (CBR). The synthesized material has a dielectric loss of 0.0048 and dielectric constant of 11.7. A novel circular anisotropic structure is used in the design of metamaterial unit cell. This metamaterial structure exhibits near-zero refractive index at 2.4 GHz. The extraction of refractive index is done from the scattering parameters using generalised sheet transition condition. An array of 3×3 unit cell is the metasurface superstrate, which is proposed for the gain enhancement. It is kept above the microstrip patch antenna working at 2.4 GHz. The proposed superstrate provides a gain enhancement of 4.6 dB. The height between the antenna and superstrate is optimized to 0.088 λ. The enhancement of gain on metasurface substrate with different loss tangents is analyzed. The simulation and measurement results of antenna with superstrate show good agreement with a peak gain of 7.6 dBi. The radiation efficiency of the antenna is increased by 42%.

1. INTRODUCTION

The advancement of communication has brought about the requirement of new techniques that could remarkably increase the performance of the antenna. The implementation of 5G networks has changed the communication world in terms of high speed and high data rate, which needs high gain antennas. Flexible substrates with low loss is another significant domain that aids in the design of antennas for many wearable applications and automotive radar applications. Increase in gain of the antenna increases the range of the antennas. Many techniques are given in the literature which can be used to increase the gain of the antenna. The use of metamaterials with antenna is one such method that has considerably increased the gain of antennas. Metamaterials are artificially made structures [1] that have remarkably changed the antenna performance in terms of gain, miniaturization, multiband, and low radar cross section. This periodic structure has the dynamic property of changing the characteristics of the electromagnetic waves which is instrumental in gain enhancement. Gain of the antenna is enhanced by incorporating metamaterials as superstrates above the antenna. Metamaterial lens antenna is used in the gain enhancement of horn antenna [2]. Metamaterial superstrates with high refractive index with microstrip patch antenna are used in the gain enhancement [3]. Metamaterial radome structure operating in THz band enhances the gain of the antenna, and it has reconfigurable characteristics [4]. Metamaterial superstrates are used with MIMO antennas for gain enhancement [5]. Dimensional optimization techniques in the metamaterial unit cell in the metamaterial superstrates also help in gain enhancement [6]. Coded metasurface acts a superstrate with low scattering improves the gain of the antenna [7]. The gain of a fractal shaped slotted patch is enhanced using compact metasurface [8]. Fractal metamaterial superstrates with microstrip patch antenna form a cavity that enhances the gain of the antenna [9]. Near-zero refractive index metamaterial has made remarkable contributions in the gain enhancement of antennas when it is used as a superstrate. Near-Zero metamaterial has the ability of focusing the electromagnetic waves by converging it to the normal of the superstrate, which is applied to obtain high gain directional antennas with bandwidth enhancement [10, 11]. The gains of compact antennas and slot antennas are also improved by near-zero metamaterial superstrate with high aperture efficiency [12–14]. Wide band gain enhancement [15–19] is achieved using metamaterial superstrates. Dual polarized wideband gain enhancement is obtained using partial reflective surfaces [15]. Graded refractive index metasurface is a class of metasurface, whose unit cell refractive index characteristics in the array can be modulated based on the requirement. Applying it as a superstrate gives wideband high gain with beam steerability [16]. Complementary metamaterial superstrates and partial reflective surfaces as a single layer are used in directional and wide band gain enhancement [17, 18]. Wideband gain enhancement and radar cross-section (RCS) reduction is obtained using a chessboard metamaterial superstrate [19]. Broad band metasurface [20] is used for polarization independent wave focusing. Gain enhancement of sub 6 GHz band 5G applications [21] is done by metasurface that possesses epsilon near zero property. The majority of metamaterial superstrates have the disadvantages of being inflexible, employed in the high frequency zone, and constructed using expensive substrates to achieve minimal loss.

To overcome these drawbacks, in this paper a new low-loss & low-cost high dielectric substrate is developed for designing

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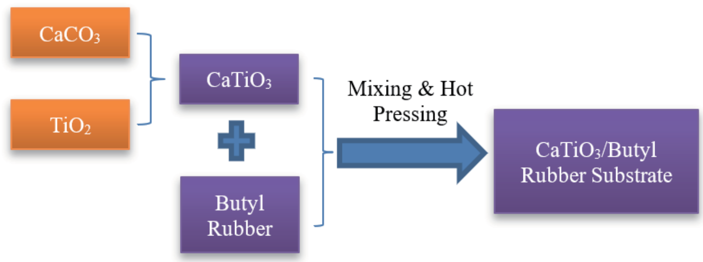

FIGURE 1. Evolution of the metamaterial unit cell.

a novel metamaterial unit cell. It shows near-zero refractive index, which enhances the gain of antenna working at 2.4 GHz. The high dielectric property of the substrate reduces the dimensions of the unit cell. The created unit cell has a dimension less than $\lambda/4$, where λ represents the resonance wavelength. The paper is organized as follows. Section 2 talks about the design of the unit cell and its characteristics. Section 3 deals with design of the antenna. Section 4 deals with the results and discussions of the antenna, and Section 5 concludes the paper.

2. DESIGN OF UNIT CELL

2.1. Synthesis and Characterization of the Low Loss Substrate

Owing to the low cost and easiness in fabrication, polymer-based composite substrate materials have attracted a lot of interest in the last decade. Among them, high dielectric constant substrate materials have a particular advantage in the miniaturization of electronic components. $CaTiO_3$ incorporated butyl rubber composites were used in this work as the substrate material to fabricate the antenna. $CaTiO_3$ powder was synthesized by the conventional solid-state ceramic route [22] by taking $CaCO_3$ and TiO_2 as the raw materials. The ceramic filler was then mixed in the butyl rubber matrix by employing mixing in an internal mixer followed by hot pressing in a compression moulding machine. The dielectric properties of the material thus synthesized were found using the cavity perturbation method [23]. The complex permittivity and loss tangent of the material were then found using the following equations:

$$\varepsilon'_r = 1 + \left[\frac{V_c(f_o - f_s)}{2V_s f_s}\right] \tag{1}$$

$$\varepsilon''_r = \frac{V_c(Q_o - Q_s)}{4V_s Q_o Q_s} \tag{2}$$

$$\tan\delta = \frac{\varepsilon''_r}{\varepsilon'_r} \tag{3}$$

where f_o is the cavity's resonant frequency; f_s is the resonant frequency of the sample; V_c and V_s are the volumes of the cavity and the sample, respectively; Q_o and Q_s are the quality factors of the empty cavity and the sample, respectively.

The $CaTiO_3$ filled butyl rubber composites showcased a dielectric constant of 11.7 along with a low loss of 0.0048 for the optimal filled fraction of (filler volume fraction of 45%) in the X-band regime. Figure 1 shows the diagrammatic representation of the synthesis of the substrate. The substrate material has better electrical properties than the most commonly used radio frequency (RF) substrate (FR4) and is flexible. It can also be employed for flexible RF circuit applications. The materials temperature stability got improved by the addition of ceramic filler particles. The temperature stability was up to 281° centigrade after which 1% weight reduction was observed. The substrate material exhibited very good flexibility and an elastic modulus of 13.5 MPa.

2.2. Design Steps of the Unit cell

The design of the metamaterial unit cell for gain enhancement has a few constraints that need to be addressed. The gain of antennas is increased by superstrates made of metamaterial unit cell which has both real and imaginary refractive indices near zero [24]. The high value of imaginary refractive index indicates the metamaterial to be lossy, hence it does not contribute to gain enhancement. Thus, a metamaterial unit cell with near-zero imaginary value of refractive index is a design constraint. The gain of the antenna is proportional to the array size of the superstrate as indicated in [25]. Hence to incorporate a greater number of unit cells in the superstrate is the second design constraint. These constraints were taken into consideration for the design of the superstrate. To increase the number of unit cells on the superstrate, a high dielectric substrate is used for the unit cell design. As the value of dielectric constant increases, the size of the unit cell decreases.

The evolution of the structure is given in Figures 2(a)–(d). The circular outer ring as shown in Figure 2(a) resonates at 2.66 GHz. The addition of an inner circle as shown in Figure 2(b) shifts the frequency to 2.6 GHz. To further reduce the resonant frequency, rectangular rings are added symmetrically with the structure as shown in Figure 2(c), and two slits are made on the outer circular ring in a single axis to make the phase reversal of 90 degrees at 2.4 GHz and also to obtain near-zero refractive index.

The variation of the transmission phase with respect to the different steps of design is shown in Figure 3, and the corresponding variation in the transmission phase is shown in Figure 4. Case IV represents the final structure of the unit cell at which there is a phase change at 2.4 GHz, where the metamaterial property is analyzed.

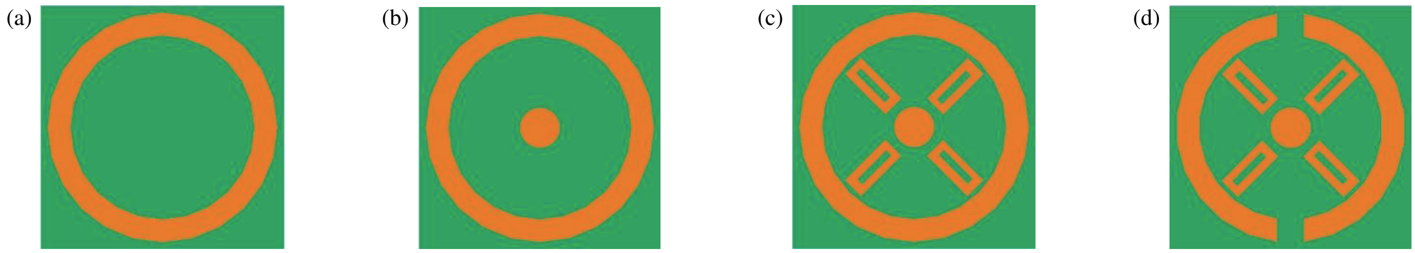

FIGURE 2. Evolution of the metamaterial unit cell. (a) CASE I. (b) CASE II. (c) CASE III. (d) CASE IV.

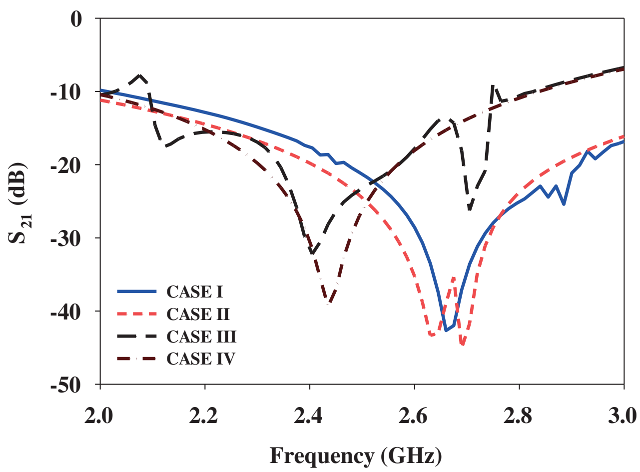

FIGURE 3. Variation of transmission coefficient of the unit cell.

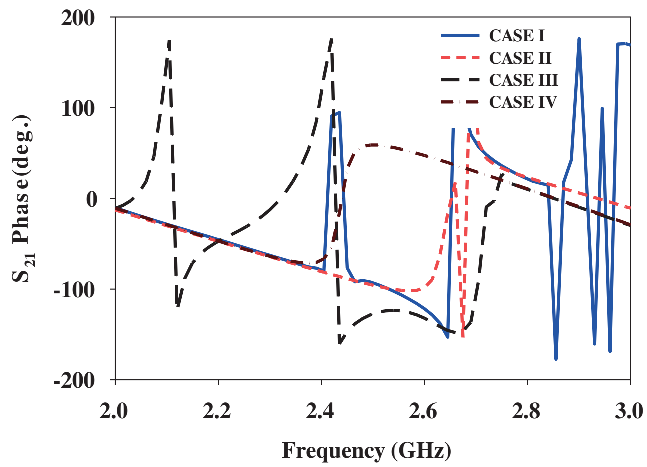

FIGURE 4. Variation of transmission phase of the unit cell.

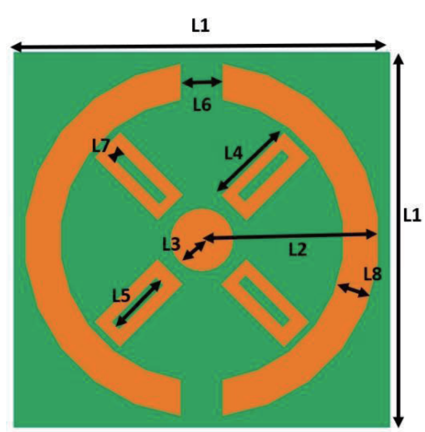

FIGURE 5. Unit cell and its dimensions ($L1 = 23.76$ mm, $L2 = 9.9$ mm , $L3 = 1.98$ mm, $L4 = 5.61$ mm, $L5 = 3.96$ mm, $L6 = 2.64$ mm, $L7 = 0.66$ mm, $L8 = 1.98$ mm).

2.3. Metamaterial Unit Cell

The metamaterial unit cell is finally made on a high dielectric low-loss substrate with a thickness of 1.6 mm, relative permittivity of 11.7, and loss tangent of 0.0048. The dimension of the unit cell is 23.76 mm × 23.76 mm, which is much less than 36 mm × 36 mm, when the unit cell is designed on an FR4 substrate. The dimensions of the unit cell are also given in Figure 5. The parameters of the unit cell are extracted [26] from the scattering parameters of the unit cell using generalized sheet transition condition (GSTC).

This method is used for the analysis of anisotropic metasurfaces. The unit cell exhibits near-zero refractive index at 2.4 GHz. The extracted real and imaginary refractive index values of the unit cell are shown in Figure 6. The imaginary refractive index value is also near zero, which indicates that the metasurface is less lossy. According to Snell's law, the refracted electromagnetic waves bend towards the normal of the superstrate, and it increases the boresight gain of the antenna.

Using GSTC condition the magnetic and electric susceptibilities are extracted initially. The permittivity value is obtained

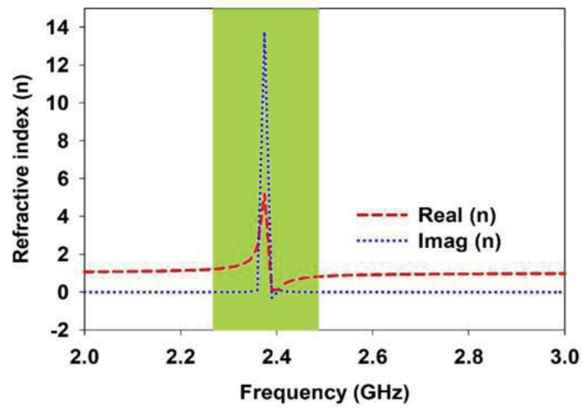

FIGURE 6. Extracted refractive index.

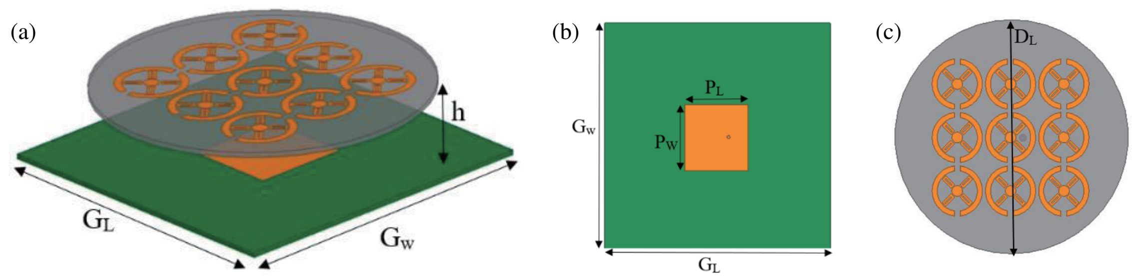

FIGURE 7. (a) 3 D Geometry of the proposed Antenna ($G_L = 104$ mm, $G_W = 104$ mm, $h = 11$ mm). (b) Microstrip Patch antenna ($P_L = 29$ mm, $P_W = 30.5$ mm). (c) Superstrate ($D_L = 104$ mm).

from the electric susceptibility, and the permeability is obtained from the magnetic susceptibility. The unit cell is analysed using Floquet port, and the co polarised and cross polarised reflection parameters $\Gamma^{TE/TE}$, $\Gamma^{TM/TM}$, $\Gamma^{TE/TM}$, $\Gamma^{TM/TE}$ and co polarised and cross polarised transmission parameters $T^{TM/TM}$, $T^{TE/TE}$, $T^{TE/TM}$, $T^{TM/TE}$ are observed and utilized for arriving at the electric and magnetic susceptibilities χ_{es} and χ_{ms}. k_o represents the free space wavenumber.

3. DESIGN OF THE ANTENNA

3.1. Proposed Antenna

The proposed antenna is formed by the combination of the metasurface superstrate and microstrip patch antenna. Metasurface is a 3×3 array of metamaterial unit cell on a high dielectric low loss substrate. The 3D geometry of the proposed antenna is shown in Figure 7(a). The metasurface shows a periodic arrangement of the unit cells. The thickness of the metasurface is 1.6 mm. The distance between the antenna and superstrate is optimized for higher gain. The metasurface is kept at a distance of 11 mm from the surface of the antenna. The superstrate is kept above the antenna by means of a spacer. The antenna with the metasurface gives a gain enhancement of 4.6 dB.

3.2. Reference Patch Antenna

The rectangular microstrip patch antenna is designed on a FR4 substrate with a thickness of 1.6 mm, relative permittivity of 4.4 and loss tangent of 0.02. The dimension of the patch is $L = 29$ mm and $W = 30.5$ mm. The dimension of the ground plane is 104 mm $\times$ 104 mm. The antenna is coaxially fed and resonates at a frequency of 2.4 GHz. The patch antenna has a peak gain of 3 dBi. The schematic of the patch antenna is shown in Figure 7(b). The antenna is linearly polarized with broadside radiation pattern. The superstrate is formed by a high dielectric low loss circular substrate which is shown in Figure 7(c).

4. RESULTS AND DISCUSSIONS

The antenna parameters were simulated using Ansys HFSS, and all the parameters were measured using Anritsu MS46122b Vector Network Analyser. The simulated and measured reflection characteristics of the patch antenna and the antenna with superstrate are shown in Figure 8. The simulated and measured antennas show good agreement. The E-plane gains of the patch antenna and the antenna with superstrate are shown in Figure 9. The H-plane gains of the patch antenna and the antenna with superstrate are shown in Figure 10. It can be observed in Figure 9 and Figure 10 that the directivity of the antenna with metasurface (MS) is improved compared with the conventional antenna. The beamwidth of the antenna in the E-plane is reduced by 12 degrees, and the beamwidth of the antenna in the H-plane is reduced by 30.5 degrees.

The distance between the patch and superstrate is optimised as 11 mm which is equal to 0.088λ where "λ" is called the resonant wavelength of the antenna. The measured gains of

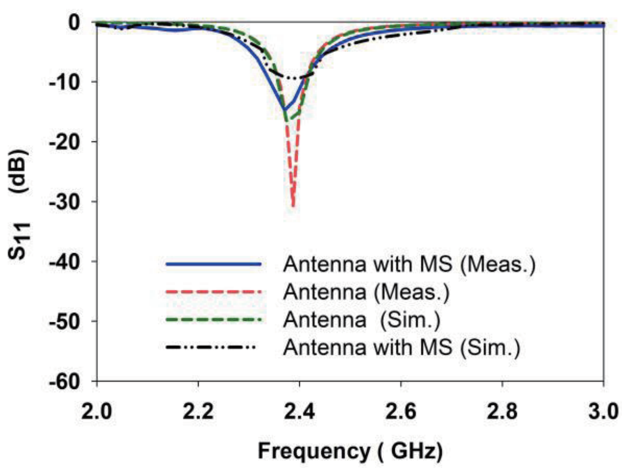

FIGURE 8. Reflection characteristics of the antenna.

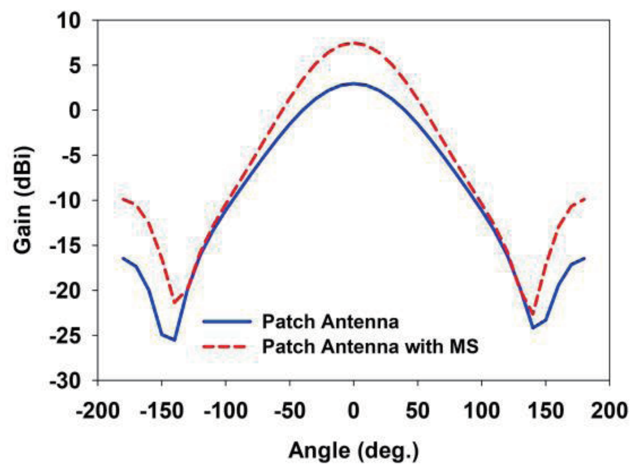

FIGURE 9. E-plane gain.

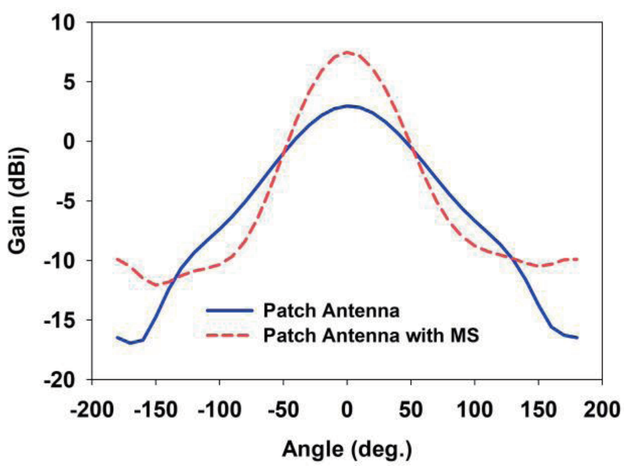

FIGURE 10. H-plane gain.

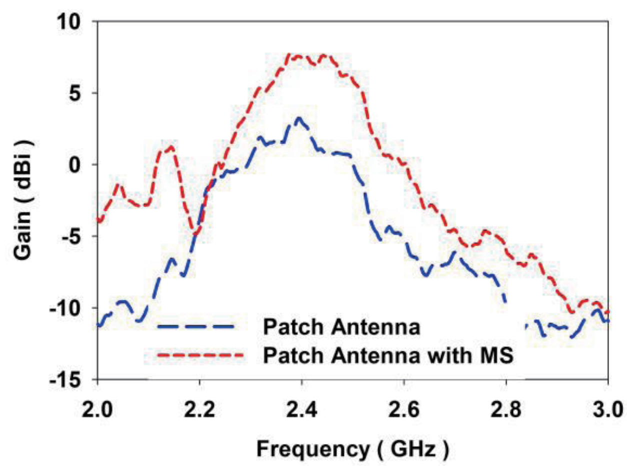

FIGURE 11. Gain Vs Frequency.

TABLE 1. Comparison of gain with loss tangent.

Dielectric constant	Loss tangent	Gain (dBi)
11.7	0.0048	7.6
11.7	0.02	7
11.7	0.1	5

the patch antenna and the patch antenna with metasurface are shown in Figure 11. It is seen that the antenna with metasurface gives a gain enhancement of 4.6 dB.

The high dielectric value of the substrate reduces the size of the unit cell as the size of the radiating element is inversely proportional to the dielectric constant. The low loss of the superstrate does not have effect on the dimensions of unit cell, rather as the loss is reduced the gain is improved. Hence, an analysis with a high dielectric superstrate with different loss tangents is done. Superstrates with loss tangents 0.1, 0.02, and 0.0048 were analyzed as shown in Table 1, and it was found that superstrates with low loss provide more gain enhancement than the others.

This is due to the reduction in the surface waves for the low loss superstrates. Also, the dimensional parameter of the unit cell design is not affected by the change in the value of loss tangent. The measured co and cross polarized radiation patterns of the antenna in E-plane and H-plane are illustrated in Figure 12. The proposed antenna is directional in the broadside direction. The difference between the co and cross polarizations depicts the presence of linear polarization in the antenna. The radiation efficiency of the antenna is increased by 42%.

TABLE 2. Comparison of proposed antenna with existing antennas.

Ref.	Substrate thickness (mm)	Freq. (GHz)	Distance of superstrate from patch antenna (mm)	Combination of MTM unit cells	Dielectric constant	Loss Tangent	No. of layers	Gain Enhancement (dB)
[6]	0.762	10.09	$0.578\lambda_o$	5×5	3.55	0.0027	1	12.5
[9]	1.6	2.4	$0.096\ \lambda_o$	2×2	4.4	0.02	1	4
[11]	0.8	10	$0.76\ \lambda_o$	7×7	2.65	0.001	3	7.8
[12]	1.575	2.44	$0.097\ \lambda_o$	4×3	2.2	0.0009	1	2.3
[14]	2	10.8	$0.555\ \lambda_o$	12×12	2.2	0.0009	1	4.9
[19]	1.524	10.75	$0.482\ \lambda_o$	8×8	2.65	0.002	1	6.3
This Work	**1.6**	**2.4**	**$0.088\ \lambda_o$**	3×3	**11.7**	**0.0048**	**1**	**4.6**

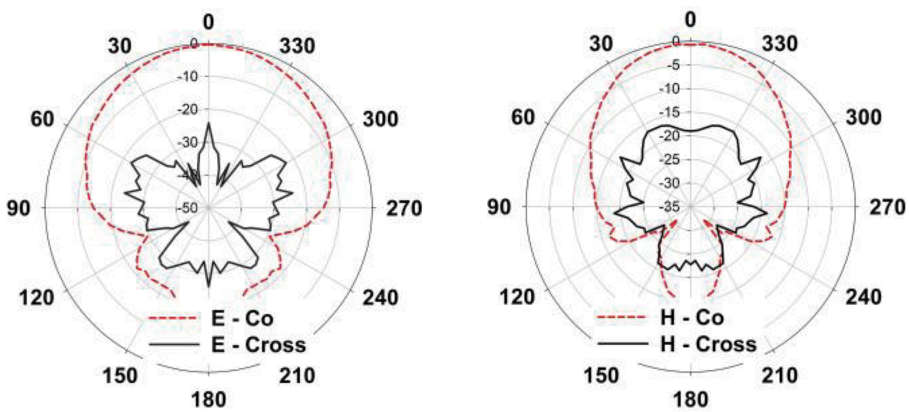

FIGURE 12. Measured E-plane H-plane radiation pattern.

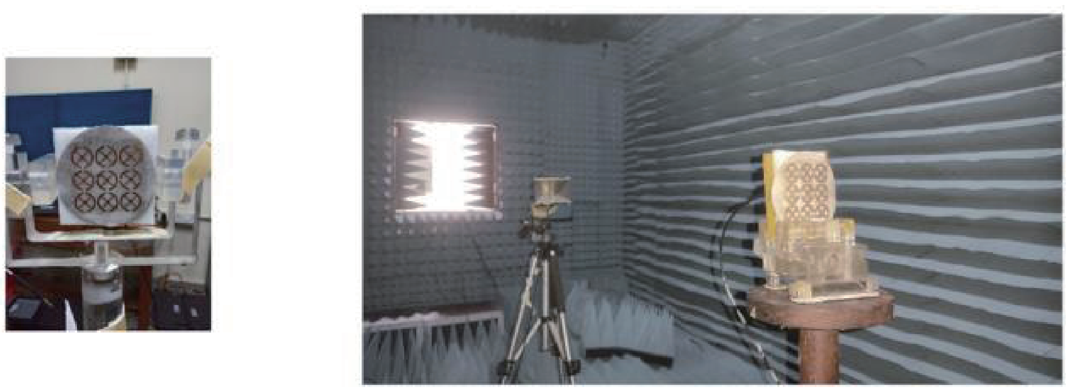

FIGURE 13. Fabricated prototype and the measurement setup.

TABLE 3. Angle vs Gain.

Angle (degree)	Gain Enhancement (dB)
10°	4.6
20°	3.5
30°	3

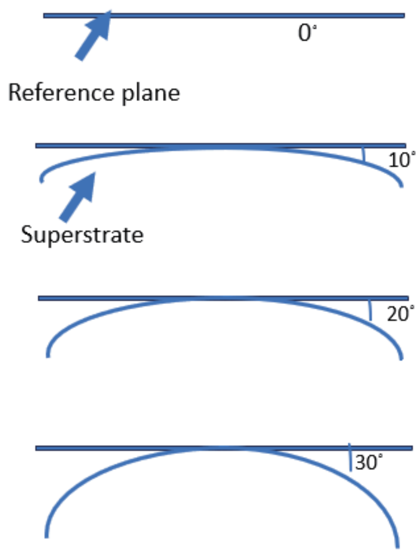

FIGURE 14. Schematic representation of the superstrate at various angles.

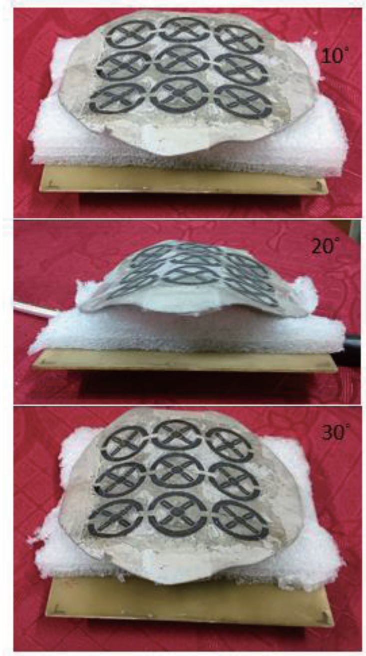

FIGURE 15. Practical demonstration of the superstrate at 10°, 20° and 30°.

The fabricated antenna prototype and measurement setup are shown in Figure 13. A comparison of this work with previous works is presented in Table 2. This work has used a high dielectric constant substrate compared to all other substrates and has low loss tangent. The gain of the antenna is enhanced more at 2.4 GHz band. Also, the distance between the antenna and superstrate is less than the other reported antennas with gain enhancement better at the frequency of 2.4 GHz.

5. FLEXIBILITY STUDIES

The substrate used for the design of the superstrate is flexible that can be used for applications where flexibility nature of the antenna is a concern. In order to study the effect of gain on the flexible nature of the superstrate, the superstrate is bent at different angles. The schematic of the superstrate at different bending angles is shown in Figure 14.

The superstrate without bending is 0°, and the superstrate is further bent at different angles like 10°, 20°, and 30°.

The flexibility nature of the superstrate is also experimentally demonstrated as shown in Fig. 15. The superstrate is supported over the antenna by means of Styrofoam which has less effect on the electromagnetic radiations. It can be seen that the gain enhancement of the antenna is affected by bending the metasurface, but can still improve the gain of the patch antenna because of the presence of metamaterial property. The gains of the antenna observed at different angles are shown in Table 3.

6. CONCLUSION

A new low loss substrate with a loss tangent of 0.0048 and dielectric constant of 11.7 is developed as the substrate for the metasurface.

The novel circular anisotropic metasurface is designed to operate at 2.4 GHz. The unit cell exhibits near-zero refractive index at the same frequency. The designed antenna is fabricated and tested. The antenna with a superstrate gives a peak gain of 7.6 dBi, enhancing the gain of antenna by 4.6 dB. The variation of gain with respect to different dielectric losses is analyzed, and the superstrate with less loss contributes more gain enhancement. The proposed design provides high gain compared to the conventional antenna. As the substrate is flexible, it can be used for wearable applications and in applications where vibrations is prone to affect the antenna performance like aircrafts.

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