Wideband Circularly Polarized Metamaterial based Antenna employing Metasurface Structure

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***Abstract*—In this work, a novel wideband compact and low-profile metamaterial-based antenna has been proposed. The introduction of metasurface layer between the patch and ground plane improves antenna's performance, considerably. Our proposed circularly polarized (CP) antenna has been realized by two pairs of radiators. The CP characteristics have been obtained by placing two radiators in X-polarized wave and two in Y-polarized wave. Each radiator is carefully designed with epsilon negative transmission line (ENG-TL) to generate zeroth-order resonance (ZOR). Our proposed antenna achieves a gain of 4.94 dBic, which is almost 0.58 dBic higher than the structure without metasurface. Also, the operating bandwidth and the simulated axial ratio bandwidth (ARBW) of our proposed antenna improve to 698.6 MHz and 450.3 MHz.**

***Keywords*—metamaterial, metasurface, circularly polarized**

I. Introduction

The increasing demand of high data-rate wireless communication motivates us to design compact size antenna, which is a major component of wireless transceiver. Researchers and academia are putting lots of effort to improve the antenna performances to implement low-loss and compact wireless systems. To solve the issue of transmitter and receiver orientation in sensitivity, circularly polarized (CP) structures have been immensely used. Park et. al. used zeroth order resonance based omni-directional CP antenna to improve the axial ratio [1]. Coplanar waveguide fed dual band linear and circularly polarized antenna with composite split ring resonator has been designed to reduce size and improve gain [2]. Also, dual band circularly polarized antenna with small size has been designed by incorporating a trimmed square patch antenna and a (2×2) triangle mushroom antenna [3]. But the entire aforementioned antenna suffers from narrow bandwidth, narrow axial ratio bandwidth, poor gain, larger size and design complexity.

Metamaterials (MMs) are three-dimensional (3D) artificial composite nanostructures which have extraordinary properties. They are used for guiding and controlling the flow of electromagnetic waves. They possess various attractive novel optical effects and applications not attainable using natural materials [4]-[5]. Metamaterial structure realized by composite right-left handed (CRLH) has been extensively used for both size reduction and performance enhancement. The CRLH transmission line was realized to design compact zeroth-order resonating wideband antennas [6]. A metamaterial based CP antenna [7] employing ENG-TL has been designed to improve the gain with lesser size of single feed. A metamaterial surface also known as metasurface is a two-dimensional (2D) structure of a metamaterial with sub-wavelength thickness [8]. The performance of the metasurfaces is controlled by the sizes and shapes of the unit cell of the metasurface that are fabricated on the dielectric substrate [9] which can be explained with the following expression:

$$n_{eff} = \eta_g(x n_{sub} + (1 - x) n_{air}) \qquad (1)$$

Here, n_{eff} is the effective refractive index, x is substrate weight factor, η_g is the geometrical factor, n_{sub} and n_{air} are refractive indices of substrate and air, respectively. η can be varied with respect to the structures of the unit cell [10]. Metasurface structure can be easily fabricated due to their planar structure using planar fabrication tools [9]. Low profile circularly polarized antenna based on fractal metasurface and fractal resonator has been designed to obtain high gain and wide axial ratio bandwidth [11].

In this work, introduction of metasurface into the CP antenna results in an improved antenna gain. Also, a higher bandwidth and improved axial ratio bandwidth are achieved. The electromagnetic (EM) simulations throughout the manuscripts has been done using Computer Simulation Technology (CST) design studio.

II. Proposed Antenna design

Our proposed CP antenna is comprised of four-unit cells interconnected to each other. The CP antenna is widely used because of its better flexibility towards the orientation of the transmitting and receiving antenna. It also minimizes the multipath effects including constructive and destructive interference and phase shifting of the signal. The equivalent circuit of the proposed antenna unit cell is shown in Fig. 1(a). The equivalent circuit is realized by using two rectangular patches and a spiral strip to connect the patches, as shown in Fig. 1(b) [7]. The series inductance (L_{R1}) is realized by the rectangular patch of area $(h \times c)$. The interconnected spiral strip of area $(a + g + f) \times j$ and reactangular patch of area $(e \times d)$ is contributing to the other series inductance (L_{R2}). Coupling capacitor (C_C) is realized by the capacitive coupling between the patch and spiral strip. The shunt inductance (L_L) is realized by the shorted via between the smaller patch and ground plane. The shunt capacitor (C_R) is due to the capacitive coupling between the top radiator and ground plane. The orientation of the radiators is shown in Fig. 1(c), where cells A and B are interconnected with each other through a port (P), which

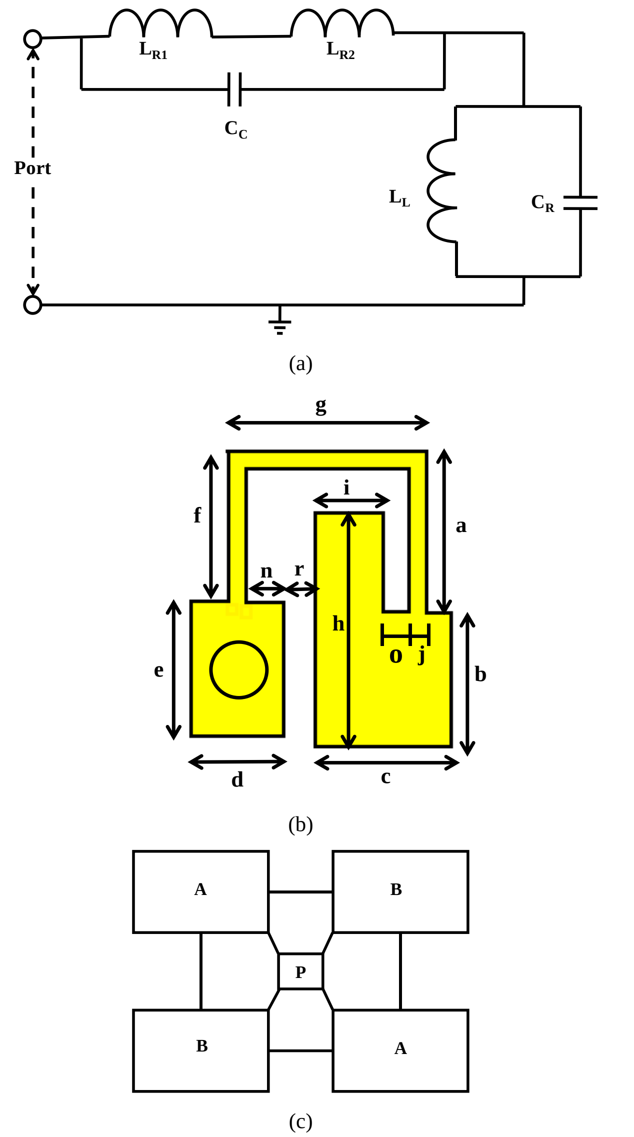

Fig. 1. (a) Equivalent circuit diagram of unit cell of patch. (b) Top view of unit cell of patch realization. (c) Block diagram of the proposed CP antenna.

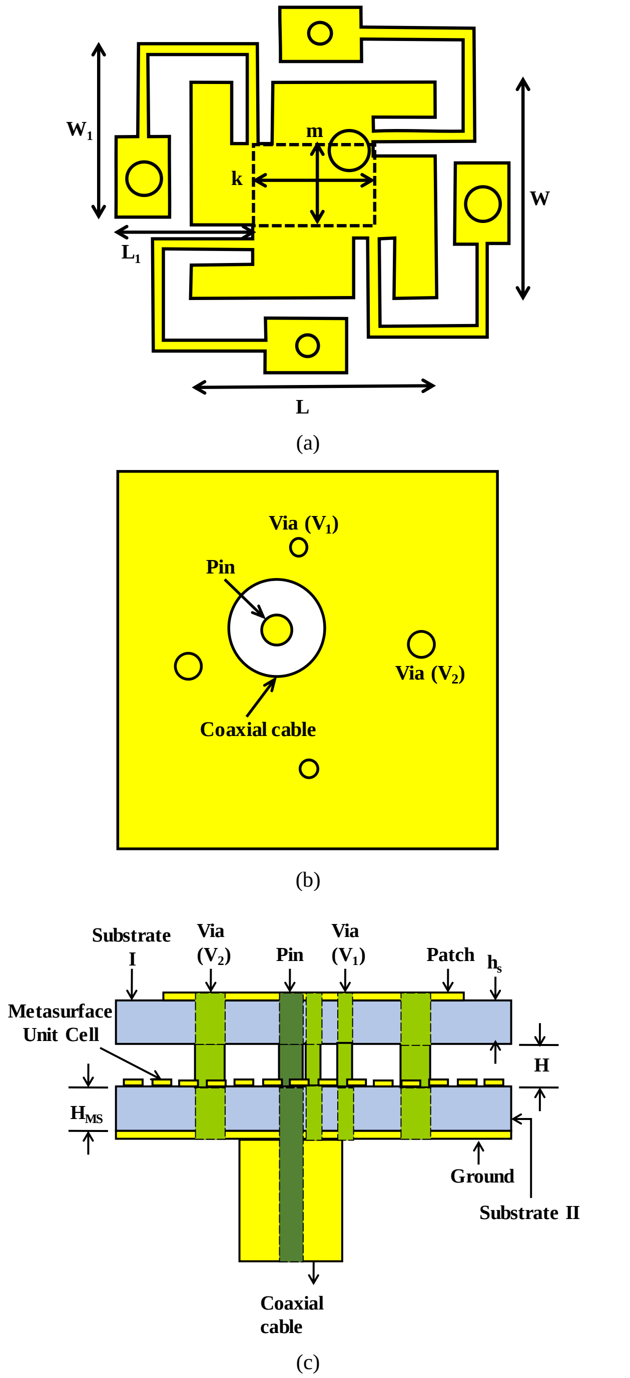

Fig. 2. (a) Front view (b) Back view & (c) Side view of the proposed antenna.

possesses an area of $(k \times m)$.

For the measurement of the proposed design, a coaxial cable is inserted in the top metal layer through the ground plane and positioned in port (P), which is pointed in Fig. 2(a). The total size of the antenna is $(20\,mm \times 20\,mm \times 2.4\,mm)$. The position of the coaxial cable and vias is shown in Fig. 2(b). The circular white colour shows the port entry point. Here, Coaxial feeding technique is used. Coaxial feed point is at $(X, Y) = (1.5\text{ mm}, 1.5\text{ mm})$ with an inner and outer diameter of 1.4 mm and 5 mm. To design this antenna, substrate of FR-4 is chosen with a given dielectric constant (ε_r) and loss tangent (δ). Copper is used for the design of patch, ground and metasurface. Dimensions of optimized parameters of the proposed antenna are given in Table I and Table II. There are two types of polarized waves- (i) X-polarized waves and (ii) Y-polarized waves. The size of the unit cells A and B in Table I is different for the generation of Y and X -polarized waves, respectively and this eventually contributes to the CP waves. Unit cells A and B are orthogonal to each other. Resonance frequency of these cell can be controlled by controlling the radius of shorted vias (V_1) and (V_2).

Metamaterial based CP antenna is suitable for the design of miniaturized low-profile antenna. We choose epsilon negative (ENG) metamaterial which uses spiral strips for obtaining negative value of epsilon. These metal spiral strip exhibit high-pass behavior for an incoming plane wave, whose electric field is parallel to the spiral strip [12]. For bandwidth and gain enhancement, a metasurface is employed between the top and bottom metal layers. A metasurface has the advantages of being ultrathin, ultralight and low cost. A finite sized metasurface structure yield extra resonances for the radiation structures [13], which can be calculated by using (2). The propagation of surface waves

TABLE I. OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA UNIT CELLS

Parameter	Unit cell A (mm)	Unit cell B (mm)
a	3.65	3.65
b	2.75	3.75
c	3	2.8
d	2	2
e	3	3
f	3.4	4.15
g	4.4	4.15
h	5.25	6
i	1.5	1.25
j	0.4	0.4
n	0.8	0.8
o	0.55	0.55
r	0.75	0.75

on the metasurface contributes to this extra resonance frequency. The propagating constant (β_{SW}) of the surface waves travelling and decaying away from the metasurface is related to the decay constant (α) and the frequency (ω) by the expression of (3).

$$\beta_{SW} = \frac{\pi}{N \times P} \qquad (2)$$

$$\beta_{SW} = \sqrt{\eta^{2}\omega^{2} + \alpha^{2}} \qquad (3)$$

Here,
β_{SW} = Propagating constant of the surface wave resonances
N = The number of cells
P= Periodicity of the metasurface
η= Intrinsic impedance

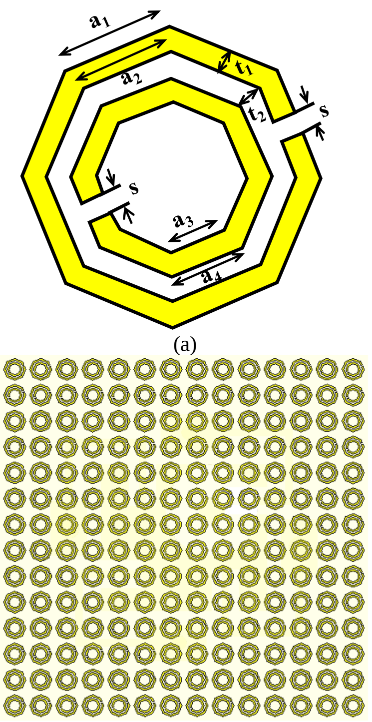

Fig. 3. (a) Geometric configuration of metasurface unit cell. (b) Top view of metasurface with (14×14) unit cells.

TABLE II. OPTIMIZED DIMENSION OF THE PROPOSED ANTENNA

Parameter	Value (mm)
h_s	0.8
H_{MS}	0.8
H	0.8
W	8
L	9
W_1	6.4
L_1	5
k	4.5
m	3
ε_r	4.3
δ	0.025
V_1	0.4
V_2	0. 65

TABLE III. OPTIMIZED DIMENSION METASURFACE UNIT CELL

Parameter	Value(mm)
a_1	0.46
a_2	0.38
a_3	0.23
a_4	0.31
t_1	0.1
t_2	0.1
s	0.08

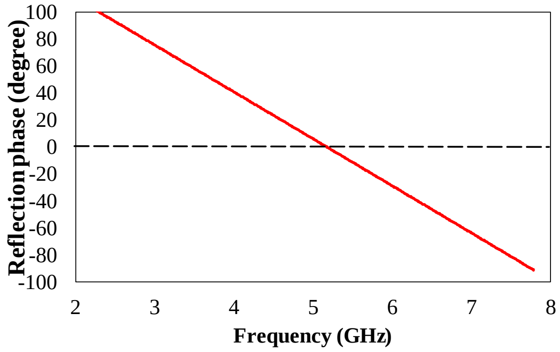

Fig. 4. Simulated reflection phase of the metasurface unit cell.

ω= Frequency
α = Decay constant

The heights of substrate I and II are h_s and H_{MS}, as shown in Fig. 2(c). The height, H represents the air gap between the two substrates.

Octagonal split resonant ring (SRR) [14] is used as metasurface unit cell which is based on the C shape SRR shows in Fig. 3(a). Bandwidth enhancement is achieved with the proposed antenna having multiple octagonal split resonant ring structures. This unit cell is simulated in a periodic boundary condition along the x and y-axes. A single mode wave port is used as a stimulus at the top [15]. The metasurface layer is shown in Fig. 3(b), where octagonal periodic structures are realized in between the top and bottom metal layer. The metasurface consists of (14×14) unit cells, which are printed periodically on the substrate II. Reflection phase of the metasurface unit cell is shown in Fig. 4. Resonance frequency for 0° reflection coefficient is 5.18 GHz. $\pm 90°$ reflection phase bandwidth is $(2.5939 - 7.7606)$ GHz. Dimensions of optimized parameters for metasurface unit cell are given in Table III.

III. SIMULATED RESULTS

The simulated scattered (|S|) parameter (S_{11}) and ARBW (Axial ratio bandwidth) of our proposed antenna are shown in Fig. 5 and Fig. 6, respectively. The calculated bandwidth (BW) of the antenna is 698.6 MHz $(6.4656 - 7.1642)$ GHz within the range of $\pm 90°$ reflection phase bandwidth of the unit cell. The calculated fractional bandwidth (FBW) is 10.25%, which can be calculated as (4).

$$FBW = \frac{f_{max} - f_{min}}{f_C} \times 100\% = \frac{BW}{f_C} \qquad (4)$$

Where, $f_C = 6.815$ GHz is the centre frequency of the antenna. The FBW of our proposed antenna improves by 1.075 times compared to [7]. The simulated axial ratio bandwidth (ARBW) is 450.3 MHz $(6.2404 - 6.6907)$ GHz, which is improved by 320.3 MHz in comparison to the work in [7]. According to our proposed antenna's VSWR (Voltage Standing Wave Ratio) curve in Fig. 7, we can see that the calculated value is less than 2 throughout the operating band $(6.454 - 7.174)$ GHz, which makes the antenna suitable for most antenna applications. The

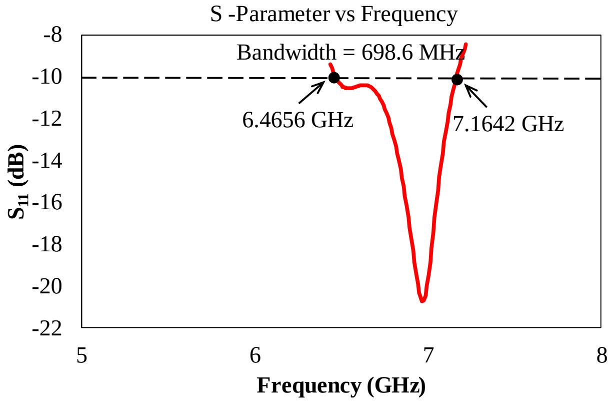

Fig. 5. Simulated scattered parameter ($|S_{11}|$) of the proposed antenna.

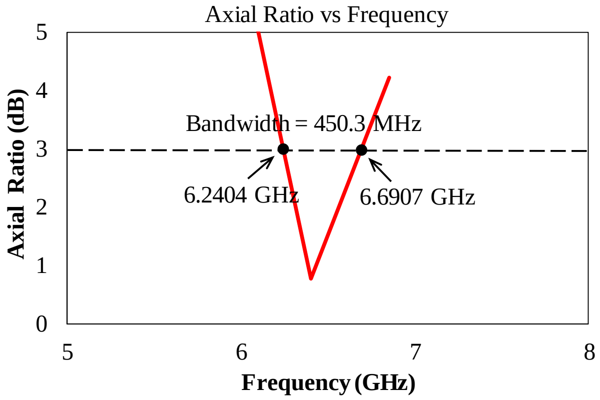

Fig. 6. Simulated ARBW of the proposed antenna.

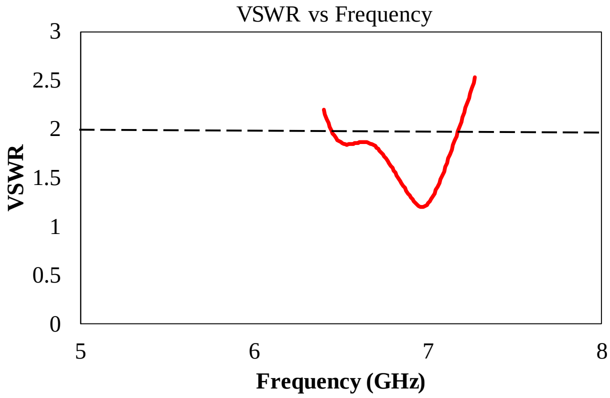

Fig. 7. VSWR vs Frequency curve.

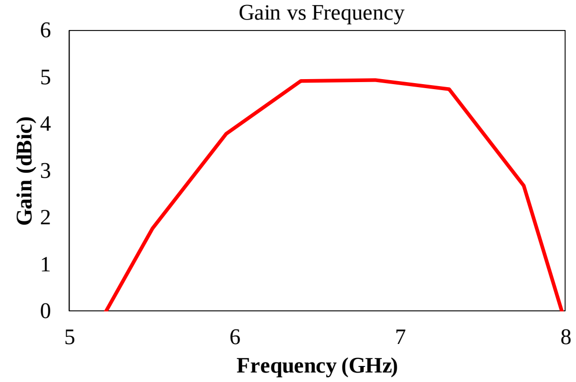

Fig. 8. Simulated gain of the proposed antenna.

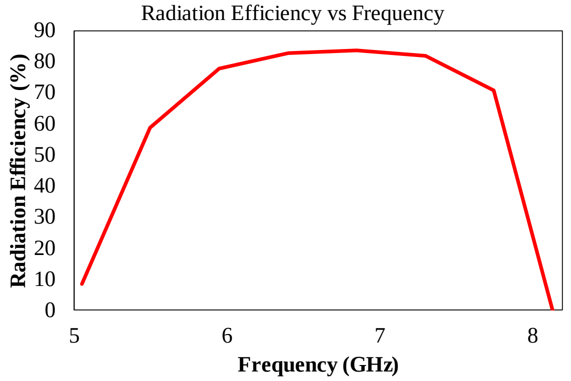

Fig. 9. Simulated radiation efficiency of the proposed antenna.

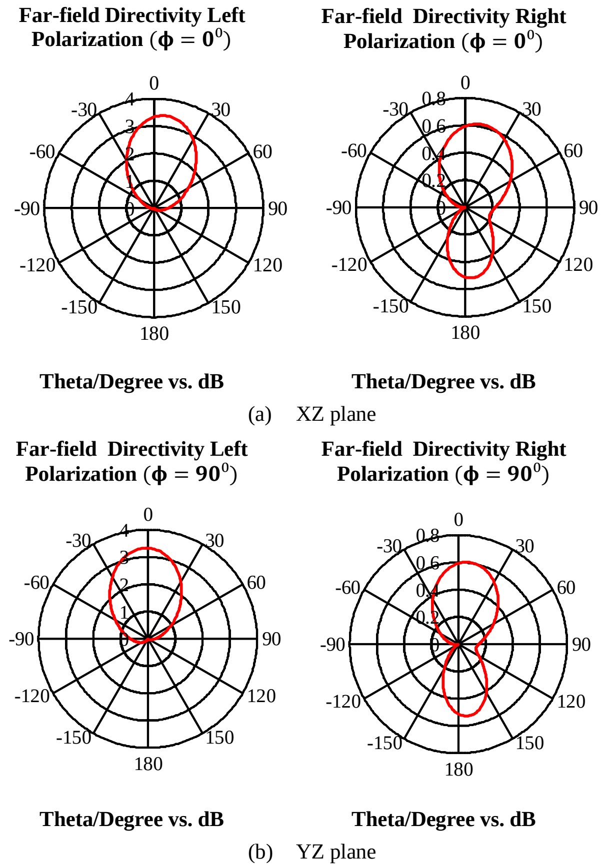

Fig. 10. Simulated radiation patterns of the proposed antenna.

TABLE IV. COMPARISON OF THE CP ANTENNA WITH AND WITHOUT METASURFACE STRUCTURE

Parameter	With metasurface structure	Without metasurface structure
BW (MHz)	698.6	650
Gain (dBic)	4.94	4.36
ARBW (MHz)	450.3	130
Radiation efficiency (%)	>83	>72

TABLE V. COMPARISON OF THE SIMULATED RESULTS OF PROPOSED CP ANTENNA WITH OTHER RECENTLY PUBLISHED ANTENNA

Ref.	f_{ZOR} (GHz)	Overall antenna size (mm)	BW (%)	ARBW (%)	Gain (dBic)
[7]	5.5	20×20×2.4	11.55	2.54	4.36
[16]	5.2	60×60×2	4	4	8.6
[17]	5.8	32.3×32.3×1.5	3.97	---	0.92
[18]	2.64	25×25×1.6	7.6	---	3.17
[19]	2.08	70×78.5×0.8	22	---	1.4
[20]	2.4	66×66×258	10.10	6.06	4.6
This work	6.4	20×20×2.4	10.25	6.96	4.94

calculated gain against frequency at $(\theta = 0^0, \phi = 0^0)$ is plotted in Fig. 8, where we can conclude that the introduction of the metasurface structure improves the antenna gain to 4.94 dBic at 6.85 GHz. The radiation efficiency is shown in Fig. 9, which is greater than 83% throughout the operating band. Fig. 10(a) and Fig. 10(b) depict the simulated radiation patterns at XZ and YZ plane, respectively. Main lobe magnitudes for left and right polarization $(\phi = 0^0)$ are 3.42 and 0.609. Again, for left and right polarization $(\phi = 90^0)$, main lobe magnitudes are 3.34 and 0.593. Good left-handed circular polarization has been observed at 6.4 GHz.

The performance of our proposed metasurface based CP antenna is compared with the CP antenna without implementing metasurface structure in Table IV. From the table, we can conclude that the implementation of the metasurface structure to the CP antenna improves the antenna performance significantly. Our proposed antenna is also compared with the other recently published work in Table V in terms of its size, BW, ARBW and gain. The comparison shows that the proposed antenna achieves a better gain and wider bandwidth than the other state-of-arts.

IV. CONCLUSION

An antenna with wide bandwidth has been proposed by implementing metasurface structure. Employment of the metasurface structure improves the antenna gain as well. The simulated results show an impedance bandwidth of 698.6 MHz with a gain of 4.94 dBic, ARBW of 450.3 MHz and radiation efficiency of greater than 83%. These performances prove that the antenna has potential applications. The antenna's operating frequency is 6.4656 GHz to 7.1642 GHz, which is applicable for Indian National Satellite System (INSAT). It is a multipurpose geostationary satellite launched by Indian Space Research Organisation (ISRO). It is used for the telecommunications, broadcasting, meteorology and search and rescue operations. The proposed low-profile and compact antenna can be easily incorporated to the other microwave devices that working at the same frequency band for particular application.

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