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LINEAR PHASED METAMATERIAL INCORPORATED PATCH ANTENNA ARRAY AT 28 GHZ FOR 5G BASE STATIONS

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Abstract

This article presents a 1×6 linear phased antenna array implemented with metamaterial incorporated patch antennas for 5G base stations. The single element antenna was modelled on Rogers RT/duroid 5880 substrate in the dimensions of $7.8 \times 7.8 \times 0.254$ mm^3 with metamaterial incorporated partial ground plane and complementary metamaterial incorporated patch. This metamaterial incorporated antenna structure is resonating in 22.03–33.55 GHz at central frequency of 28 GHz with 40% impedance bandwidth with respect to the -10 dB return losses. With aim to design a radiating structure for 5G base stations and in order to enhance the gain, a six element phased array was developed using the abovementioned single element antenna with inter element spacing 7.8 mm between the adjacent antenna elements. In the analysis of this phased array, we observed acceptable diversity parameters (isolation, ECC, DG, CCL, and MEG) and presented beam steering capabilities by changing the phase difference between the adjacent ports. The proposed six element phased array antenna is capable to steer the beam to $\pm 43.5°$ and capable to cover 5G NR n-257, n-258 and n-261 bands with significant gain and efficiency.

Key words: 5G, base station, beam steering, metamaterial, millimetre wave, phased array

Introduction. Fifth generation (5G) wireless system is a term used to denote the next level of 4G mobile telecommunications standards [1]. Across the world

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mobile data traffic is exponentially increasing year by year and the continuation of this data traffic will be expected in future as well [2]. The traditional microwave bands face the problem of shortage in their spectrum. Due to the shortage of that spectrum millimetre wave (mm-wave) bands have been populated as suitable spectrum bands for 5G mobile communication [3]. The fifth generation wireless technology has the goal of enhancing the capacity and efficiency of communication network. Increasing the capacity of 5G communication networks aims to deliver the communication services with respect to meet the requirements and demands of network users with faster and higher data rates. As a communication device [4, 5], the antenna plays a dynamic role in the field of communication. So, such deployment of a 5G communication technology needs the antenna infrastructure which can serve with high data rates and good channel capacity.

Beam control antennas have always been an extremely important part of modern wireless communication systems applied in radar, satellite and localization technologies and have the essential need of good progress in the transmission quality and channel capacity with low channel interference in wireless communication systems due to continued growth of data traffic and device connectivity.

Minimum 7 dBi gain is required for array antenna as per the rules of Equivalent isotropic radiated power (EIRP) [6]. Incorporation of metamaterials in antenna technology is gaining importance, particularly in increasing gain and bandwidth. Implementing Multiple-Input Multiple-Output (MIMO) antenna system with metamaterial loaded microstrips, makes possible to achieve high gain significant data transmissions and good channel capacity [7]. Generally enhancement in the gain of antenna will degrade the coverage area of the wireless signal transmission; that is why the antenna system needs to have beam steering capabilities in order to maintain the wireless link over spatial coverage area [8]. Phased array antennas are good candidates in order to achieve high gain and beam steering capabilities. Because of high performance and low energy consumption at lower frequencies, employing of phased array techniques is a good idea for beam steering [8]. The change in amplitude and phase in the excitation of individual radiating antenna elements in the phased array results to tilt the beam to desired direction [9].

The proposed antenna structure in this article was capable to operate in 5G New Radio (NR) n-257, n-258 and n-261 bands. It was designed by employing metamaterials and phased array in order to meet the above discussed 5G requirements for base stations.

Materials and methods. ***Why is the antenna designed at 28GHz?*** A Local Multipoint Distribution Service (LMDS) broadband spectrum exists at 28 GHz. It consists of very low atmospheric absorption, like 1 GHz to 2 GHz frequency cellular band spectrum. The 28 GHz frequency band spectrum also has very comparable free space path loss. One more advantage of 28 GHz band spectrum is that it does not significantly increase the rain attenuation and oxygen

loss at 28 GHz. Because of these facts, the antenna design at 28 GHz frequency band spectrum may give better radiation [10]. At 28 GHz band the atmospheric absorption is negligible. It is 0.06 dB/km [11].

Theoretical discussion about beam steering in linear phased antenna array. The linear phased array antenna is a linearly arranged group of individual radiators (elements) separated by the inter element spacing constant (d). The signal to be transmitted is fed each antenna component separately. The direction of the beam in space can be controlled electronically by changing the phase and amplitude in the excitation of the individual elements. Generally as per the basic rule, the beam is focused in a particular direction when all the elements are excited with same phase in an array. It is possible to change the direction of the beam with an angle of 'θ', by exciting the radiators with the phase difference (ψ). The phase movement of the signal of phased array can be calculated with the sine theorem and it can be expressed as:

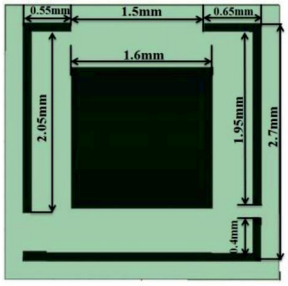
$$\psi = \beta d \sin(\theta) + \alpha, \tag{1}$$

where $\beta = 2\pi/\lambda$ is the phase constant, λ is the wave length, d is the distance between each radiator and α is the initial phase, generally it is zero degrees.

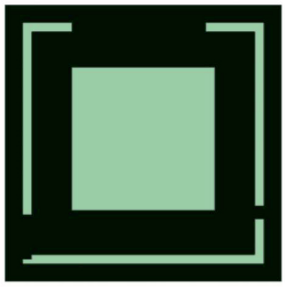
In this article, phased array antenna was resonated at the central frequency 28 GHz. For example, consider that the inter element spacing constant between two adjacent radiators is $d = 7.8$ mm. From theoretical aspect (as per equation (1)) at 28 GHz the radiators excited with the 0° phase difference (ψ) gives the beam in the direction of angle $\theta = 0°$ and the radiators excited with the 180° phase difference (ψ) gives the beam in the direction of angle $\theta = 43.5°$.

Design of metamaterial at 28 GHz. In the literature survey, it was observed that incorporating metamaterials in antenna structure gives significant radiation enhancement in terms of return losses, bandwidth, gain, and radiation efficiency. The metamaterials are the artificial materials having the dielectric permittivity and magnetic permeability simultaneously negative in the same region. The metamaterials have the properties of backward propagation, negative refraction and ability to control the electromagnetic signal. So, in this article, a metamaterial as shown in Fig. 1(a) and its complementary structure as shown in Fig. 1(b) was implemented and that improved the radiation capability of the antenna. The complementary split ring resonator (CSRR) is the mirror image

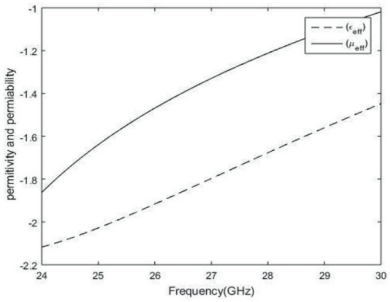
Fig. 1. Prototype and results of single element antenna structure. (a) Proposed metamaterial structure; (b) Complementary metamaterial; (c) Permittivity (ε) and Permeability (μ) of proposed metamaterial structure; (d) Refractive index (n) and impedance (z) of proposed metamaterial structure; (e) Top view prototype of proposed single element antenna; (f) Bottom view prototype of proposed single element antenna; (g) Return losses of proposed single element antenna; (h) Gain plot of proposed single element antenna; (i) Efficiency plot of proposed single element antenna →


0.55mm
1.5mm
0.65mm
1.6mm
2.05mm
1.95mm
2.7mm
0.4mm

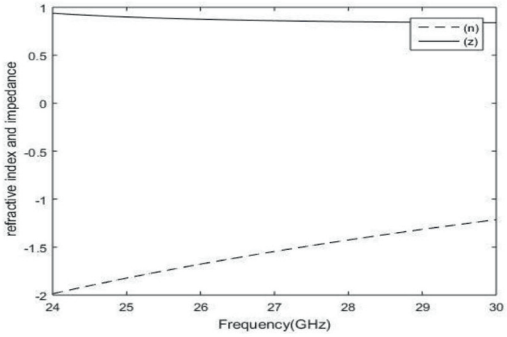
(a)



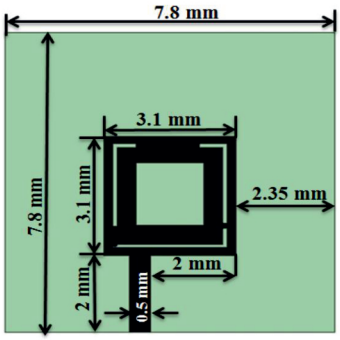
(b)


permitivity and permiability
Frequency(GHz)

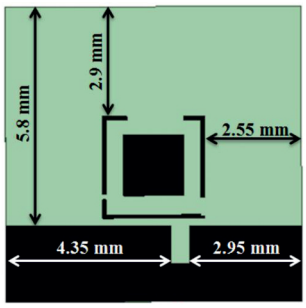
(c)


refractive index and impedance
Frequency(GHz)

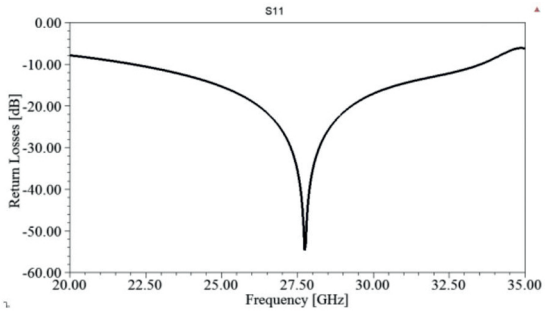
(d)


7.8 mm
3.1 mm
7.8 mm
3.1 mm
2.35 mm
2 mm
2 mm
0.5 mm

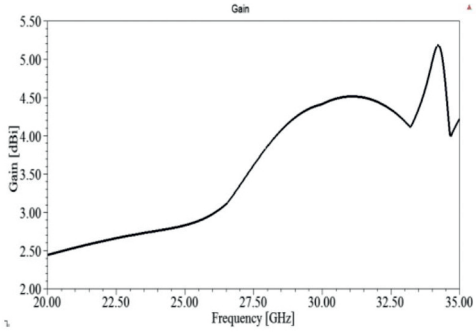
(e)


5.8 mm
2.9 mm
2.55 mm
4.35 mm
2.95 mm

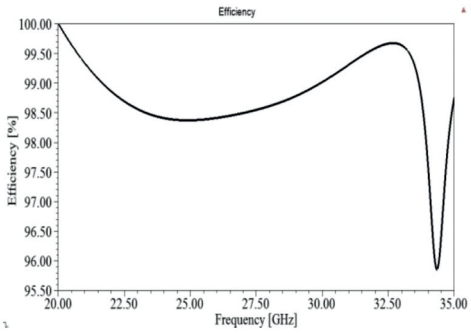
(f)


S11
Return Losses [dB]
Frequency [GHz]

(g)


Gain
Gain [dBi]
Frequency [GHz]

(h)


Efficiency
Efficiency [%]
Frequency [GHz]

(i)

of split ring resonator with equivalent basic operation [12]. The proposed metamaterial reflects negative permeability (μ), permittivity (ε) and refractive index (n) properties at 5G NR n-257, n-258 and n-261 bands, which can be observed in Fig. 1(c) and (d).

Results and discussion. ***Design and result analysis of proposed single element metamaterial incorporated patch antenna.*** The presented antenna structure was designed on dielectric substrate Rogers RT/duroid 5880, its dielectric constant is 2.2 and it was simulated on HFSS-19 software with the dimensions of $7.8 \times 7.8 \times 0.254$ mm^3 with respect to length, width and height.

A 3.1×3.1 mm^2 dimensioned complementary metamaterial patch was etched on top face of substrate as shown in Fig. 1(e). The bottom surface of substrate is filled with metamaterial incorporating partial metallic ground as shown in Fig. 1(f).

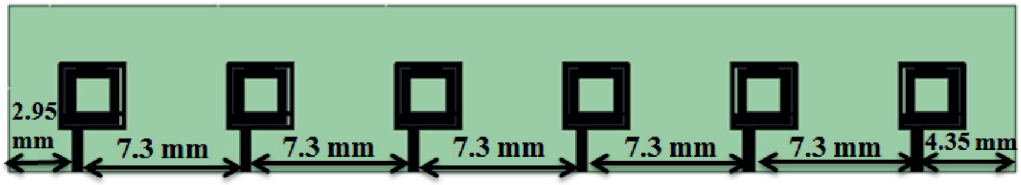
After studying several parameters (parametric analysis), the proposed antenna structure was optimized as shown in Fig. 1(e) and (f) with the dimensions of substrate length 7.8 mm, substrate width 7.8 mm, height of substrate 0.254 mm, patch length 3.1 mm, patch width 3.1 mm, feed-line width 0.5 mm and feed-line length 2.0 mm.

The proposed metamaterial incorporated single element patch antenna radiating structure is resonating over the band 22.03–33.55 GHz with 40% impedance bandwidth as shown in Fig. 1(g). Here, we observed the gain 2.5 dBi to 5.2 dBi as shown in Fig. 1(h) and efficiency greater than 95% as shown in Fig. 1(i) over the resonated band.

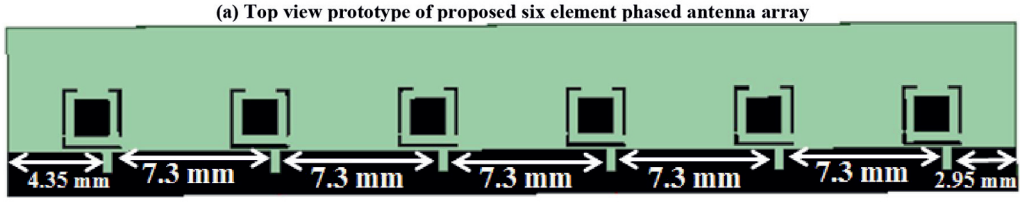
Design and result analysis of proposed six element phased array antenna. The major goal of this article was to design significant gain beam steerable radiating structure, which is capable to fulfill the requirements of 5G base stations. So, with that aim 1×6 linear phased array was developed using proposed single element metamaterial incorporated microstrip antenna with inter element spacing 7.8 mm between the adjacent radiating elements in the dimensions of $7.8 \times 46.8 \times 0.254$ mm^3. The top and bottom views of proposed six element phased array antenna are shown in Fig. 2(a) and (b), respectively.

The acceptable results obtained as shown in Fig. 2(c)–(d) from proposed phased array gave good agreement in order to fulfill the requirements of 5G base stations. The reflection parameters (S11, S22, S33, S44, S55 and S66) are shown in Fig. 2(c). Here it was observed that the proposed phased array antenna is capable to operate in 5G NR n-257, n-258 and n-261 bands with significant return losses. The transmission parameters (S12, S13, S14, S15 and S16) are shown in Fig. 2(d). It was observed that the proposed phased array antenna has significant isolation between the excitation ports and less than -16.25 dB isolation between the adjacent ports.

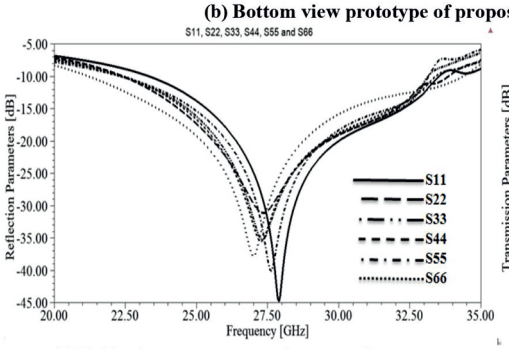
The diversity parameters such as Envelope Correlation Coefficient (ECC), Diversity Gain (DG), Channel Capacity Losses (CCL) and Mean Effective Gain



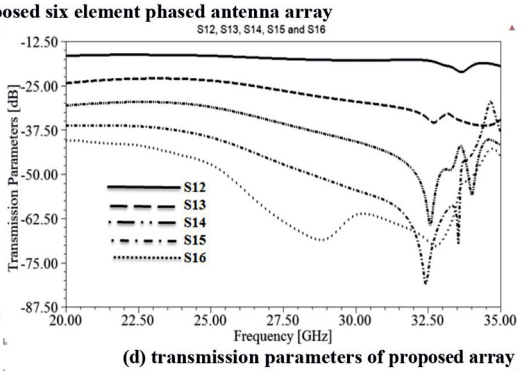
(a) Top view prototype of proposed six element phased antenna array



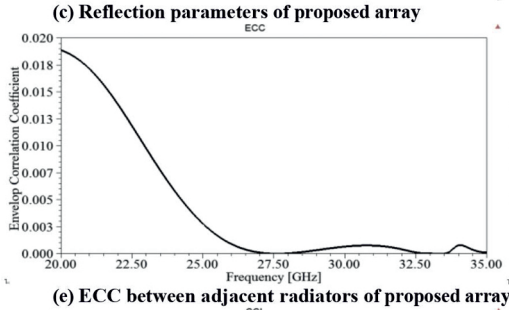
(b) Bottom view prototype of proposed six element phased antenna array



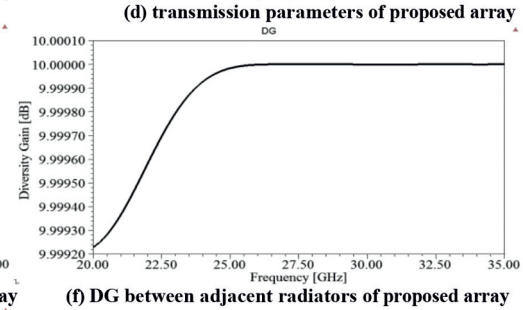
(c) Reflection parameters of proposed array



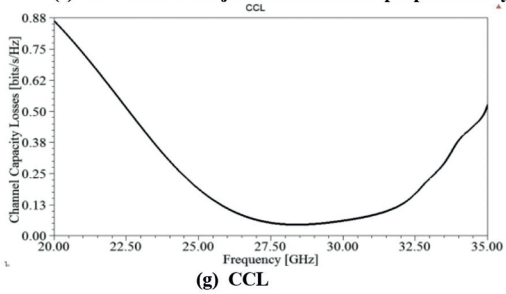
(d) transmission parameters of proposed array



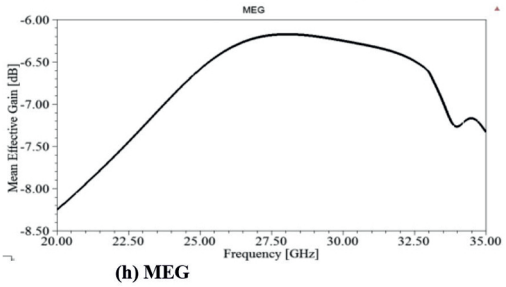
(e) ECC between adjacent radiators of proposed array



(f) DG between adjacent radiators of proposed array



(g) CCL



(h) MEG

Fig. 2. Prototype, scattering and diversity parameters of six element phased array antenna structure

(MEG) are more important to characterize the quality of MIMO antennas. From the results presented in [13], it was observed suggestible diversity parameters such as ECC < 0.02 as shown in Fig. 2(e), DG ≈ 10 dB as shown in Fig. 2(f), CCL < 0.5 bits/s/Hz as shown in Fig. 2(g), and MEG < -6 dB as shown in Fig. 2(h).

For the proposed phased array a maximum gain of 12.55 dBi and efficiency greater than 79% is observed over the pass band as shown in Fig. 3(a) and (b), respectively. The proposed phased array antenna was designed in order to fulfill the requirements of 5G base stations. So, the beam steering capabilities of proposed phased array antenna at 28 GHz was presented as 2D-polar gain patterns shown in Fig. 3(c)–(f) at different phase difference values. The beam steering mechanism of proposed array was studied theoretically using Eq. (1) and showed good matching with simulated beam steering results. From the study of beam steering it was observed that the proposed phased array antenna capable focus the beam to all directions by steering the beam to $\pm 43.5^\circ$ at various phase difference (ψ) values.

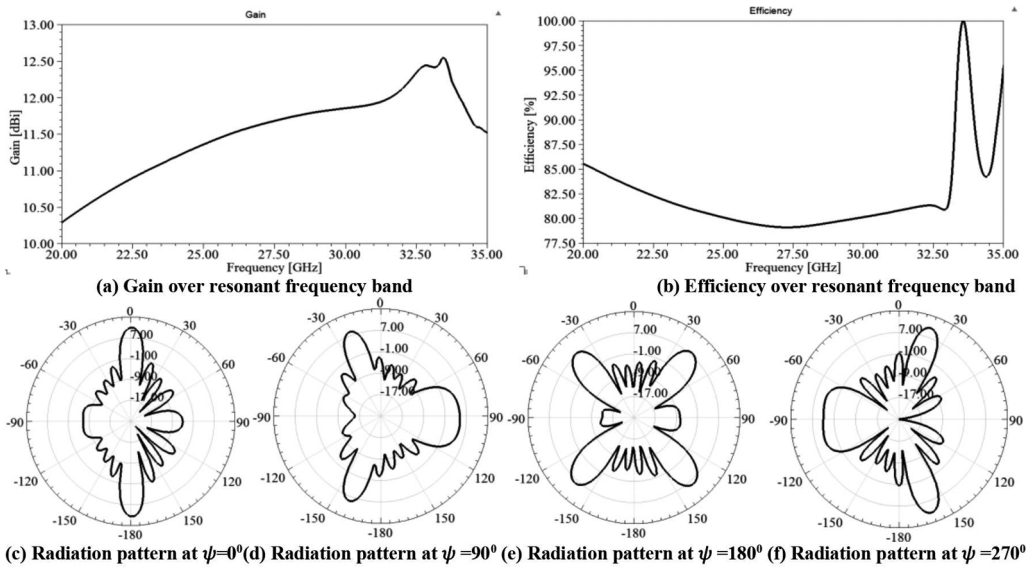


Fig. 3. Gain, efficiency and beam steering results of six element phased array antenna structure

Finally the significant results obtained from the proposed six element linear phased array antenna loaded with metamaterials were compared with the related previous works presented in literature and comparisons listed in Table 1.

Conclusions. This article developed high gain (12.5 dBi), $\pm 43.5^\circ$ beam steerable 1×6 linear phased metamaterial incorporated patch antenna array for 5G base stations. It is capable to operate in 5G NR n-257, n-258 and n-261 bands with in the dimensions of $7.8 \times 46.8 \times 0.254$ mm^3. The significance of adding

Table 1

Comparative results of proposed antenna structure with the previous work presented in literature

Ref. No.	Antenna size (mm^2)	Freq. (GHz)	Band width (%)	Isolation (dB)	Max. Gain (dBi)	Efficiency (%)	Beam steer
[14]	29.96×52	28	9.0	—	14.6	95	$\pm 90^\circ$
[15]	59.97×134.95	28	4.6	—	9.46	79.2	60°
[16]	60×120	26	8.5	16	12	90	75°
[17]	0.8×80.8	28	6.8	—	11.6	96.21	$\pm 45^\circ$
[18]	130×42	28	8.5	-21	10.33	—	$\pm 45^\circ$
[19]	51.3×72	28	9.0	-17	15	—	$\pm 60^\circ$
[20]	23.5×23.5	28	3.0	-29	15.6	79	$\pm 25^\circ$
Proposed Work	7.8×46.8	28	40	< -16.25	12.5	> 79	$\pm 43.5^\circ$

metamaterials to radiating structure and employing phased array were greatly reflected in this paper. The acceptable diversity parameters such as Isolation: < -16.25 dB, ECC: 0.02, DG: ≈ 10 dB, CCL: < 0.5 bits/sec/Hz and MEG: -6 dB was observed. The obtained results from proposed beam steering radiating structure demonstrated that it is a good candidate to use at 5G base stations.

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