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8×8 Planar Phased Array Antenna with High Efficiency and Insensitivity Properties for 5G Mobile Base Stations

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***Abstract*— An insensitive planar phased array antenna with high efficiency function for 5G applications is introduced in this study. 64-elements of compact slot-loop antenna elements have been used to form the 8×8 planar array. The antenna is designed on a low cost *FR4* substrate and has good performance in terms of gain and efficiency. This property has been achieved by applying a new slot-loop resonators. The proposed antenna is designed to operate at 21-23.5 GHz and has a same performance for different values of dielectric constant and loss tangent. It has high-gain, high-efficiency radiation beams at both sides of the substrate and could be used for mobile base station (MBS) applications. The proposed planar array could be integrated with the transceivers on the low-cost printed circuit boards (PCBs) to reduce the manufacturing cost.**

***Index Terms*— 5G communications, base station, insensitive antenna.**

I. Introduction

The ever increasing demand for higher data rates and convenience of mobile communication has led to a vast range of inventions and technology advancement in the past decade [1]. The wireless systems for the upcoming 5th generation network (5G) are increasingly proposing the utilization of the millimeter-wave (mm-Wave) spectrum [2-3]. The use of mm-Wave spectrum will change the design of antennas in 5G communication systems. One key feature of 5G systems is the use of the phased array antennas with beam forming ability at base station systems (Fig.1). Phased array is a collection of lots of antenna elements with individual phase shifters. It help the transmitter by enabling spatial power combining to steer the array beams to the desired direction. It can also improve the spectral efficiency [4-5].

We represent below an insensitive phased array antenna design with improved efficiency and constant gain characteristics for 5G application. The proposed design consists of 64 slot-loop antenna elements which are arranged as 8×8 planar array. The proposed design antenna is working in the frequency band of 21-23.5 GHz which is under consideration for 5G applications [6]. As the main substrate of the slot-loop elements is the air with permittivity of 1 and loss tangent of 0, so they can achieve low loss and high antenna efficiency.

In addition, the proposed structure has a same performance for different values of dielectric constant (ε_r) and loss tangent (δ). Which means for different kind of substrates the proposed design has a same performance. The analysis and performance of the antenna are obtained by using *CST* software [7].

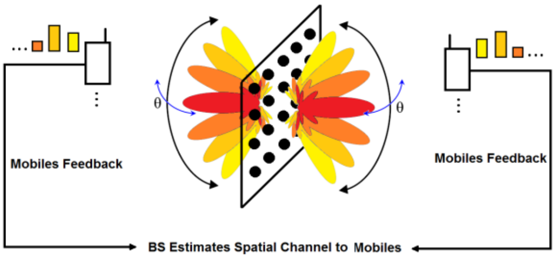

Fig. 1. Placement of the planar phased array antenna in base station systems.

II. Proposed Antenna Configuration

The presented antenna shown in Fig. 2 is designed on the FR-4 substrate with h_{sub}=0.8 mm, ε_r=4.3, and δ=0.025. The values of proposed design parameters are specified in Table I.

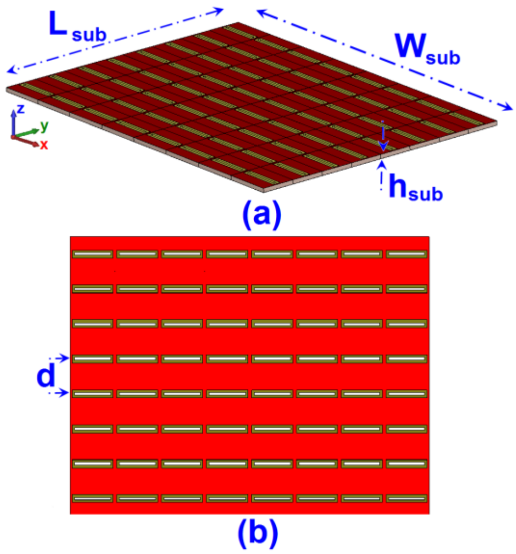

Fig. 2. Schematic of the proposed phased array antenna, (a) side view, and (b) top view.

TABLE I. FINAL DIMESIONS OF THE ANTENNA PARAMETERS

Parameter	W_{sub}	h_{sub}	L_{sub}	W_S	L_S	W
Value (mm)	72	0.8	52	6.5	9	1.5
Parameter	L	W_1	L_1	d	L_2	L_3
Value (mm)	0.5	0.5	7.25	6.5	8.4	7.4

III. SINGLE ELEMENT INSENSITIVE SLOT-LOOP ANTENNA

The conventional slot antenna is composed of a metal surface with a rectangular hole (slot). The length of slot is a half wavelength and the width is a small fraction of a wavelength. This type of antenna is called the complementary dipole antenna [8]. In this study, we started by designing a conventional slot antenna for the frequency range of 21 to 23.5 GHz. In order to improve the antenna performance and also eliminate the effect of high-loss FR-4 substrate, the resonator of the slot structure has been converted to the slot-loop structure with a thickness of h_{sub}.

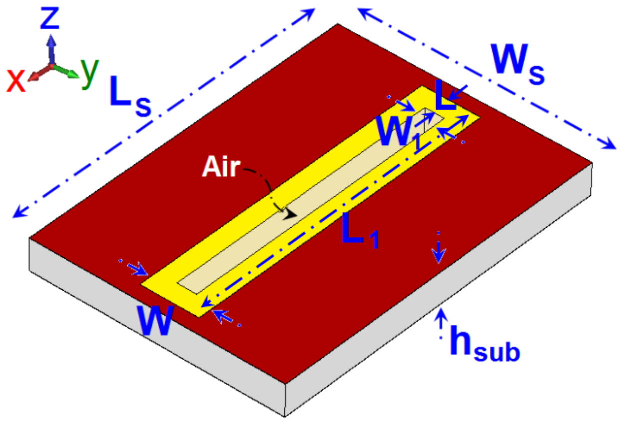

Fig. 3. Geometry of the single element slot-loop antenna.

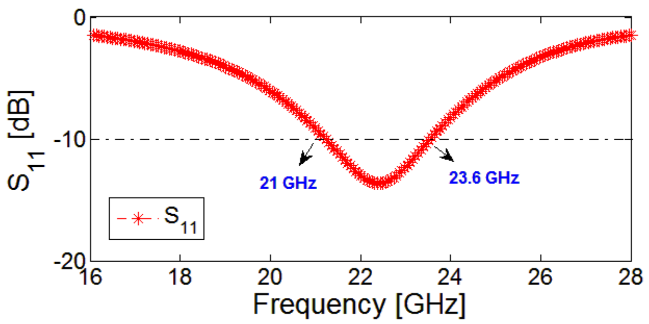

Fig. 4. Simulated S_{11} characteristic of the antenna.

Configurations of slot-loop antenna is illustrated in Fig. 3. Figure 4 illustrates the simulated S_{11} characteristic of the antenna. As illustrated, the antenna can operate at the frequency range of 21 to 23.6 GHz (more than 2 GHz bandwidth). Figure 5 shows the simulated current distributions for the slot-loop antennas at 22.25 GHz (center frequency). As illustrated that most of the currents flow around the slot-loop resonator. In addition, the simulated 3D radiation pattern of the proposed single antenna element is illustrated in Fig. 6. It can be seen that the antenna has a good radiation behaviour with 5.11 dB realized gain.

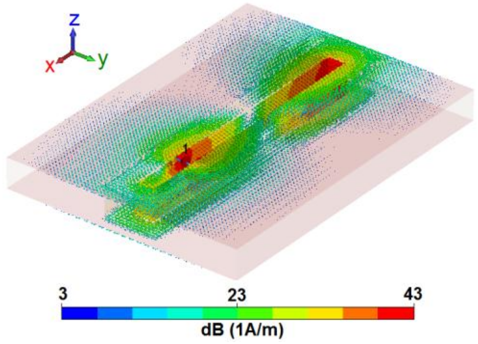

Fig. 5. Simulated current distribution of the proposed slot-loop antenna element at 22.25 GHz.

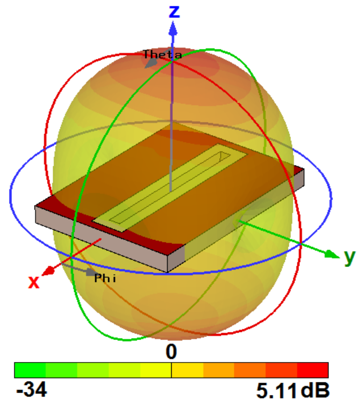

Fig. 6. Simulated 3D radiation pattern of the antenna at 22.25 GHz.

Simulated directivity, radiation efficiency and total efficiency characteristics of the single element slot-loop antenna over frequency range operation is shown in Fig. 7. As seen, the antenna radiation and total efficiencies are more than -0.5dB (90%) and 5.5 dBi directivity has been achieved at the resonance frequency (22.25 GHz).

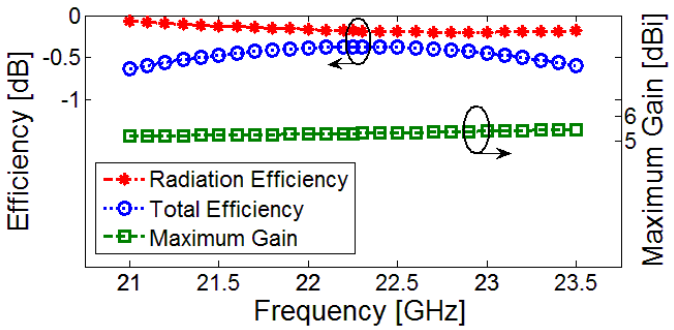

Fig. 7. Simulated maximum gain, radiation efficiency and total efficiency characteristics of the antenna entire the operation band.

In order to known the phenomenon behind the insensitive characteristic of proposed design, the performance of the proposed phased array antenna for different values of dielectric constant and loss tangent have been investigated. Figure 8(a) illustrates the simulated S_{11} characteristics of the antenna for different values of ε_r (Epsilon). As seen, the antenna has same behavior for different values of dielectric constant.

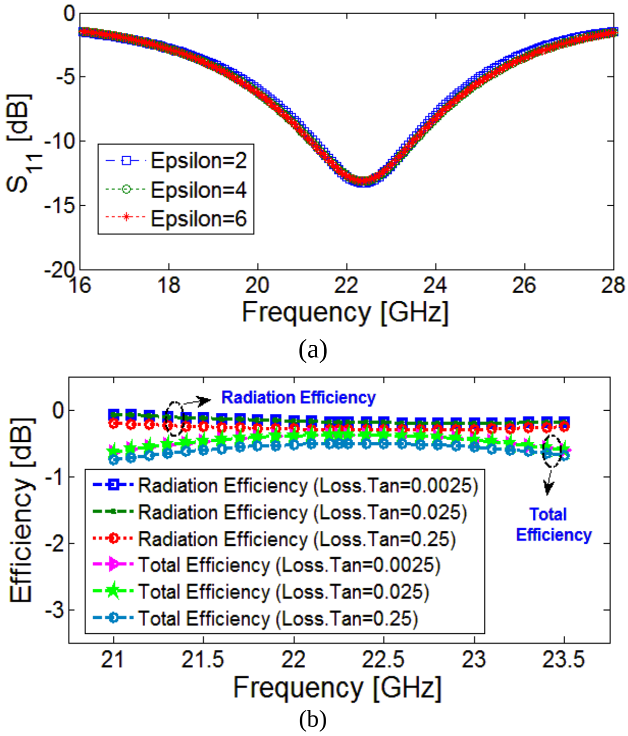

Fig. 8. Simulated (a) S_{11} of the single element antenna for different values of ε_r, (b) antenna efficiencies for values of δ.

Figure 8(b) shows the simulated radiation and total efficiency characteristics of the antenna for different values of δ (Loss Tangent) As shown, the proposed antenna has same behavior with high efficiency function for different values of δ. It can be found at the center frequency of operation band (resonance frequency at 22.25 GHz) the antenna has same values of efficiency for radiation and total properties and the variation of antenna performances are insignificant.

IV. Proposed 5G Phased Array Antenna

Figure 9 shows the configuration of the 1×8 linear array with eight elements of 22.25 GHz slot loop antennas. For beam forming array, the distance between antenna elements (d) is calculated λ/2.

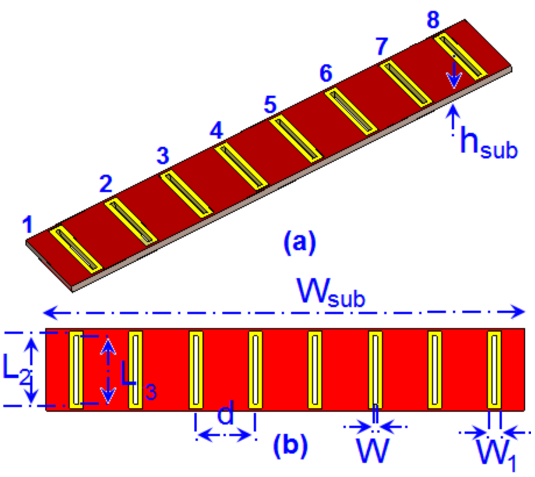

Fig. 9. Geometry of the linear antenna array, (a) side view, (b) top view.

The simulated S-parameters of the linear array is illustrated in Fig. 10. As illustrated, the antenna can operate at the frequency range of 21 to 23.5 GHz (2.5 GHz bandwidth). It can be seen that the antenna has -20 dB return loss and the highest mutual-coupling between the elements is less than -14 dB which are sufficient for beam steering issue.

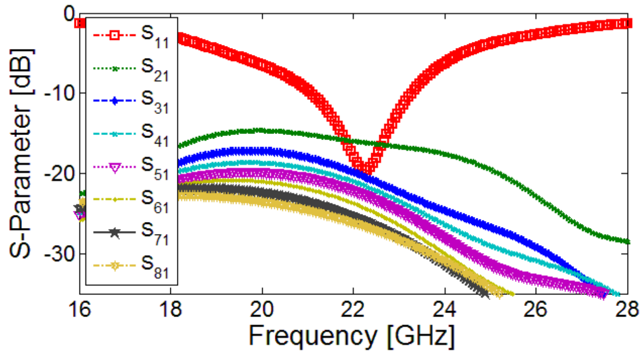

Fig. 10. Simulated S-parameters for the linear array.

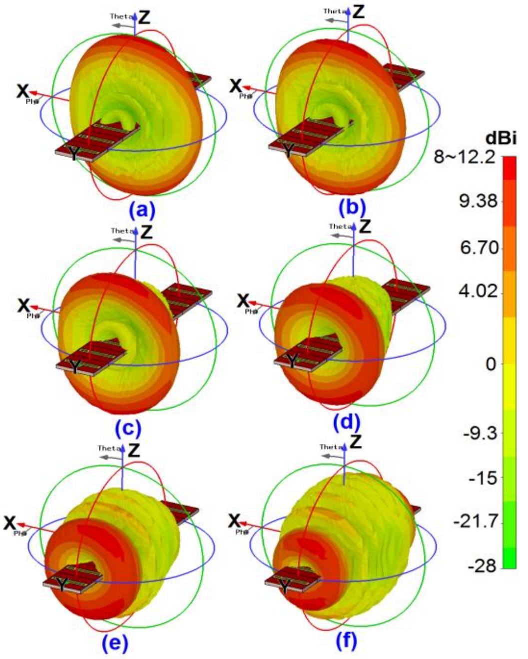

Fig. 11. 3D Radiation patterns of the linear array at different scanning angles, (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, and (f) 70°.

The beam steering characteristic of the array radiation patterns with directivity values in different scanning angles at 22.25 GHz is shown in Fig. 11. As seen, the proposed antenna has a good beam steering property which is highly effective to cover the spherical beam-coverage for 5G devices. The beam-steering characteristic of the proposed antenna for plus/minus (+/-) scanning angles are almost the same. Figure 12 illustrates the simulated realized gains of the antenna array in the scanning range of 0° to +70°. As illustrated in Fig. 12, the antenna has a good beam steerable characteristic with acceptable gain level at different scanning angles. For the scanning range of 0 to 30 degree, the antenna gains are almost constant and are than 11dB.

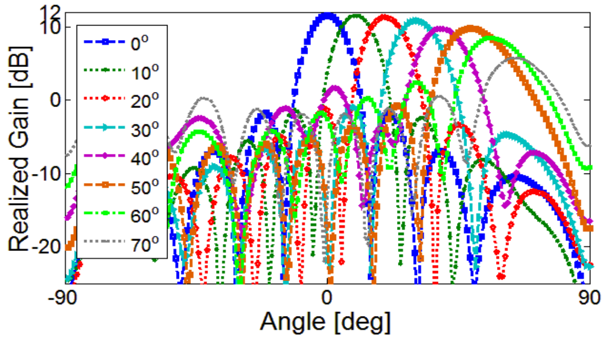

Fig. 12. Simulated realized gain characteristic of the array at different scanning angles.

Simulated directivity, radiation efficiency and total efficiency characteristics of the proposed antenna for the scanning range of 0 to 70 degree are shown in Fig. 13. As seen, the antenna radiation and total efficiencies are almost constant for the scanning range of 10° to 70° with more than -1.2dB values. Furthermore, as can be seen, when the scanning angle of beam-steering characteristic is ≤+60, the proposed antenna has more than 10dBi directivity characteristic. Considering the usage of FR4-substrate, the antenna exhibits good performance in terms of gain, efficiency and directivity.

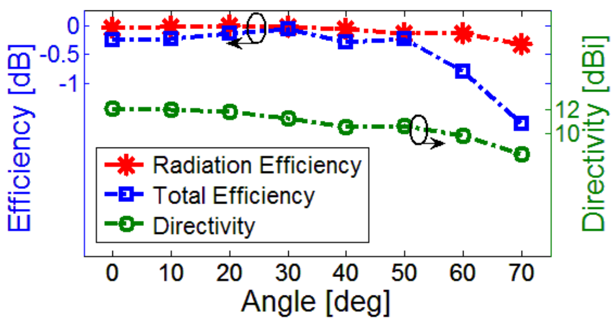

Fig. 13. Simulated directivity, radiation efficiency and total efficiency characteristics of the antenna at different scanning angles.

64 elements of the proposed single-element slot-loop antennas (8 number of the linear arrays) have been used to design the final structure on an FR-4 substrates. Surface-current distributions for the proposed planar phased array antenna at 22.25 GHz is shown at Fig. 14. As illustrated, the current flows are distributed around of the slot-loop elements and the effect of the full ground plane to reduce the power of radiation is not significant.

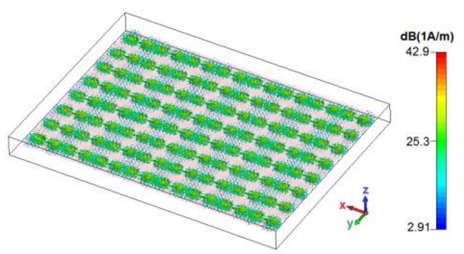

Fig. 14. Simulated current distribution of the proposed array at 22.25 GHz (resonance frequency).

Figure 15 shows the radiation beams of the proposed 8×8 phased array antenna with directivity values in different scanning angles at 22.25 GHz. It can be seen, the antenna has a good beam steering characteristic with high-level directivity characteristic at different scanning angles.

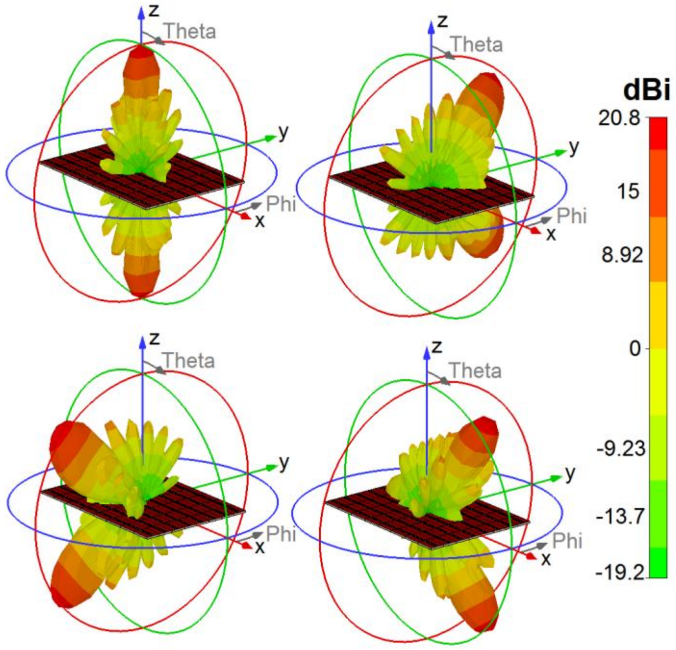

Fig. 15. 3D Radiation patterns of the antenna array with directivity values at different scanning angles.

V. Investigation on the Performance of the Proposed Design with Different Number of Radiation Elements

In this section, the investigation on the performance of the proposed planar array with different numbers of the antenna elements has been done. Figure 16 shows the configurations of the planar arrays with 2×2, 4×4, and 8×8 numbers of the elements. The spacing between the elements of the array is λ/2.

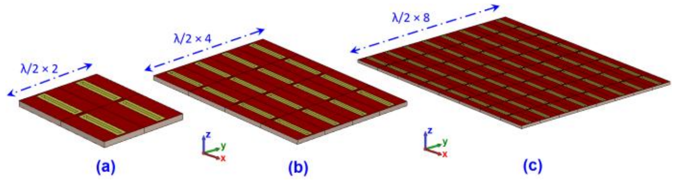

Fig. 16. Configurations of the planar arrays, (a) 2×2, (b) 4×4, and (c) 8×8.

Simulated S-parameters of the arrays are illustrated in Fig. 17. It can be seen that the designed planar antennas have same and good performances in the frequency range of 21 to 23.5 GHz. As illustrated in Fig. 17(a), -16, -17, and -17 dB reflection coefficients (S_{nn}) are achieved for 2×2, 4×4, and 8×8 planar arrays, respectively. Based on obtained results shown in Fig. 17(b), the highest mutual couplings (S_{nm}) between antenna elements for the proposed arrays are less than -13 dB.

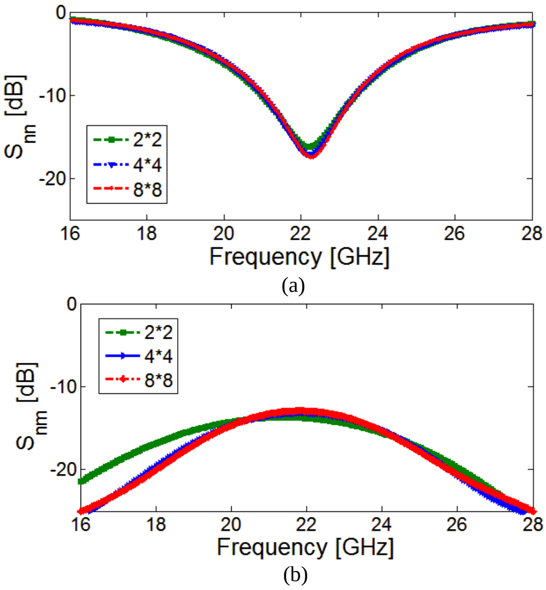

Fig. 17. Simulated S_{nn} and S_{nm} of the arrays shown in Fig. 16.

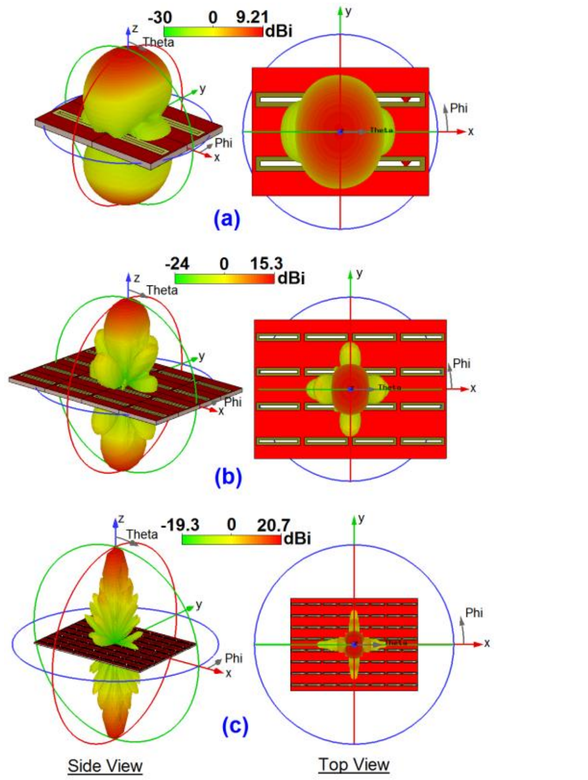

Fig. 18. 3D radiation beams of the planar arrays at 0° scanning angle for (a) 2×2, (b) 4×4, and (c) 8×8.

3D radiation beams of the planar arrays when their beams are tilted to 0° elevation are shown in Fig. 18. More than 9, 15, and 20 dBi directivities with good radiation behaviors have been achieved for 2×2, 4×4, and 8×8 planar arrays, respectively. Figure 19 illustrates the realized gain characteristics of the arrays at 0° scanning angle. As seen more than 8, 14, and 19 dB realized gains have been obtained for the arrays with different number of radiation elements.

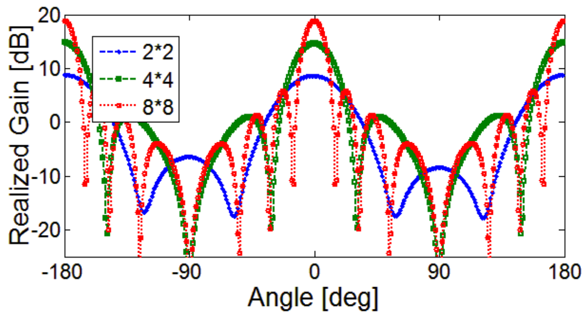

Fig. 19. Realized gains (0°) of the planar arrays.

The performances of the planar arrays in terms of realized gain, efficiency, bandwidth, reflection and mutual coefficients are summarized in Table II. As seen, the proposed array with FR4 substrates exhibit excellent performances in different terms of various antenna parameters.

TABLE II. PERFORMANCES OF THE PLANAR ARRAYS AT 0°

Param.	Gain	Effic.	BW	R.C	M.C
1×1	5.11 dB	-0.5 dB	2.6 GHz	-15 dB	--
2×2	8 dB	-0.4 dB	2.3 GHz	-16 dB	-15 dB
4×4	14 dB	-0.5 dB	2.3 GHz	-17 dB	-15 dB
8×8	19 dB	-0.6 dB	2.4 GHz	-17 dB	-14 dB

VI. CONCLUSION

Design of an insensitive phased array antenna for 5G mobile base station has been presented in this study. The proposed antenna is designed on a low-cost substrate (FR-4) to operate at 21-23.5 GHz. 64 elements of slot-loop antenna elements as eight linear arrays (1×8) have been arranged as a planar 8×8 phased array antenna. The proposed antenna has good performance in terms of S-parameter, gain, efficiency, and beam steering characteristics. The results show that the proposed phased array antenna has high efficiencies, acceptable gains and good beam steering characteristics at different scanning angles.

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