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Dense Dielectric Patch Array Antenna With Improved Radiation Characteristics Using EBG Ground Structure and Dielectric Superstrate for Future 5G Cellular Networks

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ABSTRACT In this paper, a new dense dielectric (DD) patch array antenna prototype operating at 28 GHz for future fifth generation (5G) cellular networks is presented. This array antenna is proposed and designed with a standard printed circuit board process to be suitable for integration with radio frequency/microwave circuitry. The proposed structure employs four circular-shaped DD patch radiator antenna elements fed by a 1-to-4 Wilkinson power divider. To improve the array radiation characteristics, a ground structure based on a compact uniplanar electromagnetic bandgap unit cell has been used. The DD patch shows better radiation and total efficiencies compared with the metallic patch radiator. For further gain improvement, a dielectric layer of a superstrate is applied above the array antenna. The measured impedance bandwidth of the proposed array antenna ranges from 27 to beyond 32 GHz for a reflection coefficient (S11) of less than −10 dB. The proposed design exhibits stable radiation patterns over the whole frequency band of interest, with a total realized gain more than 16 dBi. Due to the remarkable performance of the proposed array, it can be considered as a good candidate for 5G communication applications.

INDEX TERMS Dense dielectric (DD) patch, superstrate, Wilkinson power divider, fifth generation (5G) wireless communications, printed circuit board (PCB), electromagnetic bandgap (EBG).

I. INTRODUCTION

In the late 1960s, dielectric resonators have been proposed as high-Q elements in microwave circuits, such as filters and oscillators, [1]. In the early 1980s, dielectric resonators have been used as antennas (DRAs) [2]. Many researchers have shown great interest in using DRAs in many different applications because of their unique feature of low-loss and high-efficiency compared to metallic patches [3]. Dielectric resonator antenna (DRA) consists of a dielectric resonator (DR) placed either directly above the metallic ground plane or above a relatively low dielectric substrate existing between the DR and the metallic ground plane. In such case, the DR antenna mode HEM11 will be excited.

Other than exciting the high dielectric material in the HEM11 DR mode, it has been reported that a TM_{11} cavity mode can also be excited in the region between the circular di- electric resonator and the metallic ground plane. The antenna excited with this cavity mode is designated the dense dielectric (DD) patch antenna. It is considered as a member of the patch antenna family rather than the DRA. It is expected that the ef?ciency of this antenna is higher than that of the conventional metallic patch antenna, especially at higher frequencies where the radiation ef?ciency of the microstrip patch antenna becomes low [4], besides maintaining the low-profile feature.

To overcome signal attenuation due to oxygen molecules absorption at millimeter-wave frequencies high gain antenna system is required. One of the main gain enhancing techniques is using an antenna array with a proper feeding network. In addition, for extra gain enhancement superstrate technology can be adopted [5], [6]. In which, dielectric slab with an approximate thickness of λ/4 is mounted over a radiating patch antenna at a distance of approximately λ/2. Gain enhancement is obtained as a result of multiple reflections that occur between the radiating element and the dielectric slab providing multiple images of the radiator. In other words, the superstrate layer is used as a lens for focusing the main beam radiation of the antenna resulting in a noticeable enhancement for the antenna gain.

In this paper, a new DD patch array antenna prototype with a superstrate layer operating at 28 GHz for the future fifth generation (5G) short-range wireless communications applications is introduced. The proposed design offers broadside radiation pattern with compact size, simple feed structure and less optimization parameters. An array is constructed using four circular shaped DD patch radiator antenna elements and fed by a 1-to-4 Wilkinson power divider surrounded by an electromagnetic bandgap (EBG) structure. Both measured and simulated results show that the proposed array antenna can achieve a reflection coefficient S_{11} less than -10 dB over the 27-29.5 GHz frequency range (around 8.9% bandwidth). In Section II, we describe the configuration of the proposed prototype and the measured results. The configuration of the proposed array antenna and its simulated and measured results are presented and discussed in section III. Finally, the conclusions of this work are given in Section IV.

II. PROPOSED DD PATCH ANTENNA ELEMENT WITH A DIELECTRIC SUPERSTRATE

A. ANTENNA GEOMETRY AND CONFIGURATION

Fig. 1 shows the geometry and configuration of the proposed DD patch antenna. The circular DD patch has a radius R_d and a height H_d with relative permittivity of 82. It is designed and realized on RT5880 substrate (substrate 2) with relative permittivity $\varepsilon_r = 2.2$, loss tangent $tan\delta = 0.0009$ and thickness H_2). The two substrates have the same length L, width W and thickness $H_2 = H_1$. The antenna is fed through a slot of length L_S, and width WS in the ground plane in the middle layer between the two substrates. On the other side of substrate 1, a 50Ω microstrip line of width W_F and length L_F is located. For further gain improvement, a superstrate dielectric layer of a thickness H_S and located at a distance d_S from the top of substrate 2, is applied above the antenna.

B. SIMULATED AND MEASURED RESULTS

All simulations and the optimization process are performed using CST [5], an industry-standard software simulator which is based on based on Finite Integration Technique (FIT) that is equivalent to Finite Difference Time Domain (FDTD) method [8], led to the optimal parameters listed in Table I. The calculated reflection coefficient S_{11} against the frequency for the designed DD patch antenna is plotted in Fig. 2.

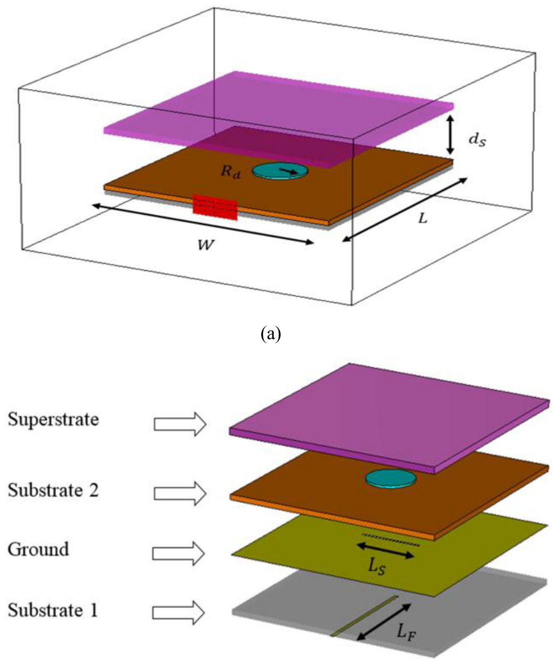

FIGURE 1. Geometry of the proposed DD patch antenna design (a) isometric view (b) detailed view.

TABLE 1. Optimized parameters dimensions for the proposed DD patch antenna design (units: mm).

PARAMETER	VALUE
W (=L)	*20*
W_S	*0.2*
L_S	*5.6*
W_F	*0.37*
L_F	*11*
R_d	*2.17*
H_d	*0.2*
d_S	*5.35*
H_S	*0.635*
$H_1 (=H_2)$	*0.508*

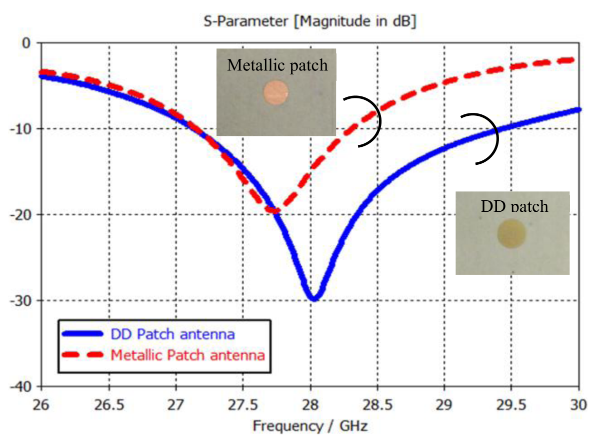

FIGURE 2. Reflection coefficient S_{11} of the proposed DD patch antenna design compared to the conventional metallic patch antenna.

Compared to the metallic patch antenna, the proposed DD patch antenna exhibits wider impedance bandwidth from 27.1 GHz to 29.5 GHz. Fig. 3 shows the calculated

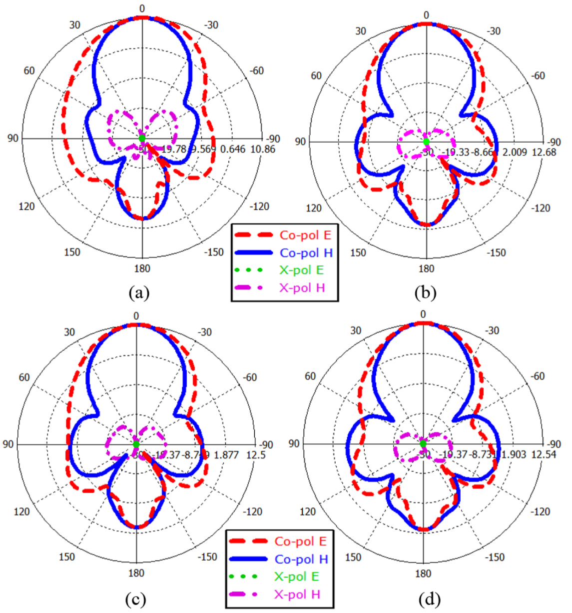

FIGURE 3. Simulated E-plane and H-plane co- and cross-polarization radiation patterns for proposed DD patch antenna at (a) 27, (b) 28, (c) 28.5, and (d) 29 GHz.

TABLE 2. Performance comparison of the proposed DD patch antenna with metallic patch antenna at 28 GHz.

		DD Patch Antenna	Metallic Patch Antenna
Bandwidth, GHz		27.1-29.5	27.1-28.3
Gain, dBi		12.48	11.61
Radiation efficiency		92 %	88.5 %
Total efficiency		91.9 %	85.8 %
FTB ratio, dB		12.97	9.97
H-plane	SLL, dB	-12.9	-10.0
	HPBW	32.6°	33.7°
	X-pol level, dB	72.5	49.6
E-plane	SLL, dB	-12.9	-9.9
	HPBW	40.3°	38.3°
	X-pol level, dB	74.7	49.6

E-plane and *H*-plane co- and cross-polarization radiation patterns at different frequencies 27 GHz, 28 GHz, 28.5 GHz, and 29 GHz. As expected, the antenna exhibits broadside radiation patterns in both *E*- and *H*-planes. A comparison of performance between the proposed DD patch antenna and the conventional metallic one have been done in detail and summarized in Table II. The proposed DD patch antenna is a good candidate for 5G short-range wireless communications.

III. PROPOSED DD PATCH ANTENNA ARRAY WITH EBG GROUND AND A DIELECTRIC SUPERSTRATE

A. ANTENNA ARRAY GEOMETRY AND CONFIGURATION

The geometrical configuration and photograph of the proposed DD array antenna prototype are illustrated in Fig. 4.

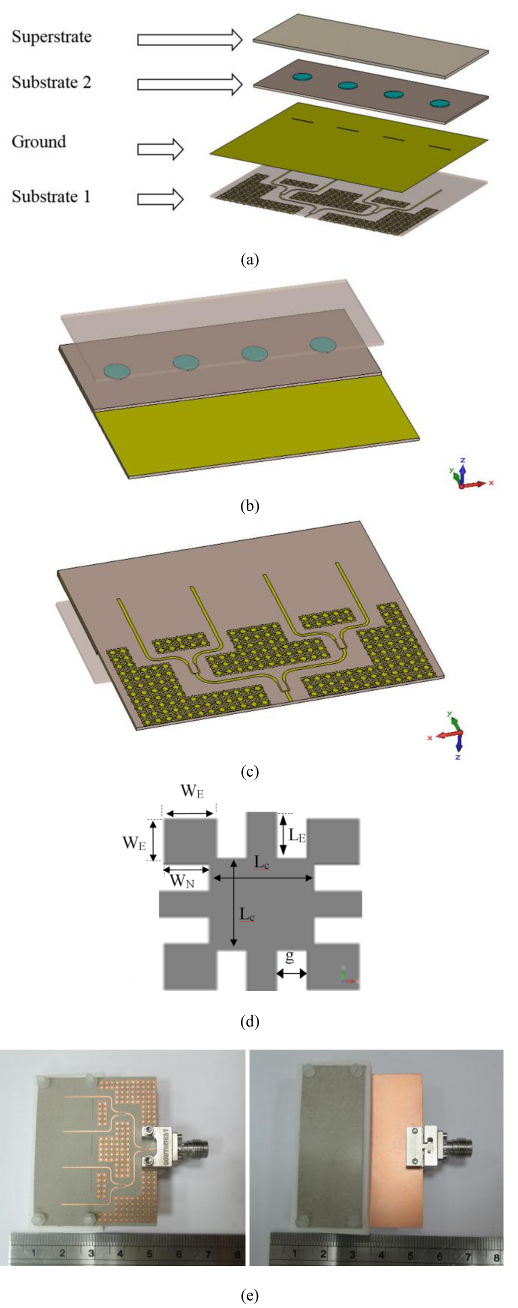

FIGURE 4. Geometry of the proposed DD patch array antenna design (a) array layers (b) top view (c) bottom view (d) EBG unit cell (e) photograph of fabricated prototype.

The array consists of four identical DD patch antennas fed by a 1-to-4 Wilkinson power divider [8]. Electromagnetic bandgap (EBG) structure has been used to reduce the losses due to surface wave. Fig. 5 presents the dispersion diagram of the proposed UC-EBG unit cell with a band-gap occurs in the 28 GHz frequency band. The inter-element spacing among antenna elements is set to $d = 12$ mm. An optimization process has been carried by a full-wave electromagnetic simulator and the optimized parameters have been tabulated in Table III.

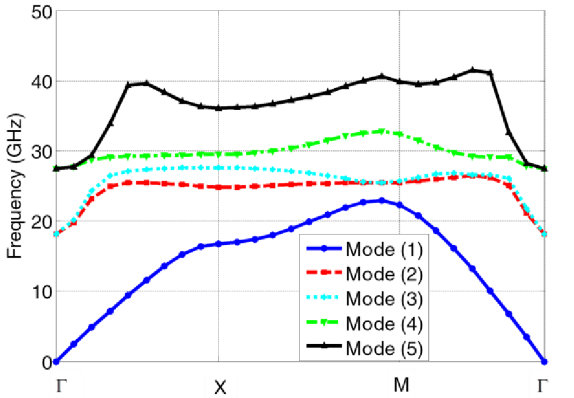

FIGURE 5. Dispersion diagram of the proposed UC-EBG unit cell shown in Fig. 4(d).

TABLE 3. Optimized parameters dimensions for the proposed DD patch array antenna design (units: mm).

PARAMETER	W_E	W_N	L_C	L_E	g	d
VALUE	0.43	5.83	0.86	0.49	0.34	12

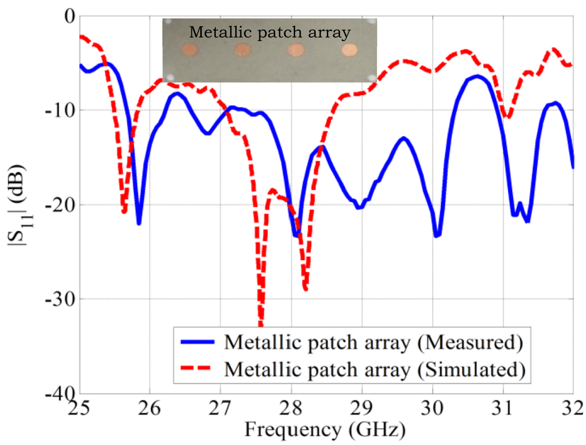

FIGURE 6. Measured and simulated reflection coefficient $|S_{11}|$ of the conventional metallic patch array antenna.

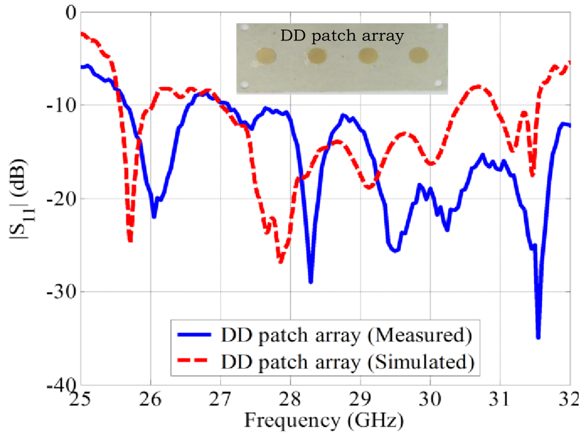

FIGURE 7. Measured and simulated reflection coefficient S11 of the proposed DD patch array antenna.

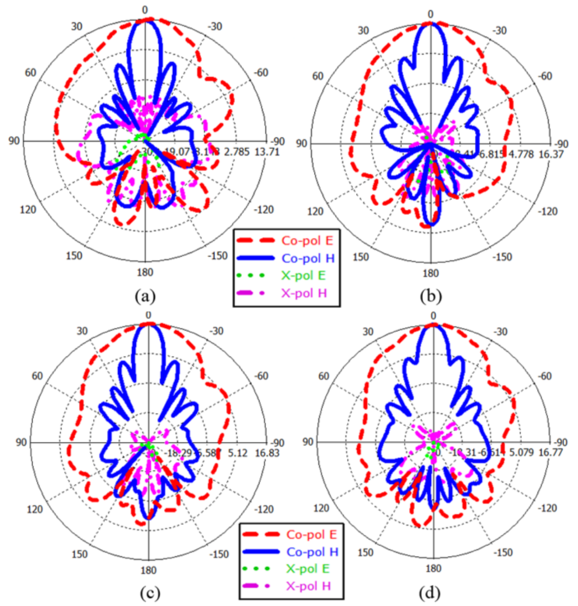

FIGURE 8. Calculated E-plane and H-plane co- and cross-polarization radiation patterns for proposed DD patch array antenna at (a) 27, (b) 28, (c) 28.5, and (d) 29 GHz.

B. SIMULATED AND MEASURED RESULTS

Fig. 6 and Fig. 7 present the measured and simulated reflection coefficient $|S_{11}|$ curves against the frequency for the conventional metallic patch array and the proposed DD patch array, respectively. The results for conventional metallic patch array are presented here for comparison with the proposed DD patch array antenna. It can be seen that the proposed DD patch array exhibits better impedance bandwidth starts from 27 GHz to beyond 30 GHz (CST simulated) and from 27 GHz to beyond 32 GHz (measured).

The simulated E-plane and H-plane co-polarization and cross-polarization radiation patterns for the proposed DD patch array antenna at different frequencies 27 GHz, 28 GHz, 28.5 GHz, and 29 GHz are shown in Fig. 8. It is very clear that the 4-element array exhibits a directional radiation pattern in the H- plane while the radiation pattern in the E-plane remains unchanged.

Fig. 9 introduces the simulated maximum realized gain for the proposed 4-element DD patch array and 4-element conventional metallic patch array. The gain for DD patch element and conventional metallic patch element are also shown in the same figure for comparison purposes. It can be noticed that the proposed 4-element DD patch array antenna exhibits a maximum realized gain better than that of the 4-element conventional patch array.

The other antenna performance characteristics such as side lobe level (SLL), front-to-back (FTB) ratio, gain, radiation and total efficiencies and cross-polarization (X-pol) level are calculated and summarized in Table IV.

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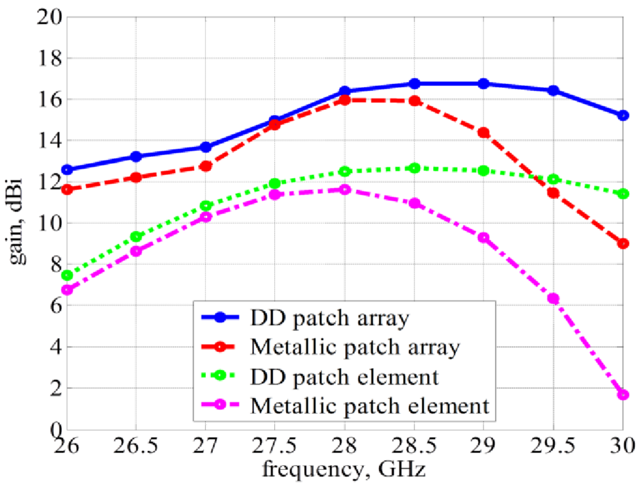

FIGURE 9. Simulated maximum realized gain for the proposed DD patch array compared to the metallic patch array.

TABLE 4. Performance comparison of the proposed DD patch array with metallic patch array at 28 GHz.

		DD Patch Array Antenna	Metallic Patch Array Antenna
Bandwidth, GHz		27- beyond 30	27.1-28.6
Gain, dBi		16.3	15.93
Radiation efficiency		71.8 %	71.8 %
Total efficiency		71.4 %	71.1 %
FTB ratio, dB		14.1	11.3
H-plane	SLL, dB	-11.6	-11.4
	HPBW	11°	11.1°
	X-pol level, dB	57.5	49.2
E-plane	SLL, dB	-10.9	-10.3
	HPBW	34.4°	33.9°
	X-pol level, dB	56.7	49.1

IV. CONCLUSION

In this paper, a new four-element dense dielectric (DD) patch array antenna design at 28 GHz for future 5G short-range wireless communications has been introduced. Its radiation characteristics can be improved by using EBG structure in the ground plane and a dielectric superstrate above it. A detailed comparison of performance between the proposed DD patch array and conventional metallic one has been presented. The proposed array antenna is a good candidate for future 5G applications.

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