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Improving the Gain Performance of Air Substrate Patch Antenna Array Using the Effect of Conductive Material Thickness Study for 5G Applications

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Abstract. Over the decade, extensive applications of portable electronic devices have progressed enormously. This has ultimately influenced the shortage of bandwidth supply. Therefore, in satisfying the demands of consumers, low-cost antennas are required to be designed specifically for the fifth-generation frequency spectrum (5G) devices. The main goal of this paper is to report a high gain enhancement in a low profile and economical antenna operated effectively using air substrate in 5G devices. This paper discusses the study effects of thickness on the substrate and conductive material, also the novel design of a cost-effective, air-substrate based microstrip antenna with enhanced gain at 28 GHz resonance for the 5G mobile phone application. In the proposed design, a 2×2 array configuration of radiating elements was designed to occupy a 35.7×31.5×0.5 mm3 volume. Copper (Cu) material was used in the fabrication of the antenna prototype. The proposed antenna was evaluated and compared to the simulation results to demonstrate the design's reliability. The proposed system provided a peak gain and performance efficiency of 15.6 dB and 86.9.4%, respectively, when operated at 28 GHz resonance.

1. Introduction

The emergence of 5G technology on user terminals requires the use of antennas with previously unseen features of the spatial beamforming radiation pattern [1-2]. In order to achieve a reasonable trade between the issues of technological design and commercial criterion such as broadband performance, low profile, enhanced gain, low cost and all that possess numerous challenges. Increasing the gain of patch antennas was the goal of many researchers in the last decade because it offers better signal quality and longer range. All these attributes are possible to be achieved with microstrip antennas when discrete patch elements are combined to form an array. Several methods in improving the gain and bandwidth of antennas were reported in literature. Roh et al [3], suggested the use of high gain antennas in both mobile and base stations to compensate for the higher path loss and wave frequencies However, there exists a problem of very low coverage of directional high gain antennas. By implementing the beam scanning options, a phased array can solve this coverage problem. These options include; (a) new 5G mm-wave antennas designed for mobile terminal applications with a wide range of polarizations such as phase array circular polarization but with gain of less than 13 dB. Antenna designs with promising coverage performance were obtained for the mobile terminal but the gain made was minimal [4-9]; (b) investigation on different compact millimeter-wave slot antenna array [10-12]; (c) Chen & Zhang [13] and Hong et al. [14] applied the method of low-profile array configurations with 10-layer FR4 substrates with a gain of 12 dB achieved; (d) new cylindrical Electromagnetic Bandgap (EBG) substrate method [15-19] which uses dielectric materials inherent properties to enhance the antenna performance but this type of configuration increases the size of the patch antenna. A 1×4 antenna array elements were designed to achieve a high bandwidth but with low gain [20-21]. Besides, a wide beam antenna design with a bandwidth of 3.9 GHz using substrate integrated wave (SIW) technology was implemented but a low gain was achieved [22]. It is indeed a challenging task to design an antenna with combined qualities of high bandwidth, high gain and wide beam width.

In this paper, a 2×2 configuration directional microstrip patch antenna with a high gain and good matching capability operated at 28 GHz resonance was proposed after parametric analysis of the effects of thicknesses of conductive material and substrate. The influence of these effects on the thickness of conductive material and substrates is quantified on the antennas ' impedance bandwidth, efficiency, and gain. This antenna was fabricated based on a single microstrip patch antenna arranged in a 2×2 matrix mode occupying a 535.7 × 31.5 × 0.5 mm3 volume to facilitate the directive radiation patterns. The proposed design combined the benefits of high gain, compactable and cost-effective antenna manufacturing since air substrate was incorporated in the design to significantly reduce its cost of production. The antennas were eventually designed and measured, and the results are summarized in Table 3

2. Antenna Design and Analysis

2.1 A. Single Patch Antenna Design

Figure 1 shows the front view of the proposed single patch antenna. All parameters were calculated manually by using the formulas as provided in the Antenna Theory (Third Edition) book by Balanis [23].

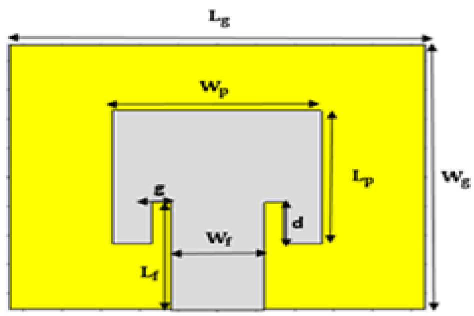

Figure 1. The front view of the proposed single patch element antenna.

Table 1. Dimensions of the proposed antenna designed

Component	**Parameter**	**Value (mm)**
Length of the patch (L_p)	L_p	4.54
Width of the patch (W_p)	W_p	5.34
Length of the ground plane (L_g)	L_g	9.08
Width of the ground plane (W_g)	W_g	10.68
Thickness of substrate (hs)	h_s	0.50
Conductor Thickness (ht)	h_t	1.00
Length of the inserted fed (f_i)	f_i	1.45
Width of the feedline (W_f)	W_f	2.45
The gap between the patch and the inserted -fed (G_{pf})	G_{pf}	0.50
Feedline length (L_f)	L_f	2.68

2.2. Two-Element Patch of Antenna Array Design

The single patch antenna was found to achieve the best condition at all the specifications based on the parametric studies conducted. In this second design, the distance between the two patches in both E and H planes were studied and the feed design of the antenna was optimized. The impedance of the quarter-wave transformer and the resonance of the edge were calculated as shown below:

$$Z_1 = \sqrt{R_{in} Z_O} \tag{1}$$

Where Z1 is the characteristic impendence, Zo is the characteristic impendence (50 Ω), Rin is the resonance edge resistance and Ge is representing of edge conductance. Rin can be calculated using Equation (2).

$$R_{in} = \frac{1}{2G_e} \tag{2}$$

$$G_e = 0.00836 \frac{w}{\lambda_O} \tag{3}$$

The design parameters of the antenna feed from 50 to 100 feedline are summarized in Table 2. After conducting a parametric study, all antennas were separated by 0.75 λ_o in the E-plane and 0.8 λ_o in the H-plane, where λ_o = 10.7143 mm.

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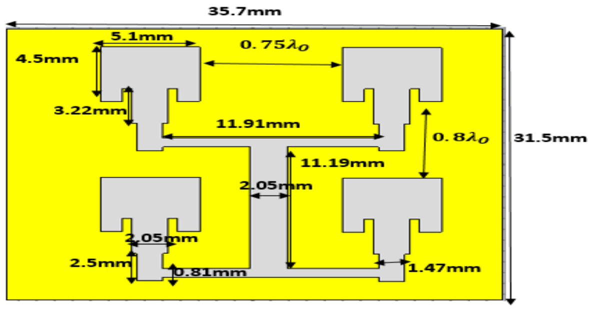
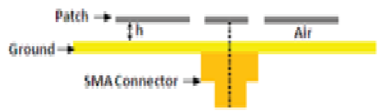
Table 2. Design parameters of antenna feedline.

Design of feedline (Ω)	Length of the feed (mm)	Width of the feed (mm)
50	2.71	2.05
70	2.68	1.47
100	2.71	0.81



(a)



(b)

Figure 2. Schematic diagram of the proposed antenna design with required dimensions. (a) Top view, (b) Side view

Figure 2 illustrate the proposed design geometry of the microstrip patch antenna planar array. Its structure consisted of an element of the antenna, air substrate (ε_r = 1) and a vertical probe connected to the patch with individual dimension of 5.1 mm × 4.5 mm. In application, a simple microsrip transmission line could be used to fed the antenna. Power was fed into the designed antenna via microstrip feed line having a dimension of 2.68 × 2.45 mm^2 and impendence of 50 Ω.and 1 mm thickness of the coductive materials are used. The proposed array element has been combined in an array of four elements and placed on the edge of the ground plane of 35.5 mm width and 31.5 mm length as shown in Figure 2. The spacing between elements at E plane and H plane has been chosen to be 0.75 λ_o and 0.8 λ_o respectively in order to reduce the grating lobe magnitude.

3. Results and Discussions

The performance of the microstrip patch antenna planar array were optimized and analysed using the 2016 CST software [24]. Initially, the air substrate thickness was expected to be 0.50 mm. Parametric simulation studies were conducted to determine the accurate resonator and ground thickness. Fifteen different thickness were considered in this investigation, ranging from 0.1 to 1.5 mm at an interval of 0.1 (Figure 3). Microstrip patch antenna arrangement of 1.00 mm thickness displayed a resonant frequency of 28 GHz with S_{11} value of -38.78 dB covering the frequency range of 27.799 GHz to 30.119 GHz. Similar measurement studies were conducted on physical microstrip patch antenna planar array using Cu of 1.00 mm thickness. To validate the effects of air substrate thickness on the S-parameter, seven distinct thickness ranging from 0.4 to 1.0 mm at an interval of 0.1 were considered

(Figure 4). From the curves presented in Figure 4, it is evident that the 0.50 mm thick air substrate yielded the optimum results. Effect of mutual coupling on the antenna parameters in the E and H planes due to change in the inter-element spacing which was varied in steps of 0.05 λ_o, from the initial value of 0.5λ_o to λ_o were also studied. An optimum design for the linear spacing was found to be 0.75 λ_o in the E plane and 0.8 λ_o in the H plane. It was found that at this spacing, the antenna was working closest to the designed operating frequency with a good return loss of -35.49 dB. Figure 5 shown the photograph of the fabricated antenna prototype with the dimension of 35.5 mm width and 31.5 mm. Measurement on the constructed systems was carried out using the N5245A PNA - X Microwave Network Analyzer from Agilent and as can be seen in Figure 6, the results showed a good agreement with the simulated results. The radiation patterns of the Cu based microstrip patch antenna planar array was obtained from the Anechoic Chamber (Figure 7). At the specific resonant frequency, the system showed a peak gain and performance efficiency of 15.6 dB and 86.9%, respectively as shown in Table 3. Figure 8 on the other hand illustrates the current distribution of the finalized antenna configuration.

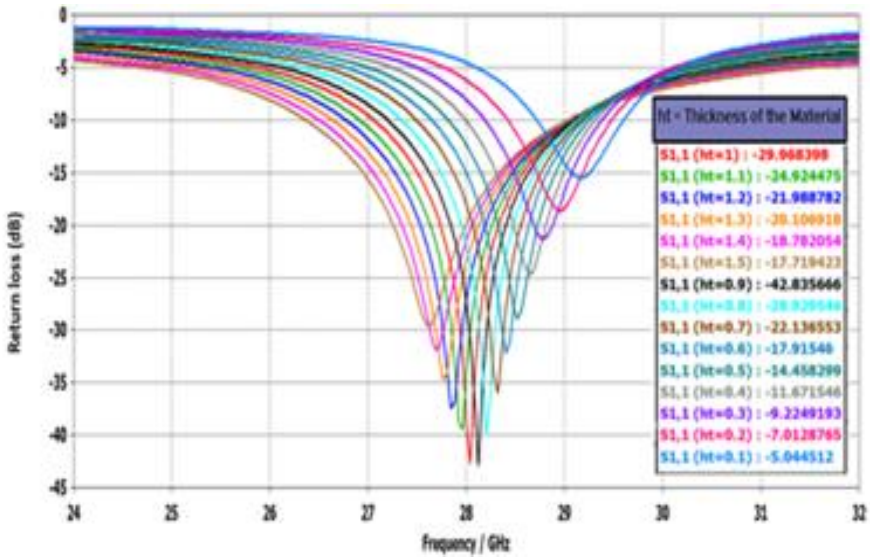


Figure 3. Return loss characteristics for different values of thickness of the conductive material at 28 GHz resonance.

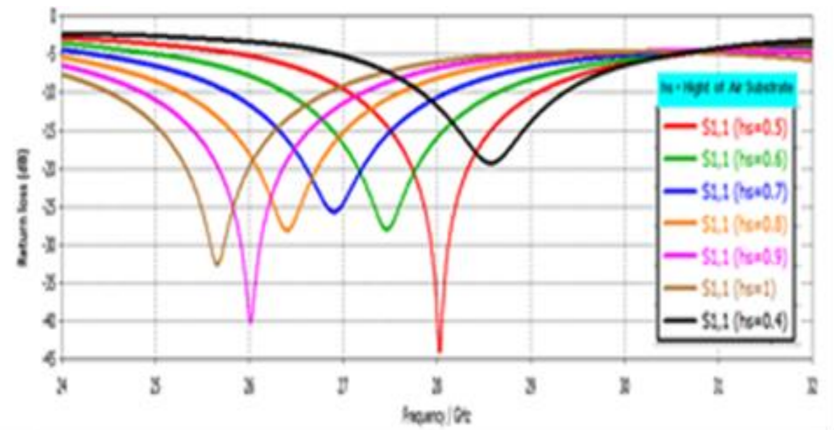


Figure 4. Variation of air substrate thickness with S11 parameters at 28 GHz resonance.

Figure 5. Photograph of the fabricated antenna prototype.

Table 3. Comparison between simulated and measured result of proposed antennas

Proposed fabricated antennas at 28 GHz	**Gain (dB)**		**Impedance Bandwidth (GHz)**		**Return loss (dB)**		**Efficiency (%)**
	Simulated	**Measured**	**Simulated**	**Measured**	**Simulated**	**Measured**	
Single patch	10.1	9.85	1.48	1.39	-24.69	- 19.20	73.2
2-Element patch array	13.50	12.86	3.40	2.99	-32.50	-25.13	82.4
4-Element patch array	15.9	15.6	1.33	1.28	-36.58	-31.87	86.9

Radiation patterns were measured using a swept frequency measurement conducted in an anechoic chamber. The measured radiating patterns of the proposed antenna were plotted at 28 GHz resonance and are shown in Figure 7. Large cross polarization was observed which indicated a common characteristic of this model of probe-fed MSA. The simulated peak antenna gain was about 15.9 dB, while the measured gain of antenna was greater than 15.4 dB, mostly throughout the band. The actual measured radiation patterns and gains of the proposed antenna were in close agreement with the simulated results.

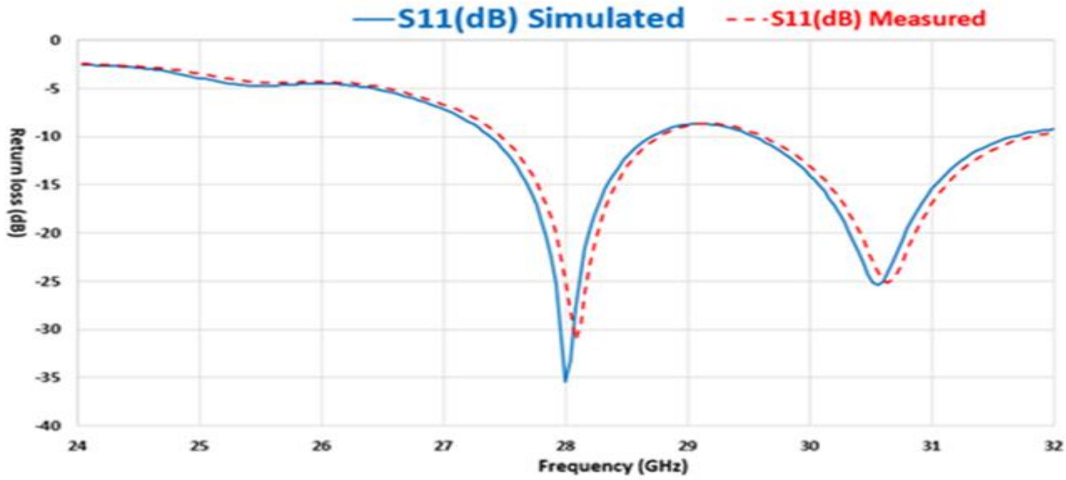


Figure 6: Comparison of measured and simulated results (return losses) of a patch at 28 GHz resonance fabricated on air substrate

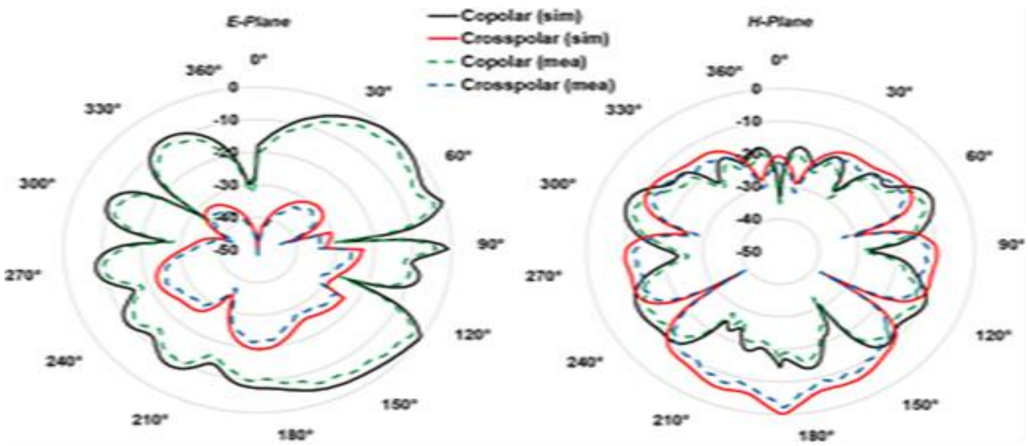


Figure 7: Comparison of measured and simulated results of radiation patterns (E & H planes) of a patch at 28 GHz resonance fabricated on air substrate.

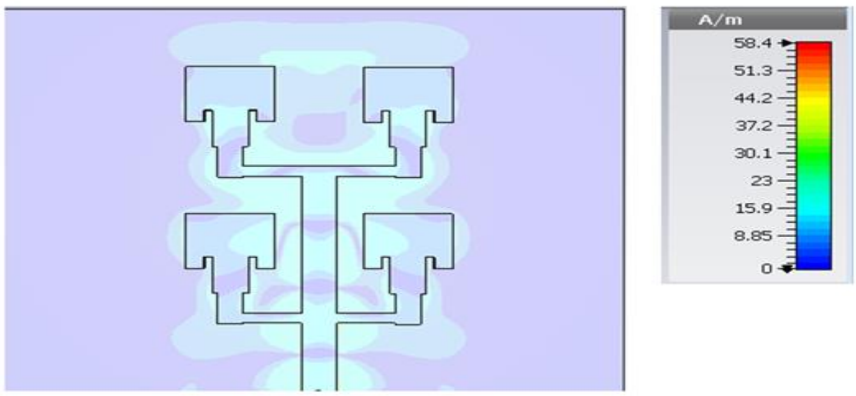


Figure 8: Current distribution of the Cu based antenna

4. Conclusion
A novel 4-element array of microstrip patch antenna with a high gain and good matching capability operated at 28 GHz resonance was proposed in this paper. The proposed design was succeeding in combining the benefits of high gain, compact size, and cost-effective antenna manufacturing. The operating frequency of the antenna was adjusted by varying the thickness of the resonator, ground and substrate. Radiating elements were designed to be located above air substrate to significantly reduce its manufacturing cost. Furthermore, the designed antenna may occupy a small volume yet providing higher gain, which can easily be fitted into current mobile devices as to comply with the upcoming 5G communication standards. The fabricated antenna was laboratory tested which provided a good agreement between the simulated and measured results of the antenna-resonant frequency relationship.

Acknowledgment
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