A Broadband Millimeter Wave Array Antenna Using Airgap and Dummy Patches

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In this paper a broadband millimeter-wave array antenna has been designed at 60-GHz band to be used in millimeter-wave small cell modules. An aperture coupled patch antenna has been used with inverted patches and air gap introduced between ground and patches. Some unfed patches (dummy patches) are applied for obtaining high gain. The performance of the antenna is dependent on the air gap, dummy patches and the thickness of the upper substrate. The air gap has been tuned and the performance has been compared. The antenna shows 55 GHz to 65 GHz bandwidth for $|S11| < -10$ *dB and very flat peak gain w.r.t. frequency for a single antenna. Peak gain for the single array is obtained 10 dBi. Beamforming with 16 such antennas has been shown to steer the beam* ± 50 *deg at a loss of less than 3 dBi.*

1. Introduction

The license-free spectrum of 60-GHz band wireless networks stimulates the short distance communication most commonly used for linking two or more wireless devices within a limited range. Millimeter-wave communication terminals need wideband, high gain beamforming antennas so that high throughput can be realized in the whole range of the operation. A number of experiments have been carried out to analyze and design wideband and high-gain antennas. Aperture coupled antenna is been a potential candidate for this end. In one of our earlier papers [1], we had provided antenna design for 60-GHz bandwidth based on multilayer aperture coupled antenna without any air gap, the design has shown very high gain of 26 dBi but the bandwidth was limited to only two channels in the Wi-Gig 60-GHz band. A PCB based microstrip–ridge gap waveguide and substrate integrated waveguide (SIW) antenna has been designed with 2 x 2 array showing very wideband and high gain [2]. This antenna shows better gain bandwidth combination but the limitation being complexity of design fabrication and it is to be modified if beamforming is to be done. In Ref [3] influence of residual air gaps on characteristics of circularly polarized aperture coupled antenna has been studied where results show that air gap enhances the reflection characteristics. A low-cost high-efficiency broadband integrated antenna for 60-GHz transceiver module has been studied where 9-dBi gain and bandwidth of 20% are realized at 60 GHz [4].

In this paper we have designed a linear array of aperture coupled antenna with an air gap between ground and patches so as to enhance the performance. The patches are designed on the lower side of a thick substrate 2 as shown in Fig. 1. The ‘H’ shaped aperture slots are etched into the ground plane. It is used to transfer the energy from feed line to the linear patch array. The central patches are fed with maximum power and it decreases to the patches towards the edge. The last two patches on either side are left unfed (dummy patches) for obtaining high gain. The air gap is used to avoid coupling loss between the aperture slots and patches.

2. Antenna design and simulation results

2.1 Antenna substrate layout and simulation results

The antenna cross section is shown in Fig. 1. Two substrates are used, substrate 1 is LCP (liquid crystal polymer) of thickness h1 (0.13 mm) and h2 (0.1 mm), $\varepsilon_R = 2.9$, tan $\delta = 0.003$, substrate 2 is ULTEM-100 of thickness h3 (2 mm), $\varepsilon_R = 3.5$ tan $\delta = 0.00145$. Substrate 2 is thick so as to provide stability and maintain the uniform air gap between ground and patch layer along with performance enhancement. Fig. 2 shows the top view of the antenna design. Four dummy patches

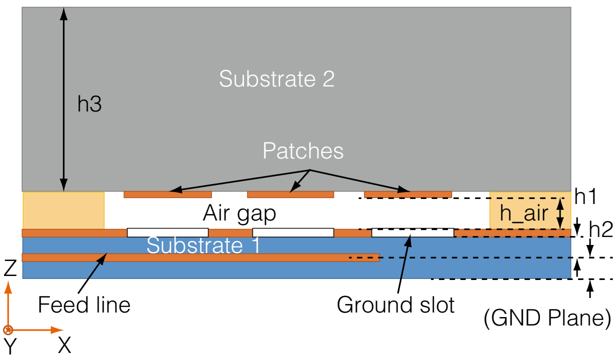

Fig. 1. Cross section view of antenna.

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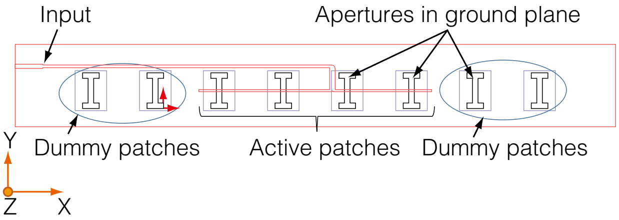

Fig. 2. Top view of antenna design.

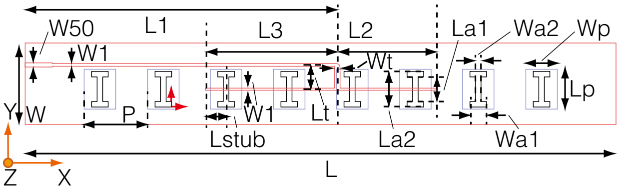

Fig. 3. Antenna dimensions.

along with slots cut in ground are shown. All the patches with feed line are labelled as active patches. Slots cut in the ground are in 'H' shape with the dimensions mentioned below and the rectangular patches below the substrate 2. The starting values of length 'Lp' and width 'Wp' of antenna are calculated by the following equations, where ε_R is the dielectric constant of substrate 2, and optimized later for good matching. Micro-strip feed is used below the ground plane of thickness h1, and a same substrate 1 is used below the feedline of thickness h2. The feed line is not symmetrical with respect to the center so that the electric current phase is unidirectional in both sides of the antenna. Patches at the bifurcation of the feed line quarter wave transformer is used to match the impedance.

$$Width=\frac{c}{2f_o\sqrt{\frac{\varepsilon_R+1}{2}}};\ \varepsilon_{eff}=\frac{\varepsilon_R+1}{2}+\frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

$$Length=\frac{c}{2f_o\sqrt{\varepsilon_{eff}}}-0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}\right)$$

The antenna dimensions as shown in Fig. 3 are: L= 22, W= 3, Lp= 1.45, Wp= 1.15, La1= 0.9, La2 = 1.3, Wa1= 0.6, Wa2= 0.2, L1= 11.66, L2= 3.65, L3= 4.9, W1= 0.08, Wt= 0.22, Lstub= 0.75, P= 2.35, W50= 0.1, Lt= 0.97, all dimensions are in mm.

The antenna is simulated on Ansoft High Frequency Structure Simulator (HFSS) and reflection coefficient and gain with respect to frequency are shown in Fig. 4. It gives a very wide band with stable broadside gain, with maximum of 10 dBi. Since the antenna is linear along X-axis so the radiation pattern in Fig. 5 shows that the beam in XZ plane is narrow whereas is wide in YZ plane.

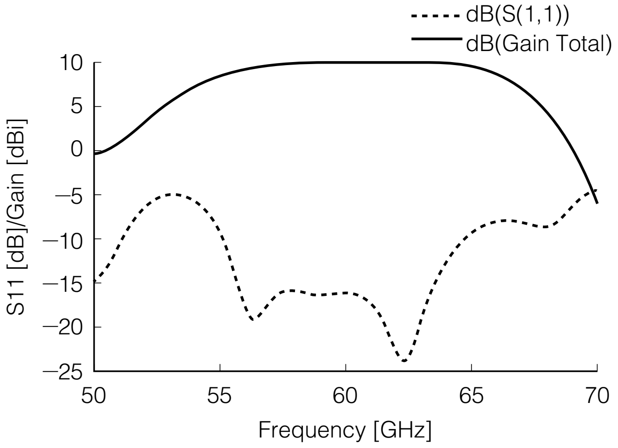

Fig. 4. Antenna S-parameters and gain w.r.t frequency.

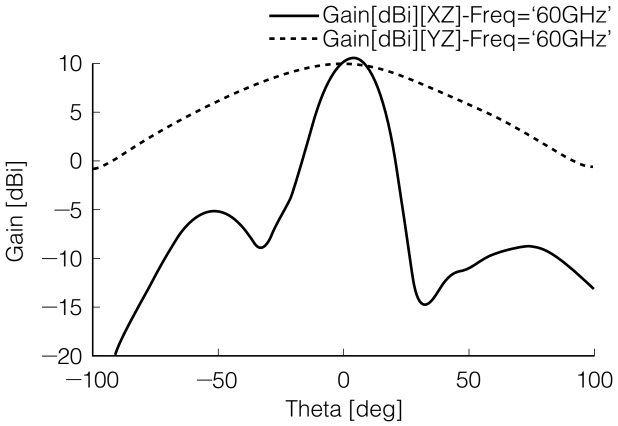

Fig. 5. Gain characteristics.

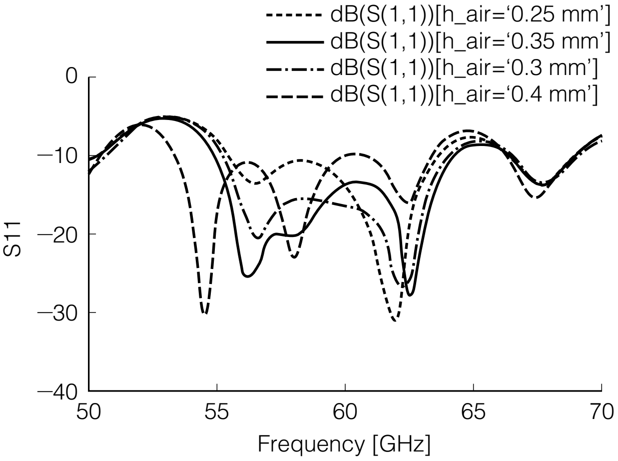

Fig. 6. Reflection characteristics with respect to h_air.

2.2 *Effect of the air gap between the ground and patches*

Air gap 'h_air' between the ground and patches has been varied from 0.25 mm to 0.40 mm at a step of 0.05 mm to evaluate the robustness of the design. The reflection coefficient in Fig. 6 and gain characteristics in Fig. 7 show that at all values of ‘h_air’ the antenna performance is acceptable, i.e. the antenna has tolerance to be used at any value between 0.25 mm to 0.40 mm.

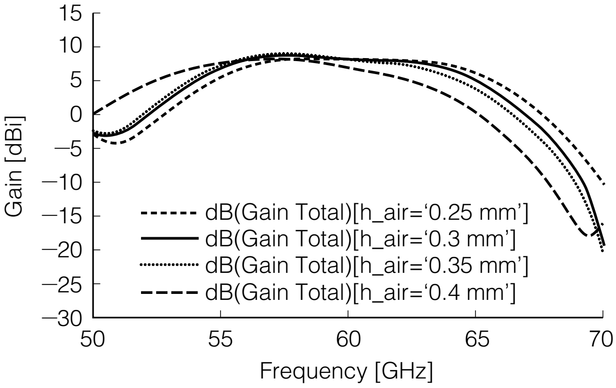

Fig. 7. Gain of antenna with respect to h_air.

2.3 *Effect of the dummy patches*

In this section three combinations of patch arrangement of the antenna have been discussed. The antenna is (a) with four active and four dummy patches which is the proposed configuration, (b) with four active and four dummy but dummy patches have no aperture slots below them, (c) all eight patches are excited with feedline, as shown in Fig. 8.

The reflection coefficients for these three antennas shown in Fig. 10 give good matching below -10 dB but the broadside gain plotted in Fig. 11 shows that the configuration (c) gives very low gain as compared to the proposed antenna design. The current in the ground plane for all these antennas in Fig. 9 shows that current density at the aperture beneath of (a) dummy elements is more as compared to other two types and is smallest in (c). That explains why we get higher than in an order of (a), (b) and (c).

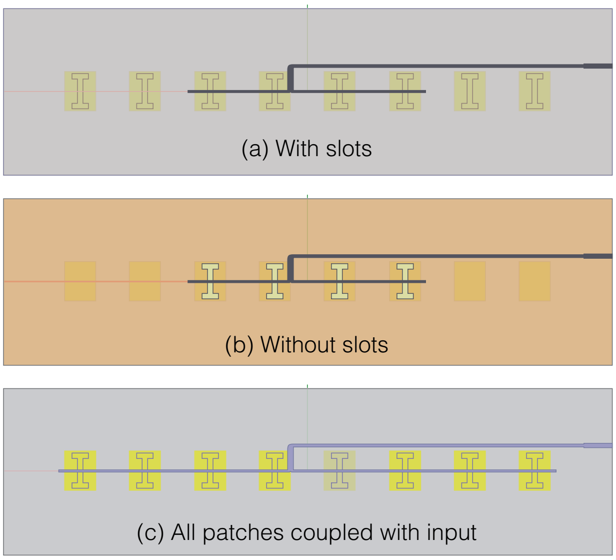

Fig. 8. Antennas with different combination of patch and feeding.

3. Antenna array layout and beamforming

The proposed antenna above is arranged in linear fashion as shown in Fig. 12 at a distance of 2.5 mm $(\lambda/2)$ to get beamforming array. The phase and magnitude of each antenna can be provided so that the shape of beam and direction can be controlled.

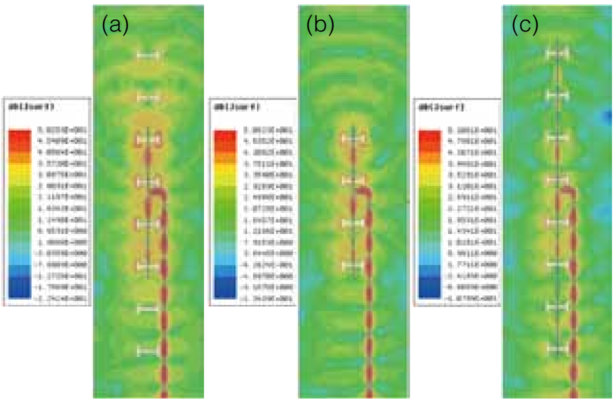

Fig. 9. Current pattern in the ground plane for these types.

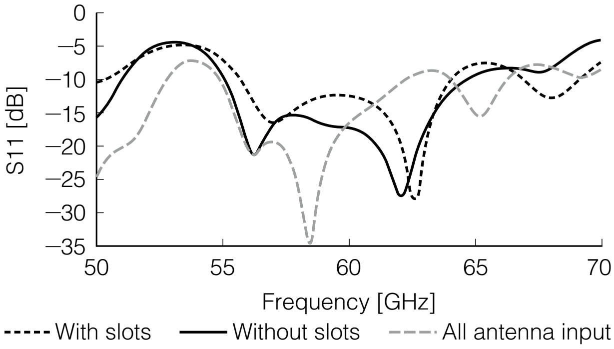

Fig. 10. Comparison of |S11|.

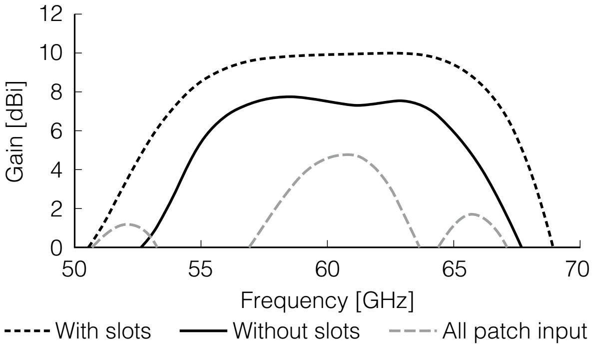

Fig. 11. Comparison of gain.

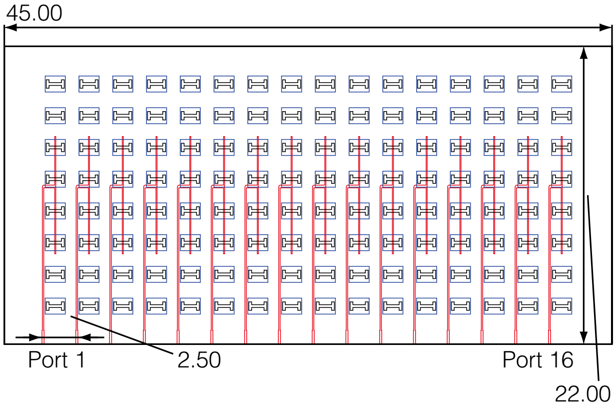

Fig. 12. Beamforming array.

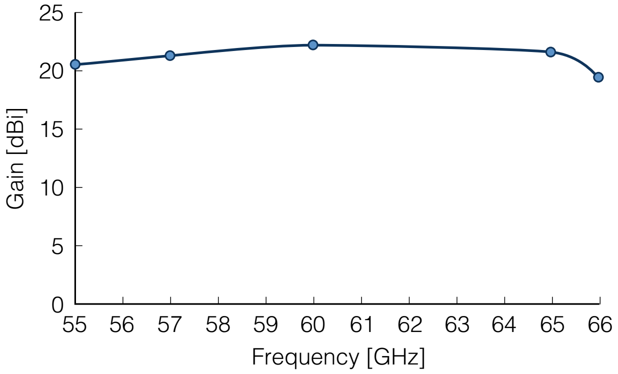

Fig. 14. Broadside gain of array.

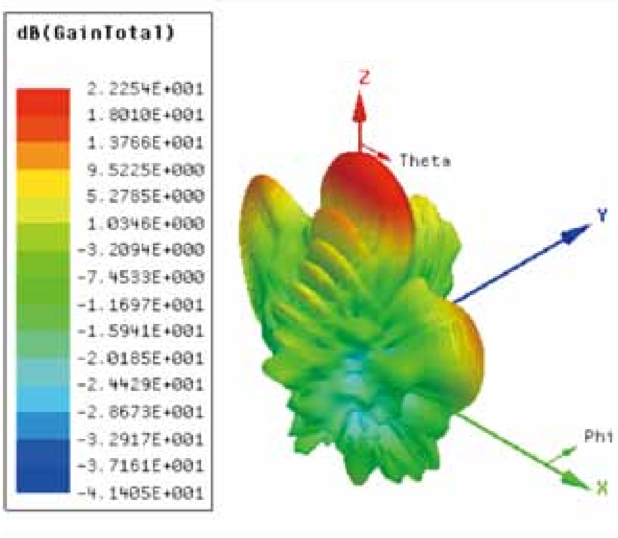

Fig 13. Array radiation pattern.

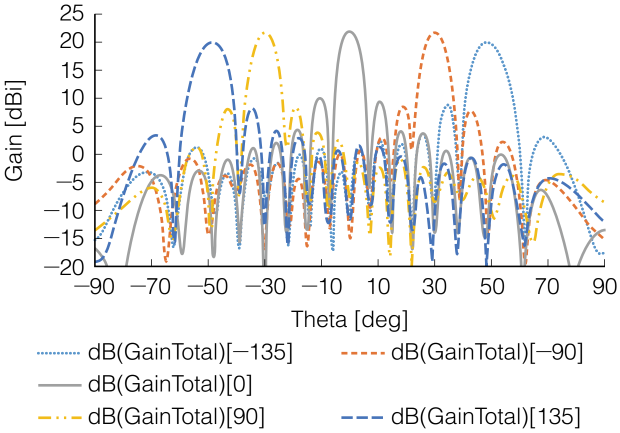

Fig. 15. Beamforming of array.

If all the antennas are fed with a same magnitude and 0 ° phase, the beam direction is in broadside. Fig. 13 shows this radiation pattern at 60 GHz with 22.3 dBi gain. The broadside gain w.r.t. frequency has been plotted in Fig. 14, shows very stable above 20 dBi. For beamforming in simulation all antennas are excited simultaneously with progressive phase shift of −135 °, −90 °, 0 °, 90 °, 135 °. According to the excitation phase the direction of the main beam steers in the different direction. For example, for −135 ° main beam steers in 50 °, for −90 ° main beam steers in −30 ° from the broadside direction and so on, as shown in Fig. 15.

4. Conclusion

The antenna discussed here shows excellent characteristics in terms of wideband characteristics, beamforming gain stability w.r.t. frequency. The single antenna gives around 10-GHz bandwidth with gain above 8.5 dB for all the frequency of operation. This also shows the advantage of using dummy patches and air gap. The array shows ± 50 ° beamforming with less than 2-dBi gain drop as compared to gain in the broadside direction.

References

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