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60 GHz High Gain Planar Antenna Array for Millimeter-Wave Industrial Applications

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***Abstract*—In this paper, a high gain and compact antenna array is designed using a parallel feed network at 60 GHz license-free band. First, the design of a single microstrip patch element is improved to achieve a high realized gain of 9 dBi. Then, a 16-way parallel feed network is designed for the 16-element array. The peak realized array gain is 18.56 dBi at 62 GHz, with -10 dB impedance of 10% (57.9 to 64 GHz). The proposed antenna array is suitable for millimeter-wave industrial applications and works on various 60 GHz protocols such as wireless local area network (WLAN) IEEE 802.11ad/ay, wireless personal area network (WPAN) IEE 802.15.3c, Wireless HD and ECMA-387.**

I. INTRODUCTION

The sub-6 GHz license-free bands such as 2.4 and 5 GHz can not fulfil the demands of modern industrial applications and factory automation due to low available bandwidth, low data rate, high interference and high spectral congestion. Therefore, unlicensed 60 GHz millimeter-wave (mmWave) communication is envisaged as a potential enabler for next-generation industrial wireless communication and control [1], [2]. The 60 GHz band covers 9 GHz of bandwidth from 57 to 66 GHz, and recently has been extended to 71 GHz in some geographical areas of the world. The 60 GHz spectrum is divided into 6 channels, each with minimum bandwidth of 2.16 GHz. Using channel bonding and aggregation of such multiple channels, tens of gigabits-per-second (Gbps) throughput can be achieved [3], [4]. Consequently, contemporary industrial applications such as remote visual monitoring and control, intelligent logistics, augmented reality and other multi-Gbps data rate applications can be supported [5]–[7]. However, the significant path loss in mmWave bands is a serious concern to compensate for which high-gain beamforming antenna arrays are crucial. High-gain antennas play a pivotal role to define the limits of mmWave wireless networks.

Various types of 60 GHz antenna designs are reported in the literature that can produce high gain [8]. Reflector antennas, lens-based antennas, multi-layer structures with parasitic elements, and partially reflecting surface antennas are some examples, to name but a few [9]–[13]. However, these antenna types are often complex to design and are often bulky. To alleviate this challenge, in this paper a low-cost, single-layer, planar PCB-based antenna array is designed at 60 GHz with -10 dB impedance bandwidth of 6.1 GHz and a peak realized gain of 18.56 dBi. Moreover, the realized gain is above 15 dBi throughout the band of interest. The array size is 15 mm × 33 mm × 0.2 mm.

II. PROPOSED ANTENNA ARRAY AND RESULTS

A. Patch Antenna Design With Enhanced Gain

The proposed antenna prototype is designed using Rogers 4003C substrate with a thickness of 0.2 mm, a dielectric constant of 3.55 and a copper thickness of 35 micrometers. The full ground plane is used at the bottom of the substrate to achieve a broadside radiation pattern. Inherently, microstrip patch antennas have low gain and narrow bandwidth. Therefore, the first step is to achieve a high-gain antenna at the element level, that could serve as a building block of a consequent high-gain array. First, a microstrip patch antenna was designed at the center frequency of 60.55 GHz with the maximum realized gain of 6.15 dBi at 61 GHz. The antenna was matched to 50 Ω using optimized dimensions for feed width and inset slots in the patch as shown in Fig. 1(a).

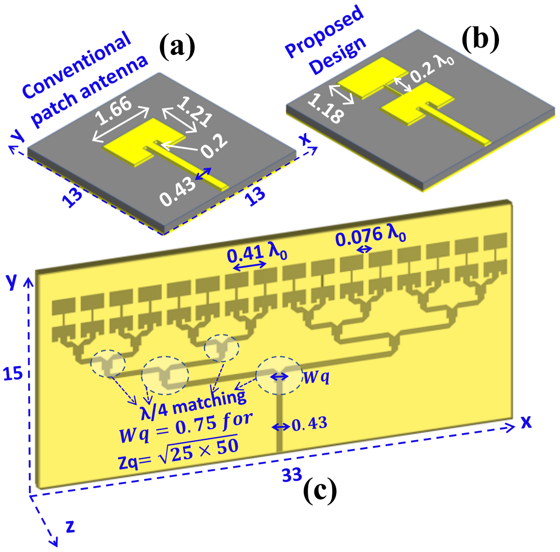

Fig. 1. (a) Design of a 60 GHz patch antenna. (b) Design of proposed patch antenna for enhanced gain. (c) Design of the proposed corporate-fed array. All dimensions are in millimeters.

Then, in order to enhance the gain of the conventional microstrip patch, a series-fed patch with optimized width and length was attached to the main patch element using a very thin transmission line having a width of 0.028 λ_0 (where λ_0 is the free space wavelength at 60 GHz) and length of 0.2 λ_0. The optimized proposed element-level design is shown in Fig. 1(b). With the proposed antenna design, the center resonant frequency is shifted to 63.65 GHz with a maximum realized gain of 9.1 dBi at 64 GHz. Thus, a gain enhancement of 3 dB was achieved at the element level as shown in Fig. 2(a). This is due to the enhancement of co-polarized current components along the added patch. The reflection coefficient and realized gain of the conventional as well as the proposed antenna design are shown in Fig. 2(a). The radiation efficiency is above 81 % in the band and the radiation pattern is towards the broadside.

B. Design and Analysis of High Gain Array

To design the array of the proposed high gain antenna element, initially a two-way power divider was designed with multiple parametric optimizations to find optimum

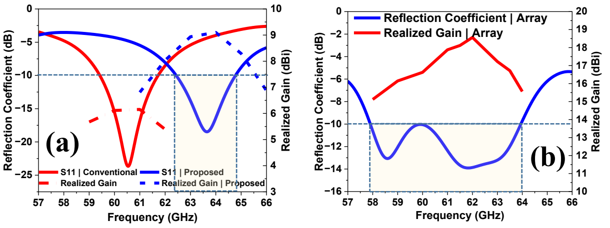

Fig. 2. (a) Simulated reflection coefficient and realized gain of the element level conventional and proposed antennas. (b) Reflection coefficient and realized gain of the proposed array.

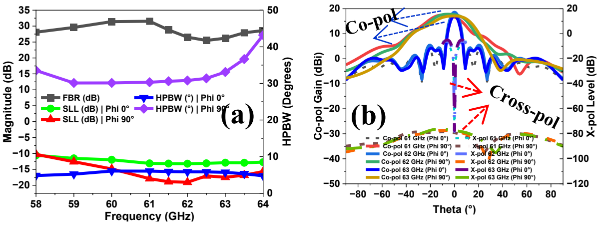

Fig. 3. (a) Simulated SLL, HPBW and FBR of the proposed array. (b) 2-D gain co-pol and cross-pol levels for phi 0° (x-z plane) and phi 90° (y-z plane) at 61, 62 and 63 GHz.

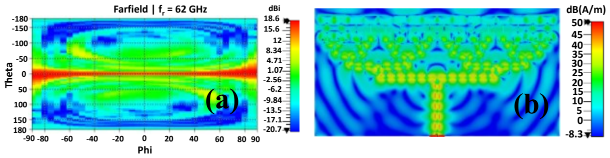

Fig. 4. (a) 2-D gain plot of the proposed array at 62 GHz. (b) Surface current distribution at 62 GHz.

inter-element spacing. The optimum center-to-center interelement gap was then chosen as 0.41 λ_0, whereas the space between any two adjacent elements is 0.076 λ_0, as shown in Fig. 1(c). The 2-way array configuration provided good gain and reduced side lobe levels (SLL). Once the 2-element array was optimized, it was then scaled to achieve 16-element array with same interelement spacing by designing a 16-way corporate-fed (parallel-fed) power divider. The power divider is symmetric from the center feed point and matched to 50 Ω. The junction lengths and transitions are matched with $\lambda/4$ transmission line sections. The edges of the divider are chamfered to avoid unwanted radiations and to provide maximum energy to the patches.

The proposed array is linearly polarized and provides the -10 dB impedance bandwidth from 57.9 to 64 GHz as shown in Fig. 2(b). The bandwidth enhancement is due to the addition of multiple resonances in power division and comparable transmission line sections to the operating wavelength. The peak array gain is 18.56 dBi at 62 GHz (Fig. 2(b)). The radiation efficiency is above 72% in the achieved band. SLLs are well below -10 dB and the front-to-back ratio is above 25 dB as demonstrated in Fig. 3(a). Excellent cross-polarization levels (less than -50 dB) are achieved in both x-z and y-z planes as shown in Fig. 3(b).

The half power beamwidth (HPBW) in x-z plane (phi 0°) is narrow and ranges between 5° to 6°, whereas is wider in y-z plane (phi 90°) and varies between 30° to 40°. This is due to the linear topology of the array. This can be confirmed by 2-D gain plot at 62 GHz in Fig. 4(a), where the elevational coverage along theta is quite narrow while azimuthal coverage along phi is quite wide. Such a fan-shaped radiation pattern is beneficial for point-to-point as well as point-to-multipoint communication at 60 GHz band depending on the orientation of the antenna array. The surface current distribution of the array is shown in Fig. 4(b) which depicts that the surface currents are confined within the power divider and the maximum energy is reached towards the patch antennas.

III. CONCLUSION

A low-cost and compact corporate-fed 60 GHz mmWave array is designed with a peak realized gain of 18.56 dBi at 62 GHz. The array covers -10 dB impedance bandwidth from 57.9–64 GHz. The array design procedure, analysis and results are elucidated. The proposed array is suitable for Industry 4.0 and beyond applications and can work with various 60 GHz WLAN and WPAN protocols such as IEEE 802.11ay/ad, IEEE 802.15.3c and WirelessHD.

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