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Design of a 60 GHz Microstrip Antenna for Multi-Gigabit Industrial Communication in Viewpoint of Industry 4.0

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Abstract**—In this paper, a planar rhombus-shaped microstrip patch antenna is proposed at 60 GHz ISM band for multi-gigabit per second level industrial communication in viewpoint of Industry 4.0. The proposed has -10 dB impedance bandwidth of 2.82 GHz at 60 GHz. The single antenna element presents excellent return loss of -65 dB at 60 GHz, high radiation efficiency of above 92.5 % in the whole band, and peak realized gain of 5.25 dBi. The radiation pattern of the antenna is stable in the whole band. The simulated 8 elements based linear array provides gain of 17.5 dBi and half power beamwidth of 8° in azimuth. The proposed antenna can be reconfigured at different resonance frequencies by altering the radius of the rhombus-shaped patch. The proposed antenna finds its applications for indoor industrial and factory automation operations in the unlicensed 60 GHz ISM band (IEEE 802.11ad and 802.11ay), as well as 60 GHz indoor localization.**

Keywords—industry 4.0, 60 GHz microstrip antenna.

I. INTRODUCTION

The industrial wireless communication bands such as unlicensed 2.4 GHz/ 5 GHz bands (also known as sub-6 GHz bands) are overcrowded and suffer from some serious problems, i.e., limited available bandwidth, and high susceptibility to interference. [1], [2]. Many sub-6 GHz wireless standards exist in industry [3], [4]. Nevertheless, in order to meet the high data rate demand and seamless connectivity of factory automation and other mission-critical scenarios of industry 4.0, a paradigm shift from sub-6 GHz unlicensed band to 60 GHz unlicensed millimeter-wave (mmWave) band (IEEE 802.11ad/ay) is considered an enabling technique [2], [5]–[8]. The term "industry 4.0" collectively refers to a wide range of concepts, some of which are the collaboration of smart devices connected through smart antennas, smart sensors, Industrial Internet of Things (IIoT), and cyber physical systems [9], [10]. Digitalization and intelligentization are the key traits of industry 4.0, which are enabled by the use of industrial internet of things (IIoT), artificial intelligence and smart adaptive antenna technology to name but a few [11], [12]. These sophisticated features require unprecedented throughput in the network, for which mmWave band is a promising choice.

The mmWave regime has been widely explored in the past couple of decades due to the promising potential features such as large spectral capacity, small antenna size, as well as compact and light equipment [13]–[15]. For multi-gigabits per second (Gb/s) level communication in industry 4.0 inspired factory automation and industrial control, 60-GHz unlicensed wireless local area network (WLAN) and wireless personal area network (WPAN) (IEEE 802.11ad and IEEE 802.11ay) possess immense potential to capture high-volume markets, which would require mass production of small, low cost, and highly integrated transceiver products. IEEE 802.11ay is the advancement of 802.11ad, and supports multiple independent data streams, higher channel bandwidth, and backward compatibility. It is the next-generation Wi-Fi standard for the 60 GHz band, through which the peak data rate is expected to increase up to 100 Gb/s [16], [17].

Smart antenna technology is crucial to develop a robust and efficient communication system for industry 4.0 based smart industries. In this view, a comprehensive survey on various mmWave array antennas and multibeam antennas for various mmWave applications is presented in [18]–[20]. Amongst different mmWave antenna types, microstrip antenna is a favorable choice due to cost effectiveness, light weight, easy fabrication and easy integration with RF circuitry [21]–[23]. Various microstrip antenna designs at 60 GHz band are proposed in literature for ultra-high speed communication [23]–[27]. Besides this, the design of 60 GHz on-chip integrated antenna structures, as well as transceiver designs using standard CMOS technology is also a demanding area for research [28]–[32].

In this paper, a simple and efficient microstrip antenna design is designed and studied for 60 GHz wireless

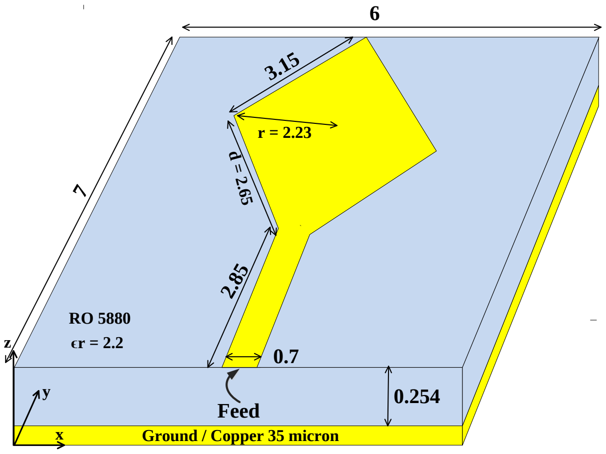

Fig. 1. A perspective view of the proposed antenna design with dimensions in millimeter.

communication. The proposed design employs a rhombus-shaped patch to resonate at 60 GHz band. The rhombus-shaped patch behaved in a different manner with excellent return loss and radiation efficiency, as compared to conventional rectangular or circular patches. The proposed antenna can also provide frequency reconfigurability to achieve different IEEE 802.11 channels, when the size of the patch is varied. Furthermore, the array performance showed high gain with low coupling coefficient values.

II. ANTENNA DESIGN

The design of the proposed single element antenna is shown in Fig. 1. The antenna is designed using low loss Rogers 5880 substrate having dielectric constant of 2.2, loss tangent of 0.0004, and thickness of 0.254 mm. The antenna consists of a rhombus-shaped patch structure with radius (r) of 2.23 mm (labelled in Fig 1) connected to the main feed line. Here, radius is the straight distance from the center of the rhombus-shaped patch towards any of its four vertices. The radius of 2.23 mm corresponds to an electrical length of 0.446 λ at 60 GHz, where λ is the free-space wavelength. Microstrip feedline is used to excite the antenna which is matched to 50 Ω. Complete ground plane was used on the opposite side of the radiating patch to obtain a broadside radiation pattern. The design was optimized for 60 GHz band and the final optimized dimensions are labelled in Fig.1. The overall size of the single element antenna is 7 mm × 6 mm.

III. SIMULATED RESULTS

The simulated reflection coefficient of the proposed antenna is shown in Fig. 2. The antenna shows an exceptional reflection coefficient of approximately -65 dB at 60 GHz. The achieved -10 dB impedance bandwidth is 2.82 GHz, from 58.44 GHz to 61.26 GHz which covers a complete channel amongst the designated IEEE 802.11ad channels of 2.16 GHz bandwidth. The radiation efficiency of the proposed antenna is above 92.5 % in the whole band and is shown in Fig. 3. The proposed antenna achieves the peak realized gain of 5.25 dBi in the band. The overall gain variation is within 1 dB in the whole band as shown in Fig. 3. The radiation pattern shows directional properties and is mainly towards the upper hemisphere because of the full ground plane opposite to the radiating patch. As depicted in Fig. 4, the radiation pattern has a null towards the broadside. This is due to the destructive interference of the field currents at the centre of the patch, as shown in Fig. 2 inset. The resultant field currents move towards the edges of the patch which are responsible for the effective radiation. Such a radiation pattern with a null at the broadside could be employed to mitigate jamming signals in the broadside direction in an industrial environment.

The placement of the antenna is in x-y plane and feed is provided in y-direction. The resultant maximum radiating field is along z-direction, therefore, in this case y-z plane (Φ = 90°) is referred to as E-plane, or elevation plane. Similarly, x-y plane (θ = 90°) is referred as the H-plane, or azimuth plane. The half-power beamwidth (HPBW) at 60 GHz is 121° in H-plane (θ = 90°), and 55.7° in E-plane (Φ = 90°), and 49.8° for Φ = 0°. The surface current density at 60 GHz is shown in the inset of Fig. 2, which depicts that the current density moved towards the edges of the patch at 60 GHz resonance and is mostly cancelled at the center of the patch, leading to the directional characteristics of the radiation pattern. Furthermore, the variations in the size of ground plane were also analyzed through simulations but the results at 60 GHz band were distorted. Thus, after the optimization process, full ground plane was an appropriate choice for this design. Nevertheless, some cautious inclusion of other defects in the ground plane such as carefully inserted small slots might produce some desirable results such as bandwidth enhancement, if required.

The proposed antenna also provides a frequency reconfigurable behavior. To achieve this reconfigurability, the radius of the rhombus-shaped patch is a decisive factor to shift the resonance frequency. When the radius is changed from 2.19 mm to 2.29 mm, the resonance frequency experiences a red-shift from about 61.15 GHz to 58.8 GHz. This reconfigurable response is depicted in Fig. 5, with the inset showing a variation in the size of the patch. In the future extension of this work, the authors anticipate producing this frequency reconfiguration in real-time by employing a varactor. The varactor can be used to change the capacitance of the whole patch, which will vary the corresponding net electrical length of the patch. Consequently, controllable frequency reconfigurability can be achieved. The reconfigurability in either frequency, radiation pattern, polarization, or in a combination of any of these is a desirable feature in smart antenna systems.

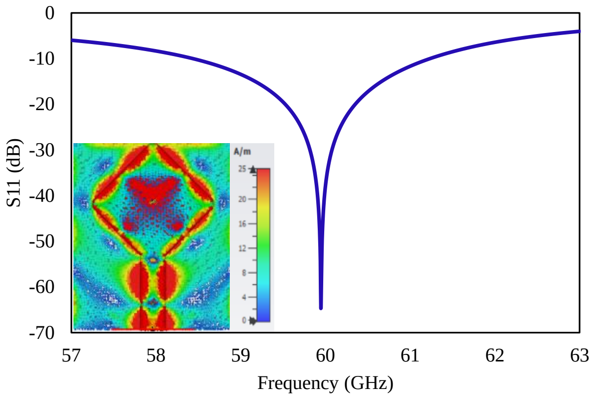

Fig. 2. Simulated reflection coefficient of the proposed antenna.

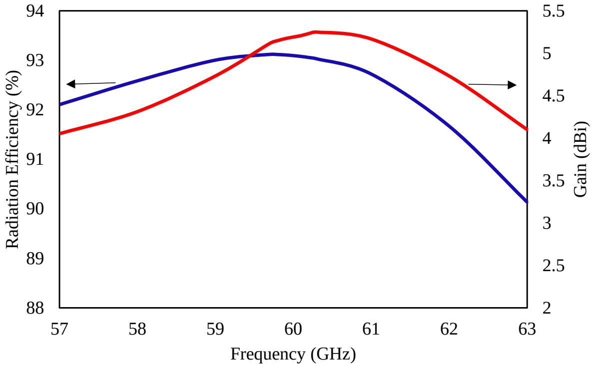

Fig. 3. Simulated radiation efficiency and gain of the proposed antenna.

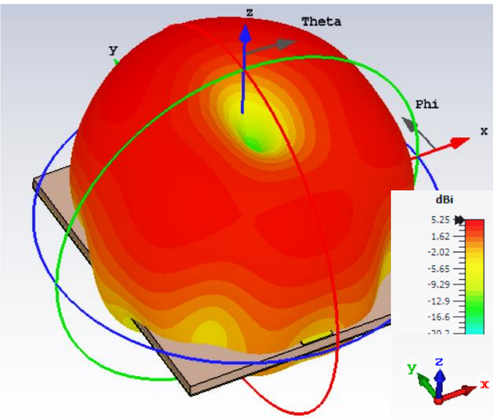

Fig. 4. Perspective 3D view of the radiation pattern of the proposed antenna. The null at broadside is due to the destructive interference of the field currents at the center of the patch.

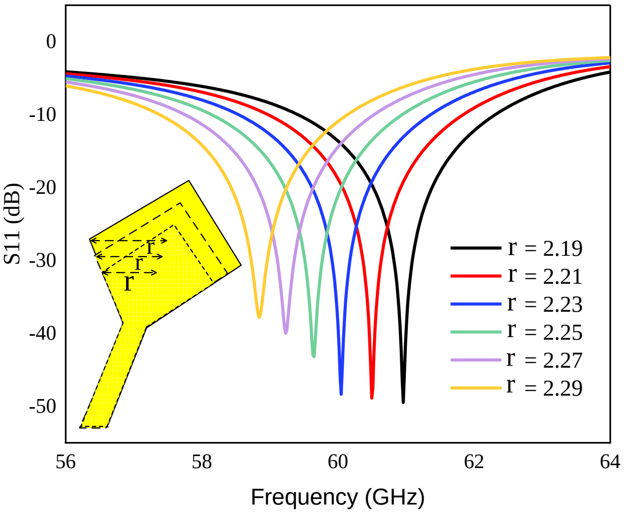

Fig. 5. Demonstration of the frequency reconfigurable behaviour of the proposed antenna. The shift in the resonance frequency is demonstrated based on the variation in the size of the radiating patch.

IV. ARRAY PERFORMANCE

As the mmWave band communication undergoes extreme path loss effects due to absorption by air and obstacles, thus an array design is necessary to be employed to provide sufficient gain and enhance signal to noise ratio (SNR). Thus, in addition to single element design, an 8-element linear array (1×8) is also simulated with 4.8 mm element spacing. The 3D radiation pattern of 1×8 array is shown in Fig. 6. The array provides a high gain of 17.5 dBi. The HPBW is 5.8° in H-plane ($\theta = 90^o$), 56.2° in E-plane ($\Phi = 90^o$), and 6.7° for $\Phi = 0^o$. The relatively wider HPBW in the elevation plane can be used in point-to-multipoint communication in an industrial environment. However, for point-to-point communication, more directive and lower beamwidth in both planes is often required [33]. The isolation level between the antenna elements is quite high and the values are well below -25 dB as shown in Fig. 7.

It is instructive to mention here that in order to design a complete smart antenna system at mmWave frequency regime, the development of the scanning performance, adaptive beamforming capabilities of the proposed antenna along with the design of appropriate feed mechanism and fabrication are of paramount importance, which are not presented here in detail due to brevity.

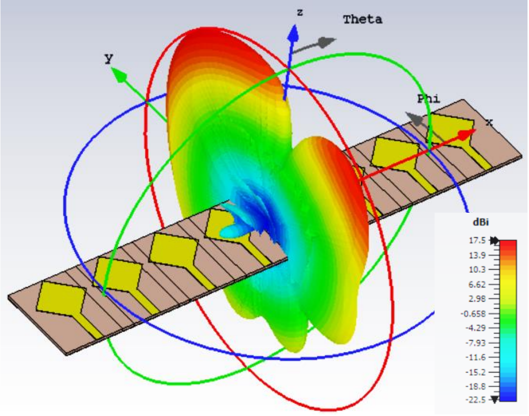

Fig. 6. Simulated 3D array factor performance of 1× 8 linear array.

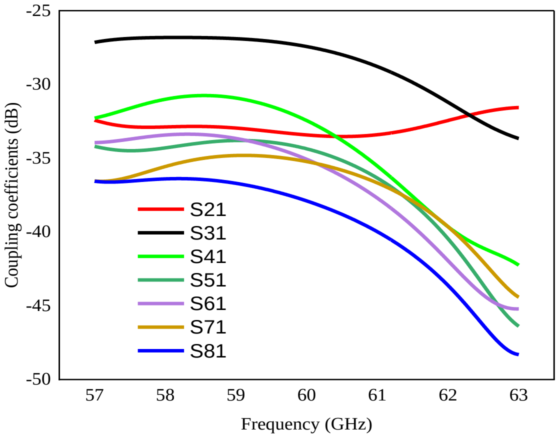

Fig. 7. Coupling coefficients for the elements of 1× 8 linear array.

V. CONCLUSION

In this paper, the design of a planar rhombus-shaped patch antenna is proposed at 60 GHz band with -10 dB impedance bandwidth from 58.44 GHz to 61.26 GHz. The proposed antenna is designed on a single-layer PCB. The single element antenna shows an excellent reflection coefficient of -65 dB at 60 GHz, radiation efficiency above 92.5 % and peak gain of 5.25 dBi. The proposed antenna is capable of producing frequency reconfigurability by varying the size of the radiating patch. This effect has been demonstrated in this work. Moreover, a linear array (1 × 8) array was simulated which shows the higher gain of 17.5 dBi at 60 GHz, and coupling coefficients well below -26 dB. The HPBW of the linear array is 5.8° in H-plane. The proposed antenna is a suitable choice for multigigabit-throughput communication in unlicensed 60 GHz to support full bandwidth of 2.16 GHz in IEEE 802.11ad standard, as well as future IEEE 802.11ay WiGig standard. The proposed antenna is anticipated to provide high data rate communication for factory automation and industrial control, motivated by industry 4.0 and beyond viewpoint. Moreover, the proposed antenna can also be used in multiple-input-multiple-output (MIMO) configuration for simultaneous communication and indoor localization for 60 GHz system.

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