Printed J-Slot Patch Antenna for Millimeter-Wave Applications

(Invited Paper)

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***Abstract*—This work introduces a wideband printed patch antenna design for 60 GHz radio applications. The proposed antenna is a single-layer structure with J-shaped slots loaded on the patch for the impedance bandwidth enhancement. The function of the J-shaped slots provides an additional current path for generating the second resonance of the patch. With this additional resonance, the antenna could find double resonances near the centre frequency of the patch. The antenna is excited by the grounded-coplanar waveguide (G-CPW) to microstrip line. This proposed antenna has an impedance bandwidth of 14.3% (8.6 GHz, 57–64 GHz) and the peak gain of 7.2 dBi. Its array of 4×1 arrangement yields impedance bandwidth of 19.2% (11.5 GHz, 55–65.5 GHz) with respect to the center frequency of 60 GHz, and rewards the maximum gain of 13.5 dBi at the broadside direction. This antenna has simple structure and is easy to fabricate by a conventional PCB technology. The proposed design finds a potential application of microstrip patch antenna in millimeter-wave wireless communications.**

***Keywords*—60 GHz, G-CPW, J-slot, signal patch antenna.**

I. Introduction

Since the Federal communication committee (FCC) allocated 57-64 GHz for unlicensed frequency band in 2001, wireless short-range communications around 60 GHz have become popular [1]-[14]. The wireless systems at 60 GHz communications would have various advantages such as high data rate transfer, ultrawide frequency bandwidth, and the possible miniaturization of the analog components and antennas. Recently, WiGig technology is considered as the most promising technology to deliver multi-gigabit throughput wireless communication [1]. There are a lot of applications such as mobile distributed computing, fast-large file transfer, uncompressed high-definition video streaming, wireless gaming, and high-speed internet access are envisioned [2].

Several studies have been focused on the development of 60 GHz antenna. To avoid the inherent disadvantages of patch and slot array antennas such as narrow impedance bandwidth, the grid antenna array(GAA) is proposed in [3] on a Ferro A6M LTCC substrate. Multilayer helical antenna array is proposed using the LTCC technology in [4]. In [5], a vertical off center fed dipole antenna on LTCC are employed to implement a 4×4 planar array for a high gain. Cavity-backed antennas (CBAs) are also widely developed and reported in microwave frequency bands, such as in [6]. However, consequences of high cost and complex structure lead these antennas which are difficult in commercialization and launching into the market. In addition, high-gain antennas [7] are also required in the 60 GHz communications owing to the compensation of large propagation loss. Some good antenna designs for 60 GHz applications can be found in [8]-[10]. They suggested high gain antenna arrays in a planar structure. However, their report results observed that an unwanted radiation may generate from microstrip lines in millimeter-wave bands. Therefore, the recent 60 GHz antenna designs should include some criteria such as low cost, low loss, high gain, simple structure, ease of fabrication, and etc.

In this paper, we propose a 60 GHz single-player printed patch antenna element and array excited by a grounded-coplanar waveguide (G-CPW) structure. The GCPW structure has been demonstrated by others [11]-[14] which are suitable for the 60 GHz application for power delivery in antenna elements. Firstly, we introduce a new wideband patch antenna element with J-slots loaded on the patch. The objective for these J-slots is to increase the bandwidth of the single-layered patch antenna. A comparison of antennas with U-slot, J-slot and a conventional patch are investigated. Secondly, an antenna array of 1×4 arrangement is suggested to the gain enhancement. The antenna array is based on the obtained result of the J-slot patch antenna element. Both proposed antenna element and antenna array are simple in structure, low-cost, high-gain, and easy to fabricate.

II. Design of J-slot Patch antenna element

A. *Antenna element design*

The geometry of a wideband J-slot patch antenna element is shown in Fig. 1. This antenna is a single-layered structure. The radiating patch is printed on a microwave substrate which is from a Rogers RT/Duroid 5880 substrate. The substrate has a relative permittivity of 2.2 and a thickness of 0.254 mm. As illustrated in Fig. 1, the proposed antenna consists of the radiating patch and two J-slots near the upper edge, the G-CPW fed attached in the bottom of the patch. In Fig. 1(a) and (b), there are some metallic vias around the upper ground which provide a good structure for realizing the G-CPW and reduce the loss in the transmission line. In addition, there are two inverted J-slots cutting on the rectangular patch as shown in Fig. 1(a). These slots introduce an additional current path from the radiating patch and result in second resonance from the patch. As a result, double resonances are generated in this proposed antenna. To obtain a 50 Ω input characteristic for this design, the GCPW line has two sections. The section of W_5 in the GCPW is connected to the patch with the characteristic impedance of ~120 Ω; while another section of W_6 has the characteristic impedance of ~90 Ω. This two sections are used for transforming the input impedance of the antenna to 50 Ω before connecting to a V-type SMA connector.

Microstrip patch antennas have advantages of simple structure and low cost, so widely be used in antenna designs [15]-[18]. For the 60 GHz antenna, , the wavelength is about 5mm. Because of the small patch size, the microstrip line causes an influence on the radiating patch and affects the antenna radiation pattern and its gain. In order to overcome this problem, the GCPW is employed into this design. As shown in Fig. 2, the GCPW is characterized by the fact that there is a ground plane on both sides of the substrate [19]. The feeding line is printed on the top layer of the substrate and placed in between the ground plane with a narrow gap on the upper side. Some metallic vias are built and connected from the upper ground plane to the lower ground plane that forms a good condition for realizing the GCPW structure

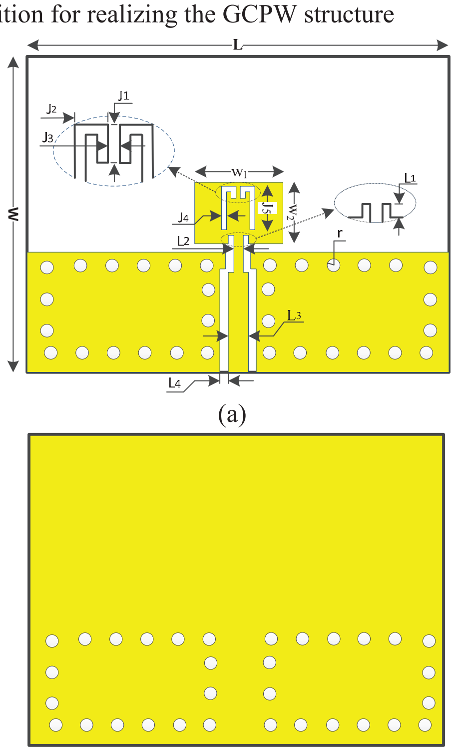


Fig. 1. Geometry of a wideband J-slot patch antenna element. (a) Top view. (b) Bottom view.

The characteristic impedance of the GCPW feed line is determined by the widths of the gaps and the centre conductor [20]. The metallic vias are placed around the feed line to short the upper ground plane to the lower, creating a cavity effect, and preventing the excitation of parasitic CPW and parallel plate modes, then implement control current focused on the feed line. We will verify this in the third section.

On the rectangular patch, two inverted J-slots are near the upper edge of the patch. For a conventional patch antenna, a fundamental mode current concentrates on the two radiating edges of the patch but it is single resonance and is narrow bandwidth which cannot meet the 60GHz application requirements. It is well-known that U-slot patch antenna is a very good method to increase the impedance bandwidth of the patch antenna due to the additional capacitance induced from the U-slot. However, the U-slot must be used in the environment of the patch with a coaxial feed such that the induced capacitance reacts with the inductance from the coaxial probe to obtain the wide impedance. Otherwise, the additional capacitance from the U-slot could not be used to enhance the bandwidth for the antenna. To demonstrate this statement, we compare three antennas which are a conventional patch antenna, a U-slot patch antenna, and a J-slot patch antenna as shown in Fig. 2. These three antennas are excited by edge feed with a single microstrip line. As shown in Fig. 2, the current paths for three antennas are illustrated. It is clearly seen that the current paths of the conventional patch antenna and the U-slot patch antenna are very similar. Although the U-slot generate a discontinues current along the slot, it is not good enough to provide the second resonance from the patch. However, the J-slot patch antenna could produce a good current patch for the additional resonance from the patch. Therefore, the J-slot patch antenna has a wider impedance bandwidth than the other two antennas. Their impedance bandwidth comparison is shown in Fig. 3.

B. Numerical Analysis

Fig. 3 shows the simulated reflection coefficient of these three different patches. It can be seen that the conventional patch antenna and the U-slot patch antenna have the impedance bandwidth of 11.2% and 11.6% (Reflection Coefficient ≤ -12.5 dB), respectively. The J-slot patch can yield the impedance bandwidth of 16.2% (Reflection Coefficient ≤ -12.5 dB).

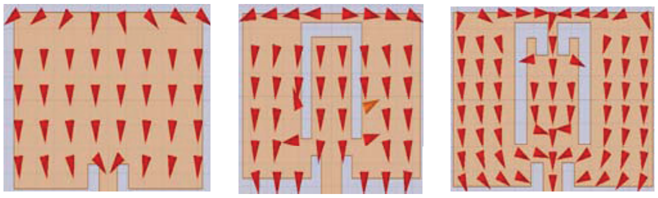
Detailed parameters of the proposed J-slot antenna element is listed in Table I.

TABLE I Detailed parameters of the proposed antenna element

Name	Unit (mm)	Name	Unit (mm)
$W1$	2.1	$J2$	0.35
$W2$	1.46	$J3$	0.1
$L1$	0.2	$J4$	0.127
$L2$	0.2	$J5$	0.9
$L3$	0.44	L	10
$L4$	0.2	W	7.5
$J1$	0.277	r	0.15

In the antenna, the width of $L4$ and the length of $J1$ can influence the impedance matching and bandwidth of the proposed antenna. To examine the effect of the function of $J1$

and $L4$, the simulated reflection coefficient as a function of $J1$ and $L4$ are plotted in Fig. 4 and Fig. 5 , respectively. It can be seen from Figs. 4 and 5 that when $J1$=0.277 mm and $L4$=0.2 mm the impedance matching achieves a better effect.



(a) Plate antenna (b) U-slot antenna (c)J-slot antenna

Fig. 2. Direction of current.

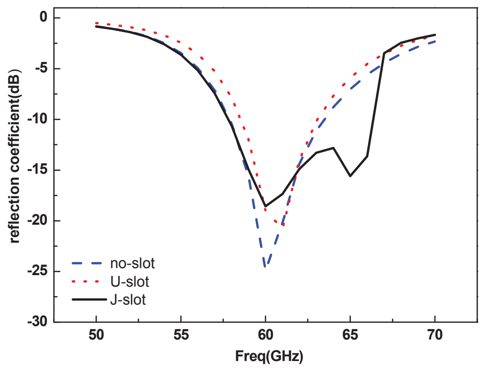


Fig. 3. Reflection coefficient of three patch antennas.

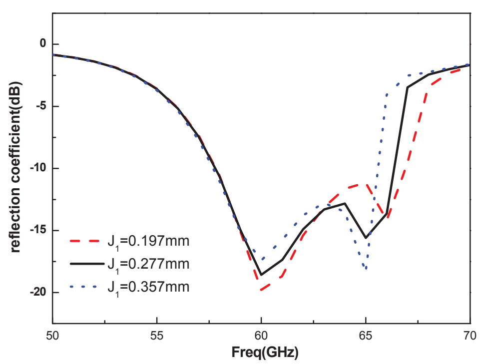


Fig. 4. Reflection coefficient as a function of J_1.

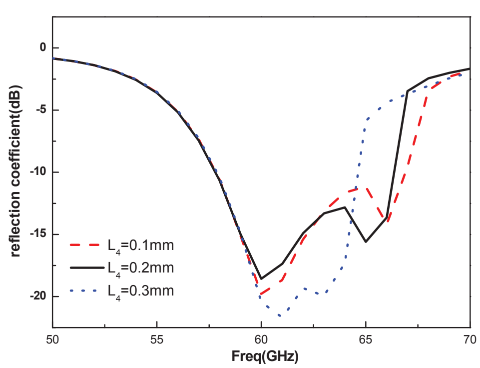


Fig. 5. Reflection coefficient as a function of $L4$.

C. Simulated Results

Fig. 6 shows the simulated reflection coefficient of the proposed patch antenna element with two J-slots. The Figures show that the measured reflection coefficient and gain are in good agreement with the simulated values. Three resonant frequencies, 60, 65 and 66 GHz, are generated by the two J-slots with lengths as shown in Fig. 1. As shown in Fig. 6, the simulated 10 dB

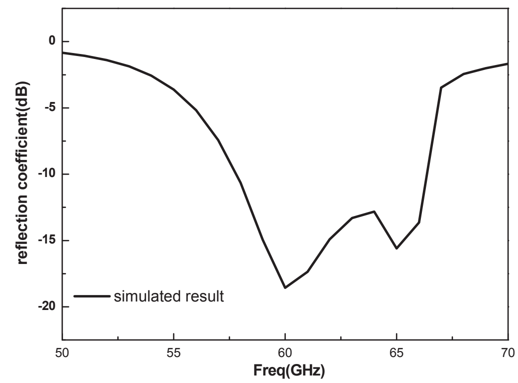


Fig. 6. Simulated reflection coefficient for antenna element.

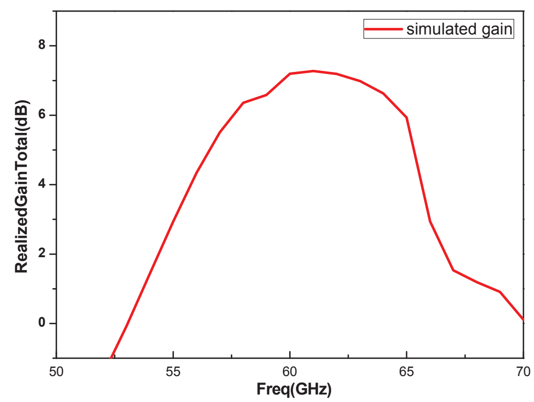
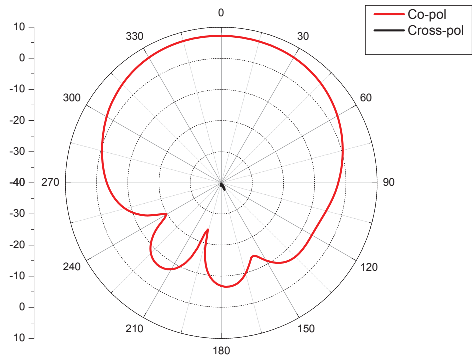
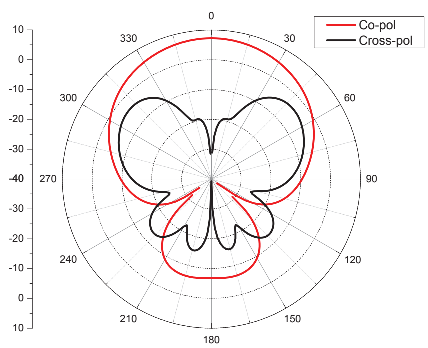


Fig. 7. Simulated realized gain for antenna element.

impedance bandwidth is 8.6 GHz (14.3% at 60 GHz) which is 57.8–66.4 GHz. In Fig. 7, the simulated gains in the respective impedance bandwidth range from 6 to 7.4 dBi. And, the simulated peak gain at 60 GHz, which is the minimum reflection coefficient frequency, is 7.4 dBi, as shown in Fig. 7. The simulated radiation patterns at 60 GHz are shown in Fig. 8 (a) and (b) for the two orthogonal planes of the E- and H-planes, respectively. It can be seen from Fig. 8 that a good symmetrical pattern can be achieved for the proposed antenna element. The 3dB beamwidths of the simulated radiation patterns in the E- and H-planes are 75° and 90°, respectively.



(a) E-Plane



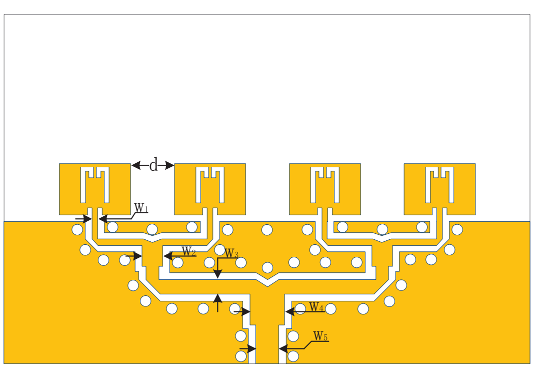
(b) H-Plane

Fig. 8. Simulated radiation pattern for antenna element at 60 GHz.

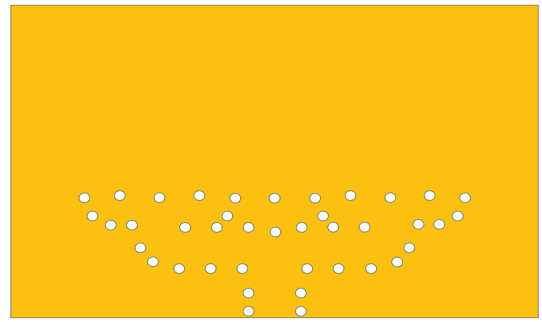
III. ANTENNA ARRAY DESIGN AND RESULTS

A. *Antenna array design and simulated results*

The arrangement of the J-slot patch antenna for the 4x1 array, which have a linear configuration, is shown in Fig. 9. The antenna array also uses a Rogers RT/Duroid 5880 substrate with a relative permittivity of 2.2 and thickness of 0.254 mm. The ground plane is in the back of the substrate and is connected by vias with the upper ground. A four power divider is used in the feed network of this array antenna. Fig. 9 (a) and (b) show the top view and bottom view of array antenna, respectively.



(a)



(b)

Fig. 9. Geometries of 4x1 array. (a)Top view. (b) Bottom view.

In Fig. 9 (a), T-junction and grounded coplanar waveguide (GCPW) to stripline transition constitute the feeding network. Its port is 50 Ω with a line width of 0.66 mm. In addition, the quarter-wave matched T-junction is used as the power divider to split the power equally and the input matching is achieved via a quarter-wave transformer. Its width and length are easily characterized according to the different size of substrate using Ansoft HFSS. Because of the extra radiation of microstrip line, it is reasonable to have a certain loss at the output port for this power divider. But through the use of GCPW, the radiation pattern is superior to that of using microstrip line.

The strip line feeding network is designed to feed each radiation element with equal amplitude and its width shown in Fig. 9(a) is determined by impedance matching conditions. Their width will affect the antenna impedance matching. The parameters of each section of the width of the microstrip line

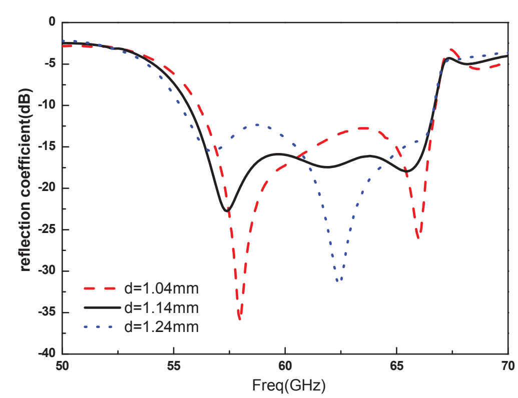


Fig. 10. Reflection coefficient as a function of *d*.

are $W1$=0.15 mm, $W2$=0.44 mm, $W3$=0.35 mm, $W4$=0.8 mm, $W5$=0.66 mm. The distance between the patch element center will also affect the impedance matching of the antenna. As shown in Fig. 10, reflection coefficient as a function of *d* verifies this distance on the influence of the impedance matching.

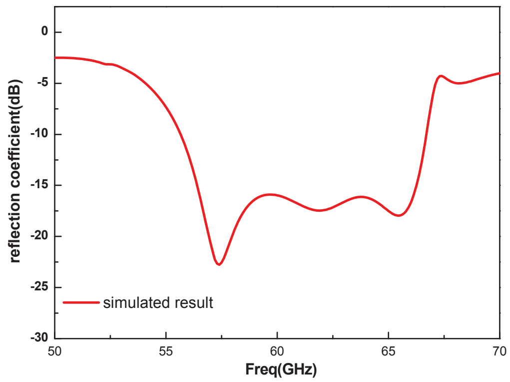
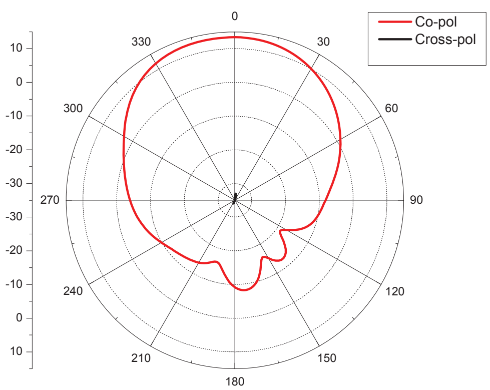
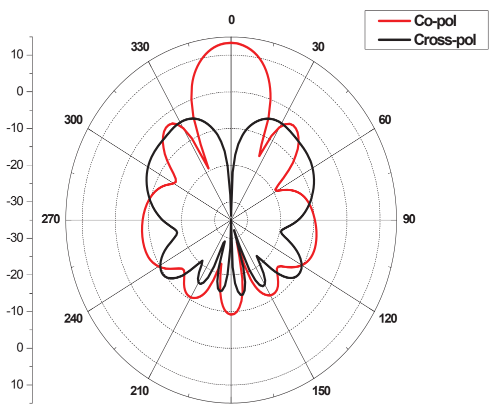


Fig. 11. Simulated reflection coefficient for proposed antenna array.



(a) E-Plane



(b) H-Plane

Fig. 12. Simulated radiation pattern for proposed antenna array at 60 GHz.

Fig. 11 shows the simulated reflection coefficient of the proposed patch antenna array with two J-slots. Fig. 14. shows measured reflection coefficient for proposed antenna. The Figures show that the measured reflection coefficient is in good agreement with the simulated values. Three resonant frequencies, 57, 60 and 66 GHz, which verify the effectiveness of the proposed two J-slot, are effectively expanded the bandwidth. As shown in Fig. 11, the simulated 10 dB impedance bandwidth is 11 GHz (18.3% at 60 GHz) which covers 56–67 GHz.

Fig. 12 (a) and (b) show the simulated radiation patterns at 60 GHz for the E- and H- planes. As shown in the figure, broadside radiation patterns are stable across the operating bandwidth. In the E- plane, the radiation pattern is asymmetric due to the asymmetry of J-slot presented in the patch. However, the radiation pattern is symmetric in the H-plane. The 3dB beamwidths of the simulated radiation patterns in the E- and H-planes are 40° and 30°, respectively.

B. Antenna array fabrication and the measured results

Fig. 13 shows photograph of the proposed antenna array which is smaller than a Chinese ten-cent coin whose diameter is 18 mm. As a result of the limitation of processing conditions, there are some discrepancy physical size compared with the simulation.

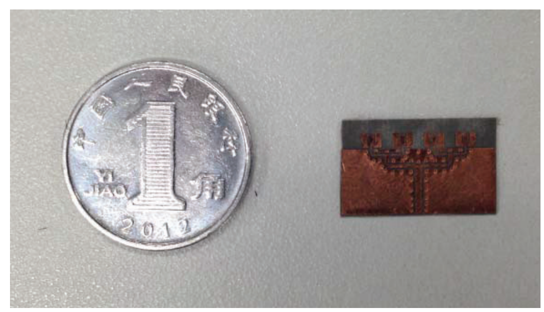


Fig. 13. Photograph of the proposed antenna array.

As shown in Fig. 14, the measured 10 dB impedance bandwidth is 11 GHz (18.3% at the center frequency of 60 GHz), which is 56–67 GHz. In Fig. 15, the measured gains in the respective impedance bandwidth range from 11 to 13.5 dBi. And, the measured peak gain at 60 GHz which is the minimum reflection coefficient frequency, is 13.5 dBi.

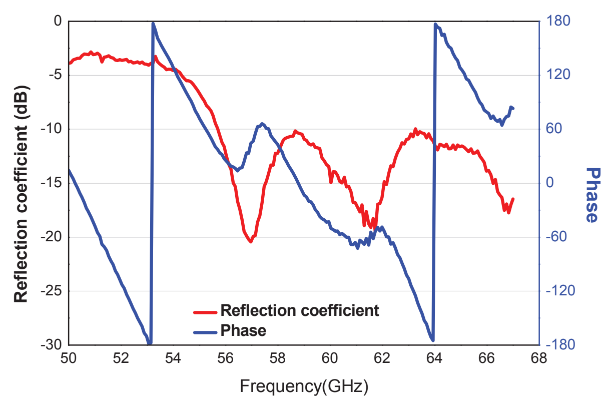
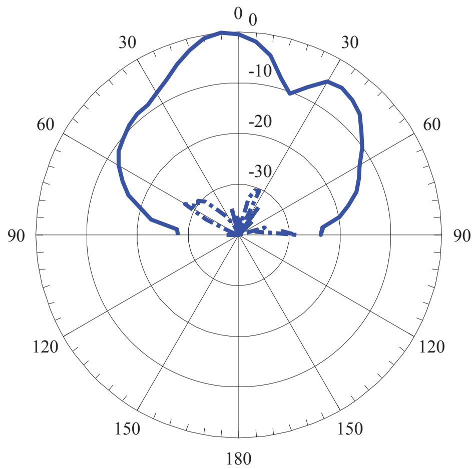
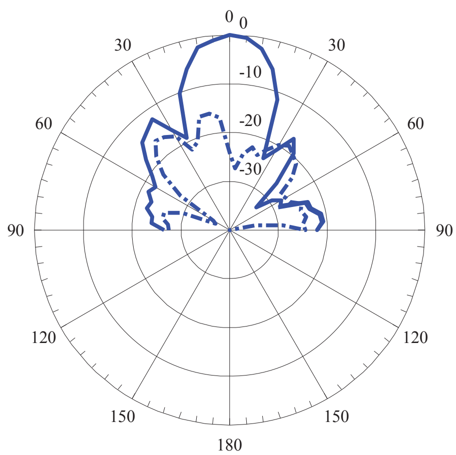


Fig. 14. Measured reflection coefficient for proposed antenna array.



(a) E-Plane



(b) H-Plane

Fig. 15. Measured radiation patterns for proposed antenna Array (Solid and dashed lines denote Co-pol and Cross-pol, respectively.).

IV. CONCLUSION

This paper demonstrated a wideband printed patch antenna element design for 60 GHz radio applications by employing a new J-slot in a side feed. On the basis of the antenna element, we also designed a 4x1 antenna array which has a bandwidth of about 11 GHz (18.3% at the center frequency of 60 GHz). The proposed antenna array has the advantages of simple structure and low cost. Through the use of coplanar waveguide, we can effectively control the antenna radiation of electric current. And the antenna array achieved the maximum gain of 13.5 dBi at the broadside direction.

Acknowledgement

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