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A LEAKY WAVE SLOT ANTENNA ARRAY USING SINGLE METAL LAYER WITH AZIMUTHALLY OMNIDIRECTIONAL PATTERN

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Abstract—This paper proposes a leaky wave slot antenna array for azimuthally omnidirectional coverage. Slot elements were arranged in cascade and series-fed by a coplanar waveguide (CPW). The most important novelty of this paper is that the whole array, including all the radiating elements and feeding structures, was arranged on a single metal layer. This simple structure has the merits of easy fabrication and low cost, especially at higher frequencies, such as millimeter wave band. Moreover, the proposed antenna array was folded around a center-hollowed columnar substrate to achieve omnidirectional radiation pattern in the azimuthal plane, with the gain variation less than 1.1 dB, which is similar to previous omnidirectional antenna array. In this paper, a prototype of the proposed antenna array at 2.3 GHz was built and tested to validate the design strategy. The measured results, including S parameters, radiation patterns, and gain, were found to agree well with the simulation ones.

1. INTRODUCTION

For the applications of portable base stations and access points, an antenna with omnidirectional radiation pattern in the azimuthal plane is required for large area coverage, which can be utilized for better performance in multiple paths environment [1, 2]. An early design of the coaxial collinear (COCO) antenna is presented in [3] for higher gain in the omnidirectional pattern. The inner and outer conductors of the coaxial transmission line are connected alternatively for the azimuthal omnidirectional coverage. Series-fed structure is utilized for antenna array feeding, with the merits of simple structure and energy

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leakage control of each element [4–7]. Based on this series-fed array structure, different types of omnidirectional radiated antenna array have been reported in the recent literatures [8–17]. For example, a dipole-structured planar microstrip antenna has been adopted in [8–11], along with the series-fed microstrip transmission line. The wire dipole elements [12, 13], ring slot elements [14], and segment loop elements [15, 16] have also been adopted in this series-fed structure to achieve the omnidirectional radiation pattern. To feed more radiating elements for higher gain, the leaky wave antenna array is one of the prospective candidates, such as the rotated dipoles [17] to achieve horizontally polarized omnidirectional pattern in the azimuthal plane.

However, all the designs in [8–17] are composed of double metal layers at least or even more complex structures, such as the folded lines in [13], the segment loops in [16] and the rotated dipoles in [17]. For frequencies above 30 GHz and up known as millimeter-wave frequencies, the conventional designs with azimuthal omnidirectional pattern [8–17] are difficult to be fabricated due to the complex or multilayer structures [18]. For this special purpose, continuous transverse stub (CTS) antenna array is an effective solution. The CTS antenna was invented in the 1990s at Hughes Aircraft Company [18], and has been widely adopted in the wireless communication systems. The coaxial cable fed omnidirectional radiated CTS antenna array was designed in [19–21] with the advantages of easy fabrication and low cost for higher frequency operation.

Based on the CTS antenna design of [19–21], we propose a CPW-fed folded slot antenna array with azimuthal omnidirectional radiation pattern. All the radiating elements and feeding structures of the proposed antenna array use a single metal layer and are folded around a columnar substrate. Compared with the CTS antenna design of [19–21], no extra stubs are needed. The fabrication of the proposed antenna array is even easier than the CTS antenna array presented in [19–21]. The proposed antenna array also has the properties of low cost and compact dimension. Due to the experiment condition, a 3-element prototype has been built and measured at 2.3 GHz to validate the design idea.

2. ANTENNA ARRAY DESIGN

Figure 1 shows the 3-D geometry of the proposed leaky wave slot antenna array. The proposed antenna array is supported by a columnar substrate of Rogers 6006 ($\varepsilon_r = 6.45$, $\tan\delta = 0.0019$). The substrate is center-hollowed with a thickness of $t = 1.9$ mm. The proposed antenna array consists of a 50-Ohm CPW transmission line and three

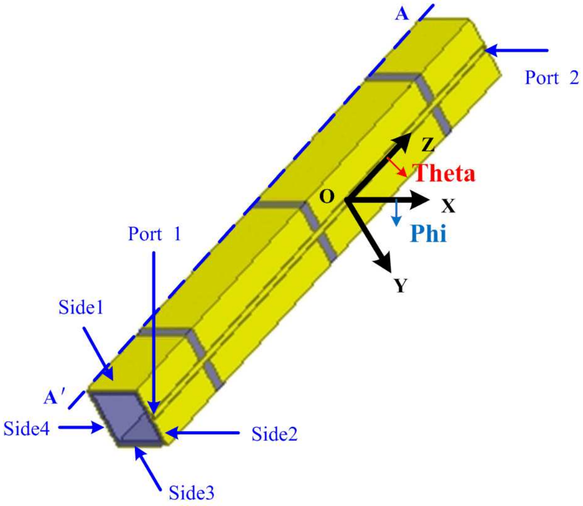


Figure 1. 3-D geometry and dimensions of the proposed antenna array.

radiating slots cut from the outer conductor of the CPW. Therefore, the whole antenna array, including all the radiating elements and feeding structure, is positioned on a single metal layer, which is folded along the four sides of the columnar substrate, named as Side1, Side2, Side3, and Side4.

Cutting along the trace AA', the expanded view of the proposed antenna is shown in Figure 2. The overall dimension of the proposed antenna array is $l_1 \times l_1 \times l_4 = 24 \times 24 \times 204\,\mathrm{mm}^3$. The three slot elements are positioned at a distance of $l_3 = 70\,\mathrm{mm}$, approximately 0.56 wavelength in free space at 2.3 GHz ($\lambda_0 = 130.4\,\mathrm{mm}$). The length and width of each slot element are $2 \times (l_1 + l_5 + l_6)$ and w_1. The proposed leaky wave slot antenna array is fed through Port 1. To avoid standing wave along the CPW transmission line, a 50-Ohm load is used at Port 2. In practical implementation of the proposed antenna array, more radiating elements should be used to minimize the lost power at the end load and increase the gain. The values of each parameter have been optimized by using the software of Ansoft High-Frequency Structure Simulator (HFSS). The detailed values are listed in Table 1.

2.1. Leaky Wave Slot Antenna Array Design

In this section, the operation principle of the radiating slot elements is examined. As shown in Figure 2, each slot is cut from the outer

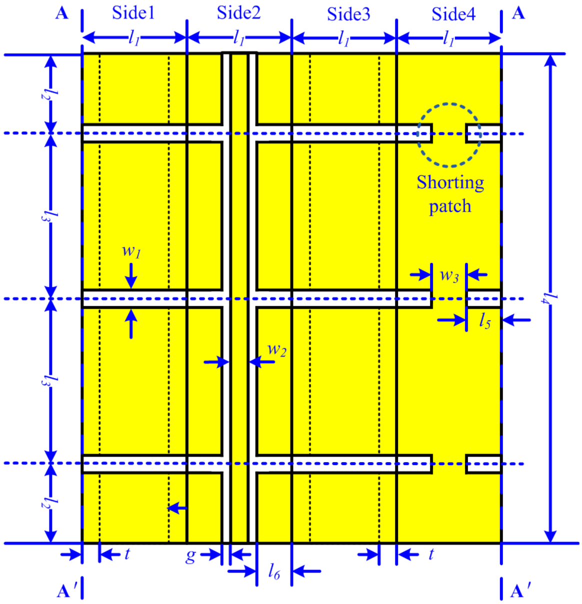


Figure 2. Dimensions of the proposed antenna array in expanded view cut along the trace of AA'.

Table 1. Detailed dimensions (unit: mm).

l_1	l_2	l_3	l_4	l_5	l_6	w_1	w_2	w_3	g	t
24	32	70	204	9	10.65	4	2	6	0.35	1.9

conductor of the CPW, with two identical arms. The two arms are shorted on Side4, and the shorting part between the two arms is named as shorting patch, with a length of w_3. For leaky wave antenna array, the element should not affect the operating mode on the transmission line. Therefore, the slot length is half of the wavelength to achieve shorting boundary condition at the slot position along the CPW transmission line (short boundary with half wavelength is still short boundary). For this reason, each arm should operate at half wavelength mode. The length of each arm is $l_1+l_5+l_6 = 43.65\,\mathrm{mm}$, approximately 0.64 wavelength in the substrate at 2.3 GHz ($\lambda s = 67.8\,\mathrm{mm}$), slightly longer than $0.5 * \lambda s$. The slot is not typical linear structure, but with folded structure. The length of each arm is not exactly $0.5 * \lambda s$. However, each slot arm is still operating at half wavelength mode, which is illustrated in the current distributions in Figure 3. The

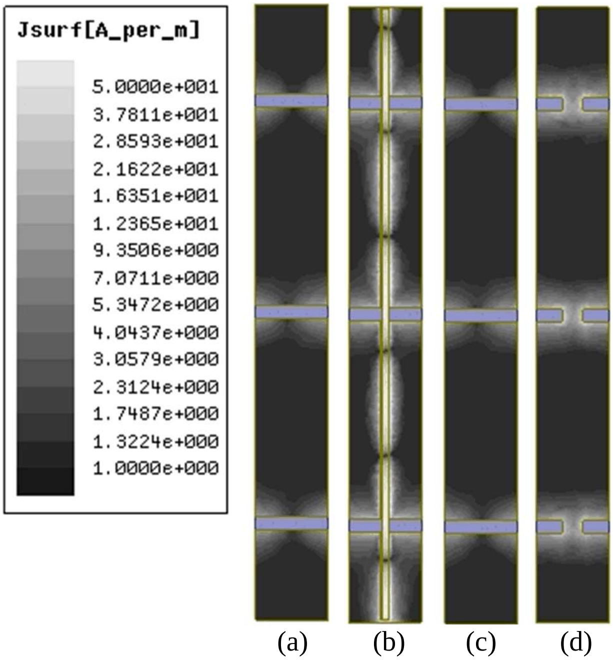


Figure 3. Magnitude of current distribution at 2.3 GHz with $w_1 = 4$ mm. (a) Side1. (b) Side2, (c) Side3, (d) Side4.

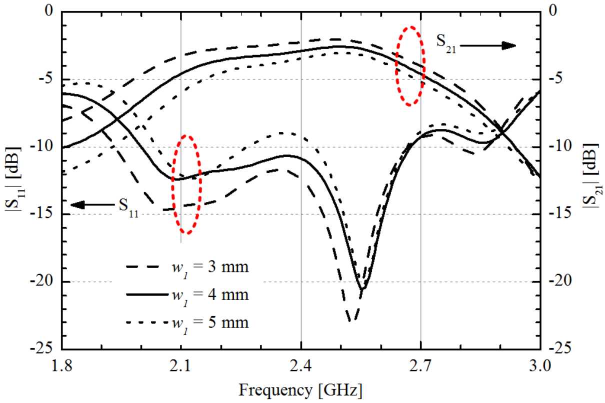


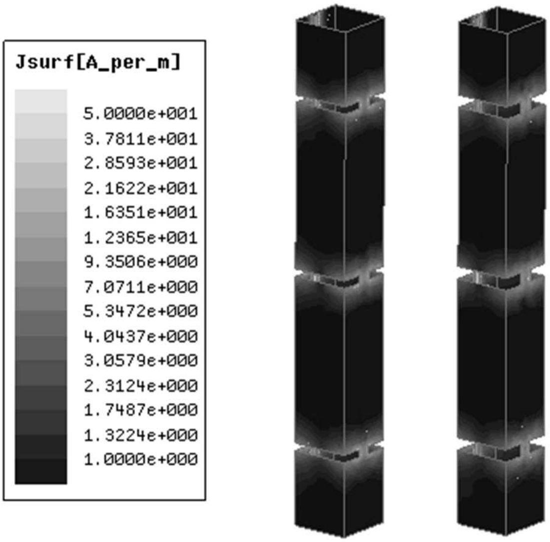
Figure 4. Simulated $|S_{11}|$ and $|S_{21}|$ with different w_1.

magnitude distribution of the current along the slots' edges at 2.3 GHz is depicted in Figure 3. It can be clearly seen that the peaks appear at the slot ends (Side2 and Side4) and a null appears in the middle of the slot (Side1 and Side3). The parameters of l_1 and w_3 have been used to tune the operating frequency of the proposed antenna array.

The width of the radiating slot w_1 dictates the radiated power ratio. The radiated power ratio is calculated based on formula (1) [22]

$$Pwr_{rad} \approx (1 - Pwr_{refl} - Pwr_{trans}) \times 100\% \tag{1}$$

where Pwr_{reft} and Pwr_{trans} are the reflected power and transmit power relative to the incident power, respectively, and can be calculated using the S parameters. The simulated S parameters with different w_1 are shown in Figure 4. When w_1 increases, more energy is radiated. For design simplicity, three slot elements have been used in the leaky wave antenna array. With different w_1 values of 3 mm, 4 mm, and 5 mm, each arm of slot operates at half wavelength mode at 2.3 GHz (as shown in Figure 3 and Figure 5), and the radiated power ratios were approximately 38.1, 45.5, and 49.3% at 2.3 GHz, respectively. An average value of $w_1 = 4$ mm was chosen for the slot elements, also considering the reflection coefficient lower than -10 dB. By adding



(a) (b)

Figure 5. Magnitude of current distribution at 2.3 GHz. (a) $w_1 = 3$ mm, (b) $w_1 = 5$ mm.

more leaky elements, the radiating efficiency and directivity can be enhanced. And the radiating power ratio and impedance matching of each element must be adjusted accordingly. Each element radiates relatively equal energy, producing little effect on the traveling wave in the feeding line.

2.2. Azimuthally Omnidirectional Pattern Design

Another property of the proposed antenna array is the omnidirectional radiation pattern in the azimuthal plane. For the reference CTS antenna array studied in [19–21], the center symmetric structure permits to obtain an omnidirectional radiation pattern. For the center asymmetrical antenna [8–14], it is important to find a way to compensate the variation in the azimuthal plane to achieve omnidirectional radiation pattern.

For the proposed antenna array design, the length of shorting patch w_3 is utilized to tune the energy radiation on Side4. Therefore, w_3 is used to tune the gain variation in the azimuthal plane. The simulated radiation patterns on the XY-plane with different w_3 at 2.3 GHz are illustrated in Figure 6. When w_3 increases, the radiating energy along the $-X$ axis (phi $= 180^\circ$) decreases. As mentioned above, each slot arm operates at half wavelength mode, which is dictated by the slot length. Therefore, w_3 also affects the operating mode of the radiating slot. As shown in Figure 7, with different values of w_3, the impedance matching characteristic and radiated power

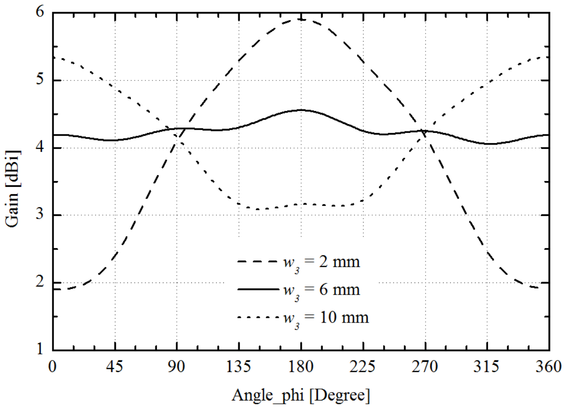


Figure 6. Simulated radiation pattern (Gain for co-polarization) on XY-plane (theta $= 0^\circ$) at 2.3 GHz with different w_3.

ratio are both changed. The parameter w_3 is tuned not only for omnidirectional radiation pattern, but also for the leaky characteristic. By optimizing the value of w_3, the omnidirectional radiation pattern with gain variation less than 0.5 dB was achieved in the XY-plane. The optimized value of w_3 was 6 mm.

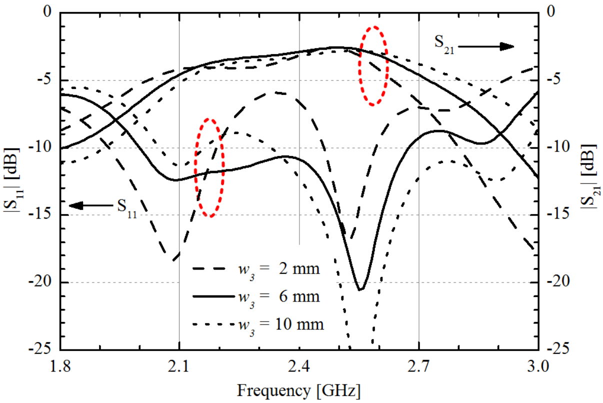


Figure 7. Simulated $|S_{11}|$ and $|S_{21}|$ with different w_3.

3. EXPERIMENTAL RESULTS

To validate the design idea, a prototype of the proposed antenna array was built at 2.3 GHz, as shown in Figure 8. Port 1 was connected to the feeding cable and Port 2 was loaded with 50 Ohm. The measured S parameters are shown in Figure 9. The 10 dB bandwidth of the S_{11} parameter is from 1.92 to 2.86 GHz. Compared with the simulated results, it can be noted that the bandwidth is wider due to loss introduced from the cables. At the desired frequency of 2.3 GHz, $|S_{21}|$ is -3.07 dB and the radiated power ratio is 45.7%, which are in agreement with the simulated results.

The normalized radiation patterns at 2.3 GHz were measured and illustrated in Figures 10–12. In the azimuthal plane (XY-plane) of Figure 10, the omnidirectional radiation pattern is achieved with a gain variation of 1.1 dB. For simulation, the gain variation is 0.5 dB. The difference is mainly contributed to the undesired radiation and reflection from the feeding cable. For the same reason, the cross-polarization level is higher than the simulated results, but still 22 dB lower than the level of co-polarization. The difference between simulation and measurement, however, is considered acceptable given

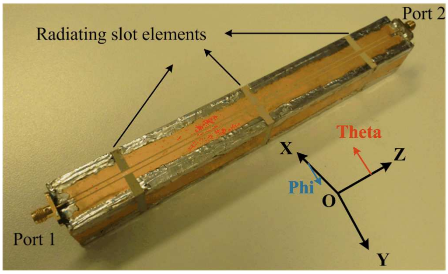


Figure 8. Photograph of the proposed antenna array.

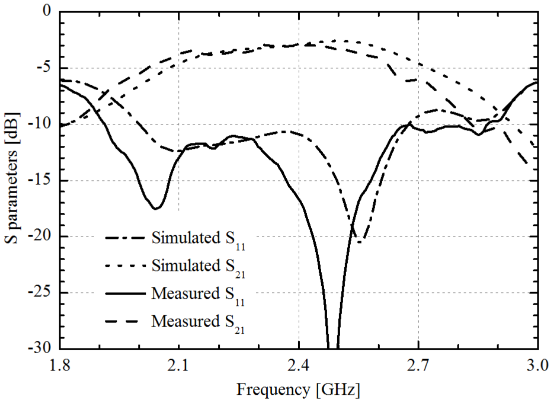


Figure 9. Measured and simulated S parameters of the proposed antenna array.

the small values of cross polarization powers. For the XZ- and YZ-plane in Figures 11 and 12, respectively, the sidelobe level is more than 5 dB lower than the mainlobe level.

The measured mainlobe is 7° deviation from the broadside. This is due to the uncertainty of substrate permittivity. The broadside radiation pattern is not exactly at 2.3 GHz. The simulated radiation patterns in YZ-plane with different ε_r are illustrated in Figure 13. As ε_r changing from 6.0 to 6.9, $\pm 10^\circ$ deviation are achieved from the broadside. When ε_r increases, the wavelength on the substrate decreases. And the phase difference between two adjacent slots increases. Therefore, the mainlobe steers backward, from $+Z$ direction to $-Z$ direction, as shown in Figure 13. The broadside radiation pattern can be achieved by tuning the distance between radiating slots.

At 2.3 GHz, the simulated directivity of the co-polarization of the

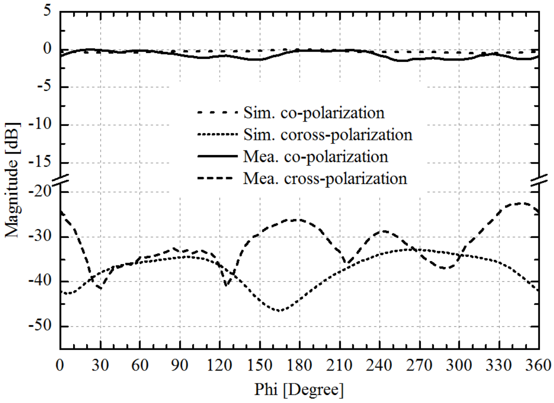


Figure 10. Simulated and measured normalized radiation patterns at 2.3 GHz in the XY-plane (theta = 90°).

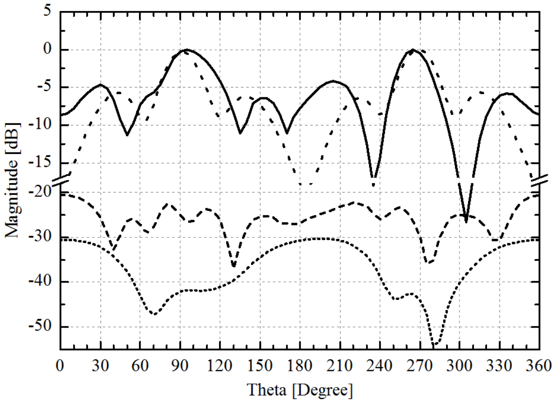


Figure 11. Simulated and measured normalized radiation patterns at 2.3 GHz in the XZ-plane (phi = 0°). [Use the legend in Figure 10].

proposed antenna array was 4.85 dBi. With the simulated radiating power ratio of 45.5%, the simulated realized gain (considering the energy of reflection and transmission) was 1.08 dBi. The measured realized gain was 1.0 dBi, and the measured radiated power ratio is 45.7%, which are in good agreement with the simulation. By adding more leaky elements, the radiating efficiency and directivity can be enhanced simultaneously, and the radiating power ratio of each element should be adjusted accordingly.

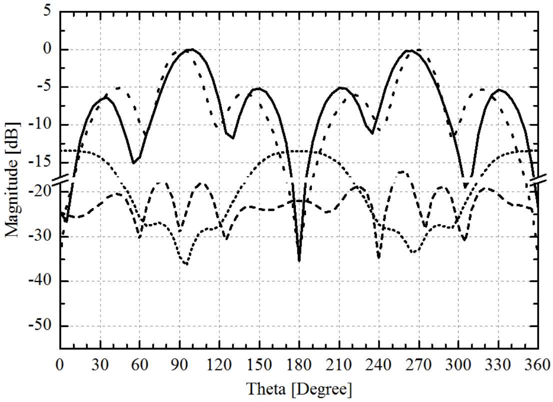


Figure 12. Simulated and measured normalized radiation patterns at 2.3 GHz in the YZ-plane (phi = 90°). [Use the legend in Figure 10].

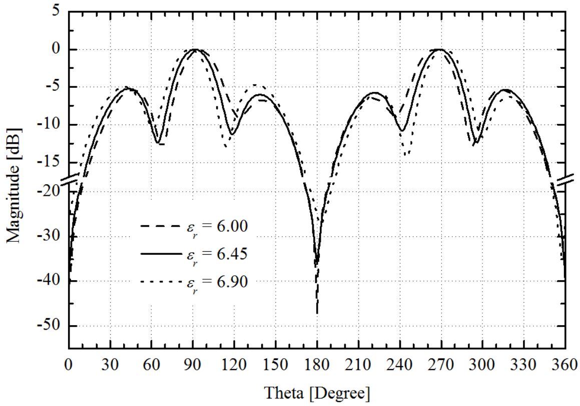


Figure 13. Simulated normalized radiation patterns at 2.3 GHz in the YZ-plane (phi = 90°) with different ε_r.

4. CONCLUSION

This paper presents a three-element CPW-fed leaky wave folded slot antenna array with omnidirectional radiation pattern. By using the columnar structure, a gain variation of less than 1.1 dB was achieved in the azimuthal plane. Once again, the whole antenna array, including all the radiating elements and feeding structure, was arranged on a single substrate layer, which has the advantages of easy fabrication and low cost for higher frequency bands, when compared with the designs in [19–21].

In the future work, the metamaterial-based phase shifters [23] will be integrated onto the proposed antenna array for beam steering capabilities, which could not be achieved in the coaxial CTS leaky wave antenna array of [20–22].

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