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Compact Circularly Polarized Antenna Based on Quarter-Mode Substrate Integrated Waveguide Sub-Array

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Abstract—A compact and circularly polarized planar antenna is presented in this paper based on a quarter-mode substrate integrated waveguide sub-array. The operating principle and design guidelines of the proposed antenna are discussed with the aid of an isosceles right triangular cavity with two magnetic side walls and one electric side wall. The mode solutions are determined and the resonant frequencies of the triangular cavity are calculated. The designed antenna is fabricated and its radiation characteristics are measured. Measured results are in good agreement with predicted ones. It is demonstrated that the proposed structure is a simple and compact candidate of high-performance circularly polarized antenna.

Index Terms—Circularly polarized antenna, half-mode/quarter-mode substrate integrated waveguide, isosceles right triangular waveguide, planar antenna.

I. INTRODUCTION

CIRCULARLY POLARIZED (CP) antennas are widely employed to mitigate the polarization mismatch and multi-path interference problems in radar and wireless communication systems. One class of the CP antennas is the microstrip patch antenna with a slight perturbation in the antenna at a specific location to excite two orthogonal modes with 90° phase difference [1]–[3], or the microstrip patch antenna with coupled cross slots in the patch [4]–[6]. Another class of the CP antennas is cavity-backed CP antennas presented in [7]–[10]. These antennas exhibit excellent radiation performances. However, the backing cavities with a depth of a quarter wavelength limit their applications, and the fabrication is also complicated.

An isosceles right triangular quarter-mode substrate integrated waveguide (QMSIW) sub-array is proposed in this paper for CP radiation. Fig. 1(a) shows the geometry of the isosceles right triangular QMSIW [11]. Metallic via hole array is introduced in the QMSIW to make the boundary equivalent to a conventional electric wall, while the other two open sides of the QMSIW are approximately regarded as magnetic walls [12].

In order to investigate the resonance properties of the QMSIW, an equivalent isosceles right triangular cavity model with two magnetic side walls and one electric side wall is used in this paper. Fig. 1(b) shows the cross sectional view of the studied triangular cavity model. Exact mode solutions are found via superposition of plane waves of the corresponding

Fig. 1. (a) Geometry of isosceles right triangular quarter-mode substrate integrated waveguide. (b) Cross sectional view of equivalent isosceles right triangular waveguide model with two magnetic side walls and one electric side wall (AOB) in the corresponding square waveguide with magnetic walls ($AOBO'$).

square waveguide with magnetic walls, as shown in Fig. 1(b) ($AOBO'$) [13]. Closed-form waveguide mode expressions can then be extracted to accurately predict the resonant frequencies and electromagnetic fields inside the cavity. From the analysis of the triangular cavity model, it is noted that the proposed structure is, in fact, a promising candidate for compact planar antennas.

A CP antenna is thus designed based on the QMSIW sub-array, which has a number of advantages. First, it is planar and can be easily integrated with other planar circuits. Second, the size of the ground plane is almost the same as the antenna patch because the four sides of the antenna are grounded with arrays of via holes that effectively become electric walls. Third, the proposed antenna retains the advantages of the cavity-backed antennas [14], such as high gain and high radiation efficiency. The reflection coefficient and radiation characteristics of the designed QMSIW sub-array antenna are measured and results show that the antenna exhibits left-handed (LH) CP radiation with a high gain of 5.58 dBic and 3 dB axial ratio (AR) bandwidth of 5.8% around 5.2 GHz.

II. ANALYSIS

The mode functions and associated eigenvalues for an isosceles right triangular waveguide with two magnetic side walls and one electric side wall are initially determined to analyze the QMSIW shown in Fig. 1. The mode functions of such triangular waveguide can be constructed by suitable linear combinations of the degenerate modes of a square waveguide with magnetic walls $AOBO'$, as shown in Fig. 1(b).

By solving the Helmholtz equations, the solutions of H_z and E_z for TE_{mn} and TM_{mn} modes of the square waveguide $AOBO'$ with magnetic side walls are obtained as

$$\begin{cases} TE : H_z = A_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{a} e^{-j\beta z}, \\ TM : E_z = B_{mn} \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{a} e^{-j\beta z}, \end{cases} \quad (1)$$

where a is the width of the square waveguide with magnetic walls, as shown in Fig. 1(b), and it is the same as the leg length of the studied triangular waveguide. A_{mn} and B_{mn} are amplitude constants, and β is the propagation constant. It is

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Fig. 2. Transverse modal field distribution of the dominant TM_{10}/TM_{01} mode for the isosceles right triangular waveguide with two magnetic side walls and one electric side wall. (a) Calculated transverse modal field distribution. (b) Simulated electric field distribution.

noted that the square waveguide enclosed with magnetic walls has a series of degenerate TE_{mn} and TM_{mn} modes with the same cutoff frequencies.

With appropriate linear combinations of these modes, the mode functions of the isosceles right triangular waveguide with two magnetic side walls and one electric side wall can be obtained. The mode function

$$\psi_{mn}^{TE}(x, y) = \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{a} + \sin \frac{n\pi x}{a} \sin \frac{m\pi y}{a}, \quad (2)$$

describes the TE mode in the triangular waveguide, where m and n are non-zero integers. In addition, the mode function

$$\varphi_{mn}^{TM}(x, y) = \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{a} - \cos \frac{n\pi x}{a} \cos \frac{m\pi y}{a}, \quad (3)$$

describes a TM mode satisfying all boundary conditions of the triangular waveguide when $m \neq n$. The dominant TM mode is TM_{10}/TM_{01} mode, which is also the dominant mode of the concerned triangular waveguide.

The cutoff wavenumber of each mode in the discussed triangular waveguide can be calculated based on the following formula

$$k_c = \frac{\pi}{a} \sqrt{m^2 + n^2}. \quad (4)$$

and the wavenumber for the dominant mode of the triangular waveguide is then $k_c = \pi/a$. It should be pointed out that the leg length a alone is sufficient to determine the cutoff frequency of the dominant mode of the triangular waveguide.

Fig. 2(a) shows the calculated transverse modal field distributions for the dominant TM_{10}/TM_{01} mode of the triangular waveguide, while Fig. 2(b) illustrates the simulated electric field distribution of the dominant mode for the same triangular waveguide by ANSYS HFSS. It is seen that they are in excellent agreement.

III. CIRCULARLY POLARIZED ANTENNA SUB-ARRAY

Based on the qualitative analysis of the QMSIW, a simple linearly polarized antenna is designed and shown in Fig. 3. The antenna uses Rogers RT5880 substrate with thickness $h_1 = 1.57$ mm, low dielectric constant ($\epsilon_r = 2.2$) and low loss tangent ($\tan \delta = 0.0011$). The via hole diameter d is 0.5 mm, and the spacing between adjacent via holes s is 1 mm. The spacing between the center of the via holes and the

Fig. 3. Configuration of the quarter-mode substrate integrated waveguide linearly polarized antenna.

Fig. 4. Simulated reflection coefficient of the quarter-mode substrate integrated waveguide linearly polarized antenna.

hypotenuse edge of the triangular patch is $v = 0.5$ mm. The side lengths $a = 17.3$ mm and $L = 24.46$ mm. The coaxial feed with a diameter $D = 0.8$ mm is located at $p = 9.67$ mm along the line of symmetry. The length w is 12.23 mm, which is quarter wavelength at the center frequency. Fig. 4 shows the simulated reflection coefficient of the linearly polarized antenna based on the QMSIW. The first resonance occurs at 5.2 GHz, corresponding to the TM_{010}/TM_{100} mode of the QMSIW cavity.

It can be seen that the size of the designed linearly polarized antenna based on the QMSIW is very small, and it is isosceles right triangular configuration. It provides an attractive way to design a compact sub-array antenna with circular polarization. By properly feeding the sub-array through a power distribution network, a compact and efficient CP antenna can be realized.

Fig. 5 shows the configuration of the proposed CP antenna based on the QMSIW sub-array, which is achieved by sequential rotation of the isosceles right triangular QMSIW antenna of linear polarization. Each element of the CP antenna has the same dimension as the QMSIW linearly polarized antenna shown in Fig. 3. The spacing g between opposite cells is chosen as 1.6 mm. Four feed-clearance disks of diameter $G = 2.4$ mm are etched out in the ground plane, each disk being centered on its respective feed probe of diameter $D = 0.8$ mm. The choice of Rogers RT5880 substrate with thickness $h_1 = 1.57$ mm has been made to obtain high

Fig. 5. Top view of the quarter-mode substrate integrated waveguide circularly polarized antenna. (a) Three dimensional model. (b) Radiator on the top layer. (c) Ground plane layer. (d) Power distribution network on the bottom layer.

Fig. 6. Simulated current distribution ($x_a y_a$ -plane) of the quarter-mode substrate integrated waveguide circularly polarized antenna at different time instants. (a) $\omega t = 0$. (b) $\omega t = \frac{1}{2}\pi$. (c) $\omega t = \pi$. (d) $\omega t = \frac{3}{2}\pi$.

Fig. 7. Simulated reflection coefficients and axial ratio for different values of element spacing g for the quarter-mode substrate integrated waveguide circularly polarized antenna. (a) Reflection coefficients. (b) Axial ratio.

efficiency and reasonable bandwidth, although at the expense of a relatively larger element size. The matching network is fabricated on Rogers RO3010 substrate with high dielectric constant ($\epsilon_r = 11.2$) for circuit compactness, whose thickness (h_2) is 1.27 mm and low loss tangent is 0.0022, to obtain a small size. The widths of the 50, 70 and 100 Ω microstrip lines are 1.13 mm, 0.51 mm and 0.16 mm, respectively. Four ports with 90 degrees phase difference between adjacent elements are designed to feed each QMSIW element, as shown in Fig. 5(d).

The QMSIW sub-array provides two orthogonal field components with equal magnitude and 90 $^\circ$ phase difference. Fig. 6 shows the time-varying electric current distributions on the patch of the proposed CP antenna at 5.2 GHz when the antenna is fed at P_0 . The distributions are observed at different instantaneous times $\omega t = 0, \frac{1}{2}\pi, \pi$ and $\frac{3}{2}\pi$, where $\omega = 2\pi f$ is the angular frequency. The magnitudes of current distributions at $\omega t = 0$ and π are almost the same, while their directions are opposite. The current rotates along the clockwise direction shown in Fig. 6 leading to an LHCP radiation.

An important parameter in designing this CP antenna sub-array is the element spacing g between opposite isosceles right triangular patches. For the considered CP sub-array, the

Fig. 8. Prototype of the quarter-mode substrate integrated waveguide circularly polarized antenna. (a) Radiator on the top layer. (b) Matching network on the bottom layer.

Fig. 9. Reflection coefficients and radiation efficiency of the quarter-mode substrate integrated waveguide circularly polarized antenna.

element spacing should be chosen as large as possible to minimize the mutual coupling between elements. However, the smaller element spacing is preferable for achieving more compact antennas. Fig. 7 shows the simulated reflection coefficient and AR results when the element spacing g is varied. If the element spacing is too small, such as $g = 0.4$ mm, the mutual coupling between the elements affects the radiation efficiency and degrade the AR performance. With the increase of element spacing, there is a slight increase in the bandwidth and the radiation performance is improved. It is shown that efficient radiation can be obtained when $g = 1.2 \sim 2.4$ mm. The value of $g = 1.6$ mm is chosen here since the simulated AR is acceptable while the structure remains relatively compact under this situation.

Fig. 8 shows the fabricated prototype of the designed CP antenna based on the isosceles right triangular QMSIW sub-array with the same dimensions indicated in Fig. 5. The simulated and measured reflection coefficients of the designed CP antenna based on QMSIW sub-array are shown in Fig. 9. It is seen that the measured resonant frequencies are slightly shifted compared to the simulated results. This is due to the material

Fig. 10. Simulated and measured gain of the quarter-mode substrate integrated waveguide circularly polarized antenna.

Fig. 11. Simulated and measured radiation patterns of the quarter-mode substrate integrated waveguide circularly polarized antenna at $f=5.2$ GHz. (a) $\phi = 0^\circ$ cut plane. (b) $\phi = 45^\circ$ cut plane.

and manufacturing tolerance. The measured bandwidth with a return loss (RL) larger than 10 dB is achieved from 5.04 GHz to 5.48 GHz, and the minimum return loss is 22.6 dB at 5.23 GHz.

Fig. 10 shows the measured and simulated peak gain of the proposed CP antenna. The measured maximum gain is 5.58 dBic, while the simulated maximum gain is 5.65 dBic at 5.2 GHz. The slight decrease in the measured gain might be due to the mismatch of the feeding network. In Fig. 9, the measured radiation efficiency is 86%, while the simulated result is 91.8% at 5.2 GHz. The simulated and measured AR results are also plotted in Fig. 10. The measured AR of the antenna is around 1.5 dB at 5.2 GHz, and the measured 3dB AR bandwidth is 5.8% from 5.02GHz to 5.32 GHz. The measured radiation efficiency is determined as the ratio of the total power radiated by the antenna to the total power received by the antenna at its terminal during radiation. Three-dimensional automatic measurement system, the fully anechoic chamber, is required to estimate the total power radiated by the antenna.

The radiation patterns are simulated and measured to demonstrate the radiation characteristics of the proposed QMSIW sub-array antenna. Fig. 11 shows the CP far-field radiation patterns of the antenna in the $\phi = 0^\circ$ and 45° cut planes at 5.2 GHz, where ϕ is defined and shown in Fig. 5(a). It can

TABLE I
COMPARISON OF THE PERFORMANCES BETWEEN PREVIOUS LITERATURE AND THIS WORK

Types of CP antennas	3dB-ARBW(M)	Freq(GHz)	10dB-RLBW(M)	Radiator-Area(λ^2)	ϵ_r	Gain(dBic)(M)	Efficiency
Asymmetric-slit patch [3]	0.49%	2.4	2.1%	0.084	3.38	4.3	—
Circular patch with cross slot [4]	0.65% (2 dB)	1.55	0.34%	0.091	2.6	6	—
SIW cavity-backed cross slot [14]	0.8%	10.1	2.8%	0.536	2.2	6.15	> 75%(S)
Square patch with slits [2]	0.84%	2.262	3.5%	0.044	4.4	2.8	—
Diagonal-fed square patch [1]	1.2% (6 dB)	3.175	1.4%	0.078	2.62	—	—
CPW-fed patch with slit inset [5]	1.6%	2.2	3.6%	0.048	4.4	—	—
CP patch in SIW cavity [6]	2.34%	10	17.32%	1.767	2.2	7.79	> 90%(S)
QMSIW resonator [11]	2.8%	10.8	21.6%	0.168	2.2	7.13	65%(M)
Cavity-backed slot [9]	15%	6	26.6%	0.922 ($h = 0.48\lambda$)	2.45	8.72	—
Proposed QMSIW sub-array	5.8%	5.2	8.4%	0.194	2.2	5.58	86%(M)

ARBW: Axial ratio bandwidth. RLBW: Return loss bandwidth. (M): Measured result. (S): Simulated result. λ : Free-space wavelength.

be seen that a good CP radiation beam is generated by this QMSIW sub-array, and the main lobe points to the broadside direction.

Table I shows the performance comparison between our structure and those in the previously reported works. The radiator area listed in the table is evaluated relative to the free-space wavelength (λ) at the corresponding center frequencies. The length of the proposed CP antenna based on the QMSIW sub-array is about half of a guided wavelength, which is almost the same size as the conventional patch antenna. However, the radiation efficiency, gain and AR of the proposed CP antenna based on QMSIW sub-array are significantly improved. It should be pointed out that a ground-plane with large size is required for conventional patch antennas, while it is not necessary for the proposed QMSIW sub-array antenna. Since the four sides of the antenna are enclosed with metallic via hole array, the ground plane can be the same as that of the antenna patch.

IV. CONCLUSION

A compact planar CP antenna has been proposed based on the QMSIW sub-array in this paper. The mode solutions of the QMSIW are determined based on the cavity model of an isosceles right triangular waveguide resonator with two magnetic walls and one electric wall. The resonant frequencies and electromagnetic field components are analytically calculated. The electric field distributions of the QMSIW obtained from simulation are in excellent agreement with the theoretically calculated results of the triangular waveguide. The proposed compact planar CP antenna has been fabricated and its radiation characteristics have been demonstrated. Both simulated and measured results have shown that the proposed isosceles right triangular QMSIW sub-array is a promising candidate for compact planar CP antennas with high gain, high radiation efficiency and good AR.

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