Metamaterial beam scanning leaky-wave antenna based on quarter mode substrate integrated waveguide structure*

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In this paper, we first propose a metamaterial structure by etching the same two interdigital fingers on the upper ground of quarter mode substrate integrated waveguide (QMSIW). The simulated results show that the proposed QMSIW-based metamaterial has a continuous phase constant changing from negative to positive values within its passband. A periodic leaky-wave antenna (LWA), which consists of 11 QMSIW-based metamaterial unit cells, is designed, fabricated, and measured. The measured results show that the fabricated antenna achieves a continuous beam scanning property from backward -43° to forward $+32^\circ$ over an operating frequencyrange of 8.9 GHz–11.8 GHz with return loss better than 10 dB. The measured antenna gain keeps consistent with the variation of less than 2 dB over the operating frequency range with a maximum gain of 12 dB. Besides, the measured and simulated results are in good agreement with each other, indicating the significance and effectiveness of this method.

Keywords: metamaterial leaky-wave antenna, quarter mode substrate integrated waveguide (QMSIW), continuous beam scanning property

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1. Introduction

Quarter mode substrate integrated waveguide (QMSIW), which realizes nearly 75% size reduction in comparison with the SIW, have received increasing attention for applications in the microwave, millimeter wave and radar systems due to its compact size, easy fabrication and easy integration with other planar components.[1–4] A lot of researches about QMSIW have been reported, such as compact bandpass filters,[5–7] circularly polarized antennas,[8,9] compact frequency-tunable antenna,[10] miniaturized frequency selective surface,[11] etc. It is very obvious that the QMSIW structure gives an attractive and promising way to design microwave devices and antennas.

Leaky-wave antenna (LWA) possesses many advantages such as low profile, beam scanning, and consistent gains. However, for the conventional uniform LWA, it can radiate only in a forward direction,[12,13] but the metamaterial based one can realize a continuous beam scanning property from backward to broadside to forward directions within its operating frequency band.[14] The previously reported SIW/HMSIW based LWA used metamaterial structure to realize continuous beam scanning from backward to forward directions.[15] However, there has been no research about QMSIW based LWA with continuous beam scanning from backward to forward directions. Only in Ref. [16], the authors first used conventional QMSIW structure to design LWA with forward beam scanning property. Therefore, it is an interesting challenge to design LWA with continuous beam scanning property from backward to forward directions by using the QMSIW based metamaterial structure.

In this paper, a novel quarter-mode substrate integrated waveguide (QMSIW) based metamaterial structure is proposed to implement leaky-wave antenna (LWA) with continuous beam scanning property from backward to forward directions for the first time. The proposed QMSIW based metamaterial structure, which is designed by etching the same two interdigital fingers on the upper ground of the QMSIW, exhibits continuous phase constant changing from negative to positive values within its operating frequency band. The designed LWA, which consists of 11 identical QMSIW based metamaterial unit cells, is fabricated and measured. The measured results show good agreement with the simulated results, indicating that the fabricated antenna obtains a continuous beam scanning angle of 75° from backward to forward directions over its operating frequency range with a consistent gain of more than 10 dB. These behaviors demonstrate that the proposed QMSIW-based metamaterial structure is a wonderful and interesting candidate for continuous beam scanning LWA.

2. Design and analysis of the QMSIW based metamaterial

According to Ref. [14], the electric and magnetic field distributions of SIW are almost the same as those of the

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waveguide cavity of the TE mode, the formulae of the TE_{110} mode of the waveguide are given as follows:

$$E_z = E_0 \sin\frac{\pi y}{W}\sin\frac{\pi x}{L}, \tag{1}$$

$$H_y = -\frac{\mathrm{j}\beta E_0}{k\eta}\sin\frac{\pi y}{W}\cos\frac{\pi x}{L}, \tag{2}$$

$$H_x = -\frac{\mathrm{j}\pi E_0}{k\eta W}\cos\frac{\pi y}{W}\sin\frac{\pi x}{L}, \tag{3}$$

where L and W denote the length and width of the SIW. It is worth mentioning that β is the phase constant, k is the wave number, and η is the intrinsic impedance.

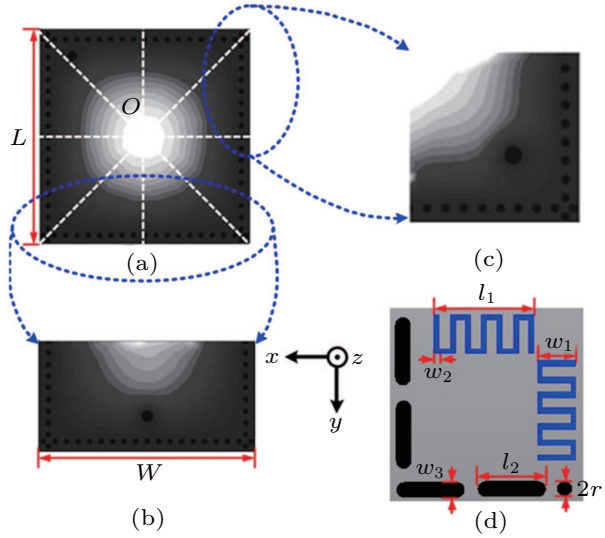


Fig. 1. (color online) (a) Full-mode SIW. (b) Half-mode SIW. (c) Quarter-mode SIW. (d) The proposed QMSIW based metamaterial.

According to the field distributions on the basis of the above equations, it is very obvious that the H field shows a circular distribution around the center of the SIW as shown in Fig. 1(a). Therefore, when the SIW is cut vertically in half, a half-mode SIW (HMSIW) is obtained, and the H field is vertically distributed, which looks like a magnetic wall. The E fields around the magnetic wall show that the in-phased fields exist on the opposite side, according to image theory. Further, the HMSIW keeps the same resonance at the same frequency and field distribution as the SIW as shown in Fig. 1(b). Similarly, the HMSIW can be cut in half, forming a quarter-mode SIW (QMSIW), and it still be able to exhibit the same performance as the SIWas shown in the plot in Fig. 1(c). The geometry structure of the proposed QMSIW based metamaterial unit cell is shown in Fig. 1(d), and it can be seen that the unit cell is designed by etching the same two interdigital fingers on the upper ground of the conventional QMSIW, which is exactly a quarter of the square SIW. While the rectangle via walls is used to replace the cylinder via holes, because they can be easily fabricated by using a typical PCB manufacturing process. The proposed QMSIW based metamaterial structure is printed on Rogers Duroid 5880 substrate, with a thickness of 0.508 mm, relative dielectric constant of 2.2, and loss tangent of 0.0009. The ANSYS high-frequency structural simulator (HFSS) is used for three-dimensional full-wave EM field analysis. The geometric parameters of the proposed QMSIW based metamaterial structure are given as follows: $L = 14.0$ mm, $h = 0.508$ mm, $l_1 = 6.75$ mm, $l_2 = 5.4$ mm, $w_1 = 3.0$ mm, $w_2 = 0.75$ mm, $w_3 = 1.4$ mm, and $r = 0.7$ mm. The simulated S parameters and phase, calculated dispersion curve and losses of the proposed QMSIW based metamaterial structure are given in Fig. 2.

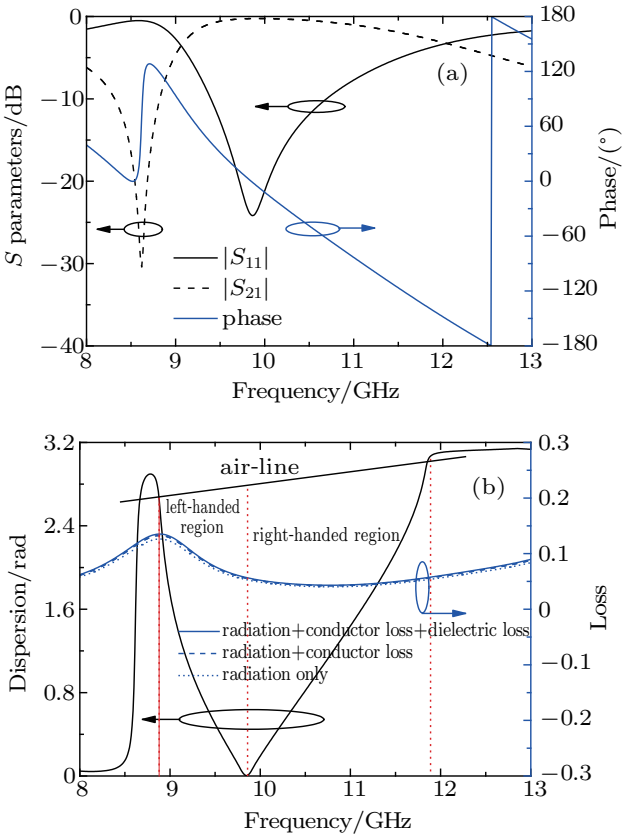


Fig. 2. (color online) (a) Simulated S parameters and phase, and (b) calculated dispersion curve and losses.

Figure 2(b) gives the calculated dispersion curve and losses of the proposed QMSIW based metamaterial unit cell by Eqs. (4) and (5) according to the simulated S parameters. The air-line is calculated by Eq. (6).

$$\beta = \cos^{-1}\left(\frac{1 - S_{11}\times S_{22} + S_{12}\times S_{21}}{2\times S_{21}}\right), \tag{4}$$

$$\mathrm{Loss} = 1 - S_{11}S_{11}^{*} - S_{21}S_{21}^{*}, \tag{5}$$

$$\beta_0 = \omega p/c. \tag{6}$$

As shown in Fig. 2(b), the air line crosses left-handed lower frequency of about 8.9 GHz and right-handed upper frequency of about 11.8 GHz, that is to say, the fast wave region of the proposed QMSIW based metamaterial structure

is 8.9 GHz–11.8 GHz, while the bands below 8.9 GHz and more than 11.8 GHz are the slow wave regions. Besides, the balanced condition of the proposed QMSIW based metamaterial structure is realized at around of 9.9 GHz, which means that the left-handed (8.9 GHz–9.9 GHz) and right-handed (9.9 GHz–11.8 GHz) regions are continuous. Moreover, according to Fig. 2(a), it can be seen that the QMSIW based metamaterial structure obtains a continuous phase constant changing from negative to positive values over the pass-band of 8.9 GHz–11.8 GHz. The loss analysis for the QMSIW based metamaterial unit cell is also shown in Fig. 2(b), and it can be seen that compared with the radiation loss, the other losses are very small and negligible, which means that the resulting results of the energy are transmission and radiation.

3. Leaky-wave antenna design and result discussion

Based on the above analysis of the proposed QMSIW based metamaterial structure, a periodic leaky-wave antenna (LWA) composing of 11 identical QMSIW-based metamaterial unit cells, is designed. For the designed periodic LWA, radiation is generated from space harmonics as follows:

$$\beta_n = \beta_0 + \frac{2n\pi}{d}, \tag{7}$$

where d is the length of the proposed metamaterial structure, and β_0 is the fundamental space harmonic. For the radiation of a space harmonic, the propagation constant β_n must satisfy the following equation:

$$\beta_n < k_0, \tag{8}$$

where k_0 is the free space propagation constant.

Due to the continuous phase constant of the QMSIW-based metamaterial changing from negative to positive values, the designed periodic LWA can realize the continuous main beam scanning from backward to forward directions. Beam scanning is a function of the operating frequency[11] as given in the following equation:

$$\theta(f) < \sin^{-1}\left[\frac{\beta(\omega)}{k_0}\right], \tag{9}$$

where k_0 is the free space propagation constant.



Fig. 3. (color online) Photograph of the fabricated periodic LWA.

For verification, the designed periodic LWA is fabricated, and finally measured through an N5230C vector network analyzer. The photograph of the fabricated antenna is shown in Fig. 3. The comparison between the measured and simulated results are given in Figs. 4–6.

Figure 4 shows the comparison between the measured and simulated S parameters of the designed periodic LWA. It is very clear that the measurement and simulation are in good agreement with each other. Specifically speaking, the measured return loss $|S_{11}|$ is better than 10 dB within the operating frequency range of 8.9 GHz–11.8 GHz. However, the measured return loss in the right/left-handed regions is better than that at transition frequency point, indicating that the radiation efficiency at transition frequency point is less than that in right/left-handed regions. Besides, there are some discrepancies between the simulated and measured insertion loss $|S_{21}|$, which are mainly due to the fabrication and material tolerances and probably the loss from the SMA connectors. The measured insertion loss is almost below -5 dB over the operating frequency band, which means very good leakage radiation. Moreover, both the return and insertion losses exhibit sharp transitions at the band edges, indicating that the LWA has good filtering functionality.

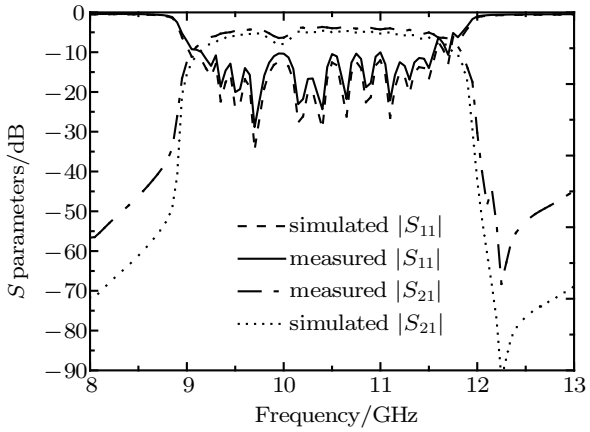


Fig. 4. The measured and simulated S parameters of the designed periodic LWA.

The measured and simulated normalized radiation patterns of backward radiation (8.9 GHz/9.5 GHz, left-handed region), and forward radiation (11.0 GHz/11.8 GHz, right-handed region) are plotted in Figs. 5(a) and 5(b), respectively. It is very obvious that the measurement and simulation are in good agreement.

As shown in Fig. 5, the measured main beam scanning angles of the designed periodic LWA at 8.9 GHz/9.5 GHz and 11.0 GHz/11.8 GHz are respectively $-43°/-9°$ and $+16°/+32°$, which means that the designed periodic LWA achieves a continuous beam scanning property from backward $-43°$ to forward $+32°$ over the operating frequency range from 8.9 GHz to 11.8 GHz.

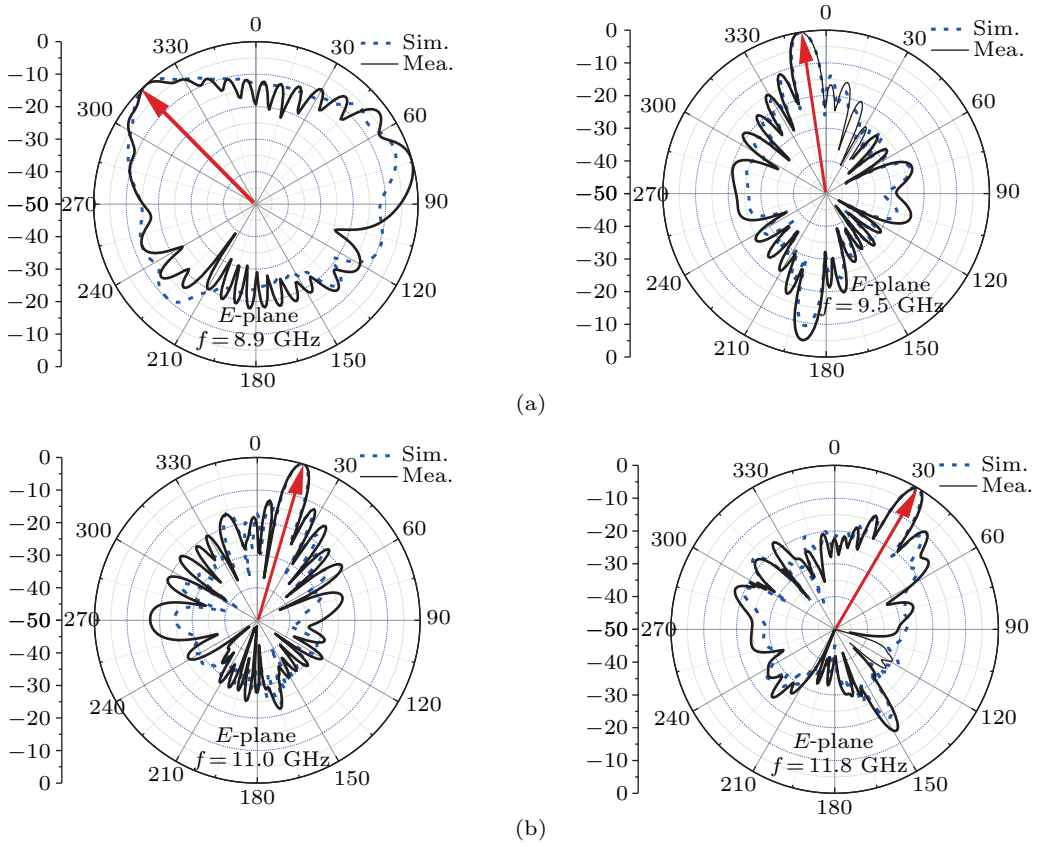


Fig. 5. (color online) Simulated and measured normalized radiation patterns of the designed periodic LWA, showing (a) backward radiation (8.9 GHz and 9.5 GHz) and (b) forward radiation (11.0 GHz and 11.8 GHz).

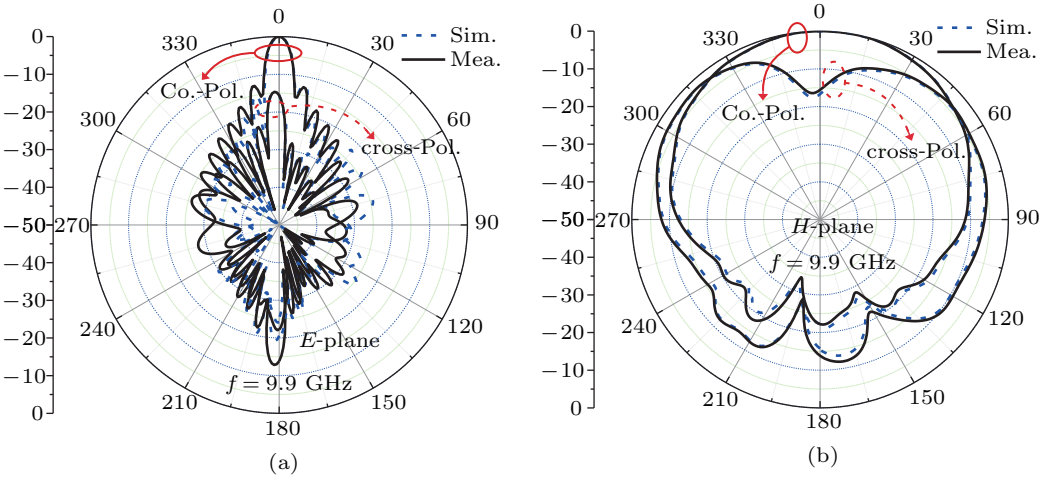


Fig. 6. (color online) Simulated and measured normalized radiation patterns at broadside radiation (9.9 GHz) in (a) *E* plane and (b) *H* plane.

The measured and simulated normalized radiation patterns of broadside radiation at 9.9 GHz are shown in Fig. 6. It can be seen that the main beam scanning angle is 0°, indicating broadside radiation. The measured cross-polarization level is low, and kept at a level of 15 dB below the measured co-polarization at broadside radiation.

The measured and simulated beam scanning angles of the designed periodic LWA are shown in Fig. 7(a), it can be seen that the designed antenna provides a continuous beam scanning angle ranging from backward −43° to forward +32° within the operating frequency band of 8.9 GHz–11.8 GHz, which has been indicated in Fig. 5. The measured and simulated 3-dB beamwidth of the designed periodic LWA are also given in Fig. 7(a), and it is very obvious that the measured 3-dB beamwidth is kept at a consistent level of around 6.5° over the frequency band of 9.4 GHz–11.8 GHz. Figure 7(b) gives the measured and simulated gains as well as the radiation efficiency of the designed periodic LWA. The measured and simulated gains agree well, but there is a discrepancy around 1.0 dB between them. The measured gain is better than 10 dB

over the operating frequency range from 8.9 GHz to 11.8 GHz, and the maximum gain is 14.0 dB at 11.1 GHz. However, the antenna gain around the transition point is lower than that in the right/left-handed regions, which is mainly due to the fact that the matching of the Bloch impedance to 50 Ω at transition point is worse than that in the right/left-handed regions. The measured and simulated radiation efficiencies are in good agreement with each other. However, the radiation efficiency around transition point is less than that in right/left-handed regions, verifying the antenna gain property effectively.

The comparisons between the designed QMSIW metamaterial based LWA and the full-mode SIW, HMSIW, and QMSIW based ones reported in recent references are given in Table 1.

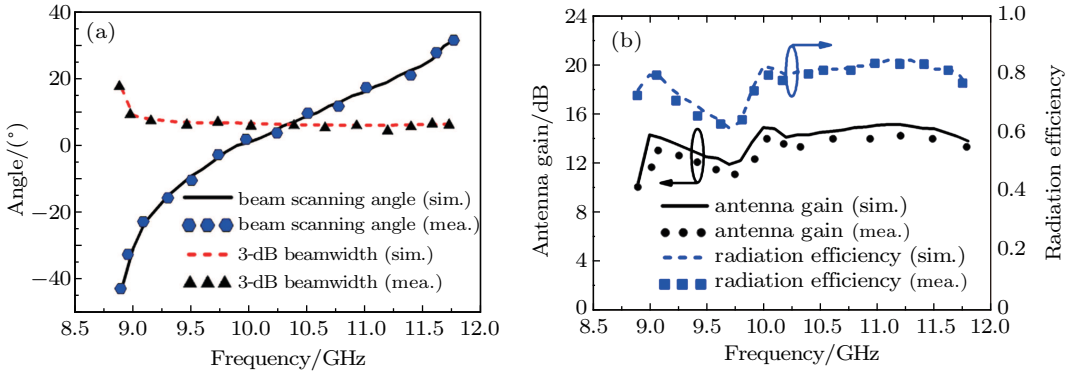


Fig. 7. (color online) Measured and simulated results of the designed LWA, showing (a) measured and simulated beam scanning angle (3-dB beamwidth), and (b) antenna gain and radiation efficiency.

Table 1. Comparison of LWA between this work and the references.

Ref.	Antenna type	Frequency band/GHz	Unit cell size	Beam scanning range	Beamwidth	Peak gain/dB
[15]	SIW	8.6–12.8	full-mode	−70°–+60°	not given	10.80
[16]	QMSIW	12.5–15.4	quarter-mode	0°–+28°	5.5°	13.17
[18]	HMSIW	7.4–13.5	half-mode	−70°–+70°	not given	12.01
[19]	SIW	8.0–13.0	full-mode	−66°–+78°	not given	12.80
[20]	SIW	8.25–13.0	full-mode	−60°–+66°	10.0°	14.80
[21]	SIW	8.0–13.0	full-mode	−72°–+75°	11.5°	12.60
This work	QMSIW	8.9–11.8	quarter-mode	−43°–+32°	6.5°	14.0

As shown in Table 1, it is very obvious that compared with the proposed conventional QMSIW structure based LWA in Ref. [16], the designed QMSIW metamaterial based LWA expands the range of main beam scanning angle, and the backward and broadside radiation are both obtained. The designed LWA in this paper achieves a continuous main beam scanning angle ranging from backward −43° to forward +32° within the operating frequency band. However, compared with the performances of full-mode SIW and HMSIW based periodic LWA, the performances of the designed QMSIW based one need to be improved.

4. Conclusions

In this work, a quarter-mode substrate integrated waveguide (QMSIW)-based metamaterial structure is investigated and used to design a periodic LWA for the continuous beam scanning from backward to forward directions with consistent gain for the first time. The measured and simulated results of the designed LWA are in good agreement with each other, indicating that a continuous beam scanning angle of 75° from backward to forward directions with consistent gain of more than 10 dB over the operating frequency band of 8.9 GHz–11.8 GHz is obtained. This work provides an interesting and wonderful methodof designing a beam scanning LWA, and further expands the applications of the QMSIW.

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