Progress In Electromagnetics Research Letters, Vol. 39, 1–8, 2013

CONICAL BEAM WINDMILL-SHAPED ARRAY ANTENNA DESIGN BASED ON QUARTER-MODE SUBSTRATE INTEGRATED WAVEGUIDE

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Abstract—This paper presents a compact conical beam antenna based on quarter-mode substrate integrated waveguide (QMSIW). The antenna array is consisted of six isosceles right-angled triangle metallic patch printed on the upper side of the substrate in a windmill-shape and diagonal periodic metallic via holes drilled along the hypotenuse of the triangle patch. The planer structure exhibits conical beam radiation. The typical radiation is obtained at 5.2 GHz with conical beam radiation pattern. The measured gain is about 5.36 dBi and the radiation efficiency is around 50%.

1. INTRODUCTION

Conical beam antennas are becoming an interesting and promising topic of research because of the explosive growth of wireless communications. The square-ring patch [1] and circular-ring patch [2] are the two excellent designs that are suitable for ultra-wideband or dual-band operations. Another kind of conical beam antennas are implemented using array configurations. An array of microstrip patch radiators arranged in a ring formation produce a conical radiation beam for a wireless local area network (WLAN) application around 5.2 GHz [3].

Substrate integrated waveguide (SIW) have been studied extensively in recent times [4–7]. SIW takes advantage of the well-known characteristics of conventional rectangular waveguides, such as high Q-factor and high power density. Several kinds of antennas [8, 12, 13] and filters [9, 14] based on SIW have been realized.

Received 25 February 2013, Accepted 27 March 2013, Scheduled 29 March 2013

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After bisecting the SIW twice along the central symmetrical fictitious magnetic wall, a new structure named as quarter-mode substrate integrated waveguide (QMSIW) is realized. Radiation occurs in the discontinuity between the lateral edge and the extended dielectric-filled ground plane [10]. This structure gives an attractive and promising way to design antennas.

This letter describes a very simple and elegant antenna based on the QMSIW at first. Full wave simulation and experiments have been done. And then, an QMSIW array arranged in windmill-shaped are designed to realize a planer antenna with conical radiation beam. The reflection coefficient and radiation characteristics are measured. The measured performance is compared with the simulated results obtained by the full-wave simulation tool, and they agree with each other well.

2. QMSIW ANTENNA

The SIW as shown in Figure 1(a) can be bisected along the central symmetrical fictitious magnetic wall and becomes an HMSIW afterwards as shown in Figure 1(b) [11]. The electric field distributions (xy-plane) in z-direction of the square SIW and the HMSIW are shown

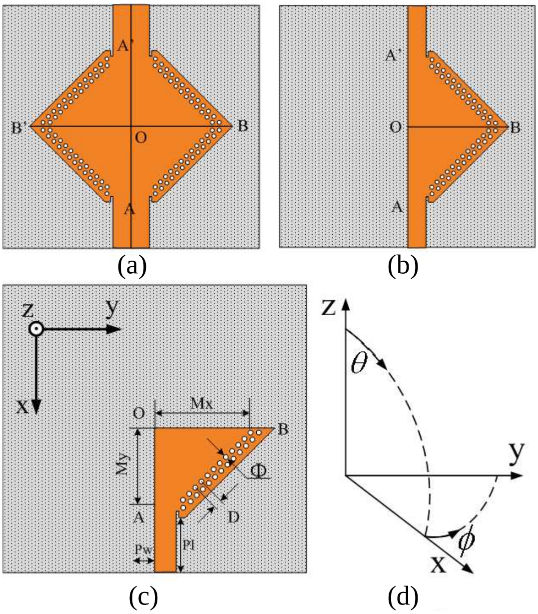

Figure 1. The evolution of the proposed QMSIW. (a) Square SIW. (b) HMSIW. (c) QMSIW. (d) Coordinate system.

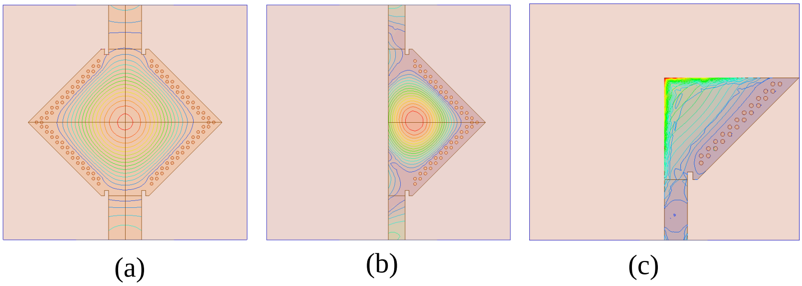

Figure 2. Electric field distribution (xy-plane) of the proposed structures in z-direction. (a) Square SIW. (b) HMSIW. (c) QMSIW.

in Figure 2. It can be observed that the electric field distribution of the HMSIW is almost the same as the one of the original square SIW.

Another symmetrical plane exists along the center of the HMSIW, which can also be equivalently regarded as a fictitious magnetic wall. The HMSIW is further bisected into two parts again along the symmetrical plane and after that a QMSIW can be obtained. Figure 1 shows the process of the evolution of the proposed QMSIW. The electric field distribution of the QMSIW is simulated by Ansofts High Frequency Structure Simulator (HFSS) as shown in Figure 2(c). The result shows that the QMSIW almost preserves the electric field distribution of quarter sector of the original square SIW and half sector of the corresponding HMSIW.

When the feeding port is placed at corner A along x-direction, the maximum electric field is generated at point O for the proposed QMSIW as shown in Figure 2(c). One radiation mode is obtained, which is actually quarter-wavelength mode. Hence, the proposed QMSIW structure can be used to design linear polarization antennas. This antenna has many advantages, such as compact structure, simple matching network, planar configuration and convenient integration with the planar circuit systems.

Figure 3 shows the prototype of the designed QMSIW antenna. The antenna is fabricated on Rogers RT/Duroid 5880 substrate with relative dielectric constant $\epsilon_r = 2.2$, loss tangent $\tan\delta = 0.0011$ and thickness of 1.57 mm. The FEM-based 3-D full-wave EM solver, Ansoft HFSS, is used for optimizing the antenna dimensions. An isosceles right-angled triangle metallic patch with the two equal sides of $M_x = M_y = 16\,\text{mm}$ is printed on the upper side of the substrate. Diagonal periodic metallic via holes with diameter $\Phi = 0.6\,\text{mm}$ are drilled along the hypotenuse of the triangle patch, each neighbor two of which follow a separated distance $D = 1.5\,\text{mm}$. The antenna is excited by an inset-feed located at corner A as indicated in Figure 1(c).

The simulated and measured reflection coefficients of the QMSIW antenna are shown in Figure 4. This measurement was conducted with an Agilent N5230A PNA-L Network Analyzer. A satisfactory reflection coefficient below −10 dB is achieved at 5.2 GHz for the IEEE 802.11a band for WLAN applications while the highest return loss is almost up to 20 dB. The measured results are deviated slightly from the simulated results, because of the effect of the tolerance in manufacturing and the SMA-connector losses in the measurement.

The simulated and measured far-field radiation patterns in the E-plane are shown in Figure 5. The E-plane of the proposed

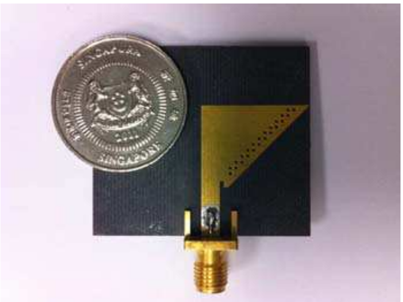

Figure 3. The prototype of the fabricated QMSIW antenna on RT/Duroid 5880 substrate with thickness of $h = 1.57$ mm.

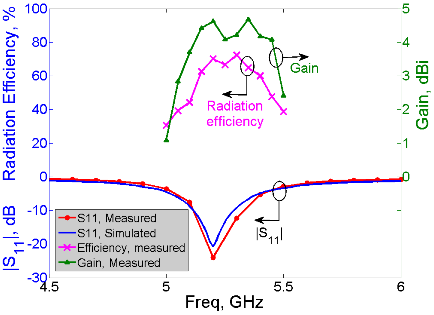

Figure 4. Measured and simulated reflection coefficient, radiation efficiency and gain of the QMSIW antenna.

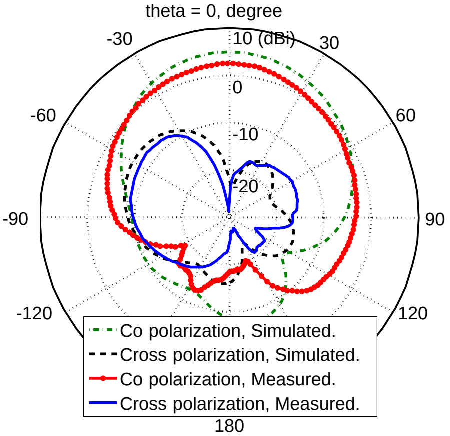

Figure 5. Measured and simulated radiation patterns of the fabricated QMSIW antenna.

QMSIW antenna is in $\phi = 45^\circ$ cut plane, where ϕ is defined as shown in Figure 1(d). The red and black curves show the co-polarization radiation patterns and the blue and green curves illustrate the cross-polarization radiation patterns. The frequency dependence of measured gain and radiation efficiency are shown in Figure 4. The measured gain is about 4.2 dBi and the measured radiation efficiency is around 70% in the radiation range.

3. CONICAL BEAM QMSIW ANTENNA ARRAY

The size of the antenna based on the QMSIW gives an attractive way to design QMSIW array, which will contribute a compact conical beam antenna with the help of a suitable matching network. Thus, compact conical beam antennas with high gain and high radiation efficiency can be designed based on the proposed QMSIW array.

The single array element can provide only broadside direction; therefore, to allow conical beam pattern for all the polarization senses, six unit cells arranged in a windmill-shaped are integrated to form a null in the broadside direction as the prototype shown Figure 6. A simple network is employed to integrate six of the single array elements as an antenna array. The design of this network was completed by performing simulation, calculation, and a trial-and-error method. An SMA coaxial cable connector is used to feed the antenna array. To achieve a 50 Ω impedance match between the SMA connector and the six coupling microstrip line, the six feed lines of the network is devised as high impedance microstrip lines in parallel.

Figure 7 shows the electric field distribution in z-direction maps

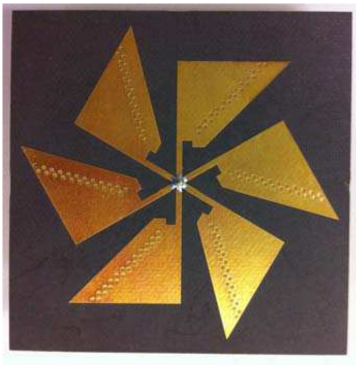

Figure 6. The configuration of the conical beam windmill-shaped QMSIW antenna.

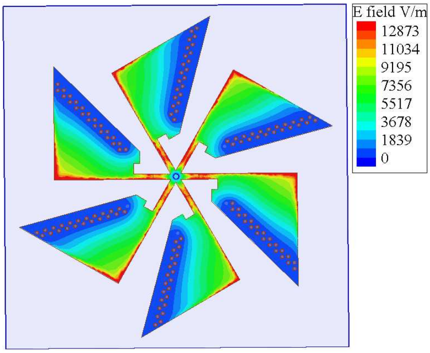

Figure 7. The electric field distribution of the conical beam windmillshaped QMSIW antenna.

at the resonant frequency. The resonant phenomena of the QMSIW cavity at the typical frequency can be clearly viewed from the electric field distribution.

Figure 8 shows the simulated and measured return loss results of the designed conical beam windmill-shaped antenna. It can be seen from Figure 8 that they are in excellent agreement. The measured center frequency is located at 5.22 GHz, which is very close to the designed center frequency of 5.2 GHz. It should be mentioned that simulated results are also obtained using Ansoft HFSS, and the measurement is conducted with an Agilent N5230A PNA-L Network Analyzer. A satisfactory reflection coefficient below −10 dB is achieved at 5.2 GHz while the highest return loss is almost up to 15 dB. The measured results are deviated slightly from the simulated results, because of the effect of the tolerance in manufacturing and the SMA-connector losses in the measurement.

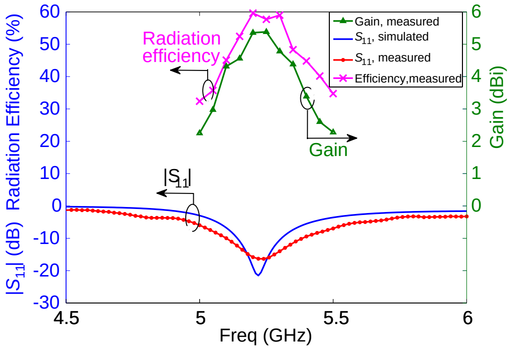

Figure 8. Measured and simulated reflection coefficient, radiation efficiency and gain of the proposed the conical beam windmill-shaped QMSIW antenna.

Next, the radiation characteristics of the antenna are studied. Figure 9 shows the simulated 3D far-field radiation pattern at 5.2 GHz. It is seen that the windmill-shaped antenna array based on the QMSIW has a very good conical radiation beam. Figure 10 shows the simulated and measured radiation pattern results of the fabricated antenna at the center frequency of 5.2 GHz. It is shown that the measured maximum radiation angle pointing toward the direction of $\theta = +13^\circ$ and $\theta = -22^\circ$, while the simulated result is $\theta = \pm 19^\circ$. The measured radiation efficiency is around 50% in the radiation range. It should also be pointed out that the simulated gain of the designed antenna is 6.12 dBi, while the measured value is 5.36 dBi.

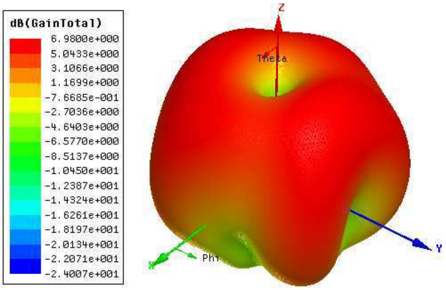

Figure 9. The simulated 3D far-field radiation pattern at 5.2 GHz for the conical beam windmill-shaped QMSIW antenna.

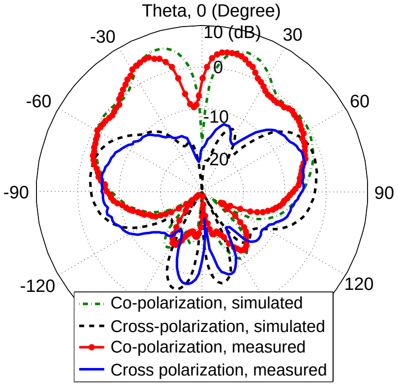

Figure 10. Measured and simulated radiation patterns of the conical beam windmill-shaped QMSIW antenna.

4. CONCLUSION

A compact conical beam antenna has been proposed based on the QMSIW array, which is consisted of six isosceles right-angled triangle metallic patch printed on the upper side of the substrate in a windmill-shape and diagonal periodic metallic via holes drilled along the hypotenuse of the triangle patch. The reflection coefficient and radiation characteristics are measured. The typical conical beam wave radiation is obtained at 5.2 GHz with the measured gain of 5.36 dBi and the radiation efficiency of 50%.

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