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BROADBAND APERTURE-COUPLED MICROSTRIP ANTENNAS WITH LOW CROSS POLARIZATION AND BACK RADIATION

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Abstract—The paper presents the performances of microstrip patch antennas excited by the aperture-coupling feed that is composed of a T-shaped microstrip feed line and an annular-ring slot. Because the annular-ring slot is designed at a full-wavelength resonant mode, a broad impedance bandwidth can be obtained by combing the resonant modes of the coupling slot and radiating patch; moreover, a low cross polarization is also observed, especially around the direction with maximum gain. For reducing the considerable back radiation induced by the resonant coupling aperture, additional slots are introduced and embedded along the perimeter of the annular-ring slot. Experimental results show that the reformed coupling slot can improve the front-to-back ratio of the aperture-coupled microstrip antenna by more than 5 dB. Simulation analyses are also performed to support the measured results.

1. INTRODUCTION

Microstrip radiating elements are a category of resonant antennas, and they can support many resonant modes. When the microstrip resonant antenna is designed at the fundamental mode, it has a minimum patch size, but the obtained impedance bandwidth is often not enough to cover the operating frequencies of present wireless communication systems. Various methods to enhance the microstrip antenna bandwidth have been proposed [1–5]. One of the methods to improve the impedance bandwidth is using a thick substrate with low permittivity. However, some unwanted higher-order modes of the microstrip antenna will be emerged with increasing substrate thickness [6], and their transverse current distributions on the radiating patch may result in polarization impurity. Moreover, if the microstrip antenna with a thick substrate is fed by a direct coaxial probe, the current distributions near the feed point on the radiating patch will be distorted [7]. The distorted current distributions as well as probe itself radiations will lead to an asymmetric pattern in E-plane and an obvious cross polarization (XP) in H-plane. Therefore, the XP for a broadband probe-fed microstrip antenna mainly stems from the higher-order modes and feeding probe. Recently, several technologies for suppressing the radiation sources of the XP have been proposed [7–14]. From the obtained results, it is found that the probe radiation can be considerably reduced by a meandering probe [8–10], and the unwanted higher-order modes and distorted current distributions can be effectively suppressed by employing a dual-feed system with a 180° phase shift [11–13]. In addition, a balance-like feeding mechanism described in [14], which is single-feed, has the similar characteristics to the dual-feed system, but it does not need any phase-delay circuit.

To avoid the degradation of the radiation performance induced by the feeding probe, an alternative method uses an aperture-coupling feed to excite the microstrip antenna. For conventional aperture-coupled microstrip antennas, a thin linear slot is often used as a coupling aperture. As the substrate thickness of the antenna is increased, the length of the thin slot has to be enlarged to achieve impedance matching, and the impedance bandwidth can be significantly enhanced while the coupling-slot size is close to its resonant length [15]. The dual-feed system using aperture coupling also has been applied to the microstrip antenna with a thick substrate in order to symmetrically excite the radiating patch and suppress the higher-order modes [16]. However, considerable back radiations will be produced by the slots, especially when the slot is near resonant. The problem can be improved by loading additional slots at the ends of the thin slot, and some types of the reformed slots have been reported, such as H-shaped slots [17] and dog-bone slots [18].

In this paper, a novel aperture-coupling feed applied to the microstrip antenna is proposed and studied to reduce cross-polarization levels (XPL) and improve front-to-back ratios. The proposed feed mechanism consists of an annular-ring coupling slot and a T-shaped feed line. The coupling slot is designed at a full-wavelength resonant mode and thus a broadband impedance bandwidth can be achieved; besides, the single resonant annular-ring slot can be regarded as a dual-slot feed system with a 180° phase shift because the electric-field distribution along the perimeter of the annular-ring slot has the variation of one wavelength, which makes the antenna have low XP radiation. To solve the problem of the back radiation, we introduce several H-shaped slots as the loading of the annular-ring slot to enhance its coupling strength. Details of the antenna designs and experimental results are presented and discussed.

2. ANTENNA STRUCTURE AND BASIC CHARACTERISTICS

Figure 1 presents the configuration of the proposed aperture-coupled microstrip antenna. The circular patch of radius R is etched on a FR4 substrate of thickness 1.6 mm and relative permittivity 4.4. The aperture-coupling feed is composed of a T-shaped microstrip feed line and a full-wavelength annular-ring slot, and they are respectively fabricated on the two faces of another FR4 substrate with the same thickness and permittivity. A foam material of thickness h is inserted between the two FR4 substrates. The mean radius of the annular-ring slot centered below the circular patch is r and the slot width studied here is fixed to be 1 mm. The microstrip feed line comprises a T-shaped coupling strip and a microstrip-line impedance transformer with the dimensions of l and w. Two open ends of the T-shaped coupling strip are protruded from the underneath of the annular-ring slot and the protruded length is l_s.

To demonstrate the low XP characteristic of the proposed microstrip antenna, an example antenna (Antenna A) operated at 2400 MHz was constructed. The dimensions of Antenna A are $R = 20\,\text{mm}$, $h = 10\,\text{mm}$, $r = 14.5\,\text{mm}$, $l_s = 1$ mm, $l = 20\,\text{mm}$, and $w = 0.3\,\text{mm}$. Fig. 2 shows the variations of the XPL measured at z-axis (on-axis XPL, $E(\theta = 0°)_{\text{crosspol}} \big/ E(\theta = 0°)_{\text{copol}}$) against frequency, and it is clearly seen that the on-axis XPL of Antenna A occurs a peak value around 2440 MHz. The XP bandwidth (BW_{XP}), here defined as the on-axis XPL less than $-40\,\text{dB}$, is about 110 MHz. Note that the

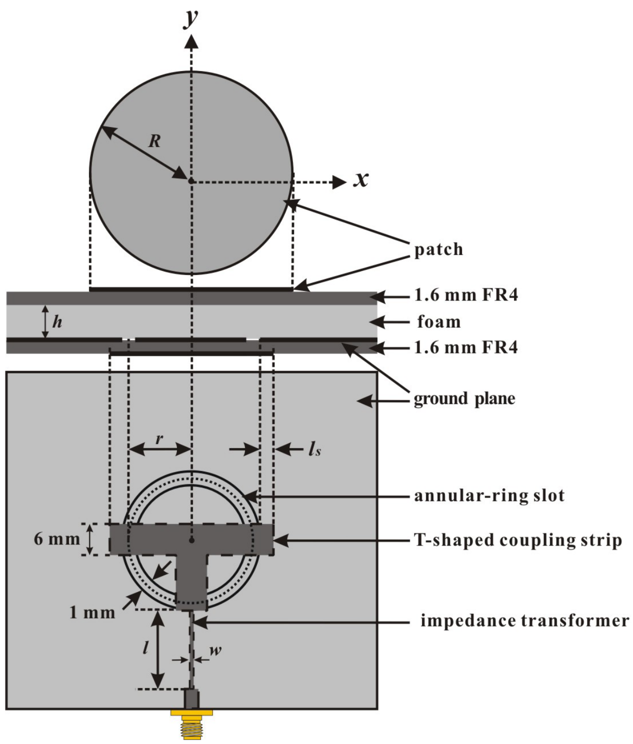

Figure 1. Geometry of the proposed ring-slot-coupled microstrip antenna.

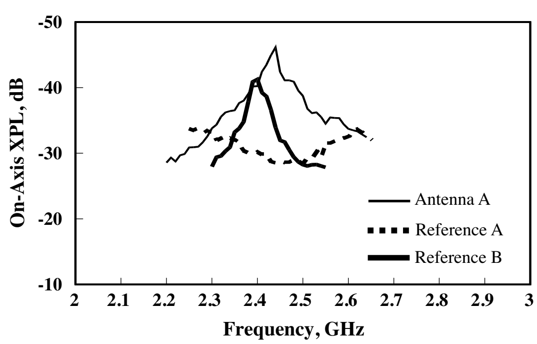

Figure 2. Measured on-axis XPL against frequency for Antenna A, Reference A, and Reference B.

very low on-axis XPL can bring good polarization purity in the main beam. By observing the simulated electric-field distributions inside the annular-ring slot at 2440 MHz, it is found that the distribution along the circumference of the annular-ring slot has the variation of one wavelength, and its maximums and nulls are just located on y- and x-axes, respectively. As a result, the annular-ring slot is resonant at the fundamental mode and its resonant frequency can be referred to the frequency where the on-axis XPL has a minimum value.

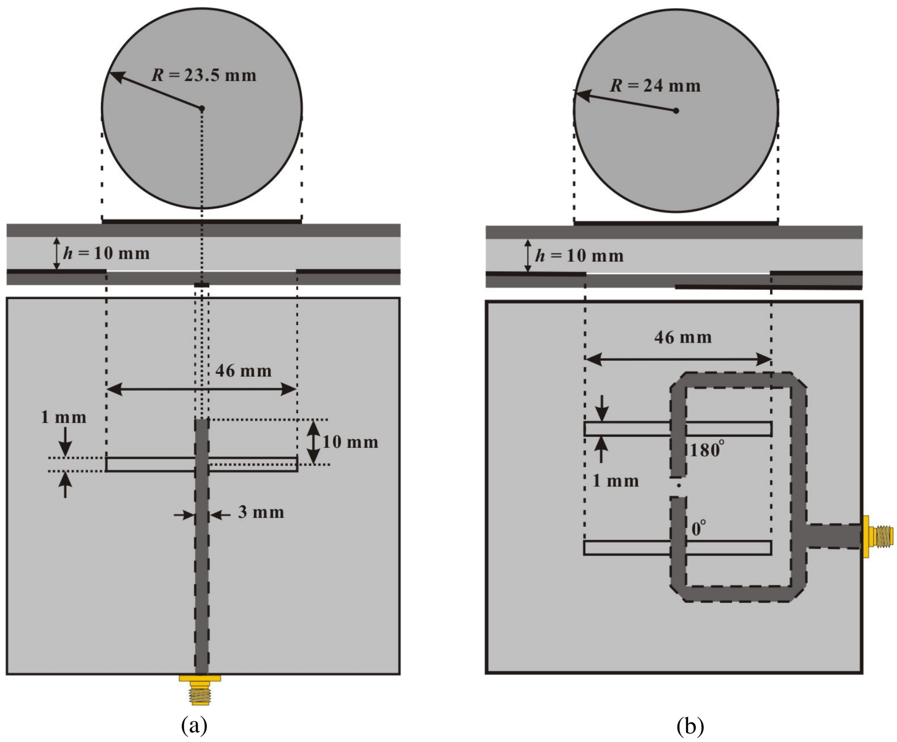

Figure 3. Geometries of two conventional aperture-coupled microstrip antennas. (a) Using a single thin slot, (b) using dual thin slots with a 180° phase shift.

For comparisons, we also implemented another two conventional aperture-coupled microstrip antennas operating at 2400 MHz. The two antennas, shown in Fig. 3, have the same geometry as Antenna A except that they respectively employ a single thin slot (Reference A) and dual thin slots with a 180° phase shift (Reference B) as the coupling apertures. For a thin open slot, the resonant length is about $0.5\lambda_e$ (λ_e is the guided wavelength in the slot), and thus the lengths of all the coupling slots in Fig. 3 are chosen to be the half of the mean circumference of the annular-ring slot of Antenna A. Fig. 2 also presents the measured on-axis XPL for Reference A and B. It is observed that only Reference B has a peak value in the variations of the on-axis XPL and the peak value appears around 2400 MHz. The result suggests that the complicated dual-slot feed system with phase differences has the same function as the single resonant annular-ring slot in reducing XP radiation. In fact, the annular-ring slot of Antenna A can be divided into the upper semi-ring and the lower semi-ring, and the electric-field distributions in the two semi-rings have the same amplitude but 180° out of phase, which are identical with those of the dual-slot feed system. While Antenna A is excited through such a resonant annular-ring slot, the induced transverse currents on the circular patch are symmetrical and their radiations are nearly cancelled at the broadside direction.

Although the one-wavelength annular-ring coupling slot has the ability to suppress the unwanted higher-order modes of the circular microstrip antenna, a considerable back radiation will be produced by the resonant slot, and the thicker the foam material, the more the back radiation. The radiation patterns of Antenna A and Reference B measured at 2400 MHz are plotted in Fig. 4. It is found that Antenna A has larger back radiations and its front-to-back ratio is about 7.5 dB, which is 3.5 dB lower than that of Reference B.

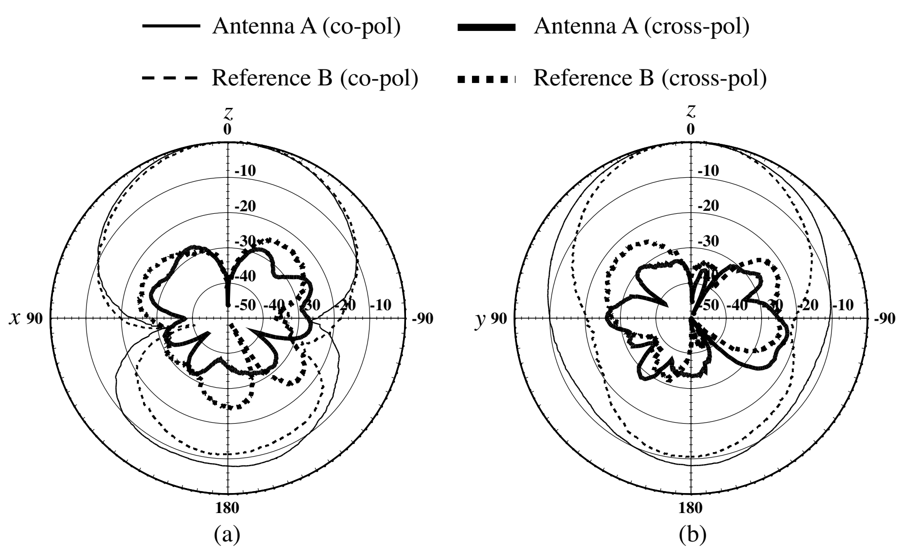

Figure 4. Measured radiation patterns at 2400 MHz for Antenna A and Reference B. (a) x-z plane, (b) y-z plane.

3. ANTENNA DESIGN WITH AN IMPROVED FRONT-TO-BACK RATIO

To effectively reduce the back radiation of Antenna A, a possible method introduces additional loading slots into the annular-ring slot, as shown in Fig. 5. The reformed coupling aperture includes six H-shaped loading slots which are symmetrically placed along the circumference of the annular-ring slot. Because the adding of the loading slots can enhance the coupling strength between the feed line and radiating patch, the reformed coupling aperture has a smaller annular-ring size than the case without the loading slots. An antenna prototype (Antenna B) using the reformed coupling aperture was constructed according the dimensions shown in Fig. 5. It is worth mentioning that the radius of the annular-ring slot of Antenna B is reduced by 35% compared to that of Antenna A. The measured performances of Antenna B are exhibited in Figs. 6–10, and the simulation analyses by HFSS are also performed to support the

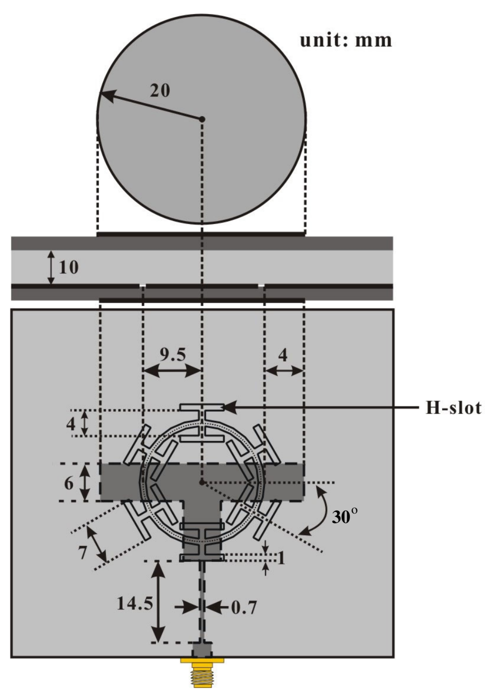

Figure 5. Geometry of the ring-slot-coupled microstrip antenna with six H-shaped loading slots.

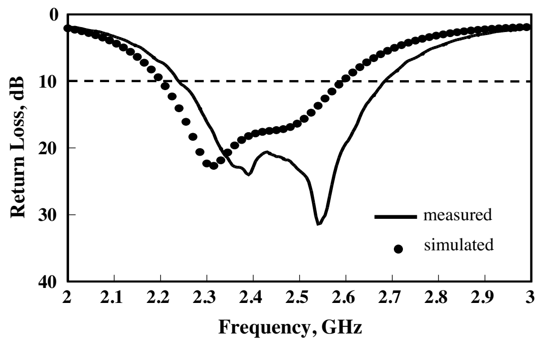

Figure 6. Return loss results against frequency for Antenna B.

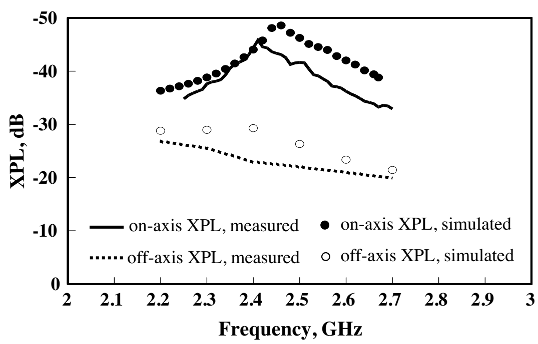

Figure 7. XPL results against frequency for Antenna B.

experimental results. From the measured return loss in Fig. 6, the BW_{RL} of Antenna B, impedance bandwidth determined by 10 dB return loss, is about 18% (440 MHz) with respect to the center frequency 2450 MHz. The variations of the on-axis and off-axis XPL ($E(\theta)_{\text{crosspol,max}}/E(\theta)_{\text{copol,max}}$, $0^\circ < \theta < 180^\circ$) against frequency are demonstrated in Fig. 7. Results indicate that the on-axis XPL still has a peak value (-46 dB) at 2410 MHz and the measured BW_{XP} is about 170 MHz. In addition, the off-axis XPL is less than -20 dB within the BW_{RL} and -23 dB within the BW_{XP}. The frequency response of the front-to-back ratio of Antenna B is shown in Fig. 8, and the ratio at 2400 MHz is about 13 dB which is 5.5 dB higher than that of Antenna A. Fig. 9 presents the gain variation, and the average gains within the BW_{RL} and BW_{XP} are about 7 and 7.5 dBi, respectively. The radiation patterns across the whole operating frequencies are stable, and the typical results measured at 2410 MHz are plotted in Fig. 10. Symmetrical broadside radiation patterns with low XP are observed.

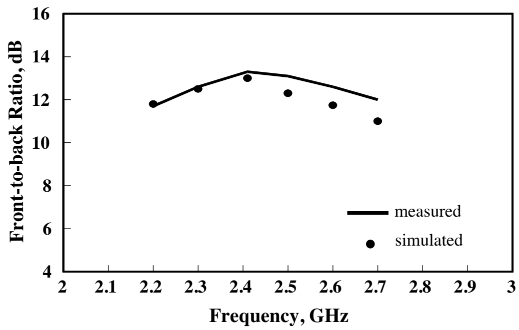

Figure 8. Front-to-back ratio results against frequency for Antenna B.

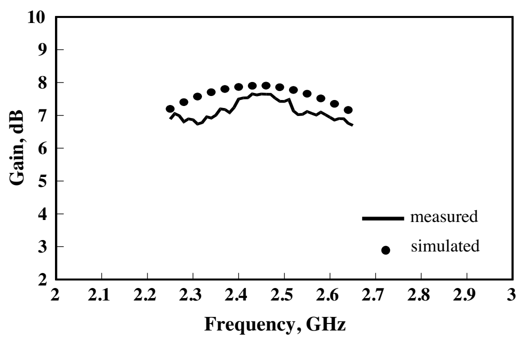

Figure 9. Gain variation results against frequency for Antenna B.

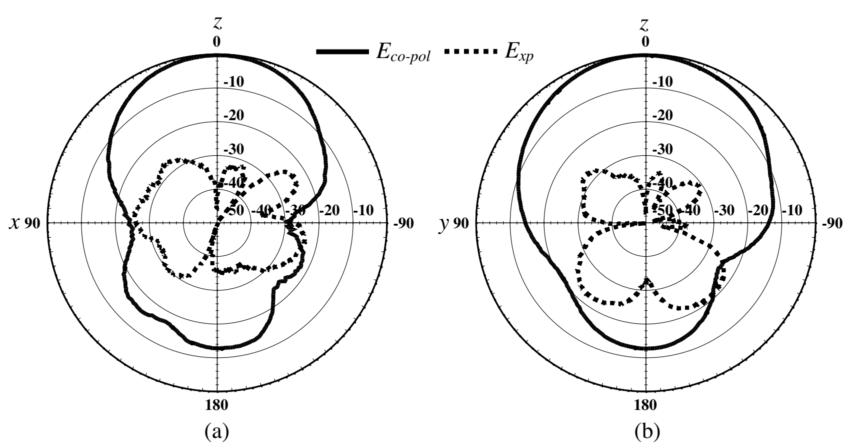

Figure 10. Measured radiation patterns at 2410 MHz for Antenna B. (a) x-z plane, (b) y-z plane.

4. CONCLUSIONS

An aperture-coupled microstrip antenna that can suppress higher-order resonant modes is proposed and studied in this paper. The proposed antenna is excited by a T-shaped feed line through the coupling of a resonant annular-ring slot in the ground plane. Because the distribution of the electric field along the perimeter of the coupling slot has the variation of one wavelength, the single annular-ring slot can be considered as a dual-slot feed system with a 180° phase shift. As a result, the aperture-coupled antenna has low XP radiation, especially at the broadside direction. In addition, the problem of the back radiations induced by the resonant coupling slot is solved by loading several H-shaped slots along the perimeter of the annular-ring coupling slot. An antenna prototype with low XP and high front-to-back ratio is constructed and tested. Measured results show that the prototype has an impedance bandwidth of 18% for return loss less than 10 dB and a XP bandwidth of 7% for on-axis XPL less than −40 dB. Moreover, the off-axis XPL of less than −23 dB, the average gain of more than 7.5 dBi, and the front-to-back ratio of larger than 12 dB are also achieved within the XP bandwidth. These characteristics make the proposed antenna suitable as an element of dual linearly-polarized antenna arrays.

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