A Circularly Polarized Short Backfire Antenna Excited by an Unbalance-Fed Cross Aperture

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***Abstract*—An unbalance-fed cross aperture is developed to excite a short backfire antenna (SBA) for circular polarization. The cross aperture consists of two orthogonal H-shaped slots with a pair of capacitive stubs and is fed by a single probe that forms an unbalanced feed with a shorting pin. It is demonstrated that the cross-aperture-excited SBA can achieve an axial ratio ($\leqslant$3 dB) bandwidth of 4.2% with a voltage standing wave ratio (VSWR) bandwidth of 6.5% ($\mathrm{VSWR} < 1.2$) and a gain of 14 dBi. The antenna structure is described and the simulation and experimental results are presented. The mechanisms for impedance matching and circular-polarization production are analyzed.**

***Index Terms*—Circularly polarized antenna, short backfire antenna (SBA), slot-fed antenna.**

I. Introduction

THE short backfire antenna (SBA) has been widely used in mobile/maritime satellite communications, tracking, telemetry, and wireless applications due to its high gain, low sidelobe level, and simple configuration [1]–[3]. For satellite communications, it is desirable to employ a circularly polarized antenna to avoid the power loss caused by Faraday polarization rotation. To achieve circular polarization, the most popular excitation structure for the SBA is a cross dipole that consists of two orthogonal dipoles. Usually the cross dipole needs an external polarizer such as a 90° hybrid coupler for circular polarization [4]. Even though the cross dipole can also produce circular polarization without the external hybrid component by the self-phasing, a balun circuit is still required for the cross dipole [5]. The cross-dipole-excited SBA also has a narrow frequency bandwidth for its input impedance because the SBA is essentially a leaky cavity structure. A nature impedance match bandwidth is only 3–5% for a 1.5:1 voltage standing wave ratio (VSWR) [6].

Another well known excitation topology for circular polarization is the cross aperture which consists of two orthogonal rectangular slots and has been widely used to excite microstrip antennas [7]–[10]. The circular polarization is generated by building two rectangular slots with slightly different lengths so that the radiation from one slot is 90° out of phase with the other. When the radiated fields from two orthogonal slots combine in the far zone with 90° phase difference, they produce circular polarization at broadside. The cross aperture is usually fed by a microstrip line [7]–[9] or by a single probe [10]. Unfortunately, neither the microstrip-line feed nor the single-probe feed could be directly applied to the SBA because the excitation structure for a SBA must be placed approximately a quarter-wavelength above the primary reflector (or the ground plane) to excite the leaky waves needed for the backfire radiation. Obviously the microstrip feed is not suitable for this situation. If a single-probe feed is adopted, it would cause a significant inductive component in the input impedance due to the parasitic inductance from the long feed probe (about a quarter-wavelength), thus leading to a difficulty in impedance matching. Furthermore, a feed probe of one quarter-wavelength itself acts as a resonant monopole antenna which could radiate a strong cross-polarized component, considerably degrading the radiation performance of the SBA.

Before a cross aperture could be employed to excite the SBA, there is an additional difficulty that needs to be overcome. To achieve circular polarization, one of the two orthogonal slots of the cross aperture has to be capacitive if the other is inductive. For a rectangular slot, its length must be longer than a half wavelength to make it capacitive [10]. As a result, the size of the patch on which the cross aperture is etched must be much larger than a half wavelength. Note that the diameter of the subreflector of an SBA is usually less than a half wavelength. Therefore the excitation structure would be much larger than the subreflector, thus blocking the reflection from the primary reflector and changing the desirable radiation performance of the SBA.

Recently, an unbalance-fed H-shaped slot has been developed for a linearly polarized SBA [11]. In this paper, an unbalance-fed cross aperture is proposed to excite the SBA for circular polarization. The unbalanced feed formed by a feed probe and a shorting pin serves as a two-wire transmission line and as an impedance matching circuit, thus alleviating the negative influence of a single feed on the radiation pattern and realizing an excellent impedance matching. The cross aperture consists of two orthogonal H-shaped slots with different lengths. (The H-shaped configuration can increase the effective length of a slot.) A pair of short stubs is introduced inside the longer H-shaped slot to make it more capacitive, allowing a further decrease in the size of the cross aperture. It will be shown that the H-shaped slots and the short stubs are necessary for the production of circular polarization. In the next section, the antenna structure is described. Then simulation and experimental results are presented. Finally the mechanisms for circular polarization and impedance matching are investigated.

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II. Antenna Structure

The configuration of the cross-aperture-excited circularly polarized SBA is illustrated in Fig. 1. The SBA contains a pair of circular reflectors (i.e., a primary reflector and a subreflector), a circular rim, and an excitation structure that consists of a cross aperture fed by a single probe with a shorting pin. The feed probe (extended from an SMA connector) and the shorting pin (connected to the primary reflector) forms an unbalanced feed which is located at the center of the SBA and is aligned along the diagonal of the cross aperture. The cross aperture consists of two orthogonal H-shaped slots (the longer one is called "Slot X" and the shorter one "Slot Y") etched on a circular patch (called "slotted patch") whose diameter is equal to that of the subreflector. The H-shaped slot is divided into two parts (i.e., a wider part and a narrower part) that play different roles. The purpose of the wider part is to increase the effective length (i.e., the perimeter) of each slot, hence making the slot close to resonance. The longer the effective length, the closer to resonance is the slot; but the maximum width of the wider part is constrained by the size of the slotted patch. The reason for introducing a narrower part in the slots is to excite over the cross aperture a stronger electric-field distribution which is coupled to the reflectors of the SBA. (Simulation shows that the electric-field distribution over the cross aperture is concentrated along the narrower parts of two H-shaped slots.) The area of the narrower part controls how much power could be transferred from the feed probe to the aperture (i.e., the region between the rim and the subreflector) of the SBA, thus affecting the input impedance of the antenna. The length of each slot makes a notable impact on the phase of the radiation field associated with this slot, especially near a resonant point. In order to accomplish a phase difference (90° for perfect circular polarization) between the radiated fields from the two slots, we set Slot X to be 0.1 λ_0 longer than Slot Y. This length difference is not enough for a 90° phase difference. Therefore a pair of short $(<0.1\lambda_0)$ stubs connecting respectively to the feed probe and the shorting pin is added to the middle of Slot X. The pair of short stubs can be considered as a capacitor parallel to Slot X, making the slot more capacitive (or look further longer).

The SBA is designed using *Micro-Stripes 6.5*—a TLM (Transmission-Line Matrix) based full-wave electromagnetic simulator. A prototype is built at 5.8 GHz ISM band (5.7–5.9 GHz). The subreflector and the cross aperture are printed on a 0.508-mm (20 mils) RT/duroid 5880 substrate $(\varepsilon_r = 2.2)$ and the printed subreflector is supported by the rim. The optimal values of the geometric parameters of the cross-aperture-excited SBA are listed in Table I. The overall dimensions of the SBA are 0.54 λ_0 (λ_0 = the free-space wavelength at the design frequency 5.8 GHz) in height and $1.93\lambda_0$ in diameter, which are close to the typical values ($0.5\lambda_0$ in height and $2\lambda_0$ in diameter) for a conventional SBA. The diameter and height of the slotted patch are $0.46\lambda_0$ and $0.27\lambda_0$, respectively. The width of the wider part of the H-shaped slots is chosen to be 6 times the width of the narrower part that is optimized to be 1.0 mm. The total lengths of Slots X and Y are respectively 20 mm $(\sim 0.38\lambda_0)$ and 15 mm $(\sim 0.28\lambda_0)$, both of which are much shorter than a half wavelength. The length and the width of the capacitive stubs are adjusted to 2.5 mm and 0.3 mm. The diameter and the center-to-center distance of the feed probe and the shorting pine are 2 mm and $3\sqrt{2}$ mm, respectively. All these parameters were optimized

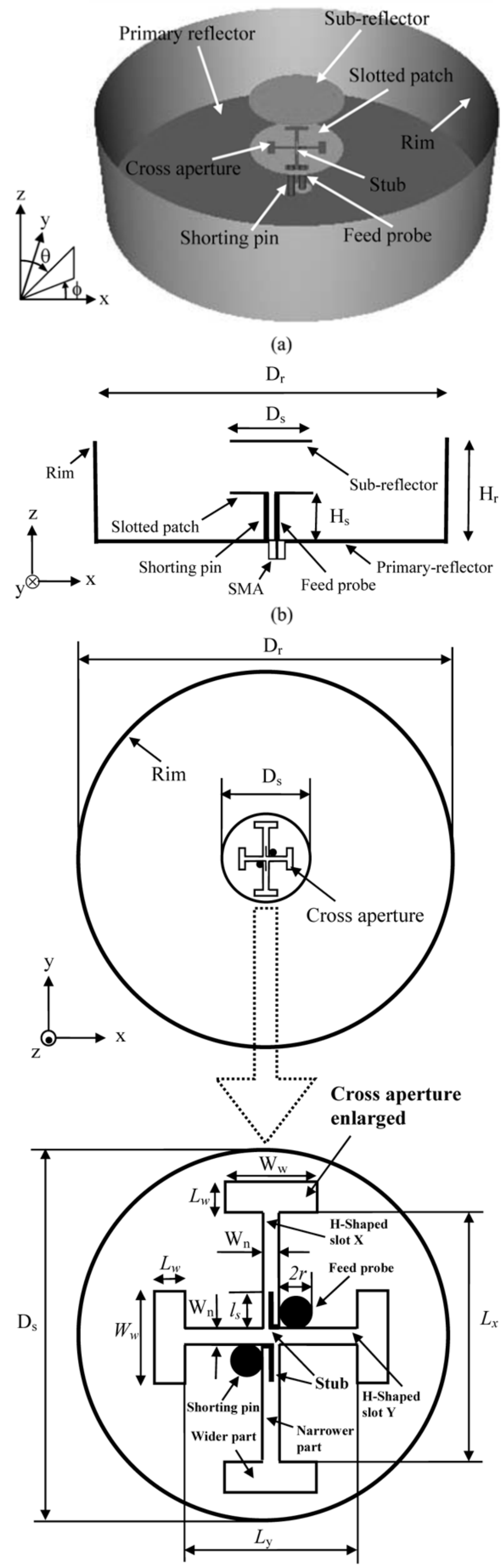

Fig. 1. A circularly polarized short backfire antenna excited by an unbalance-fed cross aperture. (The subreflector is printed on an RT/duroid substrate that is placed on the rim.) (a) Perspective view. (b) Side view. (c) Top view.

TABLE I
OPTIMIZED GEOMETRIC PARAMETERS FOR A CROSS-APERTURE-EXCITED CIRCULARLY POLARIZED SBA. (λ_0 = THE FREE-SPACE WAVELENGTH AT 5.8 GHz)

D_r	100 mm ($1.93\lambda_0$)	W_n	1.0 mm ($0.0193\lambda_0$)
H_r	28 mm ($0.54\lambda_0$)	W_w	6.0 mm ($0.116\lambda_0$)
D_s	24 mm ($0.46\lambda_0$)	L_w	2.0 mm ($0.0386\lambda_0$)
H_s	14 mm ($0.27\lambda_0$)	l_s	2.5 mm ($0.048\lambda_0$)
L_x	16 mm ($0.31\lambda_0$)	w_s	0.3 mm ($0.0058\lambda_0$)
L_y	11 mm ($0.21\lambda_0$)	$2r$	2.0 mm ($0.0386\lambda_0$)

TABLE II
ELECTRICAL CHARACTERISTICS OF A CONVENTIONAL SBA AND THE PROPOSED SBA (AT 5.8 GHz)

	Conventional SBA	Proposed SBA
Effective gain (dBi)	14.3	14.3
Half power beam width (degrees)	34°	34°
Directive gain (dBi)	14.8	14.5
1st sidelobe level (dB)	-21.0	-20.0
Axial ratio (dB)	1.28	1.5
Aperture efficiency with respect to		
Effective gain	65%	72%
Directive gain	73%	75%
Frequency bandwidth for VSWR	3% (VSWR≤1.5)	6.5% (VSWR≤1.2)

by numerous simulations. The optimization was performed by applying a general design guideline as follows: 1) Choose the diameters of the primary reflector and the subreflector (D_r and D_s), and the height of the subreflector (H_r) initially to be the same as those of a conventional circularly polarized SBA [6], namely, $D_r = 2.0\lambda_0, D_s = 0.46\lambda_0, H_r = 0.5\lambda_0$ (= the height of the rim); 2) Let the slotted patch have the same size as the subreflector and set its height (H_s) initially to 0.25 λ_0 ; 3) Design two orthogonal H-shaped slots, feed probe, and the shorting pin based on the geometric parameters presented in [11]; 4) Reduce the length of one of the H-shaped slots for achieving circularly polarized radiation; 5) Introduce a pair of capacitive stubs in the longer H-shaped slot and adjust the geometry of the H-shaped slots (i.e., W_w, W_n, L_w, L_x, and L_y) for a desirable performance for circular polarization; 6) Adjust the position and diameter of the feed probe and shorting pin for impedance matching; 7) Optimize the overall size of the SBA for the best radiation (i.e., lowest axial ratio in dB with highest gain) and impedance matching performance.

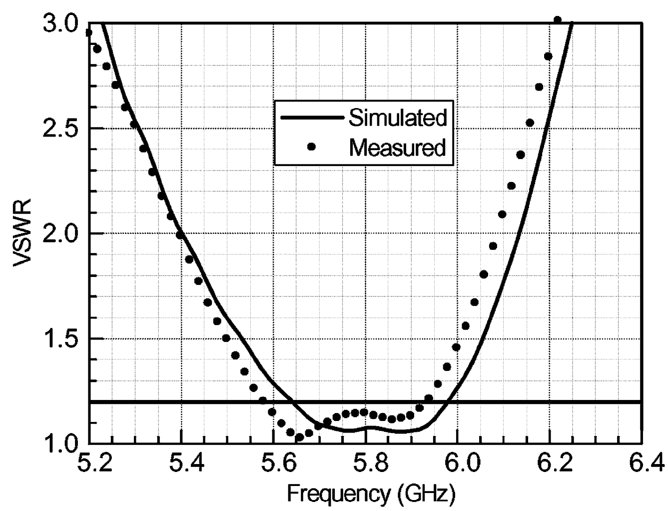

Fig. 2. Simulated and measured results for VSWR of the cross-aperture-excited SBA.

III. RESULTS

Fig. 2 shows the simulated and measured results for VSWR of the cross-aperture-excited SBA. Good agreement is observed. The bandwidth for $\mathrm{VSWR} < 1.2$ is found to be about 6.5%, much better than the conventional cross-dipole-excited SBA [6]. The axial ratio (AR) at broadside (in the z direction) and gain are plotted in Fig. 3. It is seen that the bandwidth for $\mathrm{AR} \leqslant 3$ dB is about 4.2% and the gain is around 14 dBi. The aperture efficiency is 70–80%. The radiation pattern measured at 5.8 GHz is compared with the simulated result in Fig. 4 and good agreement is observed for the co-polarization (i.e., the left-hand circular polarization, LHCP) over the main beam. The half power beam width is about 35° and the first sidelobe level is less than -20 dB. The cross-polarization (i.e., the right-hand circular polarization, RHCP) is less than -15 dB. The radiation characteristics of the cross-aperture-excited SBA are comparable to those of a cross-dipole-excited SBA [6]. A more detailed comparison of the electrical characteristics between a conventional SBA [6] and the proposed SBA is shown in Table II.

IV. ANALYSIS

The unbalanced feed of the cross-aperture-excited SBA can be decomposed into two distinct driving modes, namely, an even mode and an odd mode [11]. Since the even-mode impedance is usually higher than the odd-mode impedance around the design frequency, the unbalanced input impedance is dominated by the odd-mode impedance. It is also noted that for the even mode

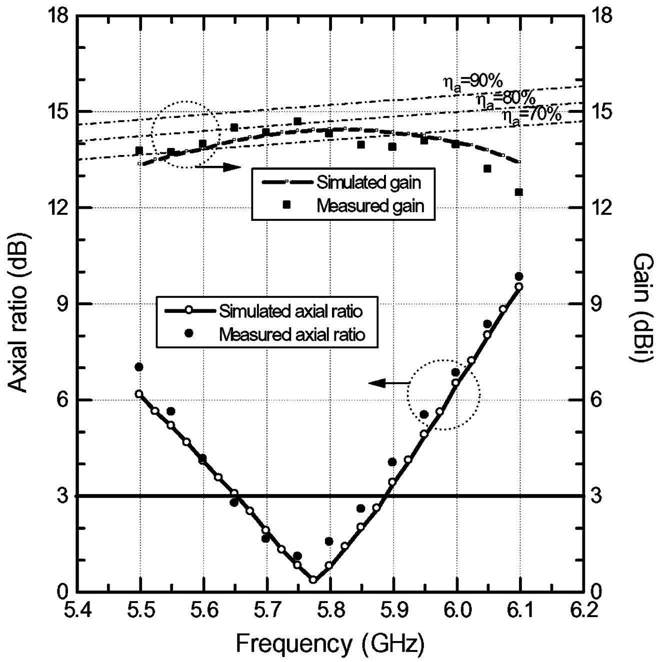

Fig. 3. Simulated and measured results for axial ratio and gain of the cross-aperture-excited SBA.

the excitation structure is essentially a cap-loaded monopole, which does not contribute to the radiation at broadside. Therefore we only need to focus on the odd mode that looks like a balanced center feed through a two-wire (the feed probe plus the shorting pin) transmission line. For a diagonally-aligned center feed (simply called "diagonal-feed"), the voltage source V_0 can be divided into two voltage components V_x (called "X-feed") and V_y ("Y-Feed"), which cross Slots X and Y respectively, as illustrated in Fig. 5. The input impedance (Z^o) of the diagonal-feed simply equals the summation of the input impedances (Z_x and Z_y) of the X-feed and the Y-feed, that is

$$Z^o = Z_x + Z_y. \tag{1}$$

The input impedance Z^o of the diagonal-feed is transformed into the odd-mode impedance Z_{in}^o through the two-wire transmission line. Therefore we can obtain

$$Z_{\text{in}}^o = Z_c \frac{Z^o + jZ_c \tan \beta H_s}{Z_c + jZ^o \tan \beta H_s} \tag{2}$$

where $\beta = 2\pi/\lambda_0, H_s$ is the length of the transmission line (or the height of the slotted patch), and Z_c is the characteristic impedance of the two-wire transmission line. Fig. 6 shows Z_x and Z_y simulated by directly enforcing a voltage source across the slot and compares the calculated odd-mode impedance Z_{in}^o with the simulated and measured input impedance Z_{in}. In the simulation for Z_x and Z_y, the feed probe and the shorting pin were removed and a wire of radius 0.05 mm was used to connect the voltage source across the slot. A more detailed description for the calculation of Z_x and Z_y is presented in Appendix.

It is seen that the calculated Z_{in}^o is close to Z_{in}. The difference between Z_{in}^o and Z_{in} is due to the contribution from the even mode and due to the approximation of the feeding structure introduced during the simulation (such as the wire introduced to connect the voltage source). It is interesting to note that the two-wire transmission line formed by the feed

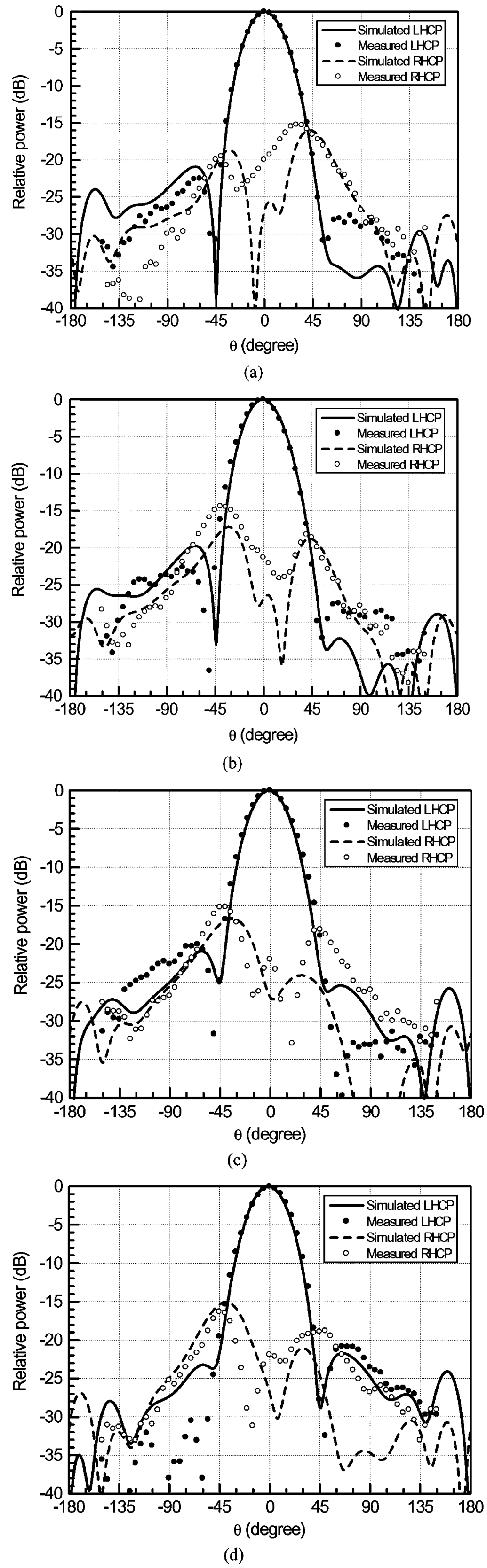

Fig. 4. Simulated and measured radiation patterns of the cross-aperture-excited SBA (at 5.8 GHz). (a) $\phi = 0°$. (b) $\phi = 45°$. (c) $\phi = 90°$. (d) $\phi = 135°$.

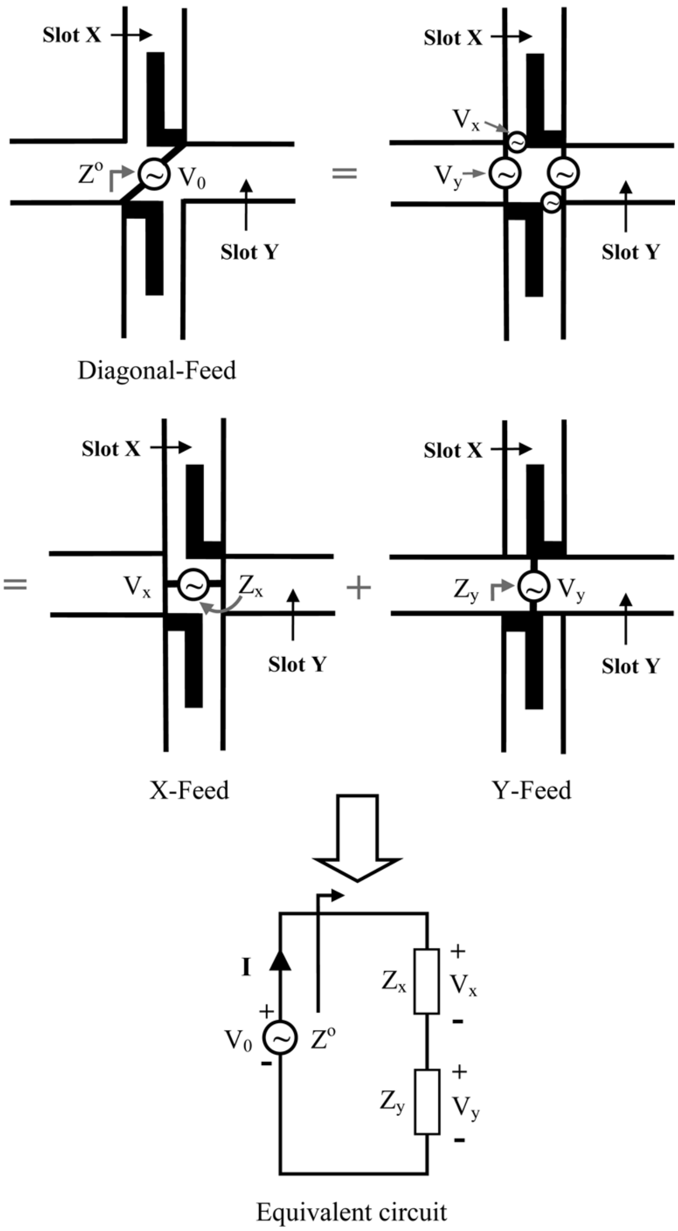

Fig. 5. The diagonal-feed (V_0) of a cross aperture is considered as a sum of an X-feed (crossing Slot X, V_x) and a Y-feed (crossing Slot Y, V_y).

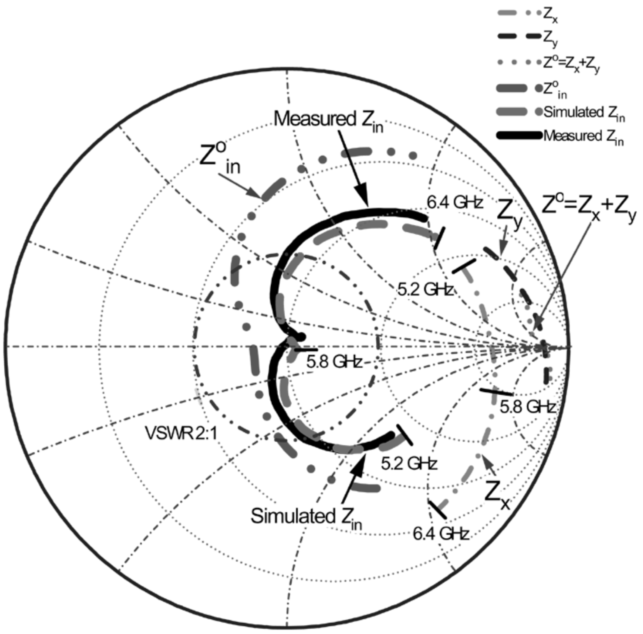

Fig. 6. Simulated and measured input impedances $(Z_{\rm in})$ of the cross-aperture-excited SBA are compared with the odd-mode impedance $(Z_{\rm in}^o)$ calculated from Z_x and Z_y.

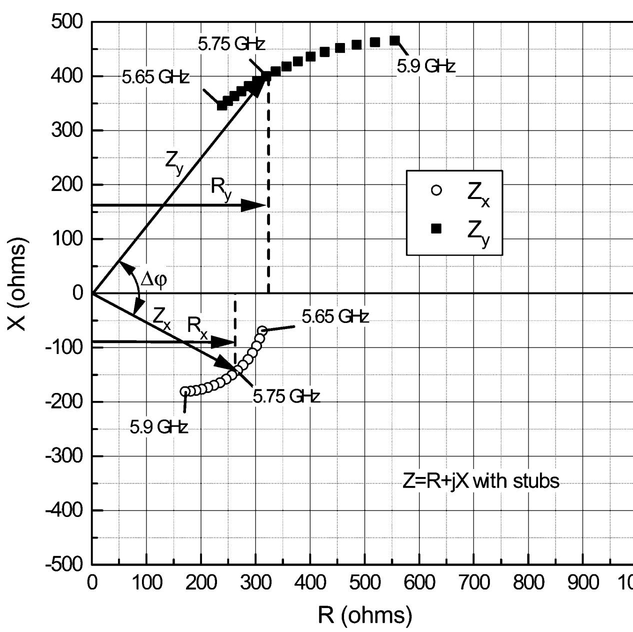

Fig. 7. $R - X$ diagram of the input impedances Z_x and Z_y for the X-feed and the Y-feed with a pair of capacitive stubs.

probe and the shorting pin can transform the high-value diagonal-fed input impedance Z^o (about several hundreds of ohms) to a lower resistance (around 50 ohms). (Virtually the two-wire transmission line can be thought of as a quarter-wave transformer since its length is close to $\lambda_0/4$.) Therefore the unbalanced feed serves as an impedance matching circuit as well as a transmission line. The impedance matching can be achieved by properly selecting the diameter and the center-to-center distance of the feed probe and the shorting pine and by adjusting the height of the slotted patch. A more detailed parametric study on the impedance matching can be found in [11].

Since the gain of an SBA is dominantly determined by the primary reflector, the subreflector, and the rim (not sensitive to the size of the excitation structure), the far-zone fields (E_x and E_y) generated at broadside by the X-feed (V_x) and the Y-feed (V_y) are proportional to the square root of their input powers (P_x and P_y), that is

$$\frac{|E_x|}{|E_y|} = \left(\frac{P_x}{P_y}\right)^{1/2} = \left(\frac{I^2 R_x}{I^2 R_y}\right)^{1/2} = \left(\frac{R_x}{R_y}\right)^{1/2} \qquad (3)$$

where R_x and R_y are the radiation resistances associated with the X-feed and the Y-feed, respectively. (It is observed by simulation that the length of each slot has little effect on the amplitude pattern of the SBA.) The phase difference (denoted by $\Delta\varphi$) between E_x and E_y is associated with the excitations, i.e., V_x and V_y, or the input impedances Z_x and Z_y of the X-feed and

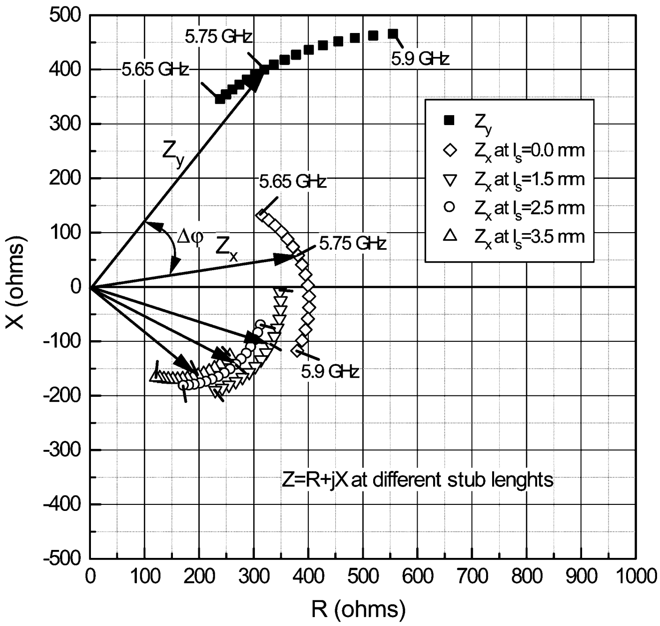

Fig. 8. Effect of the stub length (l_s) on the input impedances Z_x and Z_y for the X-feed and the Y-feed.

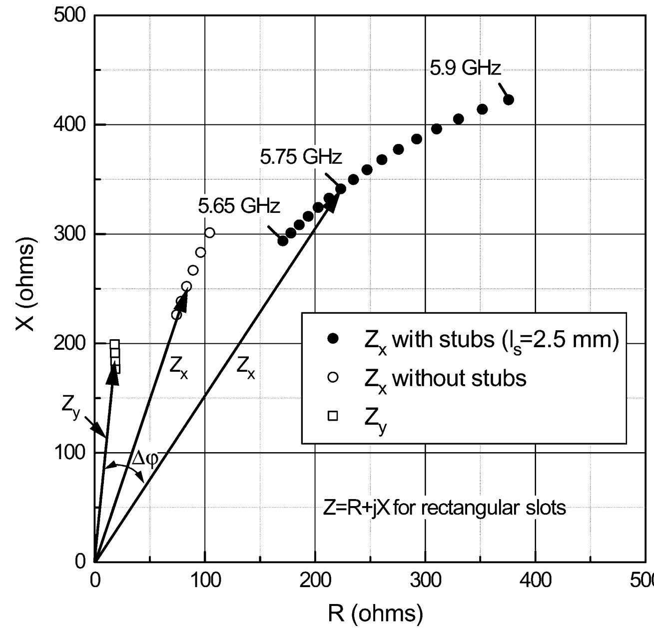

Fig. 9. $R-X$ diagram of the input impedances Z_x and Z_y for two rectangular slots ($W_w = W_n = 1.0$ mm).

the Y-feed, respectively. For a perfectly circular polarization, it is required that $|E_x|/|E_y| = 1$ (or $R_x = R_y$) and $\Delta\varphi = \pm 90°$. Fig. 7 shows the $R-X$ diagram (the real part R versus the imaginary part X of an input impedance Z) for the impedances Z_x and Z_y. As an example, looking at a frequency (say 5.75 GHz) in the 5.8 GHz ISM band, it is found that the phase difference between Z_x and Z_y is near $-80°$ (close to $\Delta\varphi = -90°$) and that $(R_x/R_y)^{1/2}$ is equal to 0.91 (close to 1), which corresponds to an LHCP wave. Using $|E_x|/|E_y| = 0.91$ and $\Delta\varphi = -80°$, we can obtain an axial ratio of 1.8 dB, close to the simulated and measured values (about 1.2 dB).

Fig. 8 demonstrates the effect of the stub length (l_s) on the impedances Z_x and Z_y. Since Z_y is decided by the field distribution in Slot Y where there is no stub, the stub length almost has no effect on Z_y. Both the real part (R_x) and the imaginary part (X_x) of Z_x vary with l_s. As l_s increases, the phase difference ($\Delta\varphi$) between Z_x and Z_y increases, but R_x decreases. This is because a longer stub tends to blocking the radiation from Slot X while making Slot X become more capacitive (i.e., X_x decreases). But if without a pair of capacitive stubs (i.e., $l_s = 0$), $\Delta\varphi$ becomes much less than 90° (only about 42°) even though $(R_x/R_y)^{1/2}$ is still close to 1. Therefore the pair of capacitive stubs is considered to be essential for the production of circular polarization and there is an optimal value for l_s. By simulation and experiment, the optimized l_s is found to be 2.5 mm. The stub width (w_s) is not critical for the achievement of circularly polarized radiation, but it is limited by the fabrication process [e.g., a printed circuit broad (PCB) technology], especially for a higher-frequency application. Usually, a PCB fabricator has a similar limitation on the minimum line width and slot width (i.e., the line to line clearance). Therefore, we selected w_s to be $\sim W_n/3$, which makes the minimum line width approximately equal the minimum line to line clearance. Fig. 8 also suggests that the performance for circular polarization will not significantly change if the stub length (l_s) varies within 2.5 ± 0.5 mm. Simulation shows that an error of ± 0.5 mm for l_s or ± 0.1 mm for w_s leads to an increase in the minimum axial ratio of ~ 0.5 dB.

Fig. 9 exhibits the $R-X$ diagram for two orthogonal rectangular slots whose lengths are equal to the total lengths of the H-shaped slots (i.e., $L_w + L_x$ for Slot X and $L_w + L_y$ for Slot Y). It clearly shows that both the amplitude [i.e., $(R_x/R_y)^{1/2}$] and the phase difference ($\Delta\varphi$) are far from the requirements for circular polarization no matter whether there is a pair of capacitive stubs or not. So we conclude that it is difficult to achieve circular polarization with rectangular slots.

Finally it should be mentioned that the bandwidth of circular polarization (i.e., the axial ratio) is limited by the leaky cavity structure of the SBA not just by the excitation topology. By simulation, we find that the excitation topology does not have a significant effect on the AR bandwidth.

V. Conclusion

A cross aperture has been proposed to excite the short backfire antenna (SBA) for circular polarization. The cross aperture consists of two orthogonal H-shaped slots fed by a single probe with a shorting pin. The feed probe and the shorting pin form an unbalanced feed which serves as a two-wire transmission line and acts as an impedance matching circuit. A pair of capacitive stubs is introduced inside the cross aperture to enhance the capacitance of one of the H-shaped slot. It has been demonstrated that the H-shaped slots and the capacitive stubs are essential for the achievement of circular polarization. The cross-aperture-excited SBA has the advantage of no need for a balun circuit and for an external polarizer. The proposed SBA achieves an impedance bandwidth of 6.5% ($\mathrm{VSWR} < 1.2$), an axial ratio ($\leqslant 3$ dB) bandwidth of 4.2%, and a gain of 14 dBi. Simulation and experimental results show good agreement.

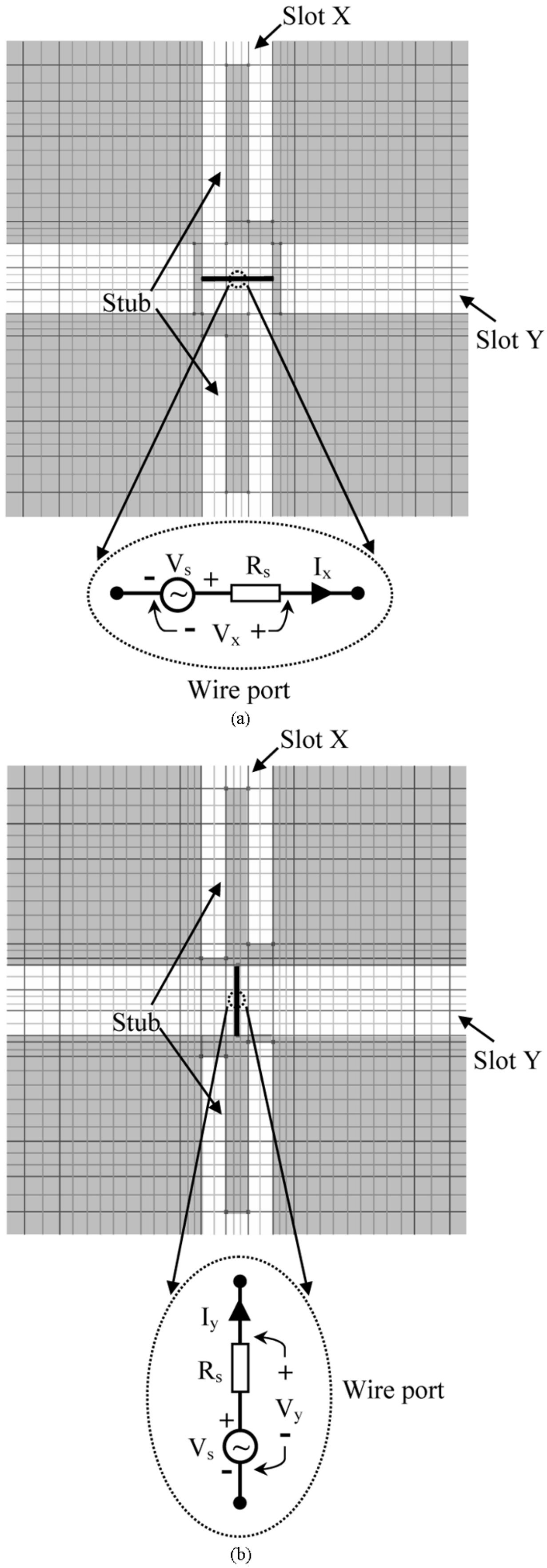

Fig. 10. TLM mesh for the calculation of (a) Z_x and (b) Z_y.

APPENDIX
CALCULATION OF Z_x and Z_y

The impedances Z_x and Z_y are calculated using *Micro-Stripes* V6.5 which is a time-domain electromagnetic solver based on the transmission-line matrix (TLM) method [12]. The TLM mesh around the center of the cross aperture is illustrated in Fig. 10. For the calculation of Z_x and Z_y a wire port is introduced across the slot X and slot Y, respectively. The wire port is formed with a voltage source which consists of the source voltage V_s and the internal source resistance R_s. Through the TLM simulation, we can obtain the wire current (I_x for Z_x or I_y for Z_y) and the wire voltage (V_x for Z_x or V_y for Z_y), from which the impedances Z_x and Z_y are determined as $Z_x = V_x/I_x$ and $Z_y = V_y/I_y$.

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Dr. Tentzeris is a member of the International Scientific Radio Union (URSI)-Commission D, an Associate Member of EuMA, and a member of the Technical Chamber of Greece. He was the recipient of the 1997 Best Paper Award of the International Hybrid Microelectronics and Packaging Society for the development of design rules for low-crosstalk finite-ground embedded transmission lines. He received the 2000 NSF CAREER Award for his work on the development of MRTD technique that allows for the system-level simulation of RF integrated modules, the 2001 ACES Conference Best Paper Award, the 2002 International Conference on Microwave and Millimeter-Wave Technology Best Paper Award (Beijing, China) for his work on Compact/SOP-integrated RF components for low-cost high-performance wireless front-ends, the 2002 Georgia Tech-ECE Outstanding Junior Faculty Award, the 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award for his activities in the area of finite-ground low-loss low-crosstalk coplanar waveguides, the 2003 IBC International Educator of the Year Award, the 2003 IEEE CPMT Outstanding Young Engineer Award for his work on 3-D multilayer integrated RF modules, and the 2004 IEEE Transactions on Advanced Packaging Commendable Paper Award. He was also the 1999 Technical Program Co-Chair of the 54th ARFTG Conference, Atlanta, GA and he is the Vice-Chair of the RF Technical Committee (TC16) of the IEEE CPMT Society. He has organized various sessions and workshops on RF/Wireless Packaging and Integration in IEEE ECTC, IMS and APS Symposia in all of which he is a member of the Technical Program Committee in the area of "Components and RF." He is an Associate Editor of the IEEE Transactions on Advanced Packaging.