Development of a Cavity-Backed Broadband Circularly Polarized Slot/Strip Loop Antenna With a Simple Feeding Structure

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***Abstract*—A cavity-backed loop antenna is developed for producing broadband circularly polarized (CP) radiation. The antenna configuration consists of a slot loop and a strip loop. The slot loop radiates a CP wave at a lower frequency while the strip loop produces CP radiation at a higher frequency. A combination of the two frequencies leads to a bandwidth enhancement. The slot/strip loop antenna is fed by a single straight microstrip line. It is demonstrated that the cavity-backed slot/strip loop antenna can achieve an axial ratio (≤ 3 dB) bandwidth of 19% with good impedance matching. The antenna configuration is described and the operating principles for broadband circular polarization and impedance matching are analyzed. The antenna performance is confirmed by experimental results.**

***Index Terms*—Broadband antenna, cavity-backed antenna, circularly polarized (CP) antenna, loop antenna, slot antenna.**

I. Introduction

CAVITY-BACKED slot antennas have two major advantages over cavity-backed wire antennas, such as dipole, helix, and spiral antennas [1]. First, a slot antenna can be flush mounted on a metal surface; therefore, it is suitable for applications in mobile communications (such as IEEE 802.20 for mobile broadband wireless access) and radar systems of high-speed vehicles or aircraft [2]. Second, slot antennas can be easily fed by a microstrip line that is fabricated on the same substrate with the slot and is placed between the cavity and the substrate, thus avoiding the undesirable radiation from the feeding network. This is particularly important for applications in antenna arrays. Many types of slot configurations have been developed for producing circularly polarized (CP) radiation, such as annual slot [3], dual-spiral slot [4], rectangular slot [5], and cloverleaf slot [6]. However, these slot antennas have a narrow axial ratio (AR) bandwidth (usually $< 5\%$ for $\mathrm{AR} \leq 3$ dB). Archimedean spirals usually offer a much wider bandwidth in free space. Unfortunately, the presence of a ground plane (or a cavity) limits the bandwidth enhancement [7]. One way to remedy this limitation is to use absorbers inside the cavity or to terminate the spiral slot with tapered resistive loading [8], [9]. But it reduces the power efficiency. Recently, a bandwidth-enhanced ($\sim 15\%$ for $\mathrm{AR} \leq 3$ dB) cavity-backed slot antenna has been presented in [10], but it requires a complicated feeding network. In this paper, we develop a broadband cavity-backed loop antenna with a simple feeding structure. The antenna configuration developed is considered to be a combination of a slot loop and a strip loop. The slot loop has a good CP performance at a lower frequency while the strip loop produces CP radiation at a higher frequency. A combination of the two frequencies leads to a bandwidth enhancement. The slot/strip loop is fed by a single straight microstrip line and a good impedance matching is achieved.

The antenna configuration is described in Section II. The operating principle for broadband circular polarization and impedance matching is analyzed in Section III. Finally experimental results are presented to verify the antenna performance.

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II. Description of the Antenna

The antenna configuration is shown in Fig. 1. The radiating element consists of a slot loop and a strip loop (so called a slot/strip loop) with a pair of parasitic slot loops inside the strip loop. The slot/strip loop with the parasitic loops is etched on a thin ($\mathrm{thickness} = 10$ mils), low-dielectric constant ($\varepsilon_r = 2.2$) substrate (RT/duroid 5880) which is backed by a rectangular cavity. The cavity-backed slot/strip loop is fed by a microstrip feeding line that is fabricated on the same substrate with the slot/strip loop and is placed between the substrate and the cavity. The feeding line is divided into three sections: an open stub, a coupling stub, and a 50-ohms microstrip line. A coaxial line is connected to the 50-ohms microstrip line for the purpose of measurement. The broadband circular polarization is achieved by adjusting the aspect ratio (W_s/L_s) of the slot/strip loop and the depth (D_c) of the cavity. By changing the length (l_{op}) of the open stub and the width (w_{co}) of the coupling stub, a good impedance matching can be obtained. The cavity-backed slot/strip loop antenna was designed for a C-band operation using *Micro-Stripes 7.0*—a transmission-line matrix (TLM) based full-wave electromagnetic simulator [11]. The physical dimensions of the antenna are attached in the caption of Fig. 1.

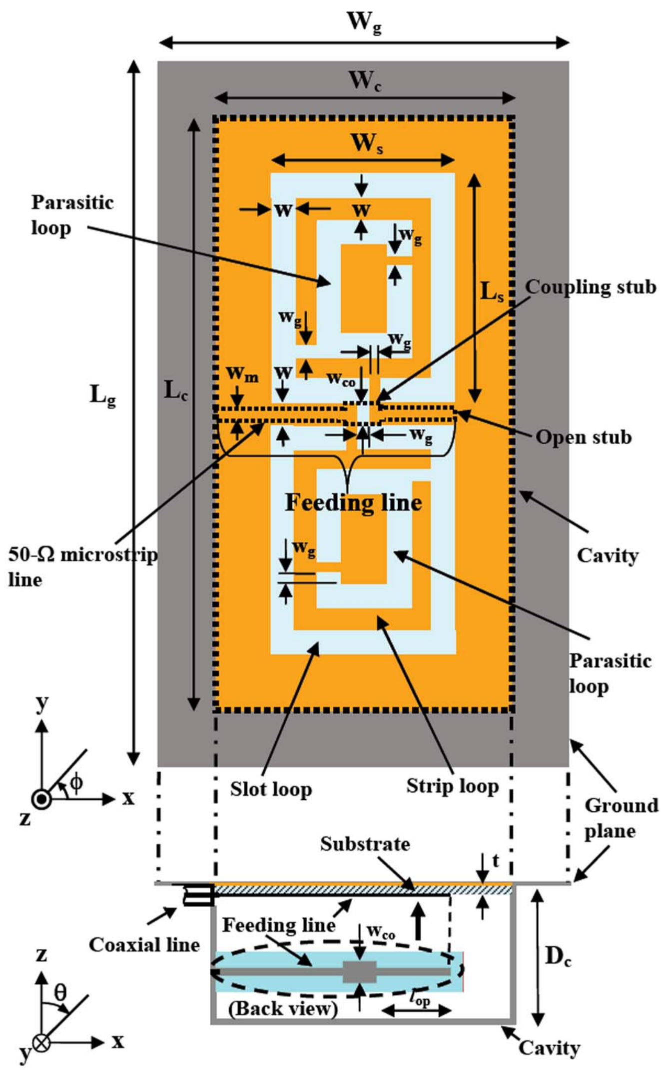


Fig. 1. Configuration of the cavity-backed broadband CP slot/strip loop antenna. ($W_g = 36$ mm, $L_g = 62$ mm, $W_c = 26$ mm, $L_c = 52$ mm, $W_s = 16$ mm, $L_s = 20$ mm, $w = 2$ mm, $w_g = 1$ mm, $w_{\rm m} = 0.78$ mm, $D_c = 12$ mm, t $= 0.254$ mm; the width ($w_{\rm co}$) of the coupling stub is $w_{\rm co} = w = 2$ mm, the length of the coupling stub is $3w_g = 3$ mm, the length of the open stub is $l_{\rm op} = 6.5$ mm.).

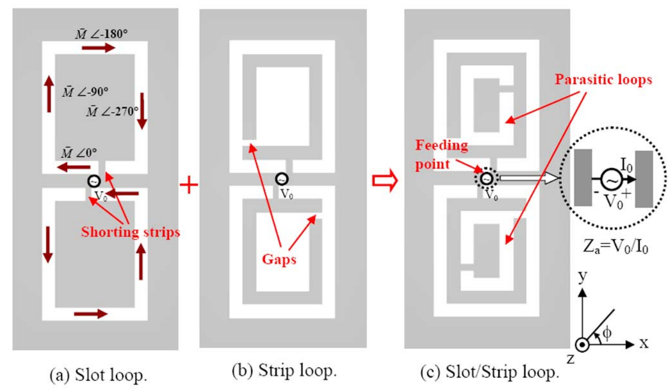


Fig. 2. Slot/strip loop considered as the combination of a slot loop and a strip loop.

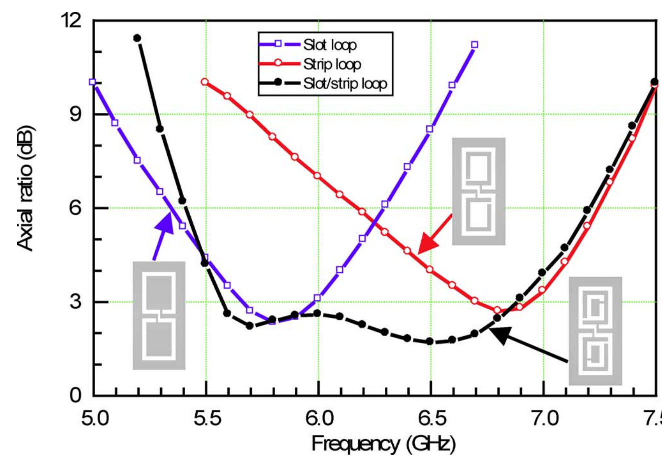


Fig. 3. Axial ratio for a slot loop, a strip loop, and a slot/strip loop.

III. Operating Principles

A. Broadband Circular Polarization

As mentioned in previous sections, the slot/strip loop can be considered as a combination of a slot loop and a strip loop (see Fig. 2). For the slot loop [see Fig. 2(a)], a pair of shorting strips must be introduced in order to produce a CP wave [3], [5]. The winding sense of the slot loop decides the sense of its CP radiation, which is left-handed in spatial phase starting from the feeding point (the CP wave is propagating in the z direction). When a voltage source is enforced at the feeding point, a traveling-wave magnetic current $\vec{M}$ can be excited on the slot loop [5]. If the slot loop has a perimeter of approximately one wavelength, the traveling-wave current can create electromagnetic waves in the far-field zone with $\sim 90\, degrees$ of spatial phase as well as time phase, thus achieving CP waves. Due to the nonuniform traveling-wave current distribution along the slot loop, the CP waves created may be not perfect. And the slot loop usually has a narrow bandwidth for CP radiation since the electrical length of the slot loop is frequency dependent. Fig. 3 shows the AR in the z direction simulated for the slot loop. It is seen that the slot loop has a minimum AR of > 2.5 dB at a lower frequency of ~ 5.8 GHz. and a narrow bandwidth of $< 5\%$ for $\mathrm{AR} \leq 3$. In order to improve the AR bandwidth, we introduce a strip loop inside the slot loop [see Fig. 2(b)]. There is a pair of gaps into the strip loop [see Fig. 2(b)] for the generation of CP radiation [12], [13]. The strip loop moves the minimum AR to a higher frequency of ~ 6.8 GHz while maintaining a narrow bandwidth (see Fig. 3). The introduction of the strip loop improves the AR at the higher frequency, but worsens the AR at the lower frequency. For the AR bandwidth enhancement, we need to combine the slot loop and the strip loop into the same antenna aperture. To do so, we introduced a pair of small slots (also with a shorting strip on them) inside the strip loop [see Fig. 2(c)]. The introduced slots can be considered as a parasitic element of the slot loop, thus improving the bandwidth of the slot loop [14], [15]. Fig. 3 shows that the AR bandwidth of the slot/strip loop is increased to $\sim 20\%$ for $\mathrm{AR} \leq 3$ dB. It should be noted that there would be no bandwidth enhancement without the strip loop (i.e., if the gaps on the strip loop were removed). Therefore, the slot/strip loop cannot be simply thought of as the complementary structure of a wire loop with parasitic elements

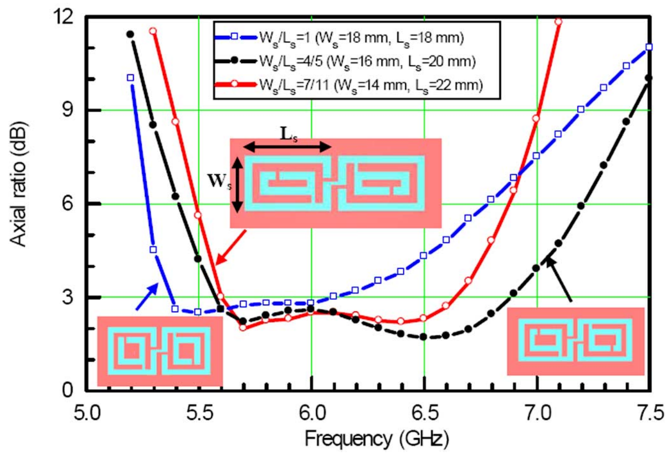


Fig. 4. Axial ratio at different aspect ratios (W_s/L_s) of the slot/strip loop. ($W_c = 28$ mm and $L_c = 48$ mm for $W_s/L_s = 1$, $W_c = 26$ mm and $L_c = 52$ mm for $W_s/L_s = 4/5$, $W_c = 24$ mm and $L_c = 56$ mm for $W_s/L_s = 7/11$.).

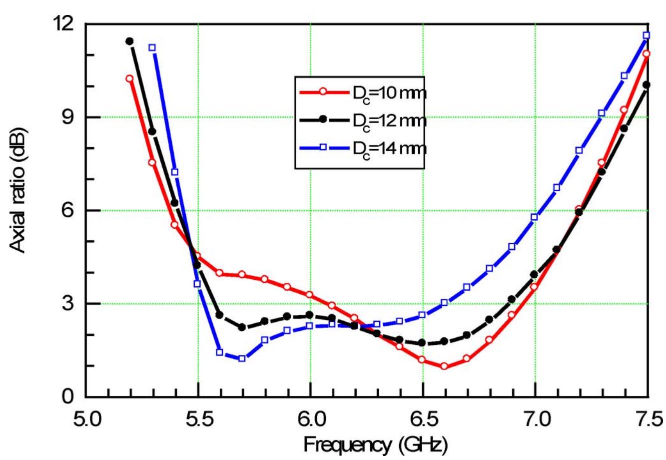


Fig. 5. Axial ratio at different depths (D_c) of the cavity.

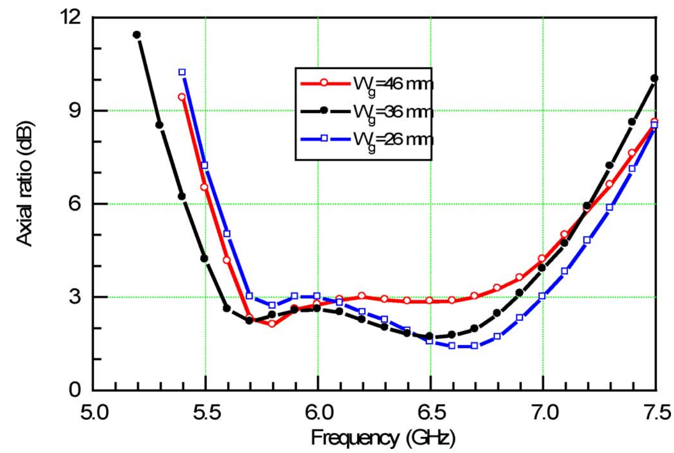


Fig. 6. The effect of the width (W_g) of ground plane on the axial ratio of the slot/strip loop antenna.

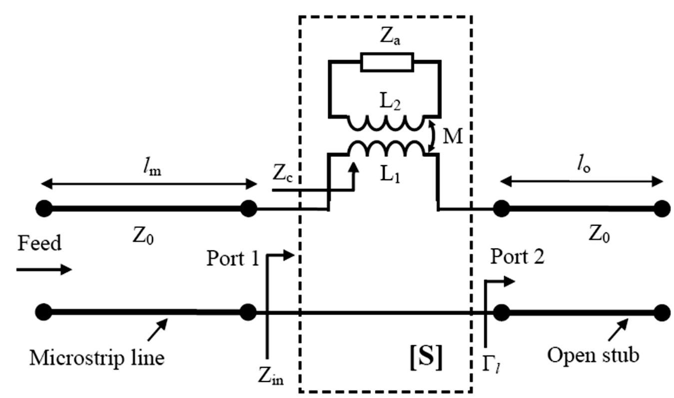


Fig. 7. Equivalent circuit for input impedance of the cavity-backed slot/strip loop antenna ($Z_0 = 50$ ohms, $l_m = W_c/2 = 13$ mm, $l_o = l_{op} + 1.5$ mm $= 8$ mm).

[15]. The AR bandwidth improvement can be considered as a result of the combination of a strip loop and a slot loop with a pair of parasitic slot loops.

The cavity-backed slot/strip loop antenna was optimized by changing the aspect ratio of the loop and the depth of the cavity. Fig. 4 shows the variation of AR as the aspect ratio (W_s/L_s) is reduced from 1 (i.e., a square) to 7/11. In the optimization, only the width and length of the cavity were adjusted with the aspect ratio to keep the distance (i.e., 5 mm) from the sidewall of the cavity to the edge of the loop unchanged. It is found that the optimized aspect ratio is about 4/5. A larger aspect ratio (e.g., 1) or a smaller aspect ratio (e.g., 7/11) would lead to a narrower AR bandwidth. The variation of AR with the depth (D_c) of the cavity is displayed in Fig. 5. At a higher depth (e.g., $D_c = 14$ mm), there is a good AR at a lower frequency but a bad AR at a higher frequency. As the depth decreases, the AR is improved at the higher frequency. But if the depth is further reduced (e.g., $D_c = 10$ mm), the AR at the lower frequency becomes worse. Therefore there should be an optimal value for the depth, which is found to $D_c = 12$ mm for the proposed slot/strip loop antenna. The effect of the width (W_g) of the ground plane on the AR performance is exhibited in Fig. 6. There is some effect due to the diffraction from the edge of the ground plane. But it is not significant. For a certain ground plane, the slot/strip loop may be adjusted slightly for an optimal performance.

B. Impedance Matching

To understand the impedance matching of the slot/strip loop antenna, an equivalent circuit for the input impedance is presented in Fig. 7, where the slot discontinuity at the feeding point appears as a simple series impedance Z_c to the microstrip line [16]. The impedance Z_a is the input impedance of the slot/strip loop when it is directly fed by a voltage source [see Fig. 2(c)]. The impedance Z_a directly simulated by enforcing a voltage gap feed is shown in Fig. 8. A loop around the center frequency (6.5 GHz) is observed at the impedance locus, which means that the broadband property of the input impedance of the slot/strip loop is inherent, but not due to the feeding structure. The impedance Z_a is coupled to the microstrip line through the self-inductances (L_1 and L_2) of the slot/strip loop and the coupling stub, and the mutual inductance (M) between the two elements [17], leading to the series impedance Z_c. Since it is difficult to determine the values of L_1, L_2, and M, we cannot directly calculate the series impedance Z_c. Instead, we can obtain Z_c by considering the microstrip line-fed slot/strip loop as a two-port device with Port 1 defined at the 50-ohms microstrip line and Port 2 at the open

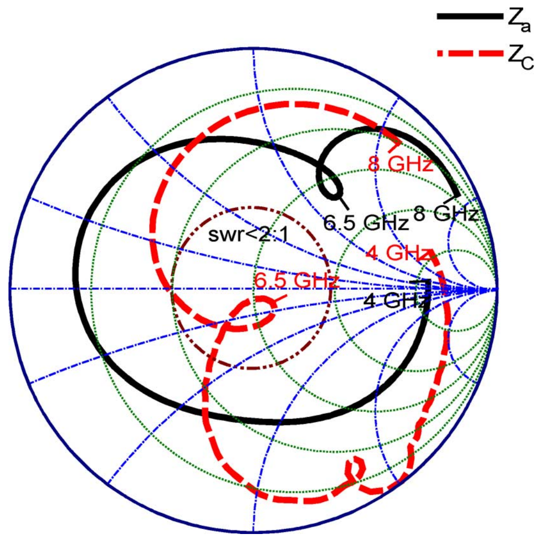


Fig. 8. Input impedance $Z_{\rm a}$ of the cavity-backed slot/strip loop antenna fed by a voltage source and the series impedance Z_c calculated using the S parameters.

stub. From the S parameters of the two-port network, we have [18]

$$Z_c = Z_0 \frac{(1+S_{11})(1+S_{22}) - S_{12}S_{21}}{2S_{21}} \tag{1}$$

where Z_0 $(= 50 \text{ ohms})$ is the characteristic impedance of the microstrip line. Note that the reference plane of the S parameters is defined at the center of the antenna (i.e., the feeding point shown in Fig. 2). The S parameters of the two-port network can be obtained by numerical simulation. The series impedance Z_c calculated using (1) is also plotted in Fig. 8. We can see that the impedance loop is moved to the inside of the circle $\text{SWR} = 2$ $(\text{SWR} = \text{standing wave ratio})$.

To demonstrate the accuracy of the impedance Z_c obtained, we compare the input impedances $(Z_{\rm in})$ obtained through three different ways.

i) By a series impedance model [16]

$$Z_{\rm in}^{\rm series} = Z_c - jZ_0 \cot \beta l_o \tag{2}$$

where β is the propagation constant of the microstrip line and l_o is the length $(l_{\rm op})$ of the open stub plus the half length (1.5 mm) of the coupling stub, i.e., $l_o = l_{\rm op} + 1.5$ mm.

ii) By a two-port network [18]

$$Z_{\rm in}^{\rm two-port} = Z_0 \frac{1+\Gamma_{\rm in}}{1-\Gamma_{\rm in}} \tag{3}$$

where

$$\Gamma_{\rm in} = S_{11} + \frac{S_{12}S_{21}\Gamma_l}{1 - S_{22}\Gamma_l} \tag{4}$$

with

$$\Gamma_l = \frac{-jZ_0 \cot \beta l_o - Z_0}{-jZ_0 \cot \beta l_o + Z_0}. \tag{5}$$

iii) By a direct numerical simulation: $Z_{\rm in}^{\rm direct}$.

Fig. 9 displays the comparison of $Z_{\rm in}^{\rm series}$, $Z_{\rm in}^{\rm two-port}$, and $Z_{\rm in}^{\rm two-port}$, showing no significant difference. This implies that the coupling between the microstrip feeding line and the slot/strip loop can be modeled by a simple series impedance. Comparing the $Z_{\rm in}$ in Fig. 9 to Z_c in Fig. 8, we can also see that $Z_{\rm in}$ and Z_c have no obvious difference, which means that the open stub of the feeding line actually acts as a short circuit. Therefore only the length ($l_{\rm op}$, $l_{\rm op} + 1.5$ mm is approximately a quarter guided wavelength) of the open stub is critical for the impedance matching, which was optimized to be $l_{\rm op} = 6.5$ mm. A good impedance matching can be obtained by adjusting the coupling between feeding line and the slot/strip loop, i.e., the width $(w_{\rm co})$ of the coupling stub. Fig. 10 demonstrates the effect of the width $w_{\rm co}$ on the input impedance of the microstrip-fed slot/strip loop antenna. The optimized value for $w_{\rm co}$ was found to be $w_{\rm co} = w = 2$ mm. The dimensions of the cavity and the ground plane have no significant effect on the impedance matching.

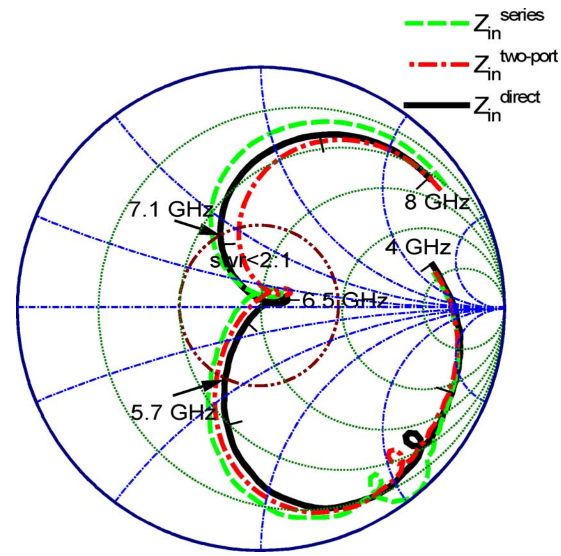


Fig. 9. Input impedance $Z_{\rm in}$ of the cavity-backed slot/strip loop antenna when fed by a microstrip line ($Z_{\rm in}^{\rm series}$: calculated using a series impedance model; $Z_{\rm in}^{\rm two-port}$: calculated using a two-port network; $Z_{\rm in}^{\rm direct}$: obtained by direct simulation).

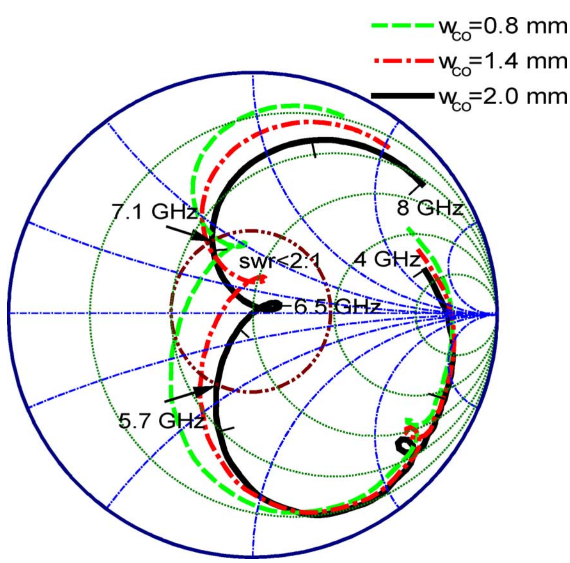


Fig. 10. Effect of the width $(w_{\rm co})$ of the coupling stub on the input impedance $Z_{\rm in}$ of the cavity-backed slot/strip loop antenna.

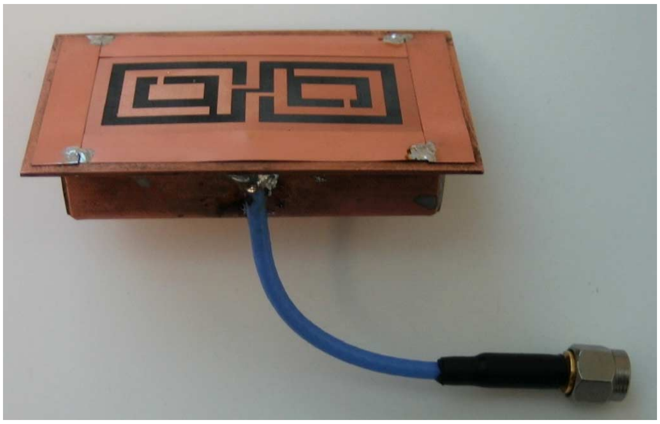


Fig. 11. Prototype of the cavity-backed slot/strip loop antenna.

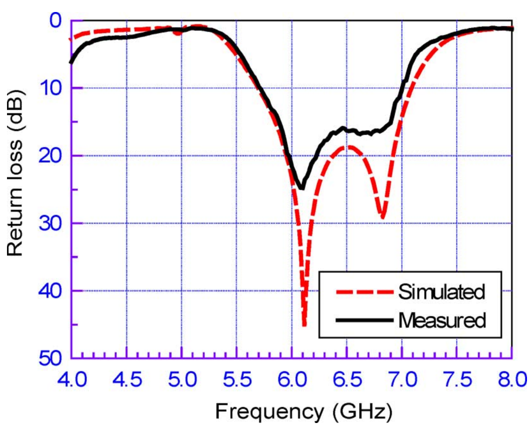


Fig. 12. Return loss of the cavity-backed slot/strip loop antenna.

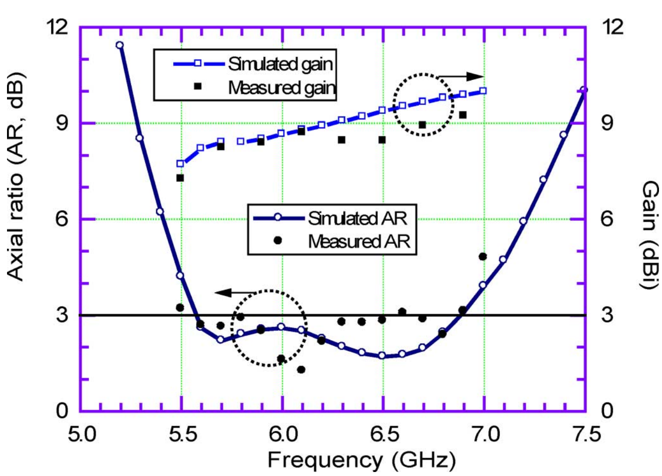
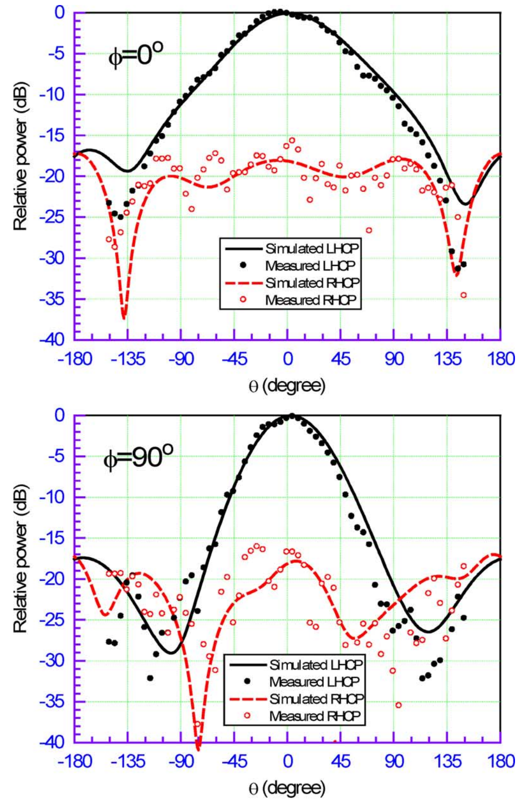


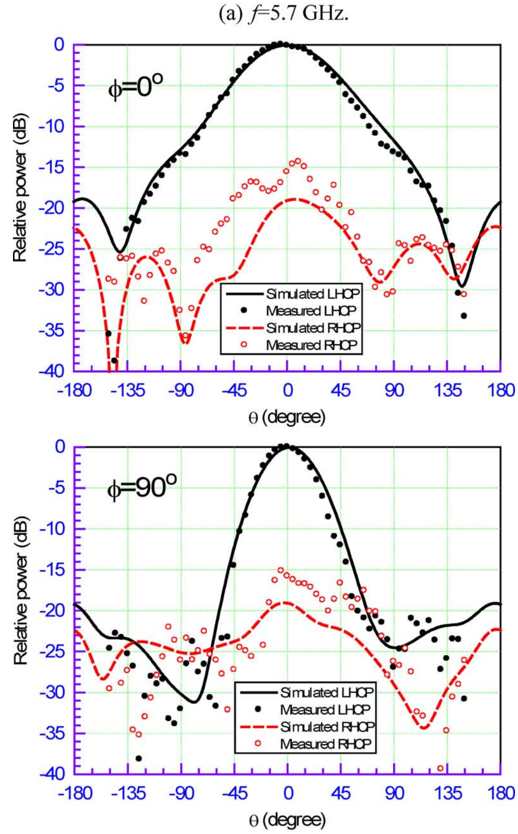
Fig. 13. Axial ratio and gain of the cavity-backed slot/strip loop antenna

IV. Experimental Results

A prototype of the cavity-backed slot/strip loop antenna is pictured in Fig. 11. A flexible coaxial cable is connected to the microstrip feeding line for measurement. Fig. 12 compares the measured return loss (RL) to the simulated result. A slight difference is probably due to the transition between the microstrip line and the coaxial cable. The measured bandwidth for $\mathrm{RL} \geq 10\ \mathrm{dB}$ is about 20%. Fig. 13 shows the comparison of the simulated AR with the measured result. The measured bandwidth for $\mathrm{AR} \leq 3\,\mathrm{dB}$ is approximately 22%, but there is a slight



(a) f=5.7 GHz.



(b) f=6.7 GHz.

Fig. 14. Radiation patterns of the cavity-backed slot-strip loop antenna.

bandwidth shift between the AR and RL. The overlapped bandwidth for $\mathrm{AR} \leq 3$ and $\mathrm{RL} \geq 10\ \mathrm{dB}$ is about 19%. The gain of the cavity-backed slot/strip loop antenna is found to be around

9 dBi. The radiation patterns measured at 5.7 GHz and 6.7 GH are compared with the simulated results in Fig. 14 and good agreement is observed for the co-polarization (i.e., the left-hand circular polarization, LHCP) over the main beam. As expected, the beamwidth in the $\phi = 0^\circ$ plane is wider than that in the $\phi = 90^\circ$ plane because the length (i.e., W_s) of the antenna aperture in the x direction is shorter than that (i.e., L_s) in the y direction. The cross-polarization [i.e., the right-hand circular polarization (RHCP)] is less than -15 dB. The discrepancies between the simulated and measured results for the axial ratio, gain, and radiation patterns are mainly due to the measurement errors. We used the *NSI* near-field antenna measurement system. Even though the antenna under test was setup at the far-field zone, the mechanical supporting structures of the system would still cause diffraction, introducing the measurement errors, particularly on the cross-polarized component. But the measurement has indeed demonstrated the broadband CP performance for the proposed antenna.

V. Conclusion

A cavity-backed slot/strip loop antenna has been developed for broadband CP operation. The slot/strip loop is a combination of a slot loop and a strip loop. The slot loop radiates a CP wave at a lower frequency while the strip loop produces CP radiation at a higher frequency. A combination of the two frequencies leads to a significant bandwidth enhancement. A simple microstrip line is introduced to feed the slot/strip loop antenna. It has been demonstrated that the proposed cavity-backed loop antenna can achieve a bandwidth of 19% for $\mathrm{AR} \leq 3$ dB with $\mathrm{RL} \geq 10$ dB. The operating principles of the slot/strip loop antenna are investigated. Simulation and experimental results show good agreement.

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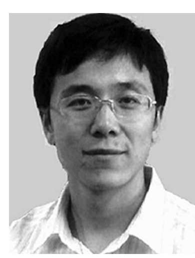

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Dr. Laskar's honors include the Army Research Office's Young Investigator Award in 1995, the National Science Foundation's CAREER Award in 1996, NSF Packaging Research Center Faculty of the Year in 1997, and co-recipient of the IEEE Rappaport Award (Best IEEE Electron Devices Society Journal Paper) in 1999. He was faculty advisor for the 2000 IEEE MTT IMS Best Student Paper award, was Georgia Tech Faculty Graduate Student Mentor of the year in 2001, received a 2002 IBM Faculty Award, and the 2003 Clemson University College of Engineering Outstanding Young Alumni Award. He was the 2003 recipient of the Outstanding Young Engineer award of the Microwave Theory and Techniques Society and was named an IEEE Fellow in 2005. For the 2004–2006 term, he served as an IEEE Distinguished Microwave Lecturer and currently is an IEEE EDS Distinguished Lecturer. He received Georgia Tech's "Outstanding Faculty Research Author" award in 2007, and has been appointed General Chairman of the IEEE International Microwave Symposium 2008.

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