Planar Circularly Polarized Microstrip Antenna with a Single Feed

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***Abstract*—A novel circularly polarized (CP) microstrip antenna is introduced. The antenna is fed with a single coaxial probe and the structure is planar. The CP bandwidth is much larger than available single-probe microstrip antennas and the CP radiation quality is excellent over the entire upper hemisphere.**

***Index Terms*—Circular polarization, patch antennas.**

I. Antenna Geometry and Design Formulas

In a recent paper [1], a novel single-probe circularly polarized (CP) microstrip antenna with an improved CP bandwidth was described. This newly developed antenna has a double-layer structure. Two orthogonal modes are excited in the upper and lower cavities. The 90° phase difference between the mode excitations is achieved by coupling holes between the two resonant cavities. In order to eliminate any unwanted mode excitations in each cavity region for CP radiation, vertical conducting foils are needed at the nonradiating edges of both the upper and lower layers, which is difficult to fabricate. Moreover, due to the altered shape of the radiating edges, the axial ratio of the radiated field away from the boresight becomes very large.

The proposed CP antenna consists of two substrate layers and two patches backed by a ground plane as shown in Fig. 1. The middle patch is a metallic surface separating the upper and lower layers. The lower layer is fed by a coaxial transmission line and the upper layer is coupled with the lower layer through small circular holes in the middle patch. The antenna is similar to the previously reported design [1] in the operation principle but does not require the vertical conducting structures. The critical condition for achieving CP radiation is that the fields radiated from the lower layer are perpendicular to those from the upper layer. In the previous design, two nonradiating sides of the lower cavity (those which in theory do not radiate) are shorted to meet this condition while the sides of the upper cavity perpendicular to the shorted sides of the lower cavity are blocked by conducting surfaces. For the improved design in this paper, the lengths of the radiating edges of the upper and lower cavities are made different to suppress field excitations of the unwanted modes. The length of the nonradiating edges of the lower layer is approximately equal to that of the upper layer, thus maintaining the same resonant frequencies in both the upper and lower cavities. In other words, b' is about the same as b in Fig. 1. To compensate the reduced radation from the upper cavity due to the shortened radiating edges, the layer thickness of the upper layer is increased appropriately.

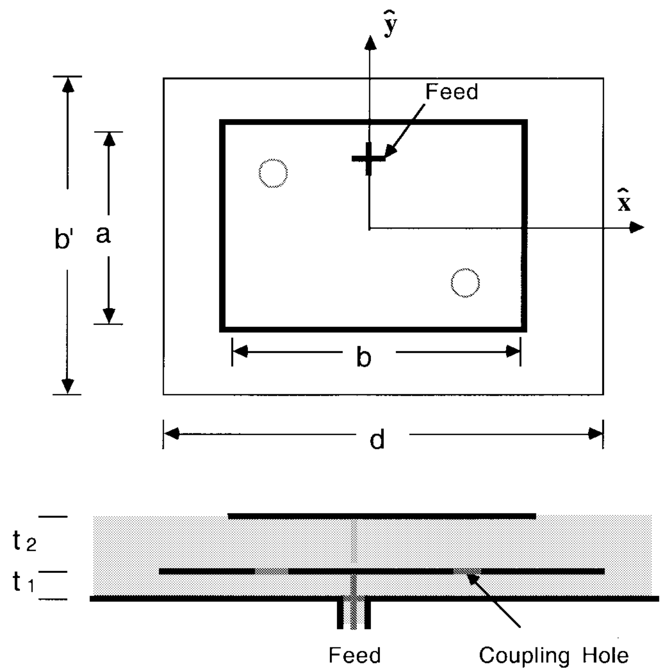

Fig. 1. Double-layer planar circularly polarized microstrip antenna.

The feed pin passes through the middle layer to the top radiating patch to reduce some of unwanted mode excitations in the upper cavity. The feed pin in this case is in conduction contact with both the middle patch and the upper patch, thus acting as a feed for the lower cavity and as a local short for the upper cavity. This arrangement will also facilitate the alignment of those two layers in the fabrication process.

Assuming the layer thicknesses are much smaller than the wavelength, only the dominant TM mode is considered as in the cavity model. The electric fields are then independent of the z coordinate and given by

$$\mathbf{E} = A\sin\left(\frac{\pi}{b'}y\right)\hat{\mathbf{z}} \text{ for lower cavity;} \qquad B\sin\left(\frac{\pi}{b}x\right)\hat{\mathbf{z}} \text{ for upper cavity.} \tag{1}$$

The radiated fields are computed using the equivalent magnetic currents at the radiating edges [2]. To obtain circularly polarized radiation, the constants A and B must have proper magnitudes with a phase difference of 90°. More specifi-

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cally, for right-handed circular polarization (RHCP) $Bt_1d = -jAt_2a$ and for left-handed circular polarization (LHCP) $Bt_1d = jAt_2a$. The holes should be small to guarantee that the small-hole approximation is valid and the desired 90° phase shift is obtained when the electromagnetic energy is coupled to the upper cavity through the holes. On the other hand, relatively large holes are needed to provide a sufficient magnitude of B for good CP radiation.

Considering only the dominant modes in the two resonating cavities coupled through small holes located at (x_1, y_1) and $(-x_1, -y_1)$ in the middle metallic patch, the field excitation in the upper layer relative to that in the lower layer is given by [1]

$$\frac{Bat_2}{Adt_1} = \frac{\frac{-4\alpha_e}{bdt_1}\sin\left(\frac{\pi x_1}{b}\right)\sin\left(\frac{\pi y_1}{b'}\right)}{\left(\frac{k_r}{k}\right)^2 - \left(1 + \frac{1-j}{Q}\right) - \frac{4\alpha_e}{abt_1}\sin^2\left(\frac{\pi x_1}{b}\right)} \quad (2)$$

where α_e is the electric polarizability of the circular hole, k is the wavenumber in the dielectric medium, k_r is the wavenumber at the loss-free resonant frequnecy and Q is the quality factor of the upper cavity, respectively. Two coupling holes, symmetrically placed with respect to the patch center on the same diagonal, are used to increase the coupling by a factor of two without increasing the hole size. Using a static approximation in a microstrip structure where the layer thicknesses are much smaller than the wavelength, the polarizability of a hole is give by

$$\alpha_e = -\frac{\pi r_0^2 t_1 t_2}{t_1 + t_2} \quad (3)$$

where r_0 is the hole radius. Resonance will occur when the real part of the denominator on the right side of (2) vanishes

$$\left(\frac{k_r}{k}\right)^2 = 1 + \frac{1}{Q} + \frac{4\alpha_e}{abt_1}\sin^2\left(\frac{\pi x_1}{b}\right) \quad (4)$$

leading to the desired 90° phase difference between A and B

$$\frac{Bat_2}{Adt_1} = -\frac{4j\pi r_0^2 t_2 Q}{bd(t_1 + t_2)}\sin\left(\frac{\pi x_1}{b}\right)\sin\left(\frac{\pi y_1}{b'}\right). \quad (5)$$

Evidently, for maximum coupling between the cavities, the hole should be located diagonally as far as possible from the center without being affected by the fringe fields as shown in Fig. 1. If the hole radius is then chosen according to the relation

$$r_0 = \left(\frac{bd(t_1 + t_2)}{4\pi t_2 Q \sin\left(\frac{\pi x_1}{b}\right)\sin\left(\frac{\pi y_1}{b'}\right)}\right)^{\frac{1}{2}} \quad (6)$$

circular polarization is achieved for the maximum beam direction. Note that for large Q, the required hole becomes small. Furthermore, (5) shows that the location (on the right- or left-leaning diagonal) will determine whether the polarization be right handed or left handed.

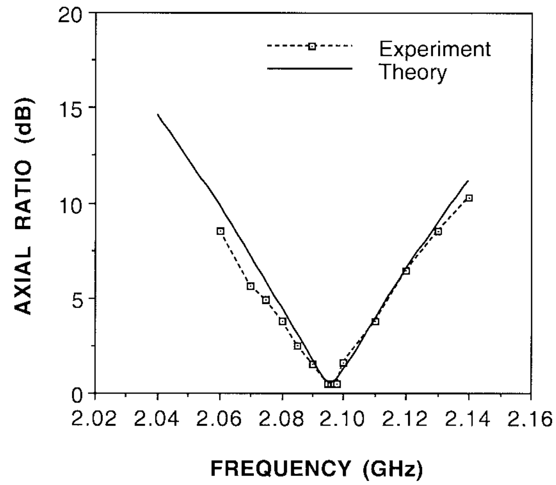

Fig. 2. Axial ratios as a function of frequency. The antenna dimensions are $a = 3.82$ cm, $b = 4.58$ cm, $b' = 4.58$ cm, $d = 5.59$ cm, $t_1 = 0.787$ mm, and $t_2 = 3.175$ mm. The dielectric constant of the substrates is 2.2 and the radius of the coupling holes is 0.50 cm. The feed pin is located 0.6 cm from the edge of the top patch. The holes are located diagonally at (−1.475 cm, 1.19 cm) and (1.475 cm, −1.19 cm). The resonant frequency (for the optimum axial ratio) is 2.098 GHz.

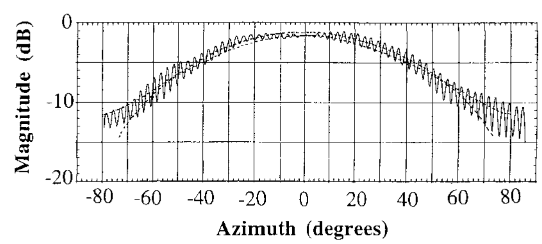

Fig. 3. Radiation patterns of the x-z plane as the linearly polarized reference horn antenna rotates. The frequency is 2.098 GHz. The solid line indicates the measured pattern and the dotted lines show the theoretical upper and lower limits of the radiation level as the reference horn rotates. Antenna dimensions are given in Fig. 2.

II. Experimental Results

The measured frequency for an optimum axial ratio is 2.098 GHz, which is almost the same as the measured resonant frequency for the least input voltage standing wave ratio (VSWR) (2.096 GHz). In other words, the input impedance is almost perfectly matched at the frequency of the optimum axial ratio.

Fig. 2 shows the measured axial ratio as a function of frequency near the resonant frequency in comparison with the theoretical results. A relatively good agreement is observed. For the theoretical evaluation, the quality factor was determined using

$$Q = R_m \frac{bd(t_1 + t_2)}{4\pi r_0^2 t_2 \sin\left(\frac{\pi x_1}{b}\right)\sin\left(\frac{\pi y_1}{b'}\right)} \quad (7)$$

where R_m was the measured axial ratio at the resonant frequency for a minimum axial ratio. The measured 6-dB CP bandwidth was 2.4%, compared with the CP bandwidth of 1.63% for the similar design with vertical structures [1] and with the bandwidth less than 1% reported in [3] for comparable antennas.

Fig. 3 shows the measured radiation pattern taken with a rotating linearly polarized receiver horn. The experimental data is in good agreement with the theoretical results. Here the effective upper radiating patch length was not theoretically computed because of the nonconventional geometry of the microstrip environment. Rather, an extension of 5.7 mm on each side was assumed to produce the radiation levels near the ground plane that matched the experimental values. The axial ratio remains within a few decibels over most of the radiating zone.

The proposed antenna has the all the advantages listed in [1] over the CP antennas using two nearly degenerate modes [3]. In addition, the two nonradiating side walls of each cavity are eliminated and the antenna structure becomes planar. With this improved antenna, the CP bandwidth is increased and the CP radiation quality is improved drastically over the entire radiation zone.

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