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A Pin-Loaded Microstrip Patch Antenna with the Ability to Suppress Surface Wave Excitation

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Abstract—A circular microstrip patch antenna design is proposed for applications that require suppression of surface waves and lateral waves. The proposed design is composed of a circular patch loaded with a single shorting pin on a grounded inhomogeneous dielectric substrate with a desired effective permittivity. The modal equation for the normalized resonance frequency of this design is solved numerically. Simulated and measured radiation patterns show that a good reduction of surface waves and lateral waves is achieved. A comparison between the present work and an alternative design in the literature is presented in this paper. The proposed design could find applications in large patch antenna arrays where mutual coupling needs to be eliminated and in high-precision global positioning system receivers where multipath interfering signals associated with low-angle reflection affect position accuracy.

1. INTRODUCTION

Due to their remarkable features, microstrip patch antennas are very attractive for many applications in modern communication systems. In addition to their ease of fabrication, they have low cost, low weight and can be integrated with other electronics. However, microstrip patch antennas in general suffer from surface wave excitation when they are mounted on a non-air substrate. Besides their contribution to power loss and reducing overall efficiency, excitation of surface waves eventually leads to undesired mutual coupling between elements of an array printed on the same substrate [1–4]. The diffraction of these surface waves at the edge of a finite-size ground plane results in a distorted radiation pattern. In addition, the presence of surface waves is usually associated with lateral waves, which reduce the accuracy of high-precision GPS receivers by causing low-angle interfering signals [5, 6]. Several designs have been proposed to suppress these undesired waves in microstrip patch antennas. In [7, 8], an annular ring patch with a properly adjusted shorted inner radius and open outer radius was proposed as a reduced surface wave antenna. The short circuit at the inner radius was achieved by using a high number of shorting pins. The same technique was used to design a dual-band microstrip patch antenna for high-precision GPS receivers [9]. In [10–13], circular patches that include shorting pins were investigated using homogeneous dielectric substrates, without regard to the experimental realizability of the resulting designs. In this paper, we propose a simple design for a microstrip patch antenna with the ability to suppress surface wave and lateral wave excitation. The design procedure starts with designing a circular patch loaded with a single shorting pin on a grounded homogeneous dielectric substrate, as depicted in Fig. 1. To ensure that the design is experimentally realizable, an inhomogeneous substrate is used to produce an effective relative permittivity equivalent to the theoretically required value.

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2. ANALYSIS

It is well known that a circular microstrip patch antenna of radius a operating at the dominant mode can be modeled as a ring of magnetic current. The surface wave excited by this ring is given by[7]

$$E_z^{sw} = A\cos(\varphi)\, J_1'(\beta_{TMo}a)\, H_1^{(2)}(\beta_{TMo}\rho) \tag{1}$$

where $J_1'(.)$ is the derivative of the Bessel function of the first kind, $H_1^{(2)}(.)$ the Hankel function of the second kind, and β_{TMo} the wavenumber of the TM_o surface wave mode, which is approximately equal to the wavenumber in air $k_o$and is the only excited mode for the case of an electrically thin grounded substrate since it has a zero cutoff frequency. As shown in [7], in order to nullify the surface waves and lateral waves, the term $J_1'(\beta_{TMo}a)$ is set to zero, leading to a reduced surface wave condition given by

$$k_o a = x_{11}' \tag{2}$$

where $x_{11}' = 1.8412$ is the first root of the derivative of the Bessel function of the first kind. Meanwhile, it is well known that the resonance frequency of a circular patch operating at the dominant mode is given by

$$ka = x_{11}' \tag{3}$$

where k is the wavenumber in the dielectric substrate. Except for the case of the air substrate, it is clear that both conditions in Eqs. (2) and (3) cannot be simultaneously satisfied. If we choose radius a to satisfy the reduced surface wave condition given by Eq. (2), the patch will not resonate at the desired frequency according to Eq. (3). As a result, the circular patch structure has to be modified in order to reduce the surface wave and have the desired resonance frequency at the same time.

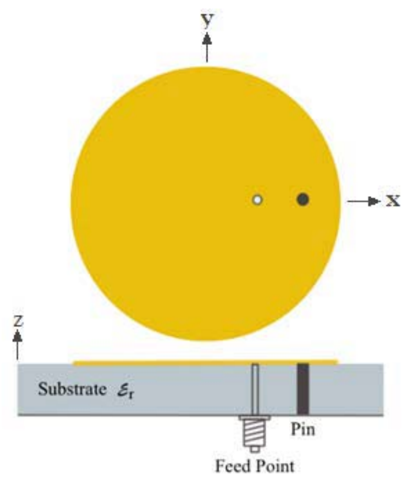

Figure 1. Geometry of the proposed antenna with a probe feed.

In the present work, we introduce a circular patch with radius a chosen according to the reduced surface wave condition in Eq. (2). The patch is loaded with a single shorting pin that has a radius $b \ll a$ and is located at radial position r_o. The pin-loaded circular patch antenna was rigorously analyzed in [12]. It was found that the modal equation for the normalized resonance frequency in the presence of the shorting pin is given by

$$Y_o(kb) - 2\sum_{n=0}^{\infty} \chi_n J_n[k(r_o - b)]\, J_n(kr_o) \left[\frac{Y_n'(ka)}{J_n'(ka)}\right] = 0 \tag{4}$$

where $J_n(.)$ and $Y_n(.)$ are the Bessel functions of the first and second kind, respectively. We solve this equation numerically to find the value of the normalized resonance frequency of the dominant mode ka, which in this case is a function of the pin position and radius and has a value greater than x_{11}'. Solving for ka will lead to finding the exact value of the substrate's relative permittivity that will make the patch resonate at the desired frequency. The relative permittivity can be calculated using

$$\epsilon_r = \left(\frac{ka}{k_o a}\right)^2 \tag{5}$$

The normalized resonance frequency ka is plotted in Fig. 2 versus the pin's position (r_o/a) for different values of the pin's radius (b/a). This result along with Eq. (2) is used to design a reduced surface wave antenna in the following section. The exact relative permittivity computed in Eq. (5) is typically not commercially available. To solve this problem, an inhomogeneous substrate is created by removing a portion of the dielectric material underneath the patch, as shown in Fig. 3, to yield an effective relative permittivity equivalent to the theoretical value predicted by Eq. (5).

It is worth noting that the analysis in [12] uses a cavity model to derive Equation (4), consequently, fringing fields which may cause minor surface excitation were not accounted for. However, as we show in the simulation and measurement results, the analytical model is highly accurate.

3. SIMULATION AND EXPERIMENTAL RESULTS

As a numerical example, a circular patch antenna of radius a with pin position $r_o = 0.75a$ and pin radius $b = 0.03a$ is considered in this section. It is worth to mention here that this value of radial position is of particular interest since it corresponds to the maximum ka which in turn leads to the highest possible value of substrate relative permittivity. The patch was designed so that it operates at the L_1-band of the GPS, which is 1.575 GHz, and at the same time has the capability to reduce surface wave and lateral wave excitations.

The radius of the circular patch was chosen according to the reduced surface wave condition in Eq. (2), which in this case is equal to 55.8 mm. Using these parameters, we obtained $ka = 2.2249$ from the data in Fig. 2. By substituting ka in Eq. (5), the relative permittivity ϵ_r was calculated to be 1.46, which is the exact value that makes the pin-loaded patch resonate at the required frequency. For practical reasons, however, we used the common Rogers RT/Duroid 5880, which has $\epsilon_r = 2.2$ as a substrate for this design. In order to reduce the effective permittivity under the patch to 1.46, hence having a resonance frequency at 1.575 GHz, a 1-mm thick portion of the substrate out of the 1.6 mm total thickness was removed with a milling machine, as shown in Fig. 3. The inner radius of the removed portion is 34 mm and the outer radius is equal to the radius of the patch. These dimensions were obtained through simulations using ANSYS HFSS to obtain the desired resonance frequency. The structure sits on 140 mm by 140 mm ground plane and is excited by a coaxial feed port located at a radial distance from the center equal to 29 mm. It is important to note here that the back of the antenna is covered with another ground plane to substitute for the metallic part that was removed with the dielectric.

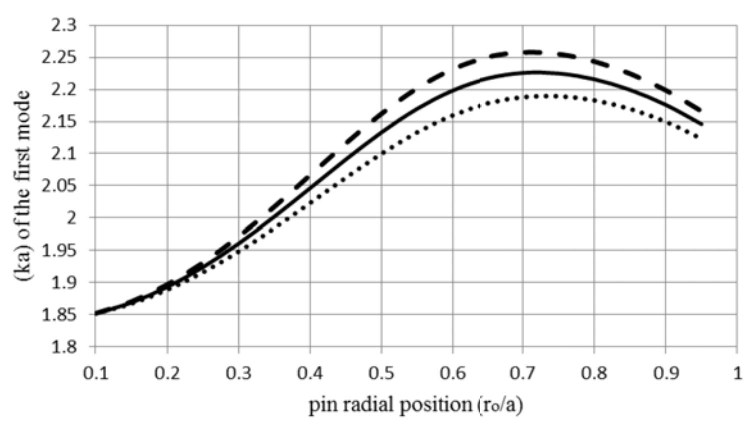

Figure 2. The normalized resonant frequency of the dominant mode for the single pin patch. Dashed line ($b/a = 0.04$), solid line ($b/a = 0.03$) and dotted line ($b/a = 0.02$).

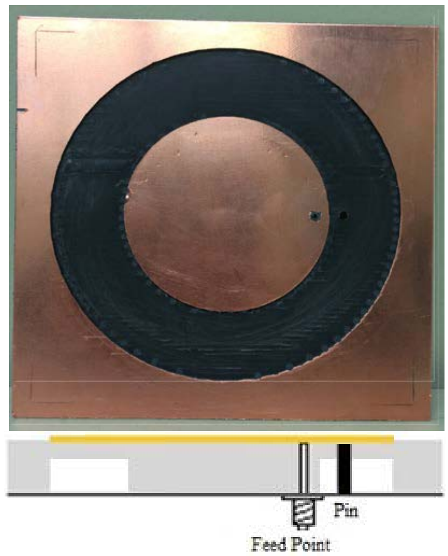

Figure 3. The back side of the fabricated design with a side view of its geometry (with the ground plane removed).

The proposed design was simulated using ANSYS HFSS software and experimentally tested. As shown in Fig. 4, it is clear that the fabricated antenna has a resonance at the desired frequency and is in good agreement with simulation results.

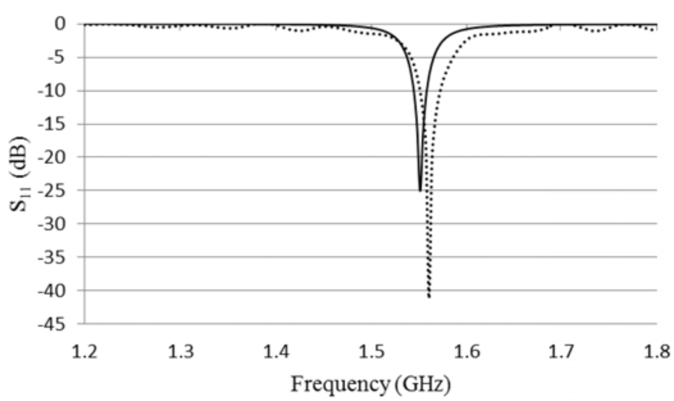

Figure 4. Reflection coefficient $|S_{11}|_{\text{dB}}$ of the proposed design. Simulation results (solid) and experimental results (dotted).

The simulated and measured radiation patterns for the E-plane and H-plane are plotted in Fig. 5(a) and Fig. 5(b), respectively. As seen in these figures, the proposed design has a smooth radiation pattern with a discrimination against the lateral waves better than 20 dB in the E-plane. However, the relative value of the lateral waves in the H-plane is about -15 dB. This is because the design lacks symmetry about the y-axis. The front-to-back ratio in the E-plane and H-plane are 20 dB and 18 dB, respectively. It is worth noting here that although the substrate is inhomogeneous due to removing a portion of it, the circular patch antenna can still be modeled as a ring of magnetic current, making the same analysis derived for the homogeneous case still applicable to this case as well. Simulation results clearly indicated that having an inhomogeneous substrate with effective permittivity of 1.46 produces a radiation pattern that is extremely close to the radiation pattern obtained using a homogeneous substrate with actual permittivity of 1.46, as can be seen in Fig. 6.

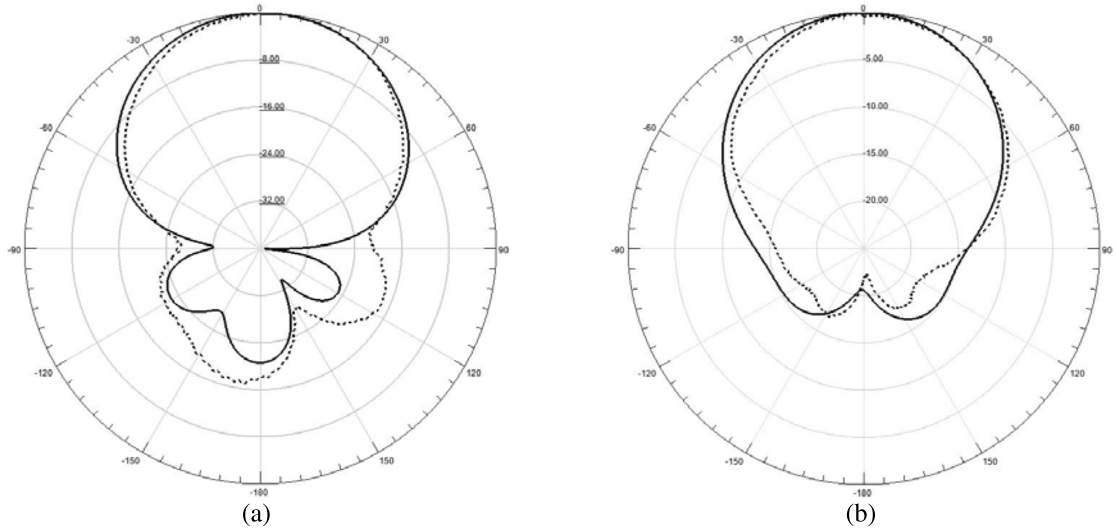

Figure 5. Normalized radiation pattern for the proposed design. (a) E-plane; (b) H-plane. Solid line, simulated; dotted line, measured.

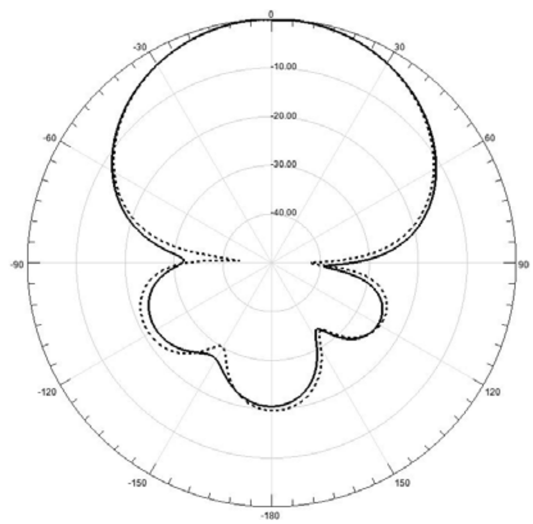

Figure 6. Simulated radiation patterns (E-plane) for the proposed inhomogeneous design (solid) and the same design with homogeneous dielectric with permittivity of 1.46 (dotted).

In order to illustrate the degree of surface and lateral wave suppression, a conventional unloaded circular patch resonating at the same frequency of the pin-loaded patch, and using the same substrate parameters, was simulated. The radiation patterns of the two designs are compared in Fig. 7, which clearly shows a substantial lateral wave reduction (more than 20 dB for $\theta = \pi/2$) by the proposed antenna.

Next, simulation results were compared between the proposed design and the two-pin design introduced in [10]. Both designs showed a good reduction of surface waves and lateral waves as can be seen from the radiation pattern in Fig. 8. Gain, Directivity, Radiation efficiency, and bandwidth for both designs are provided in Table 1. It is clear that the proposed design has better gain and directivity than the two-pin design; moreover, radiation efficiency is higher by approximately 3.5%. This is mainly due to lowering the substrate permittivity and reducing the number of shorting pins, hence minimizing the losses.

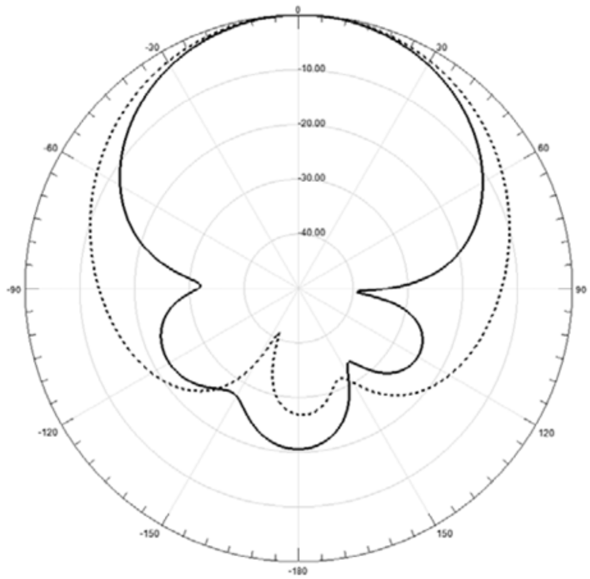

Figure 7. Comparison between simulated radiation patterns of the pin loaded design and conventional unloaded circular patch (E-plane). Pin loaded (solid) and unloaded (dotted).

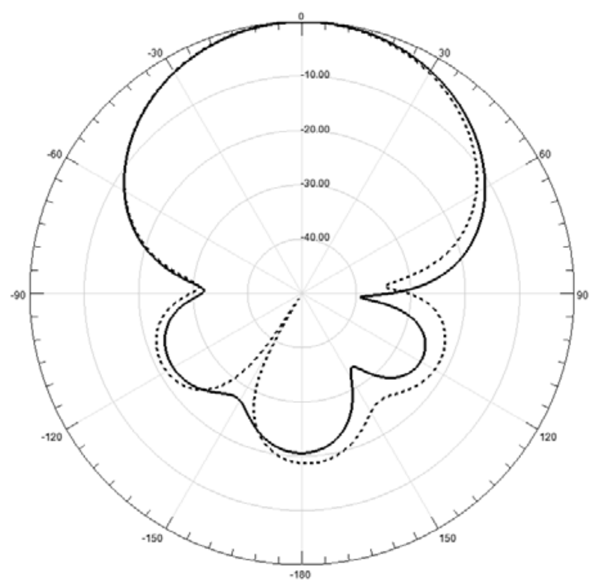

Figure 8. Normalized radiation pattern (E-plane) for both designs. Single pin (solid) and two-pin (dotted).

Table 1. Comparison between single-pin and two-pin designs.

	Gain (dB)	**Directivity (dB)**	**Radiation Efficiency**	**10 dB Bandwidth**
Single Pin	8.1	8.75	86.3%	1.01%
Two Pins	7.4	8.19	82.9%	0.8%

4. CONCLUSION

A simple design for a microstrip patch antenna with the capability of suppressing surface wave and lateral wave excitations was introduced. The design consists of a pin-loaded circular patch on a grounded inhomogeneous dielectric substrate. The suppression of surface waves and lateral waves at a specific resonance frequency was achieved by properly adjusting the patch radius, pin's position, and relative permittivity. We successfully demonstrated that partial removal of the dielectric substrate under the patch was a good solution to realize an effective relative permittivity equivalent to the theoretical value needed for achieving resonance frequency while suppressing the surface waves at the same time. Good agreement between simulated and experimental results clearly indicated that the radiation pattern of the proposed design had the capability of reducing surface waves and lateral waves. A comparison with an alternative design in the literature indicated that this new design was promising for the use in several applications, such as large patch antenna arrays with reduced mutual coupling and high-precision GPS receivers with reduced susceptibility to low-angle interference.

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