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A Miniaturized TM_{21} Mode Circular Microstrip Patch Antenna

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Abstract—A miniaturized TM_{21} mode circular patch antenna is introduced. The miniaturization is realized by loading the patch with four symmetric radial slits, which facilitate elongating the current path and thus reducing the resonant frequency and the patch size. In particular, the eigenvalue of the proposed higher order mode is reduced to that of a conventional dominant TM_{11} mode antenna, resulting in about 40% reduction in the radius. The effects of the slit geometry on miniaturization and resonant frequency are studied. The measurement results are also presented, which are in good agreement with the simulation ones. Such miniaturized TM_{21} patch antennas with conical radiation patterns have manifold applications in phased array antennas for booming communication demands.

1. INTRODUCTION

Microstrip patch antennas (MPAs) have become an appropriate candidate for wireless communication systems due to their compact and low profile configurations. More importantly, by changing the aperture size of the radiating patch, different radiation patterns can be achieved. In particular, MPAs are capable of generating broadside and conical radiation patterns at their dominant and higher order modes, respectively. Such conical-shaped radiation patterns have numerous applications in satellite communications, wireless local area network, tracking and guiding systems, and anti-jamming applications [1]. However, the main issue with these higher order modes is that they require much larger aperture sizes than the dominant TM_{11} mode, whose radius is $0.293\lambda_d$ [2], where λ_d is the guided wavelength. For the mode of interest in this letter, i.e., the TM_{21} mode, the radius of the patch should be enlarged to $0.486\lambda_d$ [2], which would hinder its applications in tightly-spaced antenna and array configurations. The aforementioned radii are proportionally related to the eigenvalues of the TM_{11} and TM_{21} modes, which are 1.841 and 3.054 [2], respectively. Previously, shorting vias were employed for the miniaturization of TM_{02} circular patch antennas [3]. The size reduction of MPAs may also be realized by dielectric loading, as any increase in the permittivity can help reduce the guided wavelength of the antenna. Moreover, magneto-dielectric substrate was also utilized for the miniaturization of microstrip patch antennas, as reported in [4], where the patch area was reduced by 65%. However, high-contrast dielectric/magnetic materials add a considerable mass to the antenna and increase losses. Other prevailing techniques in antenna miniaturization are capacitive and inductive loading [5], folded patch design [6], and altering the shape of the patch to reduce the resonance frequency [7–10]. Moreover, the meander line technique is used to realize electrically small antennas. For example, a meander line dipole antenna was reported in [11] for MHz frequency applications.

In this letter, a compact circular microstrip patch antenna operating at the TM_{21} mode is introduced using the slit loading technique. By judiciously placing four radial slits on the patch, the current path is meandered, which consequently reduces the resonant frequency and thus miniaturizes the patch size. In particular, it will be shown that the eigenvalue of the TM_{21} mode circular patch will

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reduce from 3.054 to 1.841, which becomes equal to that of the first mode. As a result, the proposed miniaturized patch antenna may readily be utilized in pertinent wireless applications, occupying the same aperture size of the conventional dominant mode patch antenna. Parametric studies are performed to study the resonant frequencies and reflection coefficients for different slit lengths and angular openings. For validation, a prototype of the miniaturized antenna is fabricated and tested, and its corresponding measured results are presented.

2. CONFIGURATION OF THE ANTENNA

To provide physical insights into the working principle of the proposed miniaturized antenna, the surface current distributions of a conventional circular patch antenna operating at the TM_{21} mode are illustrated in Fig. 1. As it is observed, there are four distinct peak intensities of the current distributions in each of the four quadrants of the disk. Therefore, if one places a radial slit in each of these quadrants, the current path will be meandered, resulting in the antenna miniaturization. The resultant antenna is depicted in Fig. 2, where four radial slits are cut from the patch. The slits are curved trapezoids to intercept the current path as much as possible and are symmetrically arranged with a 90° angular spacing. The slit is defined by its length and angular opening, denoted by L and α in Fig. 2, respectively. These two parameters play a key role in miniaturizing the TM_{21} patch size.

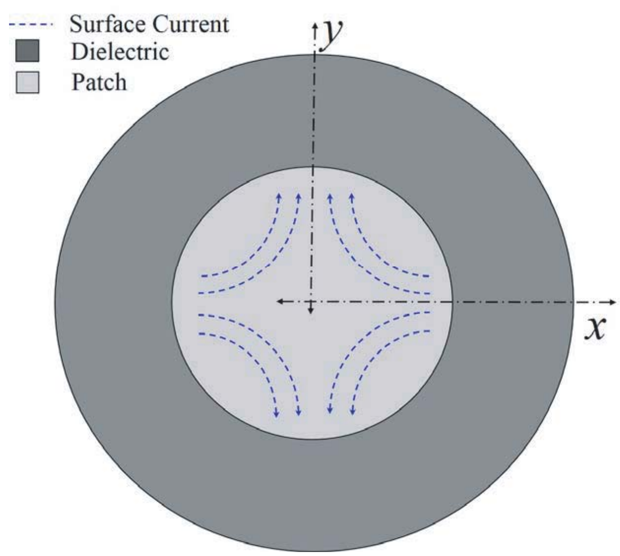

Figure 1. Geometry of a conventional circular patch antenna along with its typical surface current distribution at the higher order TM_{21} mode.

The unloaded conventional patch antenna resonates at 5 GHz. The radiating patch is mounted on a 1.6 mm thick Rogers RT/Duroid 5880 [12] substrate with a relative permittivity of 2.2 and loss tangent of $\tan\delta = 0.0009$. The radius of the patch, denoted by R_p in Fig. 2, is 19.25 mm, which is equal to $0.465\lambda_d$ at 5 GHz. The antenna is fed by a 50-Ω coaxial probe with a feed point 4.2 mm away from the center of the circular patch. The supporting ground and substrate have a diameter of 120 mm. Parametric studies are carried out to finalize the slit dimensions, such that the size of the TM_{21} patch can be reduced to that of a dominant TM_{11} patch antenna, as will be shown in Section 3.

3. PARAMETRIC ANALYSIS

An extensive parametric study has been conducted to finalize the dimensions of the radial slits placed on the patch. In this section, the effects of the slit length and angular opening, i.e., L and α, respectively, on the resonant frequency and the antenna miniaturization will be detailed.

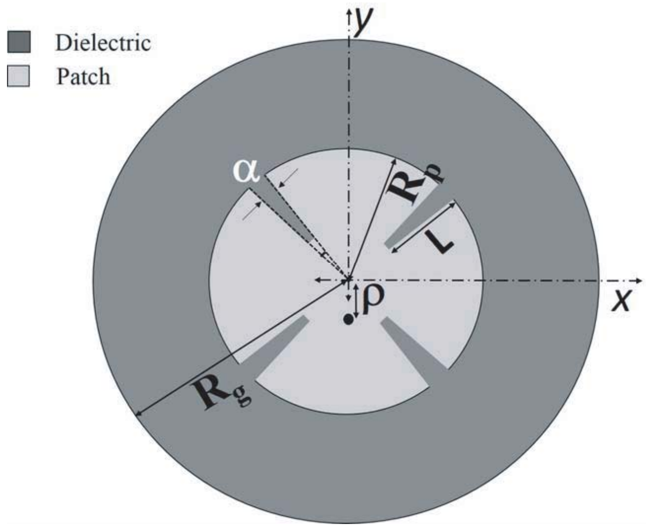

Figure 2. Geometry of the proposed slit-loaded TM_{21} circular patch antenna with $Rp = 19.25$ mm, $Rg = 60$ mm, $\rho = 4.2$ mm, $\varepsilon_r = 2.2$, and substrate thickness of 1.6 mm.

3.1. Varying L

The proposed antenna shown in Fig. 2 was simulated using the full-wave finite-element based solver ANSYS HFSS V.18 [13]. The reflection coefficients are plotted in Fig. 3, where L changes from 0 mm to 13 mm for a fixed α of 4.2°. As can be seen, the resonant frequencies of the TM_{11} and TM_{21} modes of the unloaded patch, i.e., the $L = 0$ case, occur at 3 GHz and 5 GHz, respectively. These modes were numerically confirmed through examining their respective broadside and conical radiation patterns, which are omitted here for brevity. By placing four symmetrical slits, the resonant frequency of the TM_{21} mode starts decreasing as the slit length increases. The slits force the current to meander, helping in further increasing the electric size of the patch. In particular, the frequency reaches to that of the TM_{11} mode, when the slit length is 13 mm. As for the dominant mode, its resonant frequency is slightly impacted by the slits. For example, it shifts down from 3 GHz to 2.3 GHz when L varies from 0 to 13 mm, respectively. This allows one to design a TM_{21} mode circular patch antenna with the same aperture size as the conventional dominant mode patch. The S_{11} is well below -10 dB for different slit lengths for the TM_{21} mode.

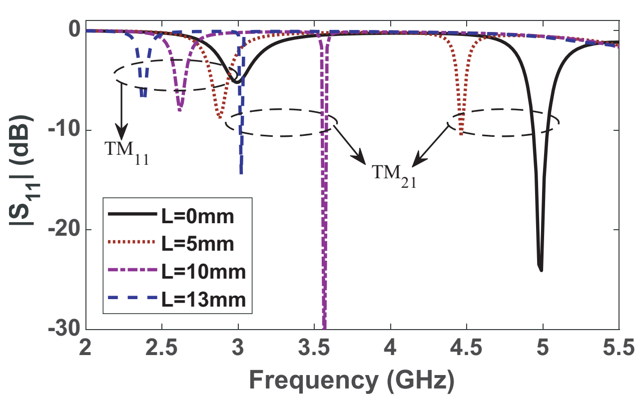

Figure 3. Reflection coefficients of the proposed antenna in Fig. 2 for different slit lengths with $\alpha = 4.2°$.

3.2. Varying α

It is instructive to investigate the effects of the angular opening of the slits on antenna miniaturization. The opening angle (α) provides another degree of freedom to further control the miniaturization such that it finely tunes the resonant frequency of the TM_{21} mode to 3 GHz, which results in an eigenvalue of 1.841 for the miniaturized TM_{21} mode. This occurs when α is equal to 4.2°. The results are shown in Fig. 4 with opening angles varying from 0° to 6° for a fixed length of $L = 13$ mm. As observed, the resonant frequency of the TM_{21} mode decreases as α increases. The S_{11} is well below the -10 dB line for different opening angles (α) for the TM_{21} mode.

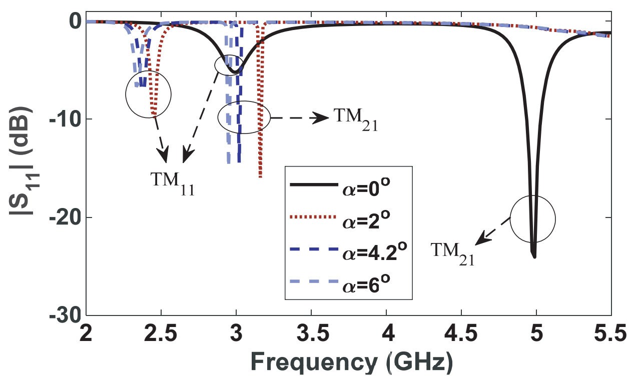

Figure 4. Reflection coefficients of the proposed antenna in Fig. 2 for different slit angles with $L = 13$ mm.

For the finalized slit size of $L = 13$ mm and $\alpha = 4.2°$, a summary of the resonant frequencies and size reduction of the conventional and miniaturized TM_{21} patch antennas is listed in Table 1. The resonant frequency of the TM_{21} mode reduces from 5 GHz to 3 GHz, resulting in about 40% reduction of its radius. Therefore, the novelty of the proposed structure is to use the same eigenvalue of the conventional TM_{11} mode, equal to 1.841, to design such a miniaturized TM_{21} patch antenna.

Table 1. Comparison of conventional and miniaturized TM_{21} patch antennas with four slits of $L = 13$ mm and $\alpha = 4.2°$.

TM_{21} Patch Antenna	f (GHz)	Radius	reduction in radius
Conventional	5	$0.486\lambda_d$	NA
Proposed Slit-loaded	3.01	$0.293\lambda_d$	$\sim 40\%$

4. MEASURED RESULTS

The proposed miniaturized TM_{21} circular patch antenna shown in Fig. 2, with the slit dimensions of $L = 13$ mm and $\alpha = 4.2°$, was fabricated and tested. A photograph of the prototype antenna is depicted in the inset of Fig. 5. The measured and simulated reflection coefficients of the proposed slit-loaded antenna are compared in Fig. 5. Good agreement is observed between the measured and simulated $|S_{11}|$. As can be seen, the frequency of the miniaturized TM_{21} mode is reduced to that of the dominant mode with no slits. This confirms that the eigenvalue and the size of the patch have accordingly been reduced to those of the TM_{11} mode in conventional patch antennas.

The radiation patterns of the prototype antenna were measured in the spherical near-field anechoic chamber of the University of Alabama in Huntsville. The results are plotted in Fig. 6 and compared with the simulated results at the E- and H-planes at 3 GHz. Overall, the results are in good agreement, except there is a slight difference in the right-hand side of the pattern, which is mainly due to the reflections from the connecting cable to the antenna, contributing to the asymmetry observed in the

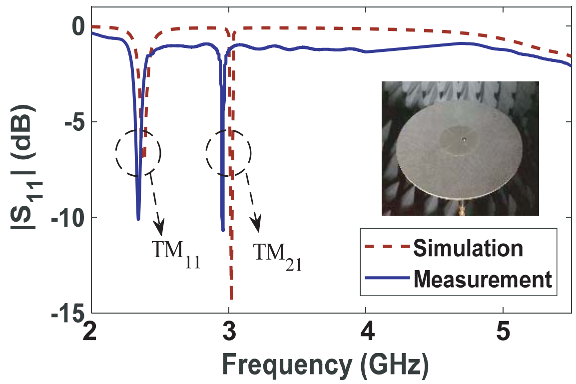

Figure 5. Simulated and measured reflection coefficients of the fabricated antenna, with its photo embedded in the plot, with $L = 13\,\mathrm{mm}$ and $\alpha = 4.2°$.

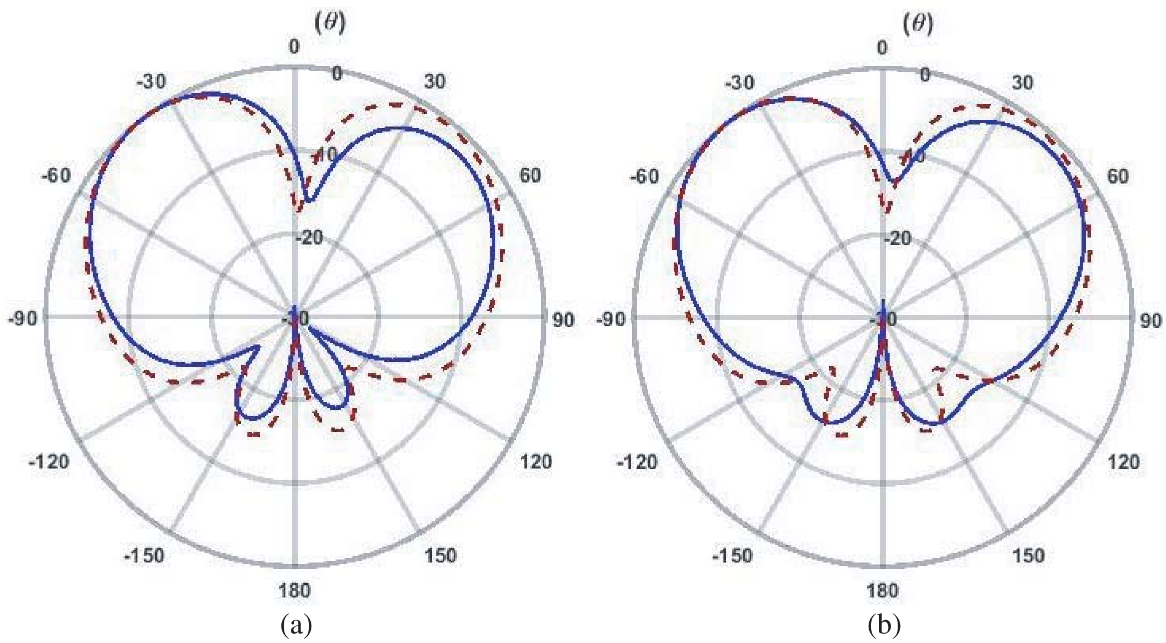

Figure 6. Measured and simulated radiation patterns of the fabricated antenna at 3 GHz, when $L = 13\,\mathrm{mm}$ and $\alpha = 4.2°$; (a) E-plane, (b) H-plane; —— Measured pattern, - - - - Simulated pattern.

patterns. Nonetheless, a conical radiation pattern is obtained with a null at the boresight direction of $\theta = 0°$, as expected for a circular patch antenna operating at the TM_{21} mode.

5. CONCLUSION

A novel miniaturized circular patch antenna operating at the TM_{21} mode was introduced. The miniaturization was realized by placing four radial slits to elongate the current path and thus reduce the aperture size of the antenna. A parametric study was conducted to understand the effects of the slits on the size reduction and reflection coefficients. It was concluded that the size of the patch can be controlled by changing the radial and angular dimensions of the slits. Reduction up to 40% has been achieved in the patch radius, which makes its aperture size equal to that of the conventional TM_{11} circular patch antenna.

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