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Amplitude Control Null Steering in a Multi-Mode Patch Antenna

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Abstract—A novel null steering method in a multi-mode circular microstrip patch antenna is presented in this letter. A stacked patch configuration, capable of exciting three different radiating modes, namely TM_{11}, TM_{21}, and TM_{31}, is investigated. When two or three modes are excited simultaneously, up to three nulls can be formed in the upper hemisphere, and by tuning the amplitude ratio of these modes, a continuous null steering pattern is realized. It is shown that a full hemispherical null steering of $\pm 90°$ range can be achieved using the proposed method. The null steering capability with different dielectric permittivities is also presented.

1. INTRODUCTION

In the recent years, with significant advancements in the cognitive communication systems, robust and compact antenna designs with pattern re-configurability features are required. In particular, the null steering capability is much sought after to mitigate interference and suppress jamming signals by adaptively creating a null in the direction of jammers. Generally, phased array antennas are widely used to steer the null positions by optimizing the amplitude and phase excitations of the selected array elements. For example, different optimization methods [1–4] have been used to effectively choose a small number of elements to adjust their amplitude and phase, which are only required to construct adequate nulls. To steer a single null in such array antennas, amplitude and phase control of only the edge elements of a linear configuration [5, 6] or a planar configuration [7] is required. Another common method of null steering is the use of diodes [8], varactors [9, 10], and reactive loading [11] or capacitive exciters [12] in the antenna design. However, the dc control circuits make the overall system complex and introduce more loss.

Other than phased array antennas, single antennas with radiation pattern diversity and without the incorporation of dc passive components are of much interest for null steering applications. In this aspect, over-moded antennas are a promising candidate due to their different radiation characteristics in the form of broadside and conical radiation patterns. For instance, a monopole antenna was used to excite conical radiation and a corner-truncated rectangular patch was utilized to obtain broadside radiation in [13], whereas boresight-null radiation pattern was achieved in [14] by exciting a four rotationally symmetric strips of micrsotrip lines. A concentric circularly-polarized patch antenna was reported in [15, 16] consisting of a circular patch and two annular rings to excite the first three modes. However, it had a limited main beam scanning [15] with only two nulls [16].

In this letter, up to three nulls are realized in a stacked three-layer circular patch antenna, where the top layer excites the fundamental TM_{11} mode with a broadside radiation pattern, and middle and bottom layers excite the TM_{21} and TM_{31} modes, respectively, with conical radiation patterns. Continuous null steering can be achieved by combining these three modes with a proper amplitude control. Three different cases will be presented: i) TM_{11} and TM_{21} modes, ii) TM_{21} and TM_{31} modes

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to achieve 0° to ±90° continuous null steering by creating one stationary null and two steerable nulls in the upper hemisphere, and iii) simultaneous excitation of all three modes, which facilitate the formation of three steerable nulls. Moreover, a parametric study of null steering capability of the multi-mode antenna with different dielectric substrates is provided.

2. ANALYTICAL MODEL OF THE ANTENNA

The antenna under study is a tri-mode stacked circular microstrip patch antenna, exciting the fundamental TM_{11} mode with a broadside radiation pattern and the higher order TM_{21} and TM_{31} modes with conical radiation patterns at the frequency of 10 GHz, as depicted in Fig. 1. For simplicity, it is assumed that the antenna is backed by an infinite ground plane. Based on the cavity model, the x-polarized radiated fields of this tri-mode circular microstrip patch antenna shown in Fig. 1 can be expressed as [17],

$$\begin{cases} E_\theta = \sum_{n=1}^{3} -j^n A_n F_{n1}(\theta)\cos(n\phi) \\ E_\phi = \sum_{n=1}^{3} j^n A_n G_{n1}(\theta)\cos(\theta) sin(n\phi) \end{cases} \tag{1}$$

where A_n $(n = 0 \sim 3)$ is the mode content factor, which is a complex number. F_{n1} and G_{n1} are the radiation functions of the E- and$H$-plane components for the TM_{n1} mode and can be expressed as,

$$\begin{cases} F_{n1}(\theta) = J_{n-1}(k_o a_n \sin\theta) - J_{n+1}(k_o a_n \sin\theta) \\ G_{n1}(\theta) = J_{n-1}(k_o a_n \sin\theta) + J_{n+1}(k_o a_n \sin\theta) \end{cases} \tag{2}$$

where J_n is the Bessel function of the first kind of order n, and k_o is the wave number. The zeros of the first derivatives of the Bessel function J'_n determine the radii of the patches. For the TM_{11}, TM_{21}, and TM_{31} modes, the associated eigenvalues are $\chi'_{11} = 1.8412$, $\chi'_{21} = 3.0542$, $\chi'_{31} = 4.2012$, respectively. In this study, dielectric substrates with different dielectric constants ranging from 1 to 4 is considered as the supporting substrate with a height of 1.6 mm between the layers and the physical radii of the TM_{11}, TM_{21}, and TM_{31} patches are calculated as $a_1 = 0.293\lambda_d$, $a_2 = 0.486\lambda_d$, $a_3 = 0.669\lambda_d$, respectively using the following equation [17]

$$a_n = \frac{\chi'_{n1}\lambda_d}{2\pi} \tag{3}$$

where λ_d is the wavelength in the corresponding dielectric substrate at the selected frequency of 10 GHz.

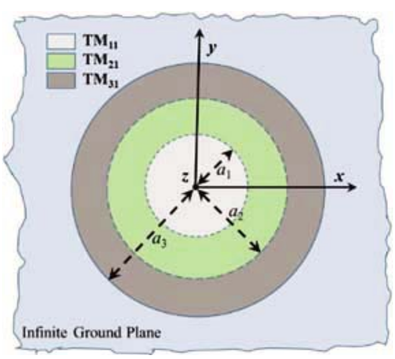


Figure 1. Top-view of the three-layer stacked circular microstrip patch antenna operating at the TM_{11}, TM_{21} and TM_{31} modes; a_1, a_2, and a_3 are the radii of these modes, respectively.

3. RESULTS OF NULL STEERING

Null steering capability of the tri-mode antenna element is investigated by only controlling the amplitude excitation with different combinations of modes. To begin with, the TM_{11} and TM_{21} modes are excited simultaneously and two steerable nulls are formed. Later, a unique combination of the two higher order modes, i.e., TM_{21} and TM_{31}, is investigated to create one stationary null at the $\theta = 0°$ direction and two independent steerable nulls in the visible region. To conclude, a simultaneous excitation of all the three modes is studied to achieve a full hemispherical null steering using three steerable nulls. In addition, the null steering capability of the tri-mode antenna is studied with different dielectric substrates, especially for practical applications, where tunable materials such as Liquid Crystals may be used to provide further adaptability.

3.1. Case I: TM_{11} and TM_{21} Modes

In this section, we focus on the TM_{11} and TM_{21} modes only, while deactivating the TM_{31} patch, i.e., only the TM_{11} and TM_{21} ports are excited, while the TM_{31} port is matched. For simplicity, the normalized (TM_{21} to TM_{11}) mode content factor A_{21} is used, which can be expressed as $A_{21} = |A_{21}|\angle\alpha_{21}$, where $|A_{21}|$ is the amplitude excitation ratio and α_{21} is the phase excitation ratio between the two modes. It is found that, when $\alpha_{21} = -90°$, the main beam is scanned over the positive elevation angles, and nulls are formed on the negative elevation angles. As the polarity of the phase excitation ratio is reversed, i.e., $\alpha_{21} = +90°$, the scanned beam and null positions are switched on the opposite elevation plane.

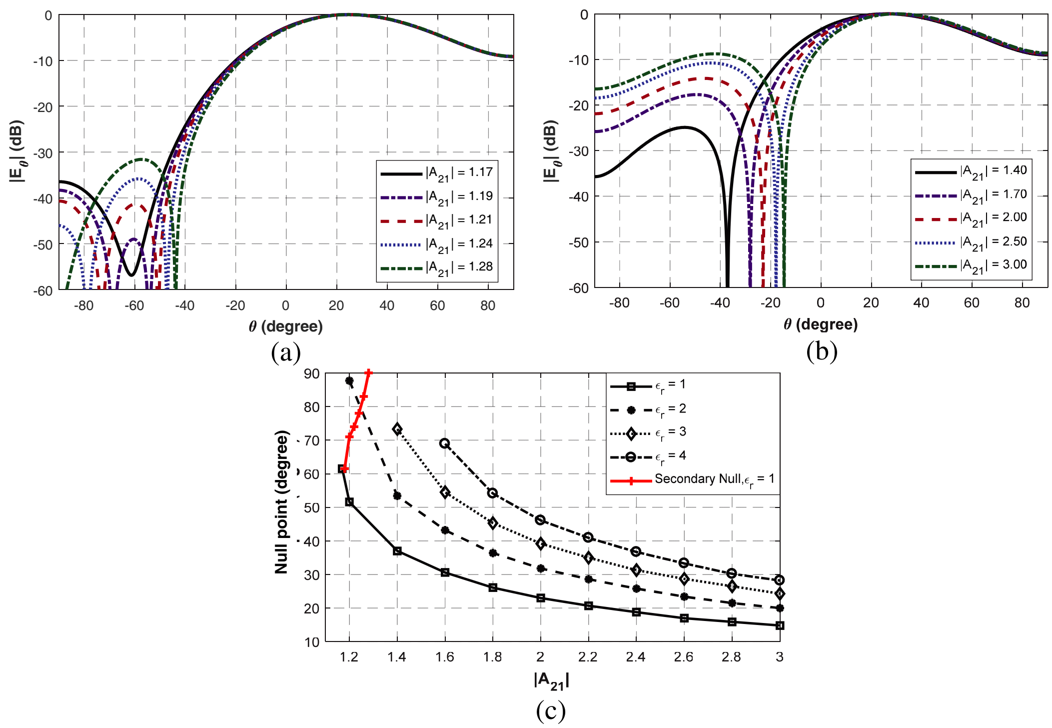


Figure 2. Normalized radiation patterns of the circular microstrip patch antenna, exciting the TM_{11} and TM_{21} modes (a) $\epsilon_r = 1$ with $|A_{21}| = 1.17 \sim 1.28$, (b) $\epsilon_r = 1$ with $|A_{21}| = 1.40 \sim 3.00$, $\alpha_{21} = -90°$, (c) primary and secondary null locations versus $|A_{21}|$ for different ϵ_r.

By exciting the TM_{11} and TM_{21} modes simultaneously, two nulls are formed, which can be steered by the amplitude excitation ratio $|A_{21}|$, when $\epsilon_r = 1$. Representative results are shown in Figs. 2(a) and 2(b) for the $\epsilon_r = 1$ case. It is observed that the secondary null position can be steered continuously by changing the amplitude excitation from 1.17 to 1.28, resulting in a 30° dynamic null range from $-90°$ to $-60°$. As for the primary null location, a dynamic range of 46°, from $-60°$ to $-14°$, is obtained, while the amplitude excitation ratio changes from 1.17 to 3. Thus, by simultaneously exciting the TM_{11} and TM_{21} modes in a circular microstrip patch antenna, one may steer both the primary and secondary nulls from $\pm 14°$ to $\pm 90°$ over the horizon. The adaptive null steering results with different dielectric constants are plotted in Fig. 2(c). It is seen that the primary null position can independently be steered from ±20° to ±90° by varying $|A_{21}|$, when the dielectric constant is close to 2. It should be noted that the secondary nulls only appear for the $\epsilon_r = 1$ case, because, for high contrast substrates, the radiation profile of the multi-mode circular microstrip patch becomes wider [18], i.e., beamwidth increases with ϵ_r, especially at the E-plane. Thus, the secondary nulls are created outside the visible region.

3.2. Case II: TM_{21} and TM_{31} Modes

As shown in Section 3.1, the simultaneous excitation of the TM_{11} and TM_{21} modes cannot nullify the interference or jamming signals coming from the boresight direction of $\theta = 0°$. Therefore, to achieve the complete null steering coverage over the horizon, we will investigate the excitation of the two higher order modes, i.e., TM_{21} and TM_{31}, in this section. For parametric analysis, a normalized (TM_{31} to TM_{21}) mode content factor of A_{32} is used throughout this section, where $|A_{32}|$ is the amplitude excitation ratio and α_{32} is the phase excitation ratio between the modes.

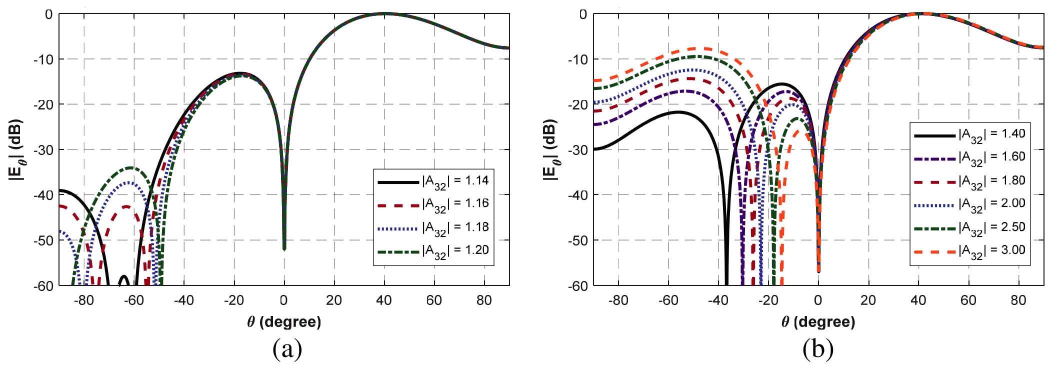


Figure 3. Normalized radiation patterns of the circular microstrip patch antenna, exciting the TM_{21} and TM_{31} modes (a) $\epsilon_r = 1$ with $|A_{32}| = 1.14 \sim 1.20$, (b) $\epsilon_r = 1$ with $|A_{32}| = 1.40 \sim 3.00$.

For the $\epsilon_r = 1$ case, Figs. 3(a) and 3(b) show the continuous null steering of the both primary and secondary nulls from 0° to 90°, by only amplitude control of $|A_{32}|$, along with a stationary null at $\theta = 0°$. As observed, by exciting the two higher order modes simultaneously, three nulls are now formed, one of which is a stationary null placed at the boresight direction. Other two nulls are steerable and can be moved to any direction in the upper half-space by varying $|A_{32}|$. As can be seen, the secondary null position is steered continuously by changing the amplitude excitation ratio from 1.14 to 1.20 and a 25° null steering coverage from −65° to −90° is achieved. The primary null location, on the other hand, can be controlled from −65° to −14° by tuning $|A_{32}|$ from 1.14 to 3. The null steering with different substrate permittivity is further investigated, while exciting the TM_{21} and TM_{31} modes simultaneously. The corresponding results are summarized in Table 1. It is worth noting that a maximum null steering range of 70° is achieved for the primary null, when the dielectric permittivity is around 2, along with a stationary null at the boresight direction.

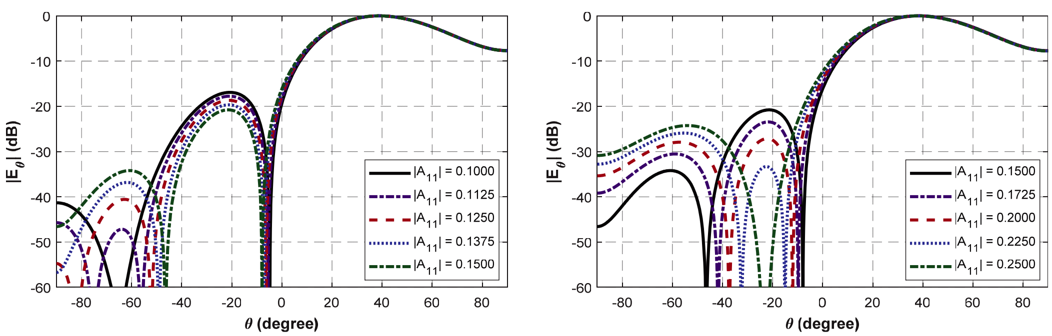
3.3. Case III: TM_{11}, TM_{21} and TM_{31} Modes

Thus far, the null steering capability of two dual-mode antennas is presented by exciting either the TM_{11} and TM_{21} modes or the $TM_{21}$and TM_{31} modes. In this section, the proposed method will further be examined in a tri-mode circular microstrip patch antenna operating at the TM_{11}, TM_{21}, and TM_{31} modes, when $\epsilon_r = 1$. For simplicity, the mode content factor is normalized with respect to both TM_{21} and TM_{31} mode, and the amplitude excitation of TM_{11} mode is varied to show the null steering capability. For this particular case, a maximum of three steerable nulls are visible in the radiation pattern, as shown in Figs. 4(a) and 4(b). As per Fig. 4(a), the two secondary nulls can be steered from −90° to −48°, when the amplitude excitation of TM_{11} mode, i.e., $|A_{11}|$, is varied from 0.10 to 0.15. Moreover, a 40° dynamic range of null steering from −48° to −8° is realized when the amplitude excitation further increases from 0.15 to 0.25, as shown in Fig. 4(b), where the primary and secondary

Table 1. Null locations versus amplitude excitation ratios for different dielectric substrates.

		A_{32}													
Nulls	ϵ_r	**1.14**	**1.16**	**1.18**	**1.20**	**1.22**	**1.40**	**1.60**	**1.80**	**2.00**	**2.20**	**2.40**	**2.60**	**2.80**	**3.00**
F. N.*	$1 \sim 4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P.N.	**1**	65			49.6		36.9	30.3	26	23	20.8	18.6	17.3	16	14
	2				90		55.2	43.4	37.5	32.8	28.9	24.6	23.8	21.9	20.3
	3						81.9	56.7	46.9	40.4	36.4	32.6	29.2	26.9	24.9
	4							74.5	56.8	48	42.7	38.1	33.9	31.8	28.9
S.N.	**1**	66	75	80	86	90									

*F.N.-Fixed Nulls, P.N-Primary Nulls, S.N.-Secondary Nulls



(a) (b)

Figure 4. (a) Normalized radiation patterns of the circular microstrip patch antenna, exciting the TM_{11}, TM_{21} and TM_{31} modes simultaneously with $\epsilon_r = 1$; (a) $|A_{11}| = 0.10 \sim 0.15$, (b) $|A_{11}| = 0.15 \sim 0.25$.

nulls are independently scanned over the horizon. Unlike Case II, the first null near the $\theta = 0°$ can now be steered to some extent.

4. CONCLUSION

Adaptive null steering mechanism was presented by exciting higher order modes in a circular microstrip patch antenna. When the TM_{11} and TM_{21} modes were excited simultaneously, two steerable nulls were realized, which could be steered continuously from $\pm 90°$ to $\pm 14°$ over the horizon. To acquire the null steering coverage over the full horizon, consisting of one stationary null at the boresight direction and two steerable nulls, the TM_{21} and TM_{31} modes were excited simultaneously. It was also demonstrated that three steerable nulls in the upper hemisphere could be obtained by the excitation of all the first three modes together, resulting in a null steering range of 82°, from $\pm 90°$ to $\pm 8°$, over the horizon. Theoretical analysis, in terms of different dielectric substrates provided here, will further enhance the new design guidelines to realize continuous null steering capability in the cognitive communications, anti-jamming, and satellite based applications, with tunable dielectric materials.

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