Oriented Design of an Antenna for MIMO Applications Using Theory of Characteristic Modes

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***Abstract*—In this letter, the Theory of Characteristic Modes (TCMs) is used to achieve pattern diversity in order to be used in multiple-input–multiple-output (MIMO) applications. It is shown that TCMs can orient the design procedure by providing an insight into the natural behavior of the analyzed radiating part of the structure. A metallic equilateral triangular-shaped plate is analyzed by TCMs, and its first seven characteristic modes are obtained. Among them, there are two sets of degenerative modes. All these modes are orthogonal. To achieve pattern diversity, it is essential to have two or more orthogonal radiation patterns with identical excitation frequency of the relevant ports. Therefore, the aforementioned sets can be used to acquire the pattern diversity. However, from obtained results, the set with the less practical implementation issues is selected to be excited. To perform the above-mentioned modal analysis, a specific method of moments (MoM) code has been developed and applied to identify different radiating modes. Two microstrip transmission lines were used as feeding parts so as to excite the suitable set of modes.**

***Index Terms*—Method of moments (MoM), multiple-input–multiple-output (MIMO), pattern diversity, theory of characteristic modes (TCMs).**

I. Introduction

MODAL analysis has long been used in electromagnetics for the analysis of close structures (e.g., waveguides and cavities) in which it is quite simple to reach close solutions by applying boundary conditions. Nonetheless, the calculation of modes in open structures, such as antennas or scatterers, is more complicated, and it is usually quite time-consuming. Probably, this is one of the reasons why modal analysis is not commonly used for antenna design at the present time. However, the information provided by modal analysis of a structure is worth trying for.

There are limited numbers of approaches to achieve the modal analysis of the electromagnetic structures, some of which are spherical modes [1], modal expansion methods [2], and eigenfunctions of conducting bodies. One subdivision of the classical eigenfunction analysis, termed as characteristic modes, was introduced by Harrington in the early 1970s [3], [4]. The characteristic modes are real current modes that can be computed numerically for conductive structures of arbitrary shapes. Since characteristic modes form a set of orthogonal currents on an analyzed body, they create a set of orthogonal radiation patterns as well. By observing this phenomenon, the idea of using characteristic modes for multiple-input–multiple-output (MIMO) systems is more prominent. In other words, our objective is to attain two or more orthogonal patterns by exciting some specific characteristic currents of an analyzed antenna structure. Such a thing was first proposed by Antonino as a multimode antenna with four ports and three radiation patterns [5].

In this letter, an equilateral triangular-shaped conducting plate is analyzed by the Theory of Characteristic Modes (TCMs) in the first step. Modal behavior of such a structure is given more or less in [6] and [7]. However, the analysis presented in this letter is more comprehensive and is performed for some different purposes. Then, an overview of the general modal behavior of the structure is given, which makes it clear why only two specific modes of the plate are suitable to be excited in order to serve our purpose. At last, a feeding structure for the excitation is suggested. By exciting those specific modes, two orthogonal radiating patterns are achieved. To summarize, modal analysis of the proposed structure has been employed to design an antenna suitable for MIMO applications.

II. Modal Analysis of an Equilateral Triangular Conducting Plate

By the method explained in [3] and [4], characteristic modes or characteristic currents can be calculated by the eigenfunctions of the following particular eigenvalue matrix equation:

$$[X]\overrightarrow{J_n} = \lambda_n [R]\overrightarrow{J_n} \tag{1}$$

where λ_n is eigenvalue, $\overrightarrow{J_n}$ is the nth eigenvector or characteristic current, and $[R]$ and $[X]$ are the real and imaginary parts of the generalized impedance matrix $[Z]$, which is produced in traditional method of moments (MoM) analysis of a structure [8]. In fact, (1) is derived from a particular weighted eigenvalue operator equation [3], [4].

One of the most important things that should be taken into consideration in (1) is how eigenvalues λ_n respond to alteration of frequency. λ_n's variation range is from $-\infty$ to $+\infty$, and λ_n's of smallest magnitude are more important from the radiation problems and scattering problems point of view. As given in [3, Eq. 20], the modes with positive λ predominantly store magnetic energy, whereas those with negative λ mainly store electric energy. The mode having $\lambda = 0$ is called the resonant mode. In other words, at a specific frequency, the eigenvalue of a particular mode becomes zero, and the mode is at resonance.

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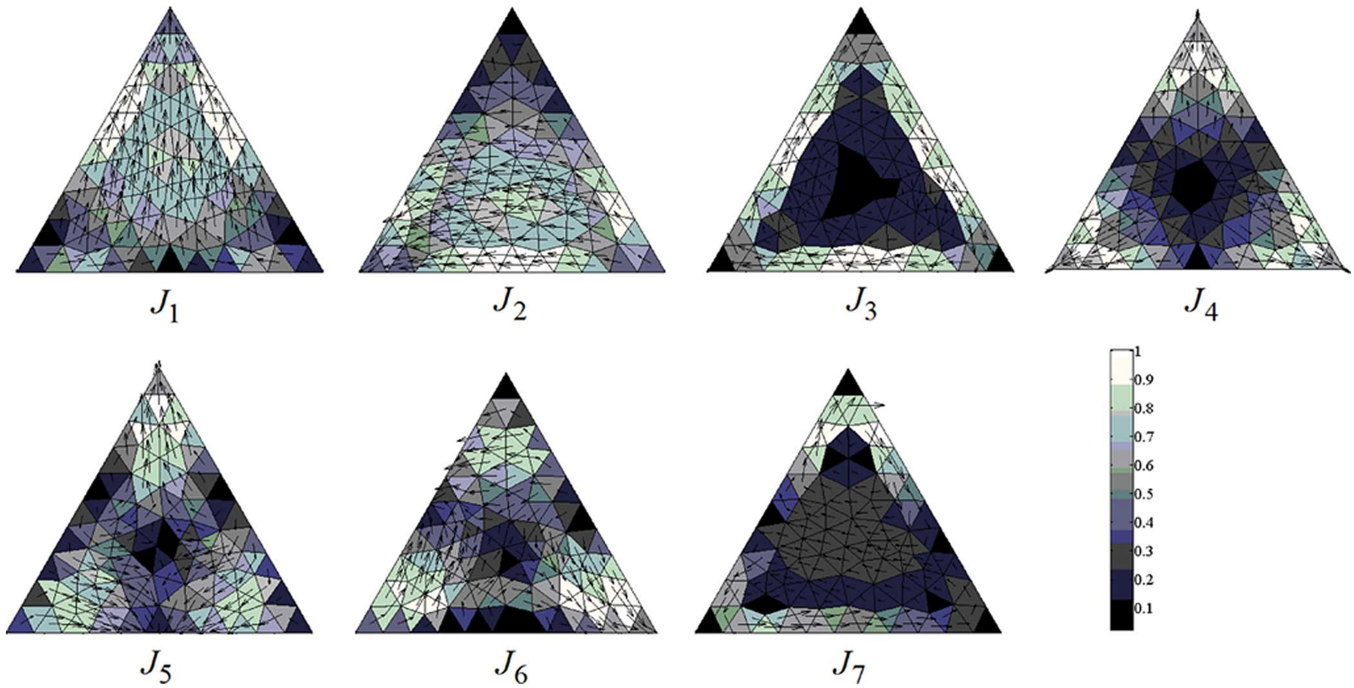


Fig. 1. First seven characteristic currents of a 4-cm-side-length equilateral triangular lossless conductor plate.

Another representation of λ_n's is α_n's, which are called characteristic angles [9]. The formulation is as follows:

$$\alpha_n = 180^\circ - \tan^{-1}(\lambda_n). \qquad (2)$$

It is obvious that at resonant frequency, characteristic angle (α_n) becomes 180°. Furthermore, due to [6], the frequencies related to angles between 135° and 225° represent the mode's bandwidth.

To study the modal behavior of a conducting body, the first seven modes would suffice due to the weakness of amplitude and intense oscillation of the modes with higher number. As a result, by developing a MoM code that uses 181 RWG [10] basis functions, the first seven characteristic currents and the corresponding characteristic angles of an equilateral triangular conducting plate surrounded by air ($\varepsilon_r = 1$)[1] have been calculated, and the results are illustrated in Figs. 1 and 2 respectively. Each side length of the triangle is 4 cm.

A similar structure is analyzed by TCMs in [7], in that work the structure is not capable to be used in MIMO applications. However, in our work eliminating the ground plate changed the antenna's modal behavior in the way that made the design of an antenna for MIMO applications possible.

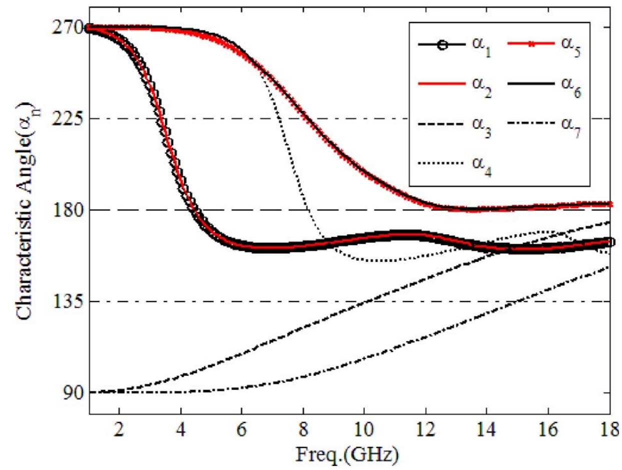


Fig. 2. First seven characteristic angle versus frequency for an equilateral triangular lossless conductor plate.

TABLE I
RESONANCE FREQUENCY OF FIRST SEVEN MODES OF DISCUSSED TRIANGLE

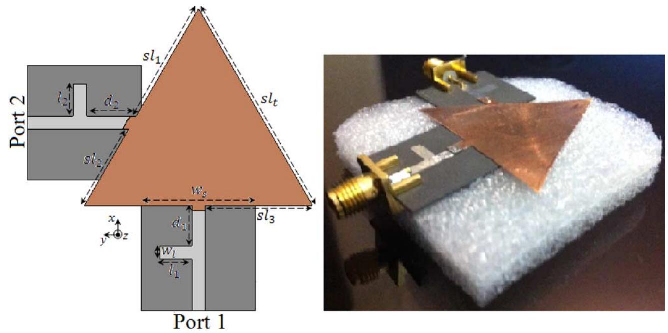
Current Mode	$J_1 - J_2$	J_3	J_4	$J_5 - J_6$	J_7
Resonance Freq. (GHz)	4.4	-	8.1	13.5	-

III. Antenna Design

According to Fig. 2, the first and second modes (J_1 and J_2) are degenerative, and both resonate at the frequency of 4.4 GHz (allocated for WLAN applications). There is also another set of degenerative modes, J_5 and J_6, at 13.5 GHz. From the figure, it is clear that characteristic angle of J_3 and J_7 are always less than 180° and cannot resonate. Moreover, in Fig. 1, the loop shape currents of J_3 and J_7 (leading to passive radiation pattern) verify that these two modes are nonresonant modes. Due to the current distribution of J_4, J_5, and J_6 in Fig. 1, it is obvious that the excitation of these three modes is not easy, and the places of feed lines are difficult to be fabricated. The resonance frequency of these seven modes is presented in Table I.

To design an antenna with pattern diversity for MIMO applications, two or more ports with the same frequency should be used. The idea of using this structure as an antenna that provides pattern diversity for MIMO applications stems from the fact that current distribution of J_1 and J_2 (Fig. 1) are orthogonal

[1]This is one of the prerequisites of TCMs to make (1) and other properties of the theory applicable.



(a) (b)

Fig. 3. Proposed structure. (a) Simulated and (b) fabricated.

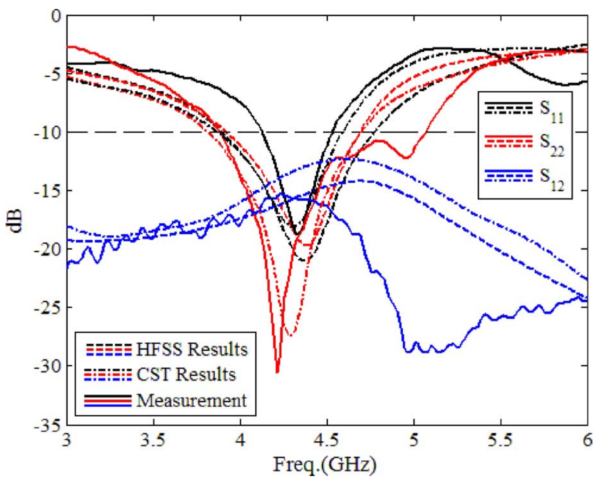


Fig. 4. Scattering parameters of the proposed structure.

TABLE II
EACH PART LENGTH (mm) OF FIG. 3 STRUCTURE

Name	s_{l1}	s_{l2}	s_{l3}	s_{lt}	d_1	d_2	l_1	l_2	w_s	w_l
Length	21.8	15.4	18.8	40	7.1	8.7	5.6	5.6	20	2.3

and these two modes resonate at the same frequency (Fig. 2 and Table I).

To excite J_1 and J_2 on the proposed triangular-shaped plate, two microstrip lines were attached to the plate corresponding to the directions of currents as illustrated in Fig. 3. The microstrip feed lines were fabricated on Rogers RT/duroid 5870 by thickness of 0.787 mm and $\varepsilon_r = 2.33$. Other parameters of the proposed antenna are presented in Table II. By using the aforementioned feed lines that create two orthogonal currents distributions similar to J_1 and J_2, it is expected that the radiation patterns of the antenna caused by excitation of port1 and port2 be orthogonal as a result of considering all TCMs proper conditions in our design procedure.

IV. RESULTS

By using two commercial packages, Ansoft HFSS and CST Microwave Studio, the S-parameters of the proposed antenna are simulated, and the results are presented in Fig. 4. This figure also illustrates the measurement of the fabricated structure's S-parameters. It is obvious that the structure works at 4.4 GHz

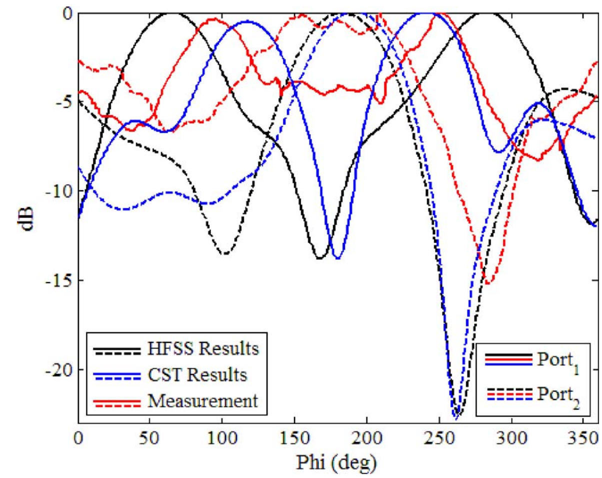


Fig. 5. Normalized radiation pattern in xy-plane of proposed structure. The orthogonality properties are well provided.

(S_{11} and $S_{22} < -10$ dB) with good isolation between two ports ($S_{12} < -15$ dB). Moreover, the simulated and measured normalized radiation patterns of the antenna from port1 and port2 are presented in Fig. 5. It is clear that by exciting two ports, the orthogonality in radiation patterns is achieved. According to Fig. 5, there is an acceptable similarity between the actual measurement and the simulated ones, especially from the orthogonality point of view in radiation patterns, and it is clear that by having orthogonal radiation patterns at the proposed two-port triangular-shaped antenna, pattern diversity for MIMO applications is obtained.

The most significant parameter in MIMO antenna design is the envelope correlation coefficient between different ports. This factor can be calculated from radiation patterns or scattering parameters.

For such a two-port network, assuming a uniform multipath environment, the envelope correlation coefficient according to [11] can be calculated as follows:

$$\rho_e = \frac{\left|S_{11}^* S_{21} + S_{12}^* S_{22}\right|^2}{\left|\left(1 - |S_{11}|^2 - |S_{21}|^2\right)\left(1 - |S_{22}|^2 - |S_{12}|^2\right)\right|}. \tag{3}$$

By using (3), the envelope correlation coefficient is calculated and is illustrated in Fig. 6. It is seen that the envelope correlation coefficient is less than 0.02 at the frequency of 4.4 GHz.

There is also another important parameter that should be taken into consideration in the design of an antenna for MIMO applications: the radiation efficiency. Since both feeds in our proposed antenna are exciting the same physical radiator at the same frequency, analysis of this parameter also becomes indispensable. To simulate radiation efficiency of the proposed MIMO antenna, three steps are done. At the first, to calculate radiation efficiency of port 1 at the resonance frequency, the simulation was done in the presence of port 1 only, and we call that "Port 1/O." At the second step, another simulation, "Port 1/E 2,"[2] was done in the presence of both ports, and finally the same was repeated for port 2. The results are shown in Table III. As it can be seen, the existence of each port does

[2]Port 1 in the Existence of port 2

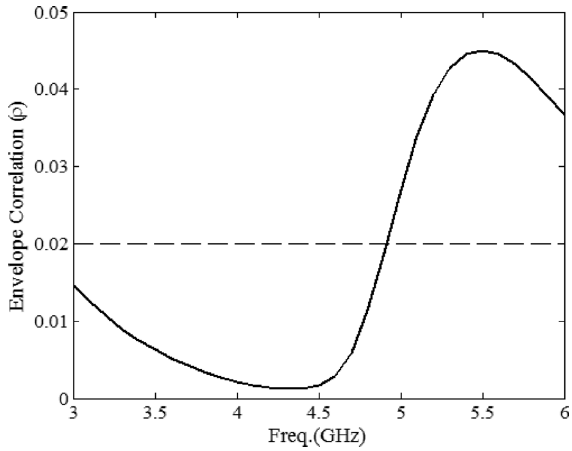


Fig. 6. Envelope correlation coefficient of proposed structure, which is below 0.02 at 4.4 GHz.

TABLE III
RADIATION EFFICIENCY AT RESONANCE FREQUENCY

Port 1/O	Port 1/E 2	Port 2/O	Port 2/E 1
88.36%	88.30%	89.74%	89.65%

not give rise to a considerable variation in radiation efficiency of the other port.

V. CONCLUSION

We use modal analysis of a structure to design an antenna whose advantage is pattern diversity. The first seven characteristic modes of a triangular-shaped radiator are obtained by a specific MoM code. It is observed that some modes are unable to radiate and some other modes are difficult to be excited. It is seen that the two first modes of the proposed antenna resonate at the same frequency and are easy to be excited by microstrip feed lines. From the TCMs, it is expected that each characteristic current leads to a radiation pattern that is orthogonal to the radiation pattern of other characteristic currents. By choosing the first two characteristic currents that resonate at the same frequency, two orthogonal radiation patterns are obtained, which result in the antenna having pattern diversity. Moreover, isolation between two ports, low envelope correlation between two ports, and also the little variation in radiation efficiency in the presence of both ports make the antenna suitable for MIMO applications.

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