Design Guidelines for the Excitation of Characteristic Modes in Slotted Planar Structures

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***Abstract*— This paper provides some design guidelines for the excitation of broadband slotted planar antennas, addressing key issues such as coupling, symmetries and multiple feeding. The Theory of Characteristic Modes is used to identify the collection of current modes that exists on these structures, dealing to a valuable understanding of the radiating mechanisms and allowing a more controlled design process. Modal analysis of a circular aperture cut on a finite square ground plane is presented in order to demonstrate that an optimum choice of the feeding mechanism can be made according to the current distribution of the desired modes. Based on the information yielded by this modal analysis, a capacitive-coupled dual-feed circular aperture antenna is presented. This antenna takes advantage of the symmetries of the characteristic currents by making use of multiple feeding, in order to excite only some particular modes. Usage of commonly-fed and differentially-fed configurations enables an increased control of the excitation of modes in the structure. Characteristic modes analysis of the antenna including the feeding structures is presented, showing the influence of the feeding lines in the performance of this type of antennas. A prototype of the antenna has been fabricated and measured. Simulated and measured results are presented, being in good agreement.**

***Index Terms*—Characteristic Modes, Antenna Design Guidelines, Printed Wide Slot Antennas, Excitation of Characteristic Modes, Theory of Characteristic Modes.**

I. Introduction

THE Theory of Characteristic Modes (TCM) [1][2] has demonstrated to be really helpful for the analysis and design of different types of antennas, such as small antennas [3][4], wire antennas [5][6], planar patches and monopoles [7][8], vehicle mounted antennas [9][10], handset antennas [11]-[13], or dielectric antennas [14][15], among others. The success of Characteristic Modes (CM) lies on the physical insight they provide of the resonances and radiating behavior of arbitrarily shaped metallic bodies. In the last years, the number of publications concerning the application of this modal theory to the design of antennas has increased exponentially. However, in the available literature, there are few examples of application of TCM to the systematic analysis of slotted planar antennas, probably because of the high number of modes that need to be considered and the great complexity involved in the analysis.

In planar antenna design, the inclusion of narrow slots is a common technique used for several purposes such as reducing size [16], creating extra resonances [17], producing dual or circular polarization [18][19], and generating band notch effects [20]. Also in mobile phone handset antennas the incorporation of slots in the ground plane is a very common technique for getting compact and multiband behavior [21]-[23]. Moreover, in the last decade a wide variety of printed wide-slot antennas have been proposed for wideband or ultra-wideband operation [24]-[26].

Different slot shapes and geometries have been investigated, and experimental design guidelines have been proposed for this kind of antennas. An excellent summary of these design guidelines has been presented in the introduction section of [24]. These design guidelines are however based on experimental results provided by many recently published papers, which are based on parametric studies or on the observation of the total current distribution associated to the different resonances of the antenna [24]-[26]. Little theoretical investigations can be found in the literature associated to this type of antennas.

TCM is an excellent candidate to be used for the analysis of this type of slotted antennas, in order to identify the different resonances exhibited and examine their properties. To authors' knowledge, this is the first time a CM analysis is presented for wide slot antennas, providing physical understanding of their radiation behavior and some design guidelines for the excitation of CM. By studying the current distribution of the collection of CM, it is possible to determine the most appropriate feeding configuration in order to excite specific modes, using capacitive or inductive coupling. Moreover, symmetry conditions imposed by the feeding configuration can reinforce the excitation of some modes, while preventing excitation of undesired modes. This can be useful to increase

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bandwidth and/or control the radiation pattern of the antenna.

This paper provides guidelines for the excitation of broadband slotted planar structures using TCM. The structure of the paper is the following: Section II reviews different approaches to analyze apertures and presents a complete modal analysis of a circular aperture etched on a finite square ground plane. Section III gives some design guidelines to excite modes with particular symmetries in order to achieve broadband matching and pattern stability. It also proposes a practical design based on the radiating aperture analyzed in section II. The paper finishes with the conclusions.

II. Modal Analysis of Slotted Planar Structures

CM analysis of slotted planar structures was first performed by R.F. Harrington in [27] using equivalent magnetic currents. Based on this magnetic approach, later works developed by Kabalan et al. studied the CM of infinite slots in conducting planes excited by TM and TE plane waves [28][29]. The characteristic magnetic currents of a rectangular aperture in an infinite perfectly conducting plane were also obtained in [30]. However, after these works, dating back more than 20 years, little research has been conducted concerning the computation of the CM in slots and apertures. To authors' knowledge, only in [20] and [31], analysis of slotted planar antennas using the Theory of Characteristic Modes has been presented. In [20], the band-notch effect in a U-slotted UWB planar monopole was explained using the CM approach, and in [31], CM were used to obtain circular polarization by modifying the geometry of a U-slot embedded in a microstrip patch.

As mentioned above, the first slotted planar structures analyzed using CM by R.F. Harrington in [27] were studied using a modal approach based on equivalent magnetic currents. In this preliminary work, it was demonstrated that CM could be defined for aperture problems in a manner dual to those defined for scattering problems, considering an admittance operator and the following weighted eigenvalue equation:

$$B(M_n) = b_n G(M_n) \quad (1)$$

where M_n are the characteristic magnetic currents, b_n are the real magnetic eigenvalues, and G and B are the real and imaginary parts of the admittance operator (Y):

$$Y = G + jB \quad (2)$$

By applying Babinet's Principle [32] it can be demonstrated that the characteristic magnetic currents (M_n) of a finite aperture etched in an infinite conducting plane are dual to the characteristic electric currents (J_n) of a metallic plate with the same shape and size as the aperture. Thus, if we consider, as an example, a circular aperture in an infinite ground plane (as shown in Fig.1(a) the associated magnetic CM (M_n) will be the same as those electric CM (J_n) exhibited by a circular plate of the same radius. The current distribution for these J_n can be found in [33].

Nevertheless, in practice, this duality is not preserved since apertures are inserted in finite conducting planes, so the electrical current modes of the conducting plane interact and merge with the aperture modes. For the case of finite ground planes, the equivalent magnetic currents defined in the aperture (3) create a radiated magnetic potential (4) that leads to the electric field and the magnetic field defined in (5) and (6), respectively. The magnetic field excites the current modes (7) in the finite ground plane. Fig. 1 (b) shows an example of the electric current distribution that appears in a circular aperture etched in a finite ground plane. The effects of the ground plane size on the performance of slot antennas have already been reported experimentally by other authors [34]. The electric currents located in the truncated ground plane suffer from diffraction at the outer edges [34], influencing very much the radiation pattern. Therefore, the ground plane plays a crucial role when radiation pattern stability is desired in an aperture antenna.

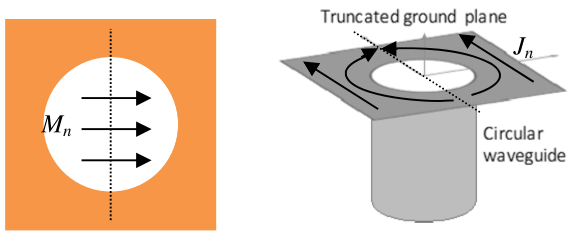
$$\vec{M}_s = 2\left(-\hat{n}\times\vec{E}\right) \quad (3)$$

$$\vec{F} = \varepsilon \iint \vec{M}_s\left(\vec{r}\,'\right) G\left(\vec{r},\vec{r}\,'\right) ds' \quad (4)$$

$$\vec{E} = \frac{1}{\varepsilon}\nabla\times\vec{F} \quad (5)$$

$$\vec{H} = -\frac{1}{j\omega\varepsilon\mu}\nabla\times\nabla\times\vec{F} \quad (6)$$

$$\vec{J}_s = \vec{H}\times\hat{n} \quad (7)$$



(a) (b)

Fig. 1. (a) Wide circular slot in an infinite ground plane. (b) Circular aperture in a truncated ground plane excited by a circular waveguide.

Most commercial electromagnetic simulators are based on the EFIE (Electric Field Integral Equation) formulation, so they analyze apertures from an electrical point of view, considering just the currents that flow along the metallic plane surrounding the aperture. In this paper, the classical electric approach of TCM is used to obtain the modal currents of a truncated ground plane with a circular aperture.

By applying the TCM, the total current (J) in the surface of the ground plane of the aperture can be expanded as a combination of its CM as follows [2]:

$$J = \sum_n \frac{V_n^i J_n}{1 + j\lambda_n} \quad (8)$$

where J_n are the eigencurrents or characteristic modes, λ_n are the eigenvalues and V_n^i is the modal excitation coefficient. This modal excitation coefficient can be obtained as:

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$$V_n^i = \left\langle J_n, E^i \right\rangle = \oiint_S J_n \cdot E^i \, dS \qquad (9)$$

The product $V_n^i J_n$ in (8) models the coupling between the excitation and the n^th mode, and determines which modes will be excited by the antenna feed or incident field (E^i).

Next section presents a complete analysis of the modal electric currents and fields of a finite square ground plane with a circular aperture.

A. *Modal Analysis of a Finite Ground Plane with a Circular Aperture*

Circular-shaped slots etched in a square ground plane have been extensively investigated for the design of UWB antennas. These structures combine in a single geometry the resonances of the ground plane and the circular aperture. As it will be shown next, the application of the TCM for the analysis of these wideband radiating apertures helps to understand the behavior of the current distribution and the radiating characteristics of the different modes.

The computation of the modes presented here has been performed by means of a self-developed electromagnetic simulation tool based on the Method of Moments programmed in Matlab, in combination with FEKO. A very important conclusion of this study is that the modes of the radiating aperture do not appear as independent or isolated modes, as in [20], but they couple in a coherent way to the modes of the ground plane with the same current variation characteristic, generating a new family of combined radiating modes.

The structure under consideration is a circular aperture of radius *R*=26 mm etched at the center of a finite ground plane of dimension *L*=80 mm. The relation *R*≈*L*/3 used in the structure has been chosen in order to obtain a good trade-off between radiating bandwidth and pattern stability. This relation has been determined and optimized by means of a parametric analysis that for brevity is not included.

Fig. 2 presents the characteristic angle variation with frequency for the most relevant CM that appear when the structure is analyzed in a wide frequency band. The resonant frequency of the CM can be determined from these characteristic angle curves, since a mode is considered to be at resonance when its associated characteristic angle is equal to 180º. Due to the symmetry of the structure, there are degenerated modes that resonate at exactly the same frequency, such as pairs J_1-J_1' and J_4-J_4'. Modes J_2 and J_2' exhibit the same current distribution but rotated 45º, however they are not degenerated modes due to the corner effect that reduces the length of the current path for the case of mode J_2' shifting its resonance to higher frequencies. Mode J_3 that exhibits rotational symmetry does not have a degenerated associated mode. Moreover, there are special non-resonant modes, such as J_0, J_{01} or J_{02}, that present inductive behavior in the complete frequency band.

Fig. 3 shows the normalized current distribution of the first eight modes of the circular aperture at their corresponding resonant frequency. Observe that the current of the non-resonant mode J_0 flows forming loops. The rest of radiating modes presents intense currents flowing around the contour of the aperture and the contour of the ground plane. This behavior of the currents reveals that the modes of the considered structure are a combination of the modes of the square ground plane and the aperture, so they account for the coupling between both structures.

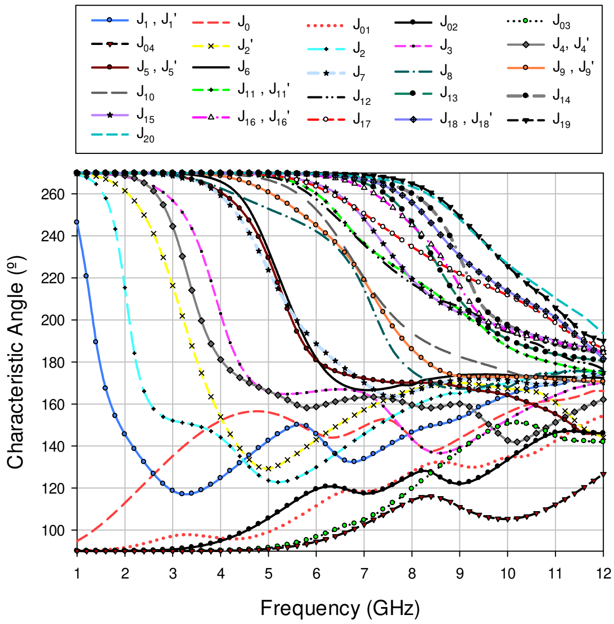

Fig. 2. Characteristic angle versus frequency for the most relevant modes of a circular aperture of radius *R*=26 mm, etched on a square ground plane of dimension *L*=80 mm.

Fig. 4 depicts the normalized characteristic electric fields ($|E_n|$) associated to the CM of Fig. 3. These modal far field patterns have been obtained with FEKO by using the Characteristic Modes request tool. As observed, the number of lobes in the radiation pattern increases with the order of the mode.

When the dimensions of the ground plane are very much adjusted to the aperture size, the structure behaves as a metallic ring that presents narrowband radiating modes. As the ground plane is made larger, the matching bandwidth increases, especially at the lower band [24], but at the expense of degrading the radiation pattern. This degradation can be associated to the excitation of an increased number of higher order modes of the ground plane that combine with the first order modes of the aperture at the frequencies of interest. If the excitation of these higher order modes is not avoided, they produce the undulating phenomenon described in [35], which degrades the radiation pattern and reduces its stability.

It should be pointed out that the number of modes to be considered in the modal analysis presented in Fig. 2 is easily manageable until 5 GHz, as only eight CM have a relevant contribution to radiation up to this frequency. Nevertheless, as the frequency increases, a huge amount of CM should be considered, leading to a very complex analysis. Note also that above 5 GHz modes appear in groups, and inside these groups they resonate very close to each others. As a result of this boost on the density of modes, there will be not a single dominant mode to be considered in the higher frequencies, but a combination of several dominant modes.

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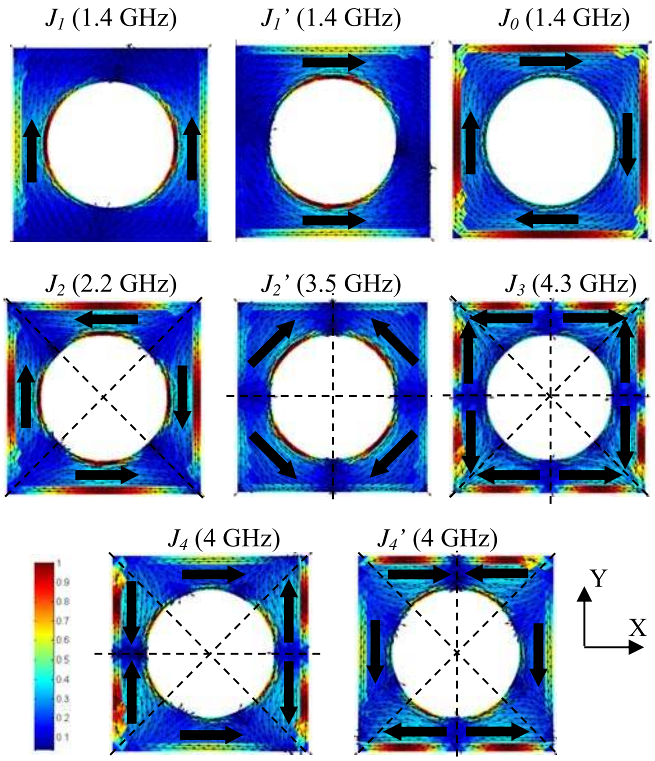

Fig. 3. Normalized current distribution of the first eight modes of a circular aperture of radius *R*=26 mm, etched on a square ground plane of dimension *L*=80 mm.

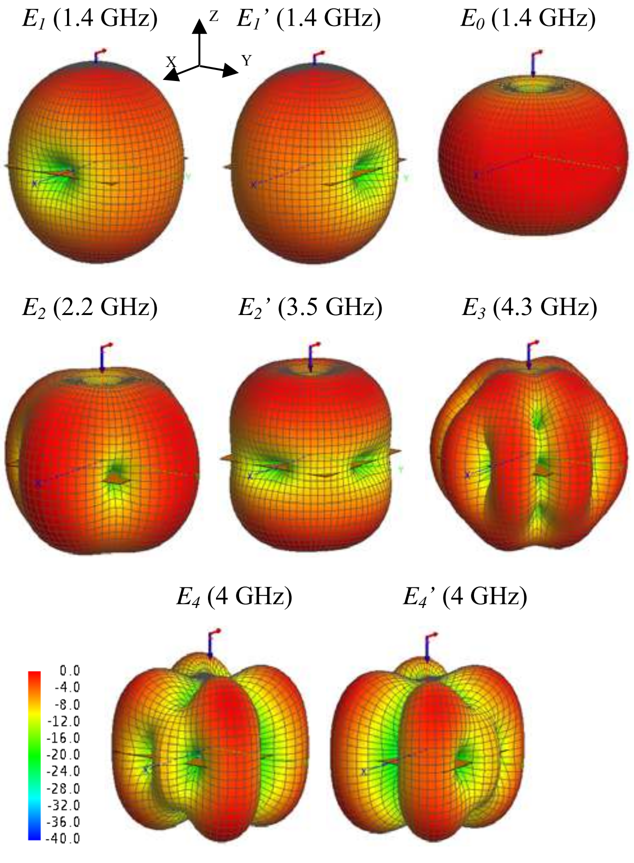

Fig. 4. Normalized characteristic electric fields of the first eight modes of a square plate of dimension *L*=80 mm with a circular slot of radius *R*=26m.

As will be shown in section III, a very powerful stategy to reduce the number of modes to be considered in a broadband modal analysis is to make an optimum choice of the feeding mechanism and to take advantage of the symmetries of the structure in order to excite only some particular desired modes.

III. Commonly-Fed and Differentially-Fed Circular Aperture Antenna

This section discusses different kinds of excitation as well as the feeding symmetries that can be exploited for selective excitation of CM in order to reduce the number of modes excited and obtain increased bandwidth and/or more stable radiation pattern. A capacitive coupled dual-feed circular aperture antenna is presented as an example of application.

A. Excitation of Characteristic Modes by Using Different Coupling Mechanisms and Feeding Symmetries

Characteristic modes are computed in the absence of any specific source or excitation. Once the modal analysis has been performed, the next step is to decide how to feed the structure in order to excite the modes that provide the desired radition characteristic (e.g. vertical polarization, omnidirectional or directional radiation, pattern diversity, etc).

In general, either inductive or capacitive coupling mechanisms can be used to excite CM, as it has been proposed for mobile terminals [36][37]. Inductive feeding will effectively excite those modes whose electric current distribution shows intense currents at the location of the source. On the contrary, capacitive coupling mechanism will excite modes with strong electric field at the source location. This means that the magnitude of the modal electric current distribution should be small at the location of the capacitive source. Moreover, polarization of the sources is critical, as they have to force the polarization of the modal currents to be excited (i.e. inductive horizontally polarized sources at points with intense current do will not excite CM with intense current distribution exhibiting vertical polarization at this point).

Additionally, not only the magnitude and polarization of the electric current or electric field, but also the symmetries exhibited by the modal current distributions are important for the excitation of CM. By taking into account even and odd symmetries of the different modal currents, effective excitation of specific modes can be achieved, while preventing excitation of undesired modes. This can be only accomplished if multiple sources are used to excite the radiating structure, setting their phase and magnitude accordingly to the symmetry condition desired for the modes on the structure.

It is true that a single feed is usually chosen to excite apertures, as it simplifies the feeding mechanism design. However, the use of a single feed only allows for a limited control of CM excitation, as it doesn't take advantage of the symmetries exhibited by the current distribution of CM on the structure.

In general terms, modes can be classified in different families according to their even or odd symmetry. By applying symmetry conditions at the excitation of the antenna, a sort of

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filtering of the CM capable of being excited will be produced. Thus, in the structure just analized, different families of modes can be excited when using different coupling mechanisms combined, for example, with double feeding. Fig. 5 proposes two alternatives for the excitation of the modes. In both cases a double feeding is used combined with commonly-fed and differentially-fed configurations, in order to take advantage of the modal symmetries. The ports (Port1, Port2) are placed along the vertical axis of symmetry of the structure.

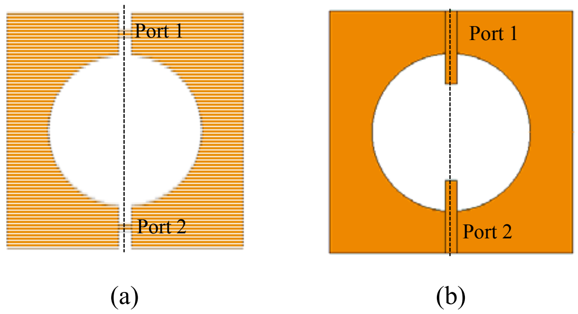

Fig. 5. Alternatives for the excitation of modes using double feeding. (a) Inductive coupling. (b) Capacitive coupling.

In Fig. 5 (a) an inductive mechanism is used, this means that modes with intense currents at the source positions, such as J_1', J_0, J_2 or J_4 of Fig. 3, are candidates to be excited with this configuration. Aditionally, a higher discrimination of excited modes can be obtained playing with the phase of the ports. The excitation of modes with even horizontal symmetry (e.g. J_1' and J_4) will be favoured when the two ports are configured in phase with a commonly-driven configuration (+1,+1). Conversely, modes with odd horizontal symmetry (e.g. J_0 and J_2) will be excited if the ports are configured in opposite phase with a differentially-driven configuration (+1,-1).

Fig. 5 (b) proposes a capacitive coupling mechanisms based on two microstrip feeding lines. This feeding configuration will couple with the modes that present very low modal current intensity at the ports, such as J_1, J_2', J_3, and J_4' of Fig. 3, among others. Once more, deeper discrimination of modes can be achieved creating symmetry conditions. With the commonly-driven configuration (+1,+1), the excitation of modes with even vertical symmetry is reinforced (e.g. J_2'and J_3). When the differentially-drive configuration (+1,-1) is applied, modes with odd symmetry are excited (e.g. J_{01}, J_1 and J_4').

Fig. 6 shows visually a classification of the characteristic angle of Fig. 2, considering the modes which are candidates to be excited with the inductive and the capacitive feeding mechanism for the cases of commonly-fed and differentially-fed configurations. When comparing with the complete collection of modes depicted in Fig. 2, it is evident that in the all cases, the number of modes to be considered is drastically reduced, dealing to an easier to handle analysis. As observed, different families of modes with different contour conditions and different symmetries are excited in each case.

The reduction of the number of excited modes is an important issue, since the excitation of several successive modes with even and odd symmetries in an antenna could create strong anti-resonances in the structure which may degrade its impedance bandwidth [38], or reduce the stability of the radiation pattern. When modes with the same symmetry are excited these effects are minimized.

Inductive coupling mechanisms are rarely used for exciting printed slot antennas, since matching to 50 Ω is difficult to achieve and narrow impedance bandwidth is obtained. Conversely, slotted planar antennas with different slot shapes have shown very broadband behavior when excited capacitively using coplanar waveguide (CPW) or microstrip feed line, terminated in a shaped stub [24]. This shaped stub acts as a tuning element that effectively matches the different resonant modes exhibited by the structure. Therefore, although the structure presents many resonant modes, it has been experimentally demonstrated that a tuning stub can provide very good transition from one mode to the next one, and obtain broadband or ultra-wideband impedance bandwidth [24][39].

In the next section, a capacitive-coupled antenna will be proposed in order to show how the excitation of CM can effectively be controlled and how different radiation patterns can be obtained by exciting different CM. Furthermore, the effect of the insertion of a capacitive feeding structure in the resonances and radiation behavior of the antenna will be analyzed using CM.

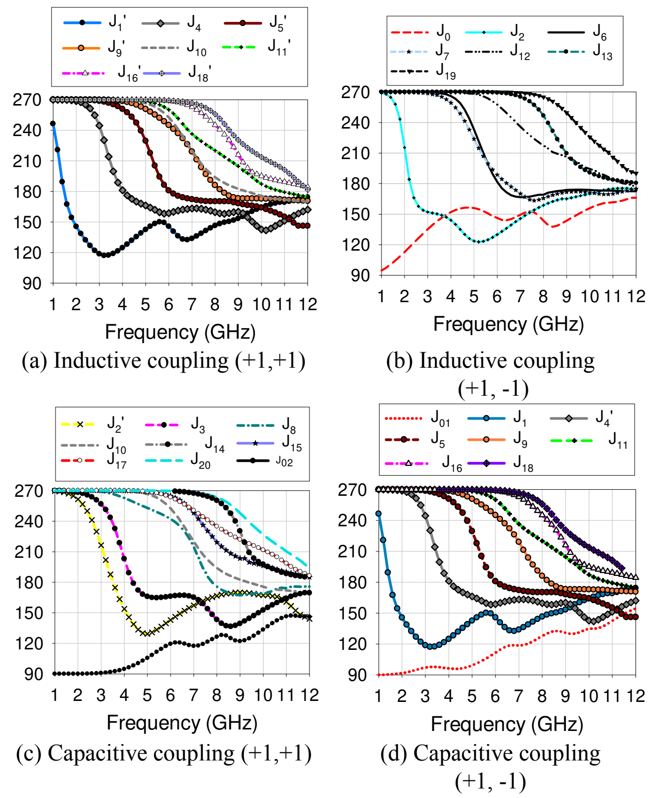

Fig. 6. Filtering of the characteristic angle of Fig. 2 considering the modes which are candidates to be excited when using different feeding schemes.

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B. Proposed Antenna Geometry with Dual-Feeding

In order to excite the CM of the circular aperture of Section II, the structure shown in Fig. 7 is proposed. As observed, two microstrip lines terminated in a rectangular stub are used to excite the aperture by capacitive coupling. As commented in previous section, capacitive excitation of wide slots using microstrip feed lines terminated in a stub has shown to provide a large impedance bandwidth. In this paper, the proposed structure is based on that presented in [39] for pattern diversity, but now the two ports are combined to selectively excite specific modes and increase stability of the radiation pattern.

The proposed antenna is printed on an air dielectric with a thickness of 1 mm. The circular aperture with radius R=26 mm is etched on a square ground plane with size 80x80 mm^2. The antenna is fed by two microstrip lines printed on the bottom side of the substrate and dimensions of these microstrip lines are L_{feed}=15.25mm, W_m=1.9mm, W_1=13.5mm and W_2=13.5 mm.

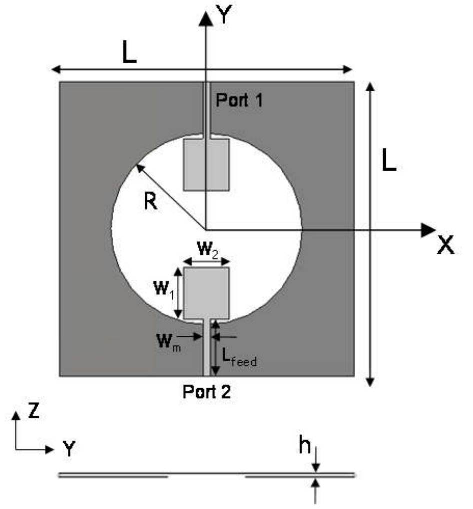
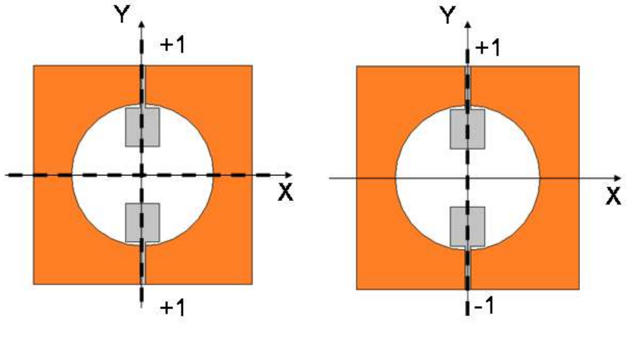


Fig. 7. Bottom view and side view of the circular aperture antenna with two feedings. The darker grey in the XY plane is the top side, whereas the lighter grey is the back side.

Excitations (+1, +1) and (+1,-1) for Port 1 and Port 2 (Port 1, Port 2) will be used, which corresponds to a commonly-driven and a differentially-driven excitation, respectively. Fig. 8 shows schematically the symmetry conditions imposed to the electric current distribution in the finite metallic ground plane by the two feeding configurations. Dashed line represents the presence of a null in the current distribution, imposed by the symmetry condition created by the phases of the sources. As observed in Fig. 8 (a), sources with same magnitude and phase will impose odd symmetry in the surface current distribution with respect to x-axis. Moreover, the use of capacitive feeding (even when using only one port) implicitly creates an odd symmetry condition for the electric current distribution with respect to y-axis, as shown in Fig. 8 (b). By using capacitive coupling excitation, only modes with low electric current magnitude (high electric field magnitude) at the location of the sources will be excited.



(a) (b)

Fig. 8. Symmetry conditions imposed on the current distribution by the feeding configuration: (a) Sources with same phase and magnitude (common feed); (b) Sources with same magnitude but opposite phase (differential feed). Dashed line in the figure represents a null of current distribution in the ground plane.

C. Characteristic Modes of a Finite Ground Plane with a Circular Aperture including the Feeding Structure

When analyzing the structure including these two microstrip feed lines terminated in a square stub, we observe that some additional resonant modes appear, which are linked to the presence of the feeding structure.

Fig. 9 shows a comparative (up to 8 GHz) of the CM associated to the circular aperture in the finite ground plane with and without the two feeding structures. In order to bring a clearer view, modes have been separated in two families. Fig. 9 (a) and (b) contain the families of modes that could be excited when the symmetry conditions of the diferentially-driven and the commonly-driven configurations are imposed, respectively. As observed, two pairs of modes associated to the feeding structures appear within the frequency range considered (J_{feed} - J_{feed_2} and J_{feed_3} - J_{feed_4} modes). The rest of the modes associated to the aperture in the finite ground plane remain almost the same, except for the separation of degenerated modes, as the rotational symmetry of the antenna is broken by the presence of the two feeding lines.

Since two feeding structures are needed in order to impose symmetry conditions, additional modes appear in pairs. Each pair correspond to the "antenna mode" (current flowing in the same direction in both feeding lines) and "transmission line mode" (current flowing in opposite direction) resulting from the combination of the two feeding lines [33]. This can be seen in Fig. 10, where the current distribution associated to the first (J_{feed} - J_{feed_2}) and second pair (J_{feed_3} - J_{feed_4}) of resonant modes associated to the feeding structures is presented.

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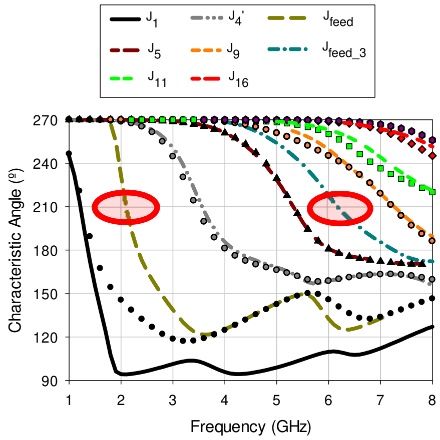
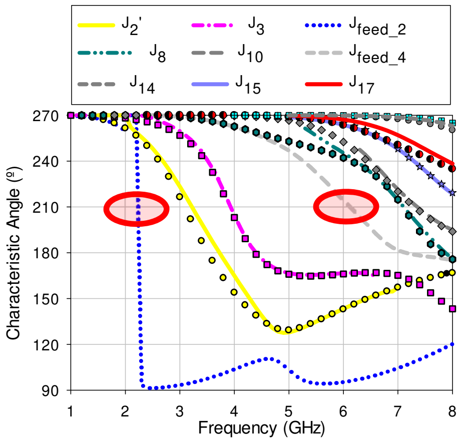
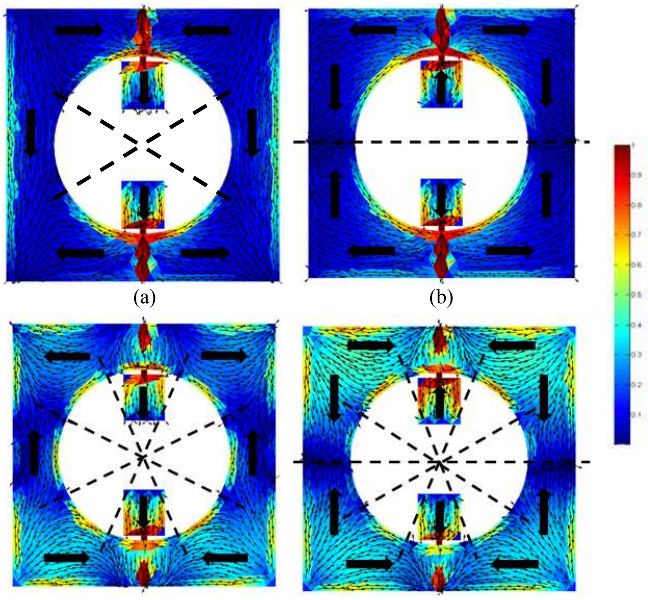


(a)



(b)

Fig. 9. Comparison of the characteristic angle vs. frequency for the first modes of a square plate of *L*=80 mm with a circular slot of *R*=26 mm, with feeding (lines) and without feeding (symbols). Modes associated to the symbols are those shown in Fig. 2. New modes linked to the feeding structure are marked with a red oval: (a) Differential feeding; (b) Common feeding.



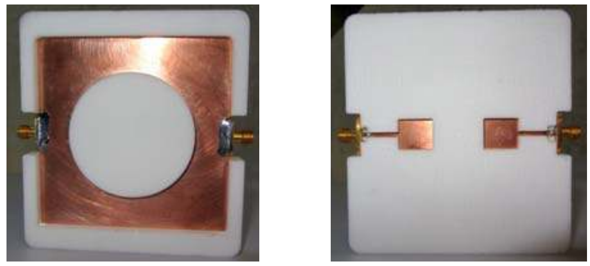
(a) (b)

(c) (d)

Fig. 10. Normalized current distribution of the two additional modes associated to the feeding structure of the structure: (a) J_{feed} ; (b) J_{feed_2}.; (c) J_{feed_3} and (d) J_{feed_4} . Dashed line in the figure represents a null of current distribution.

D. Results

Fig. 11 shows the fabricated prototype and Fig. 12 depicts the simulated and measured reflection coefficient for the circular aperture with common and differential feeding configurations. Differential-mode and common-mode measurements are performed with PNA-N5227A network analyzer. As observed, measured bandwidth from 2.6 to more than 12 GHz is obtained for $|S_{11}|$<-10 dB and differential feeding, while an operating frequency range from 3.2 to more than 12 GHz is obtained for common feeding. Simulated and measured results agree quite well, although some frequency shift is observed due to minor fabrication issues.



(a) (b)

Fig. 11. Fabricated prototype: (a) Top view; (b) Bottom view.

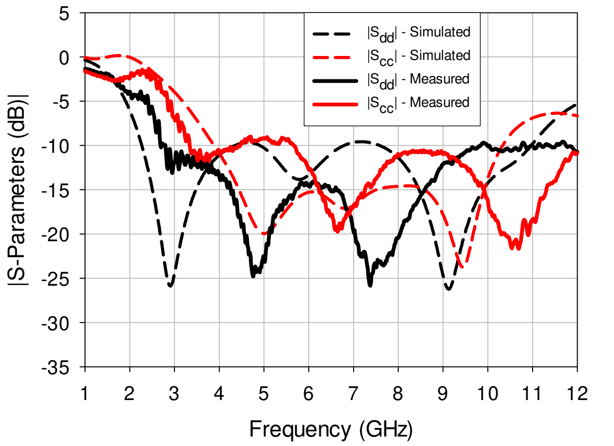


Fig. 12. Simulated and measured reflection coefficient for differential feeding ($|S_{dd}|$) and common feeding ($|S_{cc}|$).

Fig. 13 and Fig. 14 illustrates the contribution of each mode to the total power radiated by the antenna (calculated as $\langle J, RJ \rangle$ from the MoM impedance matrix $Z = R + jX$), when using common and differential feeding configurations, respectively.

As observed, common feeding facilitates the excitation of mode J_{feed_2}, J_2', J_3, J_8 and J_{feed_4} up to 8 GHz, whereas higher order modes are excited at higher frequencies. All these modes follow the symmetry condition imposed by the feeding configuration, as observed in the current distibutions shown in Fig. 3, Fig. 6 and Fig. 10. As observed, the number of modes excited increases with frequency due to the fact that the density of modes at higher frequencies is much higher, as commented in section II.

Conversely, with the use of differential feeding, a different family of modes is excited in the structure. As shown in Fig. 14, modes J_1, J_4', J_{feed} and J_{feed_3} and J_{feed} are mostly excited at lower frequencies, while higher order modes are again excited from 8 GHz up. Once more, all these modes follow the symmetry condition imposed by the sources (see Fig. 6).

As observed in Fig. 13 and Fig.14, modes associated to the feeding structure are the main radiators around their resonant frequency, while the aperture modes are also excited and contribute to achieve an appropriate transition from one mode to the following. Consequently, large impedance bandwidth can be achieved for both common and differential feedings, being the radiation pattern determined by the mode/s excited at each frequency.

Fig. 15 shows the total current distribution obtained with CST Microwave Studio for the proposed antenna at different frequencies within the operating frequency range. Total current distribution for the two feeding configurations is presented in the figure, which allows an easy determination of the dominant mode excited in the structure at each frequency.

Finally, simulated and measured radiation patterns for 4 and 6 GHz are shown in Fig. 16. As observed, radiation pattern behavior is associated to that of the characteristic mode excited in the structure at a specific frequency. As observed, measured and simulated results correlate well.

Large bandwidth is also possible with a single feeding [39], but radiation pattern in this case is much less stable in frequency, as successive even and odd modes are excited with frequency, changing the radiating performance.

Some differentially driven antennas have been proposed recently for polarization diversity [40]-[42]. By using differential feeding, very low cross-polarization level can be achieved and dual polarization can be obtained by using two pairs of orthogonal differential ports. In [42], gain and beamwidth is kept constant along the operating frequency due to the differential feeding.

CM analysis provided in the present paper brings a very clear physical insight on differentially-driven antennas and the advantages they can provide. Common feeding is also proposed now following the basic idea of selective excitation of CM. A pair of orthogonal ports (four ports in total) with common or differential feeding can also be used in the proposed antenna to obtain orthogonal polarization. Very low coupling between the two pairs of orthogonal ports would be achieved for both differential and common feed.

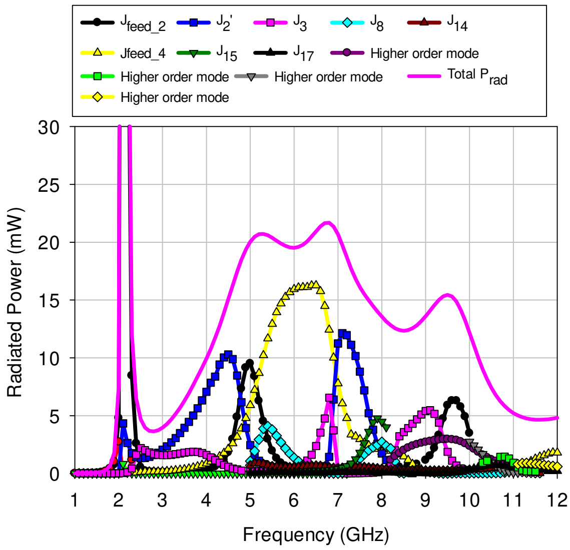


Fig. 13. Contribution of each mode to the total radiated power of the circular aperture antenna, when using common feed.

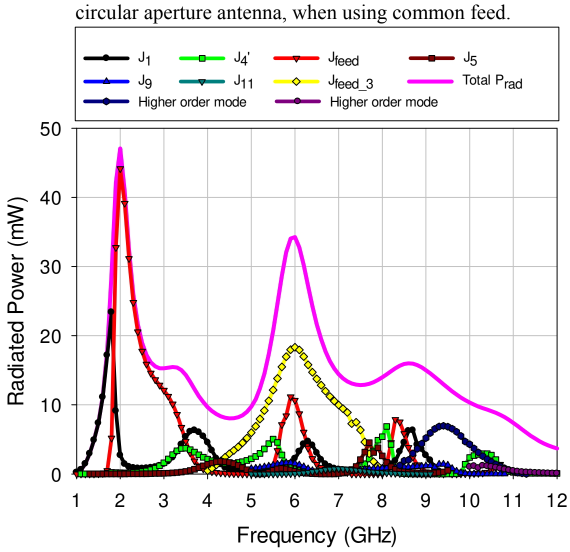
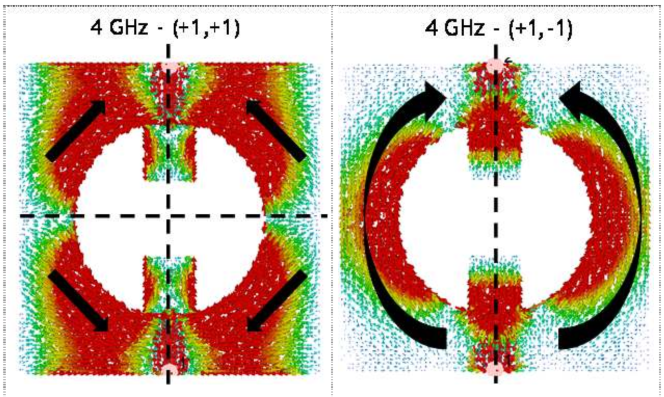


Fig. 14. Contribution of each mode to the total radiated power of the circular aperture antenna, when using differential feed.



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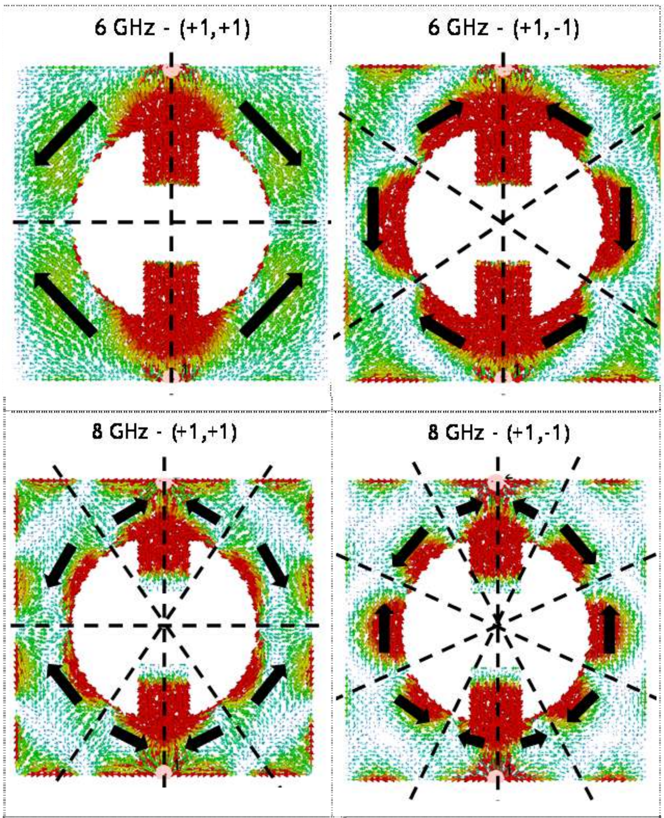
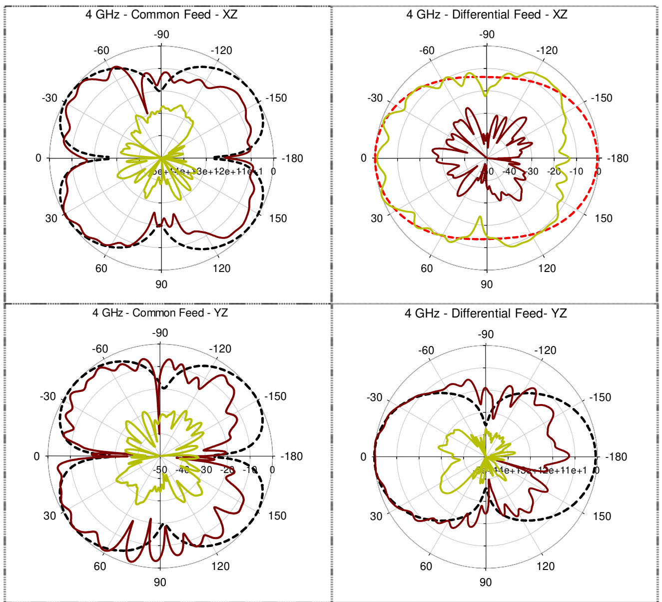
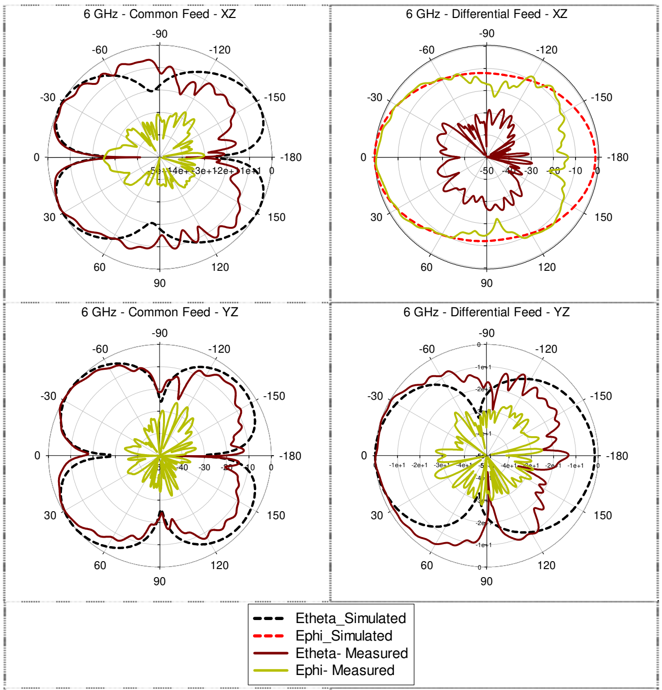


(a) (b)

Fig. 15. Simulated total current distribution on the antenna for the two feeding configurations at different frequencies within the operating bandwidth: (a) Common feed; (b) Differential feed.





(a) (b)

Fig. 16. Simulated and measured radiation patterns for the two feeding configurations: (a) Common feed; (b) Differential feed.

IV. Conclusions

TCM has been applied to a circular aperture antenna inserted in a square ground plane, in order to determine the resonance frequency, current distribution, and radiation pattern of the CM of the structure. This information is then used to provide general design guidelines for the appropriate excitation of CM with particular symmetries in order to achieve large matching bandwidth and pattern stability. Selective excitation of CM has been discussed, and a common-fed and differential-fed capacitive-coupled circular aperture antenna has been proposed. Multiple feeding is proposed as a useful technique for gaining higher control of CM excitation. A prototype of the antenna has been fabricated. Radiation patterns have been measured for commonly-fed and differentially-fed configurations. A common-fed configuration, which is not commonly used, has demonstrated to provide wideband matching and alternative radiation patterns to those associated to the differential feed.

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