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Compact Loaded PIFA for Multifrequency Applications

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***Abstract*—A new multifrequency microstrip patch antenna is presented. The antenna can be considered a PIFA since it has a metallic wall on one of its sides. The different bands of operation are independent of each other, and different radiation patterns for each band can be achieved if desired. In addition, a circuital model is introduced to explain the operation of the antenna. This model presents some similarities with composite right left handed models presented in the literature. Some prototypes have been manufactured and measurements of return losses, efficiencies and radiation patterns, have been performed for a thorough characterization of the antenna as well as to validate the simulation results.**

***Index Terms*—Composite right left handed (CRLH), dual band, multiple band, microstrip patch antenna, PIFA.**

I. Introduction

MODERN telecommunication devices are required to be small and able to integrate several functionalities. The antennas used for these wireless systems must hence possess multiband capabilities but yet remain compact. One of the most common types of antenna used for conventional devices are patch antennas, due to their low cost of manufacture and light-weight nature. In addition, they have a high radiation efficiency [1], [2]. Patch antennas are resonant antennas that typically operate at the frequency whereby the length of a dimension is half a wavelength. This requirement may render the antenna too large for low-frequency applications. Consequently, some recent studies have focused on achieving compact patch antennas that can still function at lower frequencies [3]–[5]. A classical and simple method for reducing the operational electrical-size of patch antennas is to implement a modified structure known as PIFA (Planar Inverted F Antenna), which has a metallic wall on one of the sides. In this way, the antenna fulfils the boundary conditions with a quarter wavelength distance between the open and the short-circuit, instead of the half wavelength between two open boundaries in conventional patch antennas [2], [6].

Previous works on compact PIFA antennas with slots for mobile communications have succeeded in providing different bands of operation with compact designs [7]–[9]. In addition, other new techniques have also been applied to the design of compact patch antennas. Some of them are based on CRLH (composite right left handed) transmission lines [10]–[14]. These antennas have multiple bands of operation as they allow the excitation of both right handed (RH) modes and left handed (LH) modes. According to this theory, the traditional transversal magnetic (TM) modes are produced by RH modes, and new radiation bands can be obtained from the frequencies at which the new LH modes propagate (being, TM modes too). The main advantage of this design is the possibility of achieving a compact multiband antenna with new resonant frequencies which are lower than the fundamental mode frequency in traditional patches. Different radiation patterns associated with the bands may also be generated, thus offering prospects of catering to various service requirements. This flexibility in radiation pattern for frequencies below the fundamental mode is not common for patch antennas. However, there are two drawbacks of these compact designs. Firstly, the efficiency or gain of the antennas is low if the antenna size is too small; and secondly, the new modes related to the LH modes have narrow bands.

The purpose of this paper is to present a novel compact patch antenna with a potential multifrequency response, including the possibility of obtaining a different radiation pattern at each band if desired. The theory of operation is based on [10], [11]. The paper is organized as follows. The description of the antenna *modus operandi* will be briefly explained in Section II. Examples of designs achieving dual and triple bands will be presented in Section III, including measurements of both return losses and radiation patterns. Section IV contains a study of the efficiency of the antenna, since this is one of the important parameters in compact designs. Finally, in Section V, conclusions will be derived from the results.

II. Basis of the Antenna

The proposed antenna is described in Fig. 1 (with top and side views). The basic antenna is a printed semicircle of radius R_{in}. It is a PIFA antenna since there is an electric wall that connects this semicircle to the ground plane. In addition, there is an external printed semi-ring which is also connected to the ground plane and whose external radius is R_{out}. This semi-ring is separated from the inner semicircle by an arbitrary distance (S_{io}), and it has a R_{io} width. A new resonance is created since there is an intrinsic capacitance between the inner semicircle and the outer semi-ring; and an intrinsic inductance given by the semi-ring and its connections to the electric wall. Consequently, this resonance can be used to match new radiation modes. The equivalent circuit for this antenna is the one represented in Fig. 2

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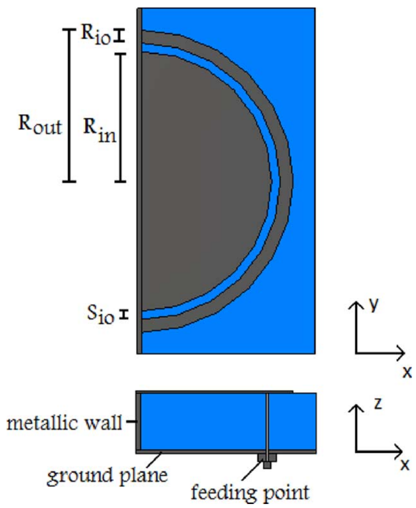


Fig. 1. Geometrical description of the antenna under study. Top and side views.

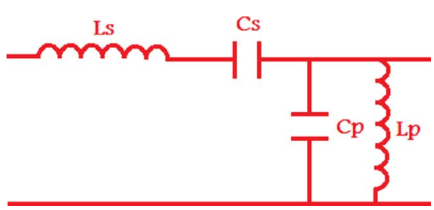


Fig. 2. Equivalent circuit for the antenna under study.

(not considering the feeding). The shunt capacitance and the series inductance correspond to the circuital model of ordinary patch modes, whilst the series capacitance and the shunt inductance model the new modes, thereby having the bi-frequency behavior.

There is no restriction *a priori* on the number of new radiation modes. The number of introduced semi-rings determines the number of added resonances, and consequently, the number of new possible radiation frequencies. In order to show this phenomenon, the simulated S_{11} for an example with three external semi-rings is included in Fig. 3. The antenna in the example has the following dimensions: a 23 mm inner semicircle radius, a 1 mm separation between rings and a 1 mm width of the rings. The thickness of the substrate is 8 mm and its dielectric constant 2.7. As predicted, three new modes appear below the frequency of the traditional TM_{11} mode (which is the fundamental one in these structures), and another three new modes are observed between the frequency of the fundamental mode and that of the second one (TM_{21} mode). We have verified that these new modes have similar radiation characteristics as those of the corresponding "conventional" ones which occur above them in frequency. For this reason, they will be denominated as "replicas" of the respective ordinary modes. However, they are in principle not necessarily all simultaneously well-matched if a conventional single-port feeding technique is used. This can be a constraint for using a high number of these new modes in practical designs when a simple feeding technique is used. With a single port, the challenge is then to find out the feeding point

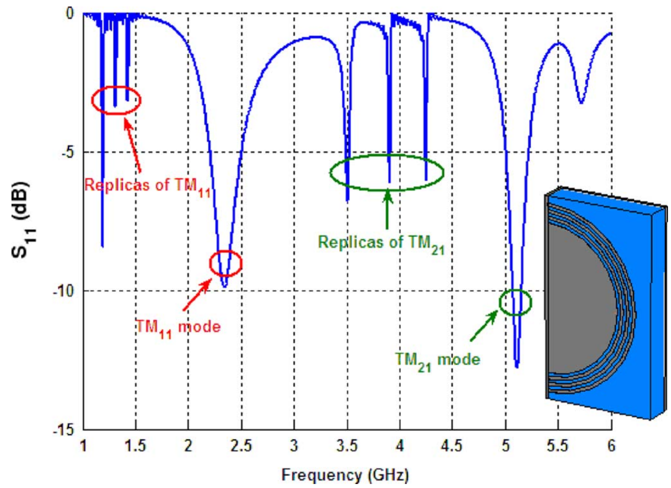


Fig. 3. Simulated band operations of TM_{21} and TM_{11} modes along with their three replicas, for an antenna with three external semi-rings, with the following dimensions: radius of the inner semicircle: 23 mm, separation between rings: 1 mm and ring widths: 1 mm. The thickness of the substrate is 8 mm, and its dielectric constant 2.7.

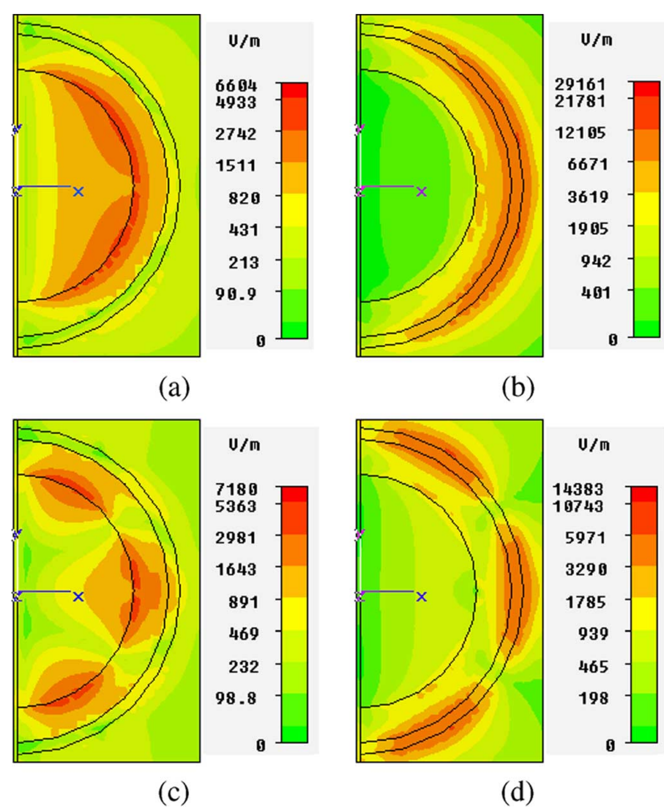


Fig. 4. Electric field distribution for TM_{11} and TM_{21} ordinary modes and their replicas.

where all the modes to be used are matched. This is a complicated task for a high number of replicated modes as the field distribution is not identical for all modes.

Fig. 4 shows the simulated absolute value of the vertical electric field ($|E_z|$) for the ordinary TM_{11} and TM_{21} modes, along with their replicas when only one semi-ring is introduced. The field distribution of a mode resembles its replica, i.e., they have the same number of maxima and minima in the same positions

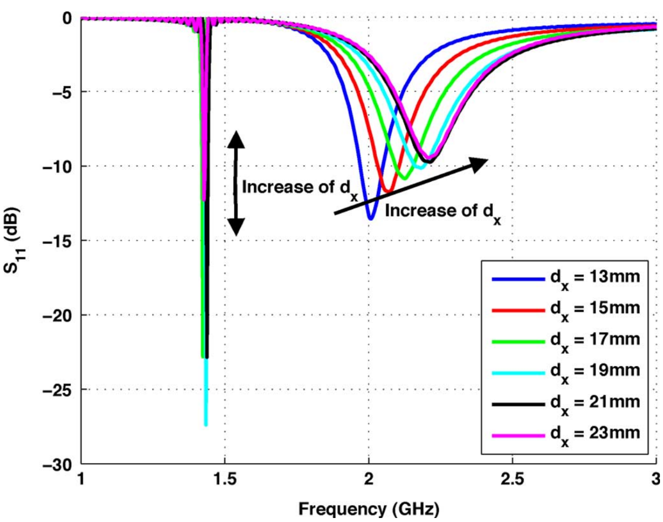


Fig. 5. Simulated S_{11} for prototypes with different feeding positions (d_x, which represents the distance to the metallic wall), with the following dimensions: $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm in a substrate with $\epsilon_r = 2.7$ and 8 mm thickness.

(following the criterion of definition of traditional modes in patch antennas [1], [2], [6]). Therefore, their radiation properties will also be similar.

Nevertheless, since each mode has a particular distribution and amplitude of the fields, the optimal matching point of each mode can also be placed at a different position. As a consequence, a preliminary study of these positions is required if a multifrequency response is desired. The optimal feeding position for each mode will depend on the dimensions of the elements, as well as on the thickness and dielectric constant of the substrate (as in conventional microstrip patch antennas [1], [2], [6]). In order to show the effect of the feeding point on the matching of the modes, a simulation study with different feeding positions for an example (with only one external semi-ring) was made. The antenna has the following dimensions: $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm in a substrate of $\epsilon_r = 2.7$ (PVC) with an 8 mm thickness. The simulated S_{11} is plotted in Fig. 5, where d_x represents the distance from the feeding point to the metallic wall. We can conclude that for the fundamental mode (for this particular case), when this distance increases, the matching becomes worse. However, for the replica of this mode, the matching does not have a clear trend as the matching level oscillates up and down with increasing d_x. Thereby, the best matching for this mode is not achieved at the same feeding point. Furthermore, the challenge posed to the antenna designer (as it would be in designing traditional patch antennas) is to find the optimal feeding point to excite the modes required by the given application of the antenna. Obviously, this is more challenging if we are limited to a single port design.

Other authors [10]–[14] have denominated the modes of similar structures as CRLH, since their designs are coming from transmission lines where the excited modes are LH. In addition, it is well known that patch antennas can be analyzed from transmission line theory, since the origin of these antennas is found in microstrip lines [6]. The antenna proposed in this paper can also be seen as an extension of those CRLH transmission lines as was the case in [10], where the grounded pins of each cell have been first moved to the edge of the cells, and later on replaced by a metallic wall. This approximation is illustrated in Fig. 6.

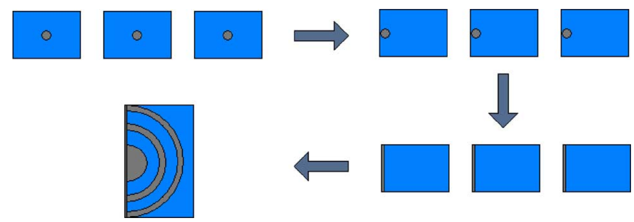


Fig. 6. Equivalent evolutionary approximation of the proposed antenna from CRLH lines as in the one proposed in [10].

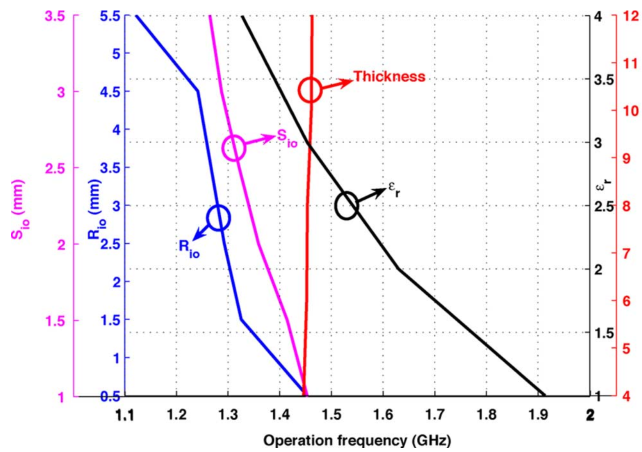


Fig. 7. Operation frequency for the replica of TM_{10}, as a function of different parameters. The reference antenna has the following dimensions: $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm in a substrate of $\epsilon_r = 2.7$ and 8 mm thickness.

The main role of the inner semi-circle of the antenna is to define the operation frequency of the ordinary modes excited in a microstrip patch antenna [1], whereas the external semi-rings and their distances to the inner semi-circle dictate the operation frequencies of the new modes denominated replicas. The latter effects are attributed to the influences which those two parameters have on the series capacitance and shunt inductance mentioned earlier. Nevertheless, the inner semi-circle will contribute also to the matching of the new modes, since the feeding point is located on it. Fig. 7 shows the variation of the operation frequency of the first replica mode as a function of the four main parameters which define its operation: permittivity ϵ_r, substrate thickness, S_{io} and R_{io}. As initial design we have considered the one analyzed previously in this Section, whose S_{11} was presented in Fig. 5.

Finally, in order to show the effect of the capacitance established by the distance between the inner semicircle and the outer semi-ring, lumped capacitors that connect these two parts of the antenna were introduced, and the measured results are plotted in Fig. 8. These results are for a structure with only one semi-ring whose dimensions are: $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with an 8 mm thickness. Although the antennas are not properly matched

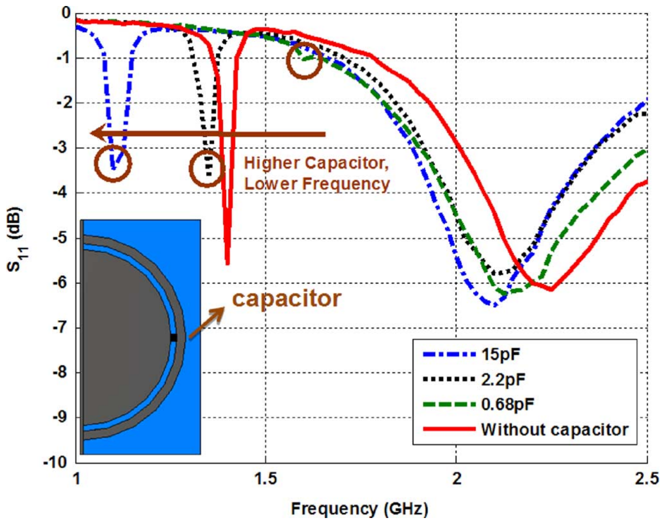


Fig. 8. Reduced operation frequencies with increased capacitances. Measured S_{11} for different prototypes with $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm and different lumped capacitors, in a substrate of $\epsilon_r = 2.7$ and 8 mm thickness.

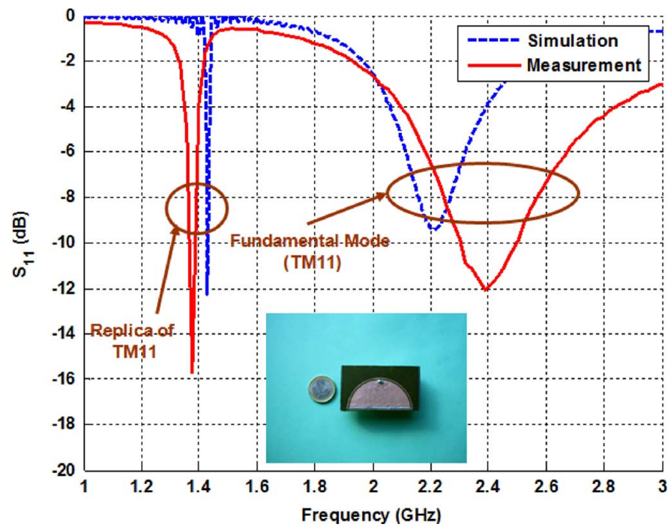


Fig. 9. Simulated and measured S_{11} for a prototype with $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with a 10 mm thickness.

(since the authors only expect to show the trend), we can conclude from these results that with higher capacitances the frequency of the new resonance is shifted down, and the traditional mode is not excessively affected. This agrees with the circuital transmission line model presented above.

All the simulations presented along this Section have been carried out with *CST Microwave Studio*.

III. Design Examples

In this section, some particular designs will be presented. Firstly, we will focus on the simplest structures, that is, antennas with only two bands of operation. To this aim, only one semi-ring is necessary. Later on, we will deal with triple band designs.

As explained above, the external semi-rings will contribute to the excitation of new modes. The operation frequency of these modes will be determined by the dimensions of each semi-ring. The larger the radius $(R_{\rm out})$ keeping the slot width (S_{io}) constant, the lower the frequency, and the same happens when the separation between the inner semicircle and semi-ring (S_{io}) is increased, since in both cases the shunt inductance and the series capacitance shown in Fig. 2 are modified. Moreover, the operation frequency of the ordinary modes is almost unaffected by the addition of the semi-rings and their dimensions.

A. Dual Band Operation

First of all, two different examples of the simplest configurations of the antenna are presented. These configurations are dual band antennas, making use of the ordinary mode of operation, and the replica of this mode or the replica of the first high-order mode (TM_{21}).

1) TM$_{11}$ and Its Replica: The most compact multifrequency antenna that we can achieve with this configuration is the one in which we excite the fundamental mode (TM_{11}) and its replica that works at lower frequencies. As previously commented, they will have similar radiation patterns since they have similar field distributions. Therefore, if we consider the case of only one external semi-ring, a dual-frequency characteristic is achieved, and these two frequencies are independent of each other. The dimensions chosen for this particular example are the following: $S_{io} = 1$ mm, $R_{\rm in} = 23$ mm and $R_{\rm out} = 24.5$ mm in a substrate of $\epsilon_r = 2.7$ (PVC) with a 10 mm thickness. The feeding point position is 22 mm from the metallic wall. The total size of the antenna is approximately $0.11\lambda_0 \times 0.22\lambda_0$ at the frequency of the replica of the TM$_{11}$, and $0.19\lambda_0 \times 0.39\lambda_0$ at the frequency of the TM$_{11}$. The simulated and measured S_{11} for this case are included in Fig. 9. The simulation predicts properly the working frequencies of the antennas although the bandwidths of the measurements are wider, due to the absence of losses in the simulation.

The radiation patterns of both modes were measured. The measurements in E-plane and H-plane are shown in Fig. 10 for both frequencies: 1.38 GHz and 2.4 GHz which correspond to the operation frequencies of the fundamental mode and its replica. Although the gain of the antenna is different for each mode (1.8 dB for the replica and 3.7 dB for TM$_{11}$), they both exhibit a broadside radiation pattern slightly tilted due to the lateral metallic wall.

2) TM$_{11}$ and the Replica of TM$_{21}$: A second example is presented in this subsection, where the fundamental mode of the patch (TM_{11}) and the replica of the second mode (TM_{21}) are excited. Thereby, each band of operation will have its own particular radiation pattern. This fact provides flexibility to the design depending on the application ([15], [16]), since various kinds of services requiring different radiation patterns can be provided by each band. A prototype was manufactured and measured, and has dimensions: $S_{io} = 9$ mm, $R_{\rm out} = 42$ mm and $R_{\rm in} = 30$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with a 12 mm thickness. The feeding point was placed at 29 mm from the metallic wall. The total size of the antenna is approximately $0.33\lambda_0 \times 0.66\lambda_0$ at the frequency of the replica of the TM$_{21}$, and $0.25\lambda_0 \times 0.5\lambda_0$ at the frequency of the TM$_{11}$. The graph of the S_{11} parameter versus frequency obtained from simulations

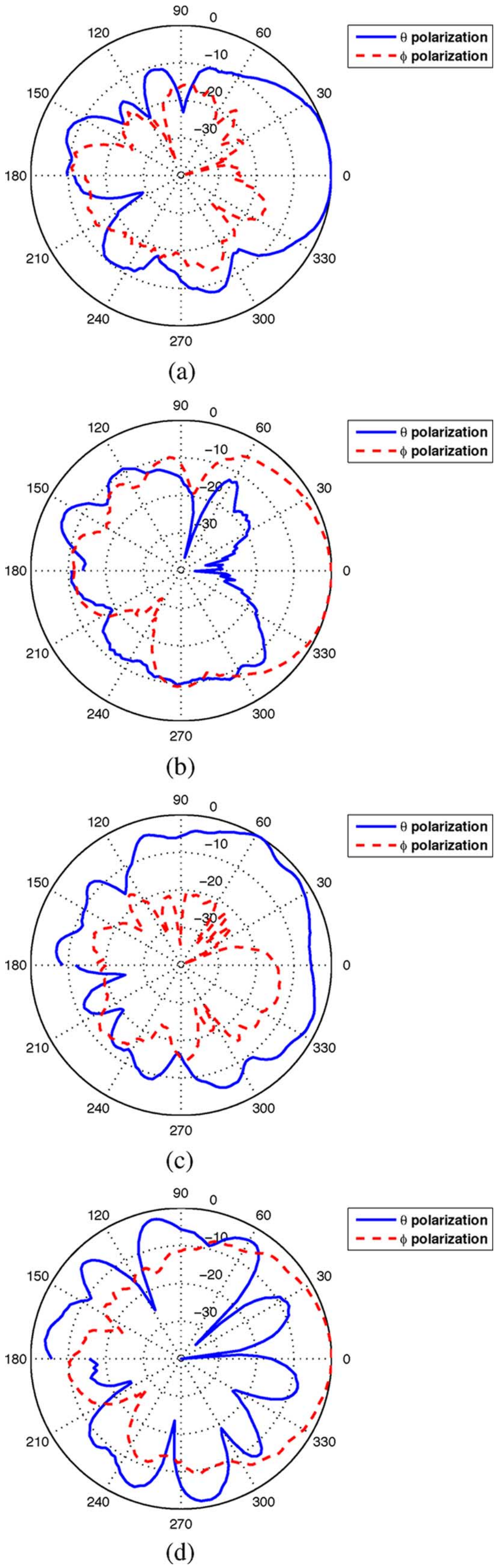


Fig. 10. Radiation patterns at 1.38 GHz and 2.4 GHz, where respectively the replica of TM_{11} mode and the ordinary TM_{11} are excited. (a) E plane (1.38 GHz), (b) H plane (1.38 GHz), (c) E plane (2.4 GHz), (d) H plane (2.4 GHz).

and measurements is shown in Fig. 11. Good agreement of the operation frequencies is achieved.

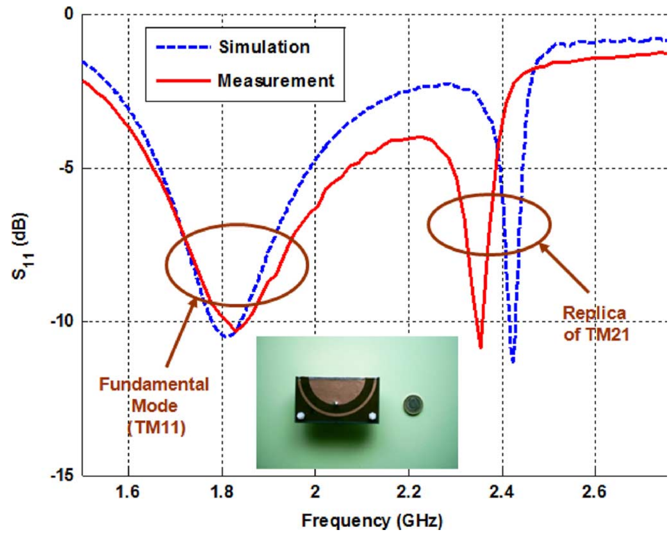


Fig. 11. Simulated and measured S_{11} for a prototype with $S_{io} = 9$ mm, $R_{\mathrm{out}} = 42$ mm and $R_{\mathrm{in}} = 30$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with a 12 mm thickness.

Here again, some measurements of the radiation patterns were also carried out. Fig. 12 shows the radiation patterns at both operation frequencies: 1.84 GHz for the TM_{11} mode and 2.34 GHz for the TM_{21} replica. They present distinct radiation characteristics since the field distributions are different. At 2.34 GHz, the pattern takes on the typical shape of a TM_{21} mode, with a minimum co-polar level in the broadside direction for the H-plane. The E-plane is not represented for the case of the TM_{21} mode, since in that plane the radiation pattern has a minimum. Moreover, the H-plane presents a high cross polarization level due to the large thickness of the substrate. Finally, the directivities are 5 dBi for TM_{11} and 5.5 dBi for TM_{21}.

B. *Triple Band Operation*

In addition to the foregoing dual-band examples, we now deal also with triple-band antennas. Two particular examples will be studied. The first one employs a single external semi-ring, for which the three operation bands are associated with the traditional TM_{11} mode, its replica and the replica of the TM_{21} mode. Following this, two external semi-rings that excite the ordinary TM_{11} mode and two of its replicas shall be dealt with. This is in virtue of a replicated mode produced by each semi-ring.

1) TM_{11}, its Replica and the Replica of TM_{21}: For this first example of triple-band design, we propose the use of only one semi-ring. Thereby, there will be only one replica of each mode, and the most compact design requires the use of the TM_{11} mode, its replica, and the replica of the second mode (TM_{21}). The dimensions of the designed example are: $S_{io} = 2$ mm, $R_{\mathrm{out}} = 33$ mm and $R_{\mathrm{in}} = 21$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with an 8 mm thickness. The feeding point is placed at 20 mm from the metallic wall. The simulated and measured reflection coefficients of this antenna are shown in Fig. 13. We see how the three bands are properly matched (below -10 dB).

2) TM_{11} and Its Two Replicas: As a final example, we propose here a design with two external semi-rings, for obtaining a triple-band operation. With the two semi-rings we obtain two replicas of each mode, but in order to have the most compact

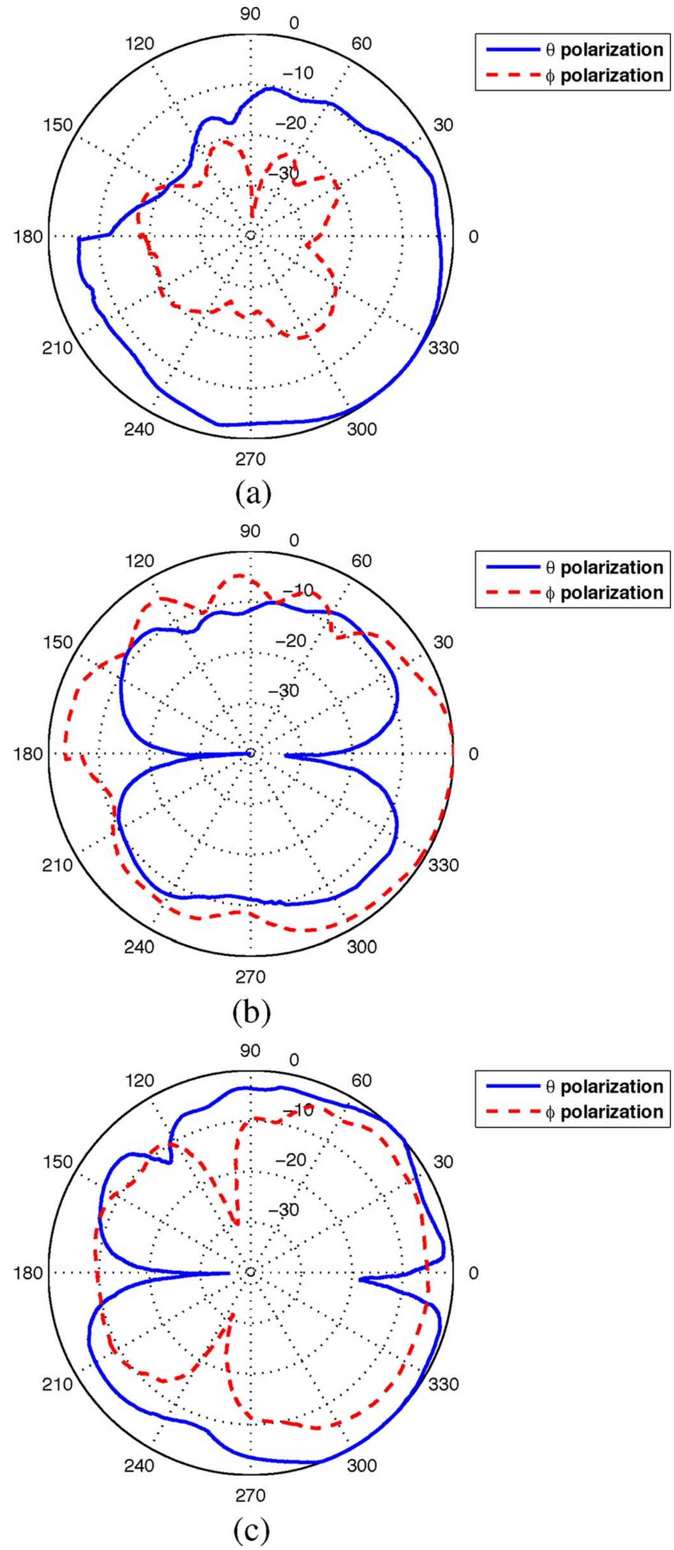


Fig. 12. Radiation patterns at 1.84 GHz and 2.34 GHz, where respectively the ordinary TM_{11} mode and the replica of TM_{21} are excited. (a) E plane (1.84 GHz), (b) H plane (1.84 GHz), H plane (2.34 GHz).

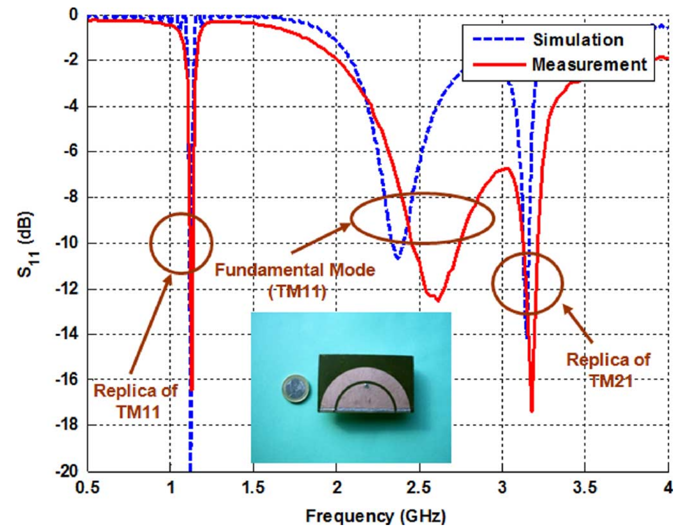


Fig. 13. Simulated and measured S_{11} for a prototype with $S_{io} = 9$ mm, $R_{\mathrm{out}} = 42$ mm and $R_{\mathrm{in}} = 30$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with a 12 mm thickness.

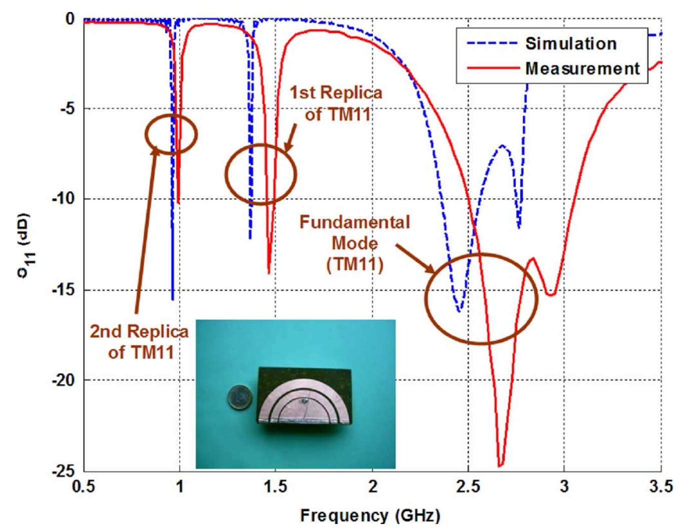
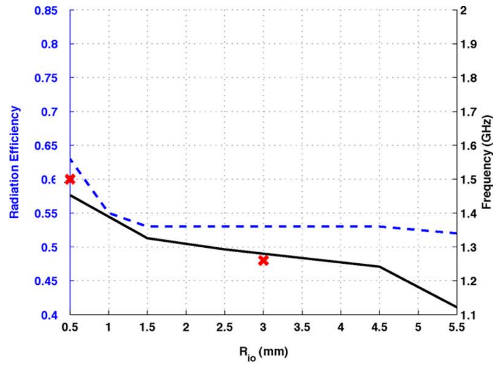


Fig. 14. Simulated and measured S_{11} for a prototype with $S_{io1} = 1$ mm, $R_{\mathrm{out1}} = 28$ mm, $S_{io2} = 2$ mm, $R_{\mathrm{out2}} = 38$ mm and $R_{\mathrm{in}} = 21$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with a 12 mm thickness.

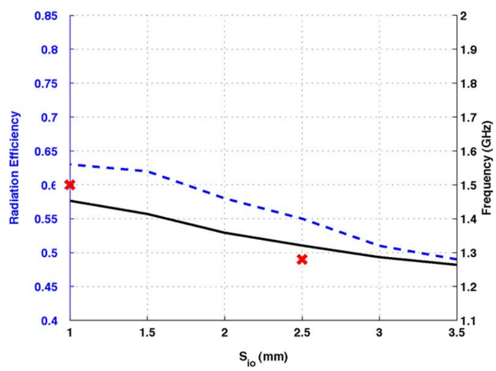
design, the fundamental mode TM_{11} and its two replicas must be used. Since this design has two semi-rings, we need to define two S_{io} and two R_{out}. We will name them with the subindex 1 for the internal semi-ring, and subindex 2 for the external one. The dimensions for this example are: $S_{io1} = 1$ mm, $R_{\mathrm{out1}} = 28$ mm, $S_{io2} = 2$ mm, $R_{\mathrm{out2}} = 38$ mm and $R_{\mathrm{in}} = 21$ mm, in a substrate of $\epsilon_r = 2.7$ (PVC) with an 8 mm thickness. The feeding point is placed at 20 mm from the metallic wall. The simulated and measured S_{11} of this antenna are presented in Fig. 14. As in the previous example, the three bands are matched (below -10 dB) with a simple coaxial probe. The size of this design is approximately $0.33\lambda_0 \times 0.66\lambda_0$ at the frequency of the TM_{11}, $0.18\lambda_0 \times 0.36\lambda_0$ at the frequency of the first replica of the TM_{11} and $0.12\lambda_0 \times 0.24\lambda_0$ at the frequency of the second replica of the TM_{11}.

IV. Study of the Radiation Efficiency

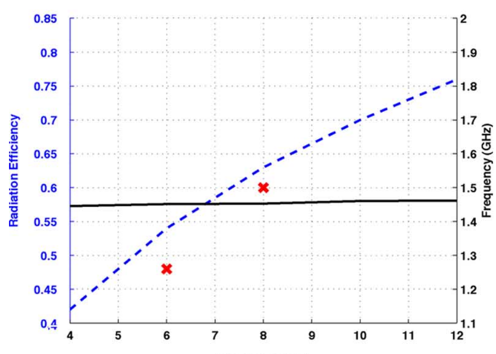
In this Section, the study will be focused on the radiation efficiency of the lowest mode of the antenna, i.e., the replica of the first mode, since this mode will be the most critical in terms of efficiency. For simplicity, an antenna with only one semi-ring was considered. The initial dimensions for this study were:



(a)



(b)



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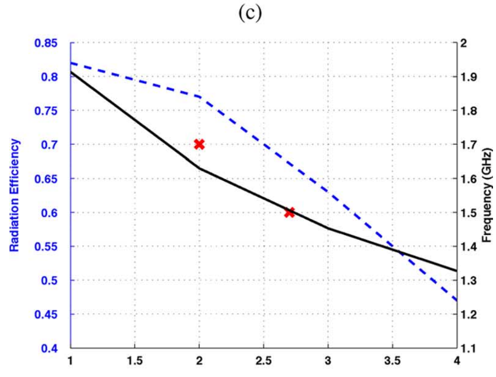

(d)

Fig. 15. Variation of the operation frequency (black solid line) and radiation efficiency (blue dashed for simulations, red cross for measurements) with different parameters: (a) semi-ring widths R_{io}, (b) distances between semi-circular patch and semi-ring S_{io}, (c) substrate thicknesses, and (d) substrate permittivities.

$S_{io} = 0.5$ mm, $R_{\text{in}} = 23$ mm and $R_{\text{out}} = 24.5$ mm, in a substrate of $\epsilon_r = 2.7$ with an 8 mm thickness. In order to properly study the structure, different parameters of the antenna were changed and the radiation efficiency was obtained for each design. These parameters were: the thickness of the substrate, the dielectric constant, the distance between the inner semicircle and the outer semi-ring (S_{io}) and the width of the semi-ring (R_{io}). With the latter two parameters, the total external radius R_{out} is varied. This study was developed using *CST Microwave Studio* and it was validated by some measurements of the radiation efficiency in a reverberation chamber ([17], [18]). Fig. 15 shows the operation frequencies of the mode and the radiation efficiencies for the studied cases, in which the red crosses represent the measured efficiencies for some examples. The measurements present a lower radiation efficiency when compared to the simulations due to uncertainties in the characteristics of the substrates. Nonetheless, the trends are similar to the simulations. The radiation efficiency is also affected by the electrical size of the structure through frequency variation. The lower the frequency, the lower the efficiency. Moreover, the efficiency varies strongly with the thickness, although the operation frequency is not changed. The larger the thickness, the higher the efficiency of this mode. This coincides with what the cavity model of a patch antenna predicts [2]. However, the increase in the substrate thickness can have some well-known drawbacks such as the strong excitation of surface waves, or problems with the matching of ordinary TM modes. Finally, the last parameter that has been studied was the permittivity of the substrate. Like in traditional TM modes, when the dielectric constant increases, the efficiency decreases. The operation frequency of the replicated mode also suffers the same effect.

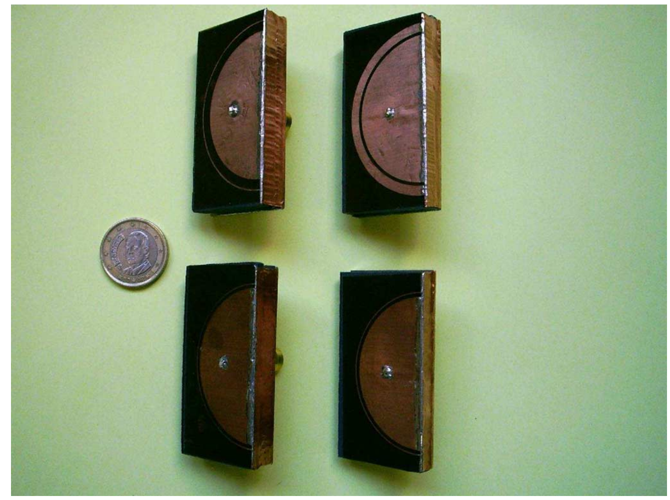

Fig. 16. Photo of some of the manufactured prototypes.

It is also important to point out how the frequency of the ordinary mode (2.1 GHz) is almost unaffected by any of the proposed changes in the antenna geometry (excluding substrate characteristics) and for that reason is not represented in the previous figures. Furthermore, the radiation efficiency of the fundamental mode was also measured, achieving a radiation efficiency above 0.95 for all the examples. Finally, Fig. 16 shows a photo of some of the prototypes which have been manufactured and measured.

V. Conclusion

A compact loaded PIFA has been presented in this paper. The antenna is composed of an inner semi-circle and an arbitrary number of external semi-rings. Each semi-ring produces the excitation of new modes that can be used in radiation. These modes are replicas of the ordinary TM modes of patch antennas, having similar radiation properties. Therefore, the proposed antenna provides multiple frequencies of operation with different types of radiation patterns, giving versatility to the design depending on the application.

Four particular examples, using only one or two semi-rings, have been manufactured. The first one uses TM_{11} mode in conjunction with its replica. This first design provides two quasi-broadside radiation patterns. The second one uses the same ordinary TM_{11} mode and the replica of the ordinary TM_{21}, obtaining two bands with two different radiation patterns. The third one provides a triple band antenna, with the traditional TM_{11}, its replica and the replica of the TM_{21}. Finally, the fourth example shows an antenna with triple band response making use of two semi-rings and two replicas of the TM_{11}. These four examples were studied by simulations and measurements (in terms of return losses and radiation patterns). The most challenging aspect is the matching of all these modes at the same time, since the optimal point for the matching of each mode is at a different position of the patch and in this work we have assumed a single port feeding technique.

Finally, a study of the radiation efficiency was carried out for the replica of the TM_{11} with only one semi-ring, since this mode is the one which works at the lowest frequency and therefore its efficiency is the most critical. The efficiency depends on the geometry of the antenna since various parameters of the geometry modify the operation frequency of the new mode. In addition, the permittivity and thickness of the dielectric are important factors, as they strongly affect the radiation efficiency. This study of the radiation efficiency was verified with some measurements.

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