# Dual-Band Patch Antennas Based on Short-Circuited Split Ring Resonators

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***Abstract*—A study of an innovative antenna based on split ring resonators (SSRs) is presented. SSRs have been exhaustively used in the literature as the unit cell of periodic structures for obtaining left-handed media, whose interesting characteristics can be applied to waveguides or antennas. In this work, the authors propose the use of only one unit cell of a double SRR as a radiator. The double SRR is printed on a grounded dielectric slab, acting as the radiating element of a microstrip patch antenna, and grounded pins are used to short-circuit the structure for size reduction. A compact dual band antenna is obtained in this way. For example, a particular design making use of PP ($\epsilon_r = 2.2$) as substrate allows a size of 0.05 $\lambda_0 \times$ 0.05 $\lambda_0$ for the lower frequency of operation with an acceptable radiation efficiency. Simulated and measured results of return losses, gain and radiation efficiency of this new type of patch antenna are provided.**

***Index Terms*—Dual band, microstrip patch antenna, split ring resonator.**

## I. INTRODUCTION

OVER the last years, the definition and study of artificially-synthesized materials known as metamaterials have been accorded considerable attention from the scientific community [1]. Basically, these materials have ordinary microscopic characteristics, but macroscopically, they exhibit properties that cannot be found in nature. The interest has typically been mainly focused on structures with unusual electromagnetic properties defined by *Veselago* [2], which can be achieved from subwavelength periodic repetitions of particular resonant unit cells. These new conditions are normally only obtained in a narrow frequency band, and they depend primarily on the periodicity and dimensions of the elements. One of the most commonly used unit cell is the SRR (Split Ring Resonator) which has been vastly studied in the literature since its inception and measurements of early prototypes ([3], [4]).

Since then, SSRs have been used for numerous purposes and applications. One of the most common is the use for obtaining the propagation of new modes or for filtering propagation bands in guiding structures. These theories are already successfully applied to different types of transmission lines, for which waveguides and microstrip lines are the most widely studied in the literature ([5]–[10]). Therefore, considering that these SSRs can eliminate or provide new bands of operation, they can be used not only in transmission lines, but also in the design of antennas. Particularly, in microstrip technology some authors have developed designs where the SSRs have for instance contributed to notch bands of traditional antennas ([11]–[14]). On the other hand, other authors have used left-handed media based on SSRs as substrates for microstrip patch antennas with different purposes such as reducing the size of the antennas ([15], [16]) or improving the impedance bandwidth ([17], [18]). In addition, other works have used left-handed media as superstrates for increasing the directivity and gain of patch antennas ([19]). Finally, some new patch antennas that use SSRs for defining new operation bands (at lower frequencies) have also been presented ([20]–[22]).

These aforementioned radiators combine SSRs or derived structures with traditional antennas for obtaining new resonances, or to modify the radiation pattern or the usual operation frequency. However, in the present paper, the authors propose the use of short-circuited SSRs themselves as main radiators to create a new microstrip patch antenna, and not only as external loads. The antenna is dual-band and highly compact, and consequently can be suitable for applications where there are size constraints. An important fact known to achieve such compactness is the use of pins which short-circuit both SSRs to the ground plane, thus creating similarities with PIFA antennas.

Other ways of obtaining compact antennas with dual band performance have been explored in the literature. Most of them use substrates with high permittivities. For example, in [23] the authors obtained a compact size of $\lambda/8 \times \lambda/8$ but using materials with relative permittivity of 16 and 30; and in [24] the authors propose an antenna with a length of $\lambda/4$ in one of its sides, making use of FR4 (that has relative permittivity of 4.2). In this paper, we propose an antenna whose size is compact even with low permittivity materials. Besides, the "self-similar" nature of the proposed concentric type double-SRR radiator is highly elegant and provides the strong compactness. This is a characteristic that is absent from most other previous works, which mainly involved PIFAs that are located at physically disparate locations, each taking care of a certain band. To possess this attribute is vital for applications in modern-day

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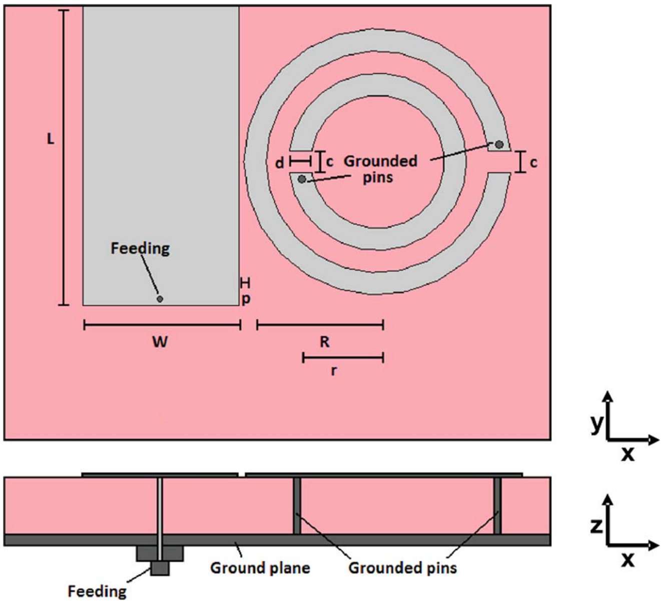


Fig. 1. Top and side view of the proposed antenna.

handheld devices where "real estate" for antenna placement is scarce.

All the results obtained in this work have been simulated with *CST Microwave Studio* and validated with measurements of return loss as well as gain in an anechoic chamber and radiation efficiency in a reverberation chamber.

## II. DEFINITION OF THE ANTENNA

In this Section, the proposed antenna is described. Fig. 1 shows the top and side views of the antenna. Since it has a grounded dielectric and a printed metallization, it can be classified as a microstrip patch antenna. The radiating face is composed of two concentric split rings with opposite gaps and short-circuited to the ground plane at one end of each ring as for PIFA antennas. The antenna is fed by a microstrip line placed beside the rings as shown in Fig. 1, although another type of excitation could be also possible as will be demonstrated later. The dielectric material of the substrate has a low permittivity, as antennas would have typically in order to provide good radiation characteristics.

Fig. 2 shows the $S_{11}$ (simulated and measured) for such an antenna whose arbitrary dimensions are as follow (with reference to Fig. 1 for the notations): $R = 6$ mm, $r = 4$ mm, $c = 1$ mm, $d = 1$ mm and $p = 0.25$ mm; for a substrate of PVC ($\epsilon_r = 3$) with 3 mm thickness. As the Figure shows for both simulation and measurement, there are two bands of operation related to the resonances established by the SSRs, although the bands are not well matched in this example. The operation frequencies obtained by simulations fit properly with the measurements. The electric field distributions for both modes are shown in Fig. 3. Assuming the antenna is in the $XY$ plane, the main field component is $E_z$ as it would typically be for patch antennas. The inner ring mainly contributes to the excitation of the higher resonance frequency whereas the outer one to that of the lower frequency. In addition the separation between the inner and outer rings affects both frequencies. Later on, a parametric study will be presented in Section IV.

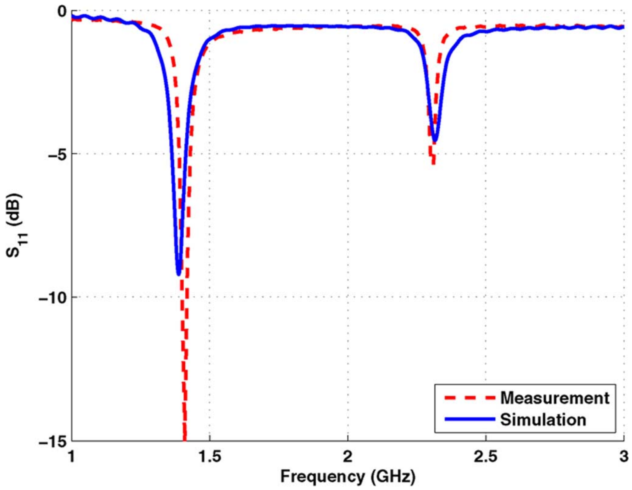
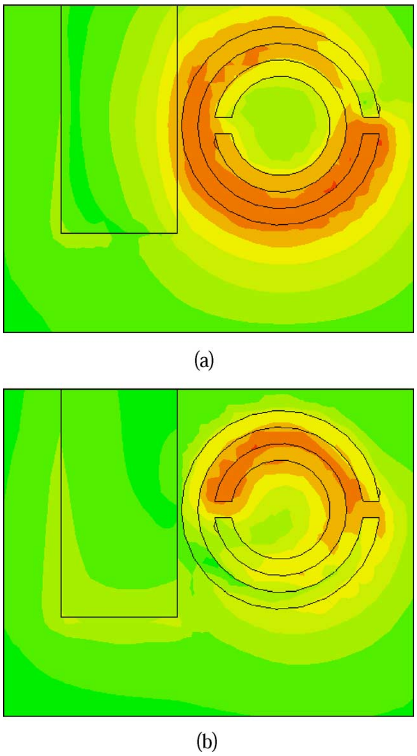


Fig. 2. Measured and simulated $s_{11}$ for an antenna with the following dimensions: $R = 6$ mm, $r = 4$ mm, $c = 1$ mm, $d = 1$ mm and $p = 0.25$ mm; for a substrate of PVC ($\epsilon_r = 3$) with 3 mm thickness.


(a)

(b)

Fig. 3. Electric field for both radiation modes shown in Fig. 2. (a) Amplitude of the electric field distribution at the lower frequency (1.4 GHz). (b) Amplitude of the electric field distribution at the higher frequency (2.29 GHz).

## III. CIRCUIT MODEL

An equivalent circuital model of the antenna is now presented. The proposed model is as shown in Fig. 4 (based on the ones presented in [5], [21]) and it is intended to qualitatively show the operation of the antenna. Firstly, $L_L$ and $C_L$ correspond to the typical equivalent circuit of a transmission line. These two elements are shunt connected to the antenna

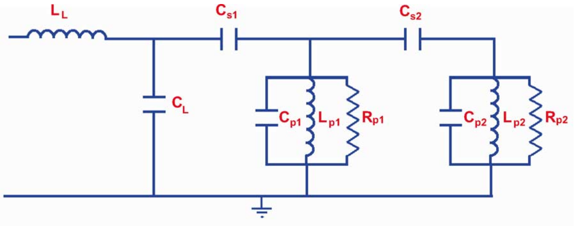


Fig. 4. Equivalent circuital model for the antenna.

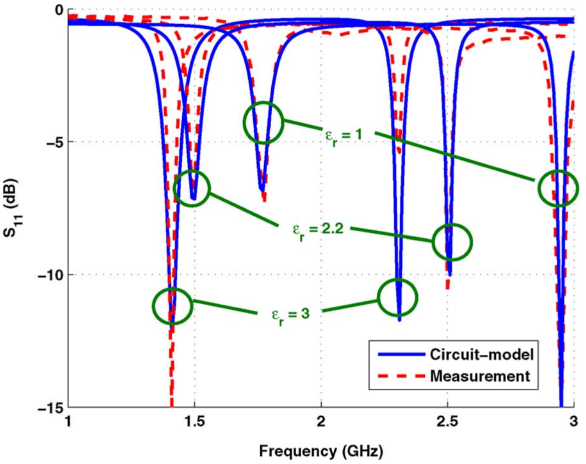


Fig. 5. Measurement and circuit-model simulation of $s_{11}$ for an antenna with the following dimensions: $R = 6$ mm, $r = 4$ mm, $c = 1$ mm, $d = 1$ mm and $c = 0.25$ mm; for the following substrates: PVC ($\epsilon_r = 3$), PVC ($\epsilon_r = 2.2$) and PVC ($\epsilon_r = 1$), all of them with 3 mm of thickness.

which is composed of two series capacitances ($Cs_1$ and $Cs_2$) defined by the coupling between the two SRRs (which depends on the distance between them) and also the gaps of both rings, two shunt inductances ($Lp_1$ and $Lp_2$) generated by the SSRs and their connections to the ground plane, and two low order capacitances ($Cp_1$ and $Cp_2$), characterized by the total surface area of the SRRs and the substrate attributes (permittivity and thickness).

By tuning the lumped element values of the equivalent circuit based on guidelines from [5], [21], [25], the frequency behavior was fitted for three particular examples that were designed with the dimensions studied in Section II, but different dielectric materials ($\epsilon_r = 3$, $\epsilon_r = 2.2$ and $\epsilon_r = 1$), thus achieving very good agreement between the measurements and simulations as Fig. 5 shows. Particularly, the case of $\epsilon_r = 3$ has the following values: $L_L = 0.26$ nH, $C_L = 25$ pF, $Cs_1 = 68$ pF, $Cs_2 = 1.8$ pF, $Lp_1 = 0.5$ nH and $Lp_2 = 3$ nH. The influence of the dielectric materials is principally modeled by the series capacitances ($Cs_1$ and $Cs_2$) and the shunt inductances ($Lp_1$ and $Lp_2$). However, in principle, the estimation of the values of all these components and how to relate them to the antenna geometry is not trivial. Therefore this model is a good tool for analyzing and understanding the operation of the antenna, but it is not suitable for design purposes.

## IV. PARAMETRIC STUDY

A parametric study of the effects which the different parameters have on the two resonance frequencies is now presented.

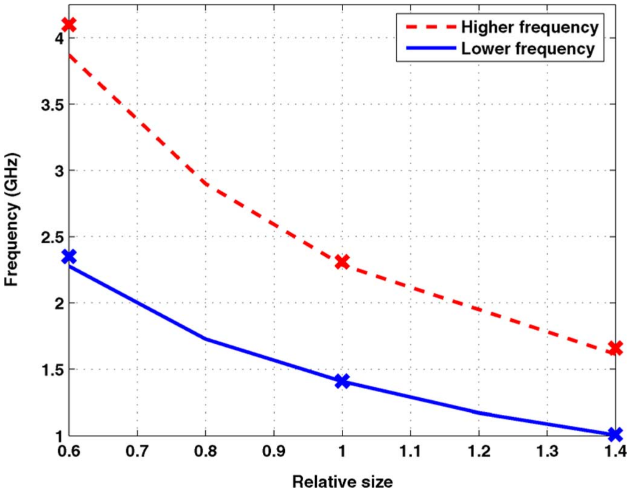


Fig. 6. Evaluation of the operation frequency of both resonances when the relative size of the antennas is changed. Crosses correspond to measured prototypes.

The results are obtained by simulations and verified by measurements. An initial antenna will be considered whose dimensions are: $R = 6$ mm, $r = 4$ mm, $c = 1$ mm, $d = 1$ mm and $p = 0.25$ mm; for a substrate with 3 mm thickness and $\epsilon_r = 3$. From this design, some parameters will be varied and their influences studied.

Obviously, depending on the total size of the SSRs, the operation frequencies will be modified as in any resonant structure. A study of this size effect was carried out obtaining the results shown in Fig. 6, whereby the two operation frequencies are represented as a function of the relative size of the antennas, which is defined by a scaling factor with respect to the size of the rings in the preliminary configuration. Thereby, when this parameter is equal to unity, we are referring to the initial case. As this Figure shows, when the relative size of the rings is increased the operation frequencies exponentially decrease, as expected.

Two other important parameters of the antenna are the thickness of the substrate and its permittivity. The influences of these two parameters on the resonance frequencies are plotted in Figs. 7 and 8, respectively. As seen, the higher and lower resonance frequencies fall considerably with increasing values of both parameters. This concurs with well known characteristics of traditional patches, whose operation frequencies are such that some dimension of the printed part of the antenna is approximately a multiple of $\lambda/2$ in the material used as substrate [26], [27]. However, in traditional patches the thickness affects mainly the bandwidth and the efficiency of the antenna (Q factor), but not meaningfully the operation frequency of the modes [28] as is the case for the proposed antennas. This can be understood by knowing that the principle which defines the resonant frequencies of these SRR-based patch antennas is different from that of classical ones. Although traditionally, the fundamental mode of patch antennas is defined by the length of one of its sides, the modes for the present case however are defined by the capacitance between rings, the capacitance of the splits, and the inductance of the rings and their short-circuited pins. Thus, if the thickness of the substrate is changed, these inductances will be strongly modified and the resonances will be shifted in frequency. The latter coincides with how the

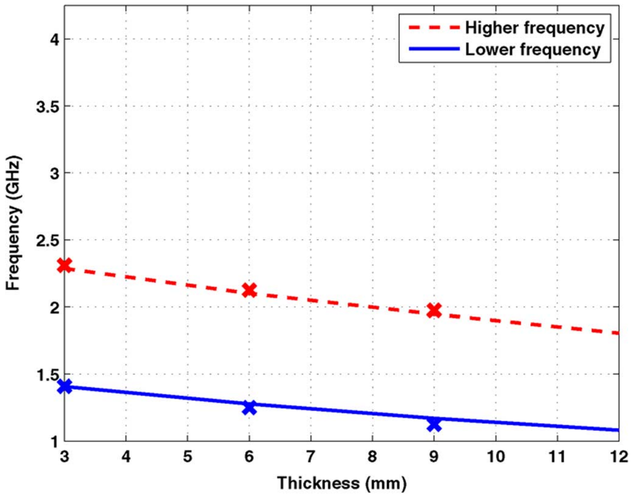


Fig. 7. Evaluation of the operation frequency of both resonances when the thickness of the substrate is changed. Crosses correspond to measured prototypes.

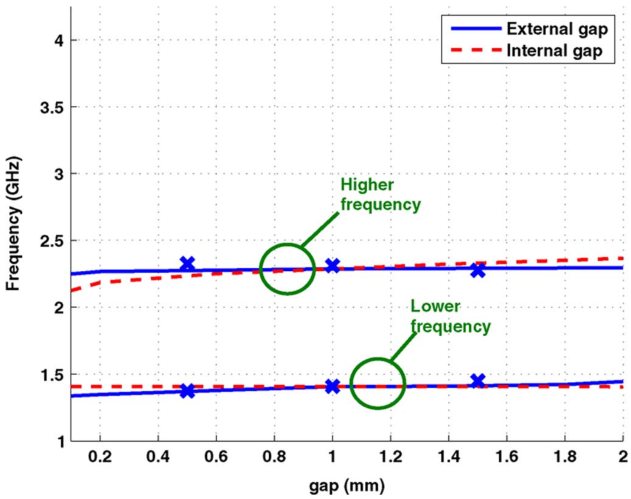


Fig. 9. Evaluation of the operation frequency of both resonances when the gap $c$ of the outer and inner rings are changed. Crosses correspond to measured prototypes.

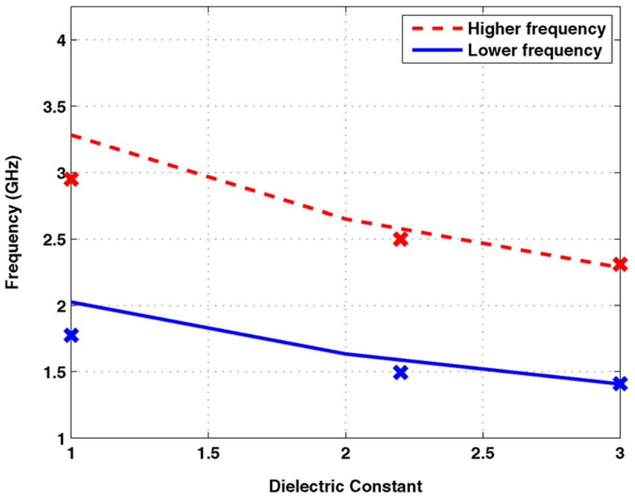


Fig. 8. Evaluation of the operation frequency of both resonances when the relative permittivity of the substrate is changed. Crosses correspond with measured prototypes.

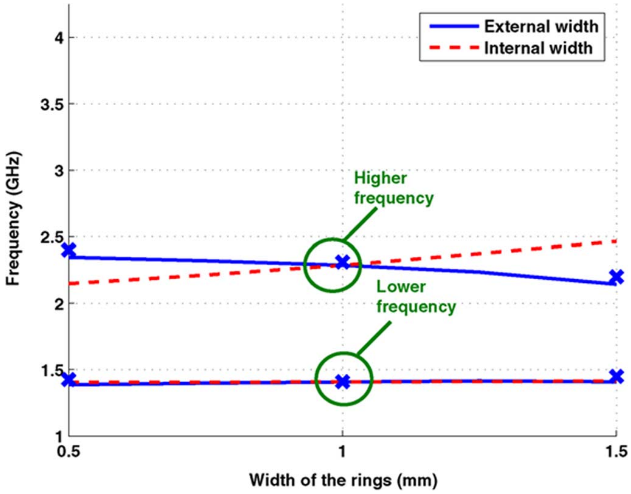


Fig. 10. Evaluation of the operation frequency of both resonances when the widths $d$ of the outer and inner rings are changed. Crosses correspond to measured prototypes.

substrate thickness affects PIFA antennas due to the similar grounded connection.

Figs. 9 and 10 show the influences of the gap of the splits in the rings $c$ and the width of the strips $d$. In studying the latter, the outer radii of both rings remain fixed as the inner ones are varied. Modifications of both parameters introduce changes in the series capacitances as well as the shunt inductance. Thus, variations in the operation frequency are obtained. However, these variations are not as strong as the ones arising from the other parameters studied before. Consequently, the gap size and strip width are ineffective parameters for adjusting the operation frequency through a wide range, but they can help in fine tuning the band in a small range if it is required. Future works on this fact open the possibilities of broadband and reconfigurable antennas by connecting lumped elements in between the gaps.

Another aspect to be investigated are the positions of the grounded vias attached to the rings. Thus far, it has been assumed that the grounding via of the external ring is situated above the gap, whereas that of the internal ring is located below its gap (as depicted in Fig. 1). However, it is also possible to place the pins of both inner and outer rings simultaneously above or below their respective gaps. This modification of the pin location produces a change in the operation frequency of the bands as can be seen in Fig. 11, which shows a comparison between two designs: one being the previous placement in opposite sense, and the other with both pins placed above the gaps of the rings which they are grounding. When the placement of both grounded vias are of the same sense, i.e., above the gap, the operation frequency of the lower band decreases whereas that of the upper band increases. As a result, the bands get more separated. Therefore, the location of the pins provides an alternative for more flexibility in the design of the bands.

Finally, the distance between the SSRs and the microstrip line ($p$ in Fig. 1), must be small in order to excite the structure. This separation changes the matching of the antenna but the

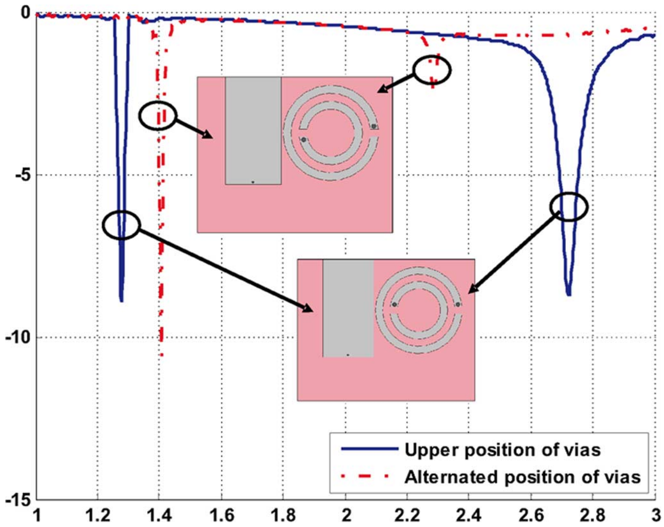


Fig. 11. Influence of the position of the grounded vias in the external and inner rings.

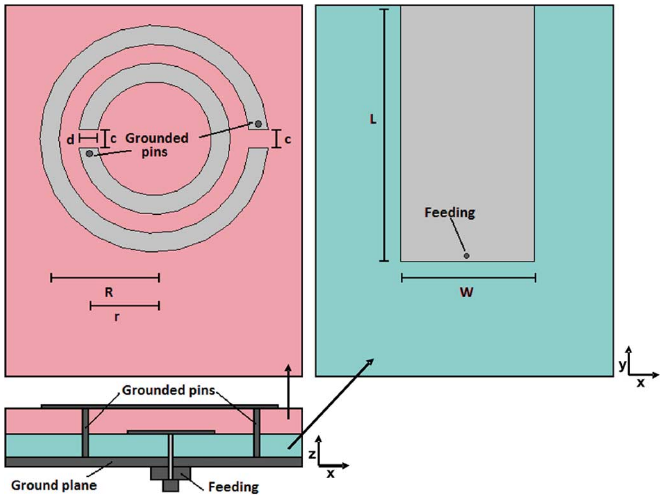


Fig. 12. Scheme of a multilayer configuration of the antenna, with the feeding located in a middle substrate.

frequency of operation remains almost unaffected. The dimensions of the microstrip line ($W$ and $L$) will affect the matching as well. Particularly, the width ($W$) can be approximately determined from classical microstrip line theories, for obtaining 50 $\Omega$, although smaller values can be used for low permittivity materials with large thicknesses.

## V. PROTOTYPE

To conclude, a particular example of fabricated prototype will be studied in terms of return losses, gain and radiation efficiency. To this aim an improved feeding based on a multilayer structure is employed for obtaining better matching and more compactness. The microstrip feed line is introduced in a middle slab below the radiant elements which are located in the top layer. The scheme of this new antenna is illustrated in Fig. 12.

The selected dimensions for this example are as follow: $R = 6.5$ mm, $r = 5$ mm, $c = 2.2$ mm and $d = 1$ mm; for two substrates of PP ($\epsilon_r = 2.2$) with 3 mm thickness of the lower one and 3 mm thickness of the upper one. The ground plane size is 22 mm × 17 mm. A photo of the manufactured prototype is shown in Fig. 13. The simulated and measured return losses are shown in Fig. 14. As seen, the antenna has two radiation bands arising from the two rings as explained in the previous section. The simulations approximate properly the operation frequency of the modes.

The antenna is not very directive since its size is small (0.05 $\lambda_0 \times 0.05 \lambda_0$ at the lower frequency and 0.08 $\lambda_0 \times 0.08 \lambda_0$ at the higher one, not including the ground plane). It is quite compact if we consider that the antenna is made of PP ($\epsilon_r = 2.2$) and it could be further reduced by using a higher permittivity material but at the price of a lower radiation efficiency. Consequently, it depends on the requirements of the given application.

The total efficiency measured in a reverberation chamber[1] has a value of 0.5 for the lower frequency (1.24 GHz) and 0.8 for the higher frequency (1.96 GHz). The maximum gain measured in an anechoic chamber was −1 dBi for the lower band of operation and 1 dBi for the higher one.

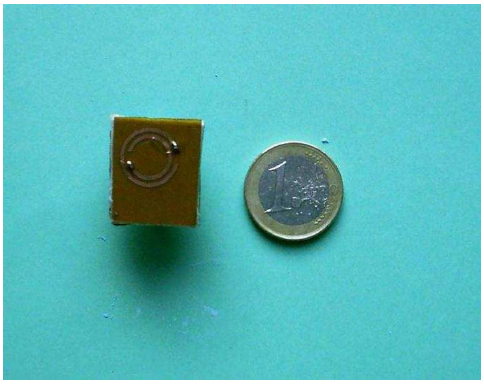


Fig. 13. Photograph of the manufactured prototype.

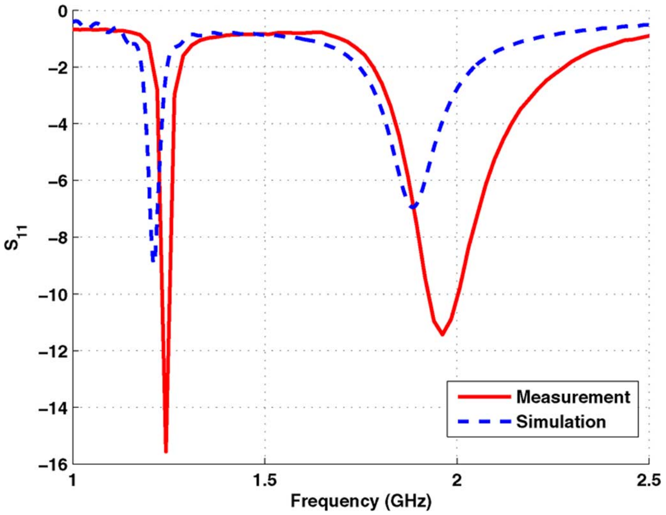


Fig. 14. Measured and simulated $s_{11}$ for an antenna with the following dimensions: $R = 6.5$ mm, $r = 5$ mm, $c = 2.2$ mm and $d = 1$ mm; for a substrate of PP ($\epsilon_r = 2.2$) with 3 mm thickness of the lower one and 3 mm thickness of the upper one.

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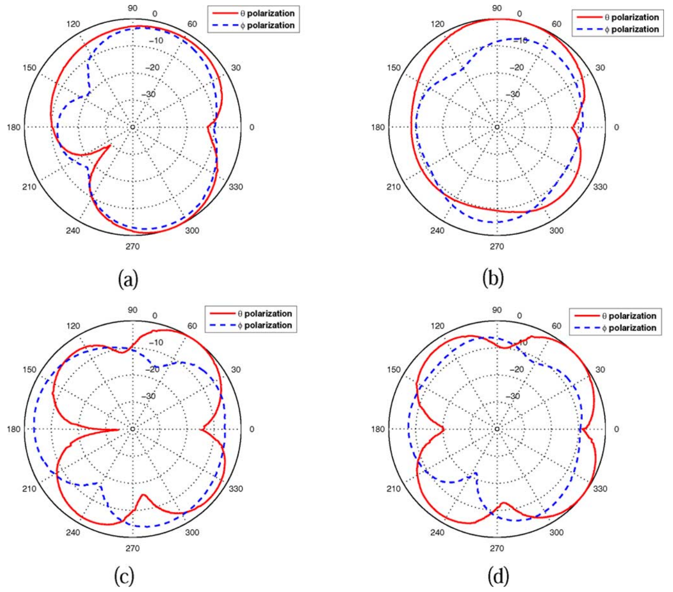
[1] It must be noted that inaccuracies in these measurements can be due to the effect of the cable connected to the antenna that can contribute to radiation.



(a) (b) (c) (d)

Fig. 15. Measured radiation pattern at 1.24 GHz and 1.96 GHz, where respectively are the operation bands of the antenna presented in Section V. (a) Plane $\phi = 90$ (1.24 GHz), (b) Plane $\phi = 0$ (1.24 GHz), (c) Plane $\phi = 90$ (1.96 GHz), (d) Plane $\phi = 0$ (1.96 GHz).

Considering that the relative 3 dB bandwidth of the antenna is 6.3% for the higher operation band, and 0.9% for the lower band; the Q factor of both bands is 15.82 and 112.94, respectively. The practical limitation of antennas in terms of size, bandwidth and efficiency comes from the Chu Limit [29], that has been reviewed by some authors [30], [31]. The lower bound of Q factor has the following expression:

$$Q_{lb} = \eta_r \cdot \left( \frac{1}{k \cdot a} + \frac{1}{(k \cdot a)^3} \right) \tag{1}$$

where $\eta_r$ is the radiation efficiency of the antenna. For the evaluation of this limit, the size of the antenna is expressed in terms of $k \cdot a$(where $k = (2\pi)/(\lambda)$, and $a$ is the minimum radius of a sphere in which the antenna including its ground plane can be contained). Therefore, according to the Chu Limit, for two antennas with same electrical size the one which provides the lowest band of operation can achieve smaller values of radiation efficiency (for the same bandwidth). In our case, $a = 14.22$ mm, since it is defined not only by the diagonal of the planar antenna but also by its thickness.[2] For the lower band this term is equal to $k \cdot a = 0.37$ and for the upper one $k \cdot a = 0.58$. Therefore, for the lower band, the lower bound is $Q_{lb} = 11.28$ and the Q factor of the antenna is almost 10 times this bound, whilst for the upper band, this lower bound is $Q_{lb} = 5.39$ and the Q factor of the antenna is 3 times the lower bound. As reported in [31], planar antennas cannot approach this lower bound.

Finally, Fig. 15 shows the measured radiation patterns for the operation bands in an anechoic chamber. The $\theta$ component is seen to be stronger for most observation directions, although the $\phi$ component is generally non-negligible.

## VI. Discussion

After the complete analysis of the proposed antenna, we need to point out what are the main advantages/differences of this design when compared to the many antennas that can be found in the literature with similar properties.

Although there had been reported prior studies on PIFA related types of antennas, there still remain major differences between those works and the present one. The following is a comparison with some of the most relevant works:

In the paper of [32], the antenna there was claimed to have efficiencies of about 40% and 62% in the lower and upper bands respectively, as compared to 50% and 80% achieved by the present design. Although higher gains were obtained in this [32] (1.62 and 2.13 dB in the bands, compared to $-1$ and $+1$ dB in this work), one has to consider the considerably larger ground plane ($0.76\lambda \times 0.24\lambda$ at 900 MHz) there as compared to ($0.09\ \lambda \times 0.07\ \lambda$ at 1.24 GHz) here. The present concentric twin-SRR configuration is far more compact, not taking up space of other displaced locations. Each of the two rings serves one band, a mechanism that is inherently different from that of [32]. Another limitation of the antenna there is its non-coplanar nature as opposed to the herein clean structure which has a gap that allows the use of capacitive lumped elements for tuning or reconfigurability purposes.

The work in [33] also dealt with miniaturized dual-band PIFA antennas. Although a dielectric slab with higher permittivity was used there ($\epsilon_r = 4.4$ versus 2.2 here), the antenna which we propose is still electrically smaller. Besides, that paper made use of a larger ground plane, which moreover, is not located below the metallization, thus not qualifying the configuration there as a patch-type antenna. Considering the fact that the gain in [33] is in the same order as what we have achieved, it is implied that the efficiency there is lower since the directivity is higher. As a consequence, the radiation patterns which we obtain are more omni-directional than those in that work. Nonetheless, while the present design appears to outperform the one in [33], the antennas are after all of different topologies and a completely fair comparison may not be possible.

Amongst the most cited papers on PIFA is that of [34], being one of the first reports on dual-band PIFAs. As interesting and pioneering a work as it was during that time, that work however, though understandably, did not venture into the study of stretching this antenna to its limits. Firstly, the PIFA size there is large, being $0.156\ \lambda$ along the largest dimension at the lower band, as opposed by a corresponding value of $0.05\ \lambda$ in the present paper. The bandwidth there, as in this paper, is modest due to the thin substrate; nonetheless bandwidths in both works are on par with each other. No information about the gain or directivity was provided there though, whereas we have presented such results here. In addition, the radiation patterns of our design are comparable to those in that [34] (compare Fig. 5 there with Fig. 15 here), thus strengthening the credibility of the present work.

Another related work may be found in [35], in which a bigger ground plane than the one considered here was used. Even discounting this, the size of that PIFA itself is still larger. Moreover, the radiation patterns there are less omni-directional than

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[2] $$a = \sqrt{\left(\frac{\text{height}}{2}\right)^2 + \left(\frac{\text{width}_{\text{GroundPlane}}}{2}\right)^2 + \left(\frac{\text{length}_{\text{GroundPlane}}}{2}\right)^2}.$$

those of Fig. 15. The PIFA considered in [36] is also large when compared to the present design, despite not even considering the ground plane. However, for the upper band, the design of that work provides a wider bandwidth than conventional PIFAs. Furthermore, the gain there is higher than ours and most other PIFAs, although this is attributable to the lager size of that antenna.

Most of the compact PIFAs that can be found in literature had been designed for integration into a mobile phone. This means that a large ground plane might have to be used, which of course contributes to the radiation and also affects the frequencies of operation. As a radical breakout, the presently proposed SRR-type dual-band PIFA antenna could offer itself to other applications, such as implantable antennas, medical sensors, or devices where the frequency bands of operation may be either close or far away from one another, thereby becoming more flexible, instead of the rigid 0.9 GHz and 1.8 GHz as considered by most papers. Another promising advancement of our configuration is its great potential of being made reconfigurable by using active devices.

We have established a theoretical equivalent-circuit modeling of our antenna which produces simulated results that are in strong agreement with experimental ones. This adds theoretical radiance to the paper and offers insights into the circuital mechanisms that are in play, something that is lacking in other works. Finally, also amiss from a vast majority of existing papers on PIFAs, a thorough parametric study is herein conducted, which provides understanding of the various factors that influence the antenna properties, thereby serving as important design guidelines. These reasons are in addition to the numerous advantages which the presently proposed antenna has over those studied by existent literature—particularly, in terms of antenna miniaturization, smallness in ground-plane size, higher efficiencies, better omnidirectionality, simplicity of design, manufacture and implementation, and at many occasions, even with regards to gain and bandwidth performances.

## VII. CONCLUSION

In this paper, a strongly miniaturized microstrip patch antenna based on short-circuited SRRs has been presented and studied. In virtue of its two concentric rings, this antenna is able to provide two simultaneous bands of operation. A parametric study of the operation frequency has been performed, showing how it is influenced by the dimensions of the rings. Results have shown that the total size of the rings and the permittivity of the dielectric substrate have a significant effect on these resonances. In addition, other parameters such as the widths or gaps of the rings are relevant but in lower order of magnitude. The thickness of the substrate is a very important parameter, since it can strongly modify the operation frequency. The grounded pins are key parameters of this design, as they are responsible for the antenna compactness.

In order to demonstrate the operation of the antenna, simulations were carried out and prototypes were manufactured and measured to validate them. A final prototype was manufactured to show in detail the characteristics of the antennas such as gain, bandwidth and radiation efficiency, the latter being measured in a reverberation chamber. The results are very promising and some designs using this unit cell as the main radiator could be useful in realistic scenarios where compactness is required, such as for instance in RFID applications or integrated body communications where the employed antennas, according to the literature, have similar or even lower radiation efficiencies for the same antenna sizes. Moreover, by adding rings, further multiplicity of bands can be achieved. The concept of a multifunctional but yet light and compact antenna has thus been mooted. Needless to say, such antennas find vast applications in the mobile wireless age of today.

The operation frequency of the antenna bands are quite independent of each other. However, in principle, there are two limitations: the minimum difference between both operation frequencies is limited by the minimum distance between rings; and the maximum difference is limited by the maximum distance between rings that allows the coupling between them. However, even then, other parameters such as the gap of the rings (that can be loaded with lumped capacitors) or the ring widths, can provide more flexibility depending on the requirements of the application.

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