Design and Experimental Verification of Frequency ReconfigurableCircularly Polarized Patch Antennas

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***Abstract*— This paper reports the design and experimental verification results of the both single and dual layer circular patch antennas with external rings divided by a gap to provide frequency re-configurability. In particular, the frequency reconfiguration has been achieved by short-circuiting some paths connecting the internal patch and the external ring by mean of conducting strips. In this way, it would be possible to reuse the antenna's entire volume at different operating bands. As a proof of concept, some antenna prototypes have been fabricated and tested, where the switching components have been mimed by the presence or absence of some metallic ribbons mounted on the patch surfaces.In this project, the proposed antenna designs are required to satisfy severalmobile communication services, which include GPS, GSM, UMTS, WiMAX and WLAN applications. In particular, the single-layer antenna is designed to cover three different bands from around 2 GHz to around 3 GHz, with a relative bandwidth of around 5% for each band. The dual-layer antenna is designed to cover two bands from around 1.5 GHz to around 2 GHz, with a relative bandwidth of around 10% for each band.For all cases circular polarization is provided.**

I. INTRODUCTION

In the era of modern wireless communication systems, antennas capable of operating at broad frequency band range are increasingly demanded. Applications include Global Positioning System (GPS), Global System for Mobile communications (GSM), Universal Mobile Telecommunications System (UMTS), Worldwide Interoperability for Microwave Access (WiMAX) and Wireless Local Area Network (WLAN). These services ranges over different frequencies and, at the same time, compactness experienced by mobile communication devices continuously reduce the room available for antennas. For this reason, a single low-profile and light-weight antenna able to support more than one communication service is considered very important. To this aim, patch antennas exhibiting multi- or wide-band frequency capabilities are good candidates.

Multi-band antennas can be based on two different approaches: a design where physically separated portions of the antenna are devoted to manage different frequencies, and a design more ambitious where the different frequencies are achieved by the use of re-configurability. In this way, a multi-band antenna can work at a given frequency, which can be modified according to internal and/or external inputs to adjust its performance to new operating scenarios. The most common ways that are used to realize the antenna re-configurability are by selective electrical switching (on or off states) of the antenna structure parts [1]-[4].

Wide-band antennas are also often adopted to cover different frequencies [5]-[7]. However, since this type of antenna is able to transmit / receive over an entire spectrum of frequencies, performance is not usually tailored and optimized for each communication channel. In addition, wide-band antennas, collecting signals over different bandwidths, exhibit more serious noise and interference problems, which must be solved at front-end level in a front-end trans-receiver. For these reasons, when a limited portion of the frequency spectrum offered by an antenna is used for any given time, multi-band antennas can be preferred over wide-band antennas.

This paper presents the design and the experimental verification of frequency reconfigurable circularly-polarized patch antennas. In particular, two different antennas are presented: single-layer patch and dual-layer patch. In both cases, the radiating element is circular patches and external rings divided by a gap, which can be short-circuited to provide frequency re-configurability. As a proof of concept, the short-circuiting is obtained using the presence or absence of metallic ribbons.

This work has been firstly performed in the Antenna and Microwave Laboratory at the San Diego State University. for the single-layer patch antenna with reconfiguration, and then completed in the Microwave Laboratory of the University of Pavia for the dual-layer patch antenna with reconfiguration.

This paper is organized as the follows. Section II presents the design and fabrication of a multi-band single-layer patch antenna while Section IIIcovers the description of the dual-layer antenna. Finally Section IV concludes the findings.

II. SINGLE-LAYER PATCH ANTENNA

The desired frequency reconfigurable circularly polarized patch antenna is based on circular-shaped metallic patches, realized on a 100 x 100 mm^2 FR-4 substrate (thickness t = 1.6 mm) backed by a metallic ground plane (dielectric constant ϵ_r= 4.4 and dielectric loss tangent $\tan\delta$ = 0.002). This substrate, widely used to fabricate microwave circuits, represent a good choice in terms of electrical performance and cost especially for application upto 2-3GHz. However, the achievable bandwidth is usually modest, around 1%. Therefore, a popular solution to obtain a larger bandwidth, up to 5% consists of increasing the overall antenna thickness by using a material with low dielectric constant added between the FR-4 substrate and the ground plane [7]. To this aim, a foam layer (dielectric constant ϵ_r = 1.06, loss tangent negligible, thickness t = 3.2 mm) is adopted and the overall structure is shown in Fig. 1. The effect of the foam layer is to provide an effective lower dielectric constant, with benefit for the antenna bandwidth, and to increase the antenna efficiency limiting surface waves, which also deteriorate the antenna polarization.

The electromagnetic modes supported by this kind of antenna structure can be found by analyzing the patch, the ground plane, and the dielectric material between the two as a circular cavity. The modes that are supported by a circular microstrippatch antenna whose substrate height is small (much smaller than the working wavelength) are TM, perpendicular to the patch as shown in Fig. 1. Unlike other patch shapes, such as the rectangular one, where the degrees of freedom to control the order of the modes are two, for the circular patch the radius is the only parameter that can be changed. However, changes in this value do not affect the order of the modes but only the value of the resonant frequency of each mode. In particular, the radius of the circular patch can be designed to guarantee the resonance at the desired value.

The feeding network of the structure consists of two coaxial probes providing two separate excitations at two different feeding points (shifted of a value indicated as "*feed position*" to the center of the structure) with a proper angular separation (90°). Additionally, the two feeds are excited in such a manner that there is 90° phase difference between the fields excited by each of them. As a direct consequence, circular polarization is achieved.

To achieve multi-band operation, it is necessary to create a radiating structure able to resonate at different frequencies. The first step in the realization of the frequency reconfigurable patch antenna is the design of two ideally separated patches resonating at two different frequencies, 2 GHz and 2.7 GHz. Then, the proper combination of these two circular patches in a unique structure must be solved.

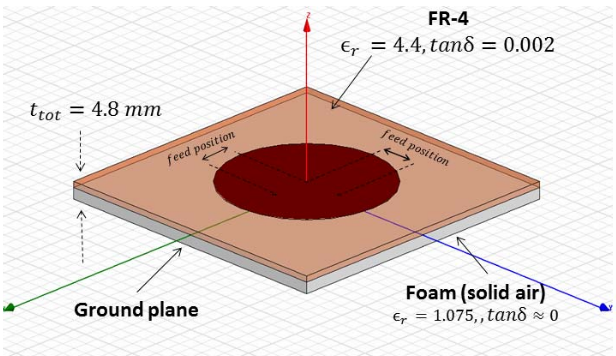
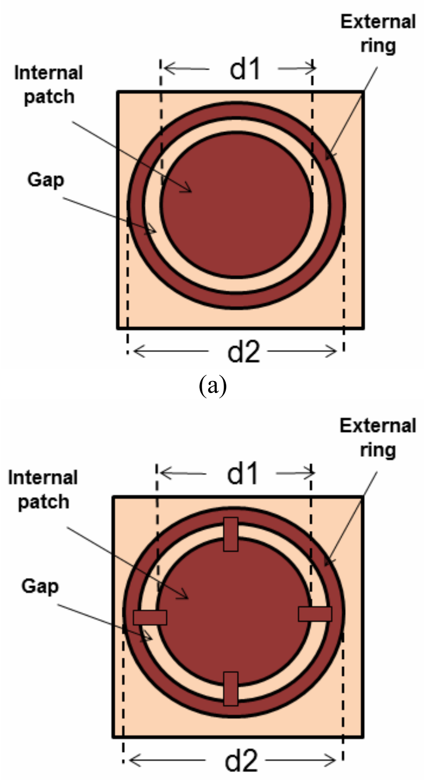


Figure 1: Single layer patch antenna with FR-4 and foam substrates.

Thus, a gap has been defined on the surface of the larger patch (the one resonating at the lower frequency) so that an internal circle, whose dimension coincides with the one of the smaller patch (higher resonant frequency), is shaped. The result is a structure composed by an internal circular patch and an external ring, shown in Fig. 2. Of course, the exact dimensions of each parameter (e.g. external ring radius and internal patch radius) are re-optimized to account for any mutual interaction. The final layout is summarized in Table 1.

Feed position	14 mm
External ring radius	28.4 mm
Internal patch radius	21.81 mm
Gap dimension	1.29 mm

Table 1: Structure dimensions.



(b)

Figure 2: Different configurations of the single layer patch antenna representing the switch OFF(a) and ON(b) states. Switchers are here mimed by absence/presence of copper ribbons.

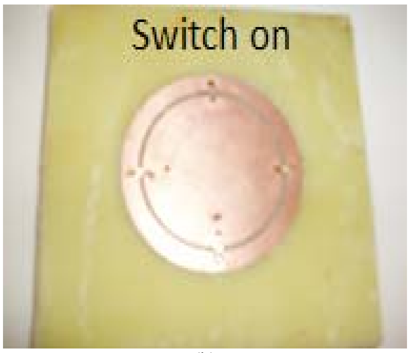
To interconnect the external ring and the internal patch (i.e. to operate the antenna at the lower or the upper frequency), switched lumped components can be used (for example, MEMS actuators or PIN diodes). When these switchers are in the ON state, they can be modeled as copper ribbons. In particular, to provide a good electrical contact between the inner patch and the external ring four ribbons separated by 90° to the others are used, as shown in Fig. 2(b). In this way, when the switchers are in the OFF state, which means no copper ribbons mounted on the patch surface (Fig. 2(a)), the structure is expected to radiate at the higher frequency, since there is no electric connection between the internal patch and the external ring, so the current flows only in the small internal patch. On the contrary, when the switchers are in the ON state, which means that the copper ribbons are applied (Fig. 2(b)), the structure is expected to present a lower resonant frequency, since the antenna experiences an increase in its physical size.

Once that the design phase is concluded, the antenna is fabricated. In particular, a LPKFmilling machine engraves the required antenna layout on the FR-4 metal top face, which is then glued on the foam layer. The ground plane on the bottom side of the foam layer is realized with adhesive strips of copper tape. Finally, 50ΩSMA connectors were mounted.

The samecopper tape was also used to create the ribbons, to be stuck on the patch surface when required. The final prototypes are shown in Fig. 3.The prototype was tested in an anechoic chamber by using a vector network analyzer as microwavesource and as signal collector, and the results are shown in Fig. 4 and Fig. 5 for the OFF state and the ON state, respectively.Fig. 4 shows a good agreement between the simulation and the measurement for the antenna matching, for both input ports. The -10 dB impedance matching bandwidth is around 5.5 % (2.65 - 2.8 GHz), as expected. Also the results achieved for cross-talk between the input ports are acceptable, with an isolation better than -20 dB for the entire bandwidth.

Fig. 5 clearly shows that a good matching is achieved around 2 GHz, the designed lower band of frequency. However, a second higher-order resonant mode is generated above 3 GHz.

(a)



(b)

Figure 3: Fabricated single layer patch antennas (a) OFF state and (b) ON state.

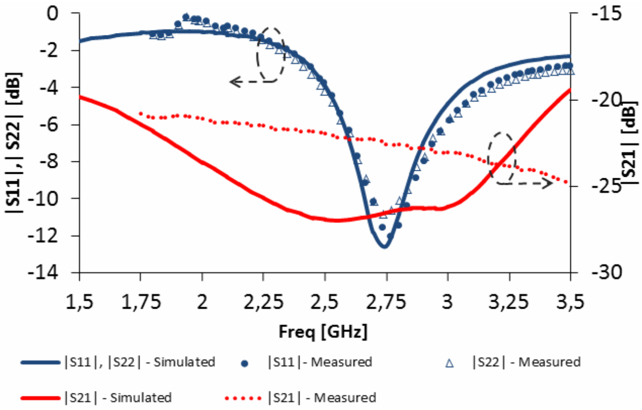


Figure 4: Single layer patch antenna with switch OFF: comparison between simulated and measured scattering parameters.Refer to y-axis on the left for thecurves representing $|S_{21}|$ parameter. Refer to y-axis on the right for the curves representing $|S_{11}|$ and $|S_{22}|$ parameters.

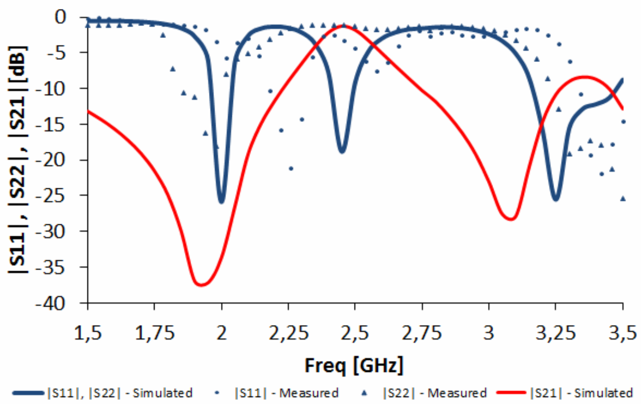


Figure 5: Single layer patch antenna with switch ON: comparison between simulated and measured scattering parameters.

In addition, around 2.4 GHz the two coaxial ports are strongly coupled and, therefore, the power incident on one port simply passes through the structure and exits from the other port, thus giving no radiation. These results, together with the limited agreement between the theoretical prediction and measurements, prevent the antenna from properly working in the ON state. After detailed analysis and verification of the structure, the reasons for these discrepancies are identified in manufacturing inaccuracies.

III. DUAL-LAYER PATCH ANTENNA

As discussed before, the maximum bandwidth achievable with a single-layer patch antenna is in the order of 5%. Therefore, if the intended applications demand larger bandwidths, different architectures will be developed. A possible solution is based on a dual-layer patch antenna, also called stacked patch antenna. In particular, the design of the stacked configuration is derived from the single-layer antenna, and the overall structure is shown in Fig. 6. Two dielectric substrates (dielectric constant ϵ_r = 3.5 and dielectric loss tangent tanδ = 0.002) are separated by a foam layer (dielectric constant ϵ_r = 1.075 and dielectric loss tangent negligible). The top side of both substrates is used to print the resonant patches, while the bottom side of the lower substrate, entirely covered by a metallic sheet, serves as ground plane. The patch printed on the lower substrate (driven element) is fed directly by coaxial connectors (as for the single-layer antenna), while the patch printed on the upper substrate (parasitic element) is excited via electromagnetic coupling.

The main advantage of the stacked patch antenna is the possibility of obtaining a bandwidth enhancement up to 10%-20%. This is achieved by a proper design of the upper and lower patch. In fact, a second patch introduces a second resonance, so that the matching of the antenna will result less than a given threshold (e.g. -10 dB) over a wider band [8]. The re-configurability is obtained via switched lumped components connecting the inner patch with the external ring, as done for the single-layer antenna.

The design of the dual-layer antenna follows the same principles used for the single-layer antenna (first step, design of the antenna patches in such a way to obtain, separately, a good matching in the lower frequency band and a good matching on the upper frequency band; second, creation of a unique layout based on the patch/ring approach a short-circuits, re-optimizing all parameters to account for mutual interactions). However, two major differences are introduced: the frequencies selected are 1.5 GHz and 2 GHz and the number of switchers is increased. Both actions aim to tackle the manufacturing problems experienced during the realization of the single-layer antenna. The dimensions of each components of the structure are reported in Table 2.

A stacked patch antenna prototype is fabricated as shown in Fig. 7. A manual fabrication is exploited, defining the patch geometries with hand-held tools, avoiding the use of a milling machine. The accuracy achievable by this technique is compatible with the working wavelength of the antenna. As in the single-layer antenna, the switchers are again mimed bymetal ribbons.

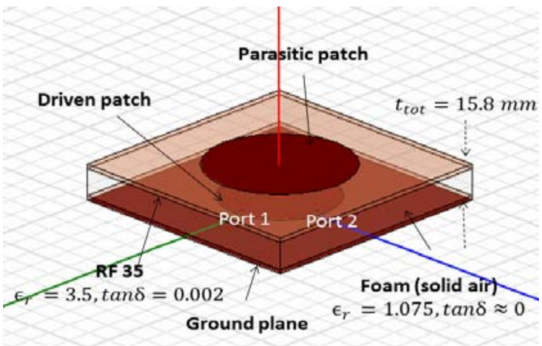
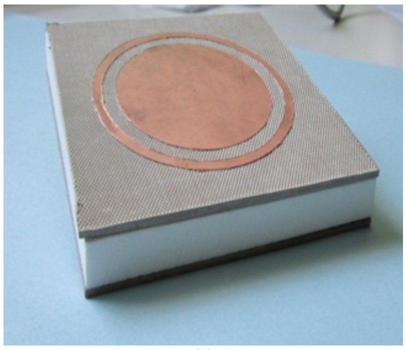


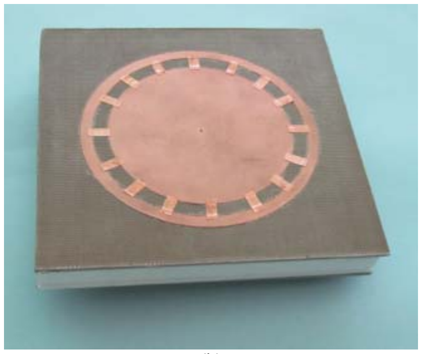
Figure 6: Stacked patch antenna with RF 35 substrate and foam layer.

Feed position	22.92 mm
Driven patch radius	24.11 mm
Driven ring radius	31.1 mm
Parasitic patch radius	29.1 mm
Parasitic ring radius	37.8 mm
Foam thickness	12.79 mm
Gap dimension	5 mm

Table 2: Structure dimensions.



(a)



(b)

Figure 7: Fabricated stacked patch antennas (a) OFF state and (b) ON state.

The prototype was tested in an anechoic chamber by using a vector network analyzer as microwave signal generator and as signal collector. The results are shown in Fig. 8 and Fig. 9 for the OFF state and the ON state, respectively. In Fig. 8 as well as in Fig 9 a very good agreement between the simulation and the measurement is shown: in both cases, in fact, the stacked patch antennas work at the desired frequencies (2 GHz and 1.55 GHz), with, respectively, a 12% (1.85 - 2.05 GHz) and 13% (1.45 - 1.65 GHz) of bandwidths.The axial ratio and the antenna gain is measured by connecting two hybrid power dividers, one for each antenna, to provide the necessary 90° phase difference in order to transmit / receive circular polarization.The axial ratio measured at 1.55 GHz is 0.1 dB, while the simulated value is 0.6 dB. At 2 GHz, the measured axial ratio is 2.1 dB, while the simulated value is 0.8 dB.

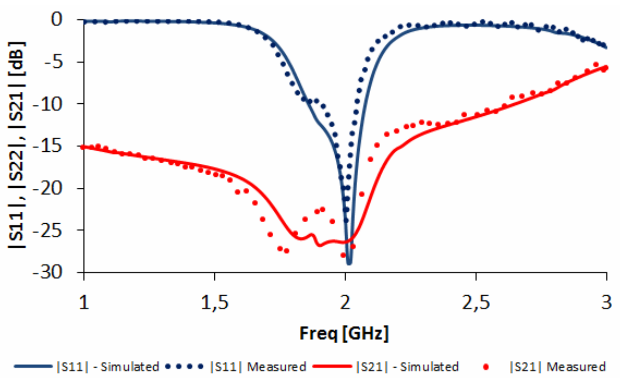


Figure 8: Stacked patch antenna with switch OFF: comparison between simulated and measured scattering parameters.

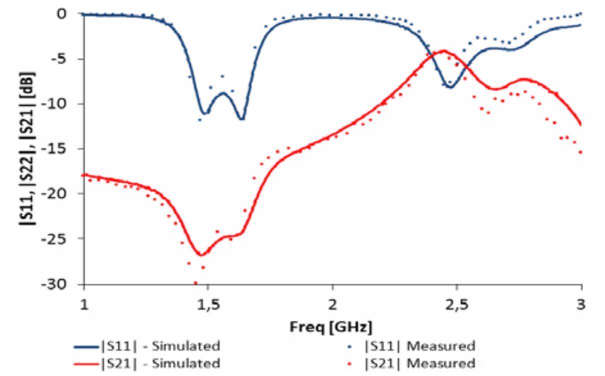


Figure 9: Stacked patch antenna with switch ON: comparison between simulated and measured scattering parameters.

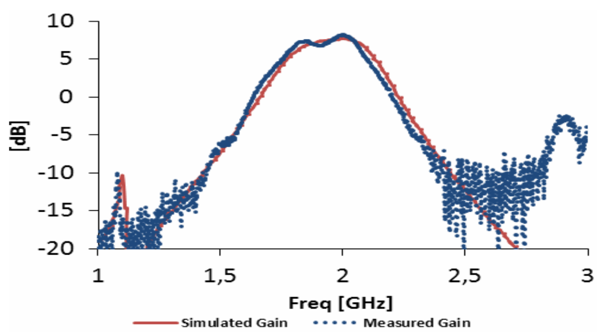


Figure 10: Stacked patch antenna with switch OFF – Comparison between simulated and measured peak gain (dBi).

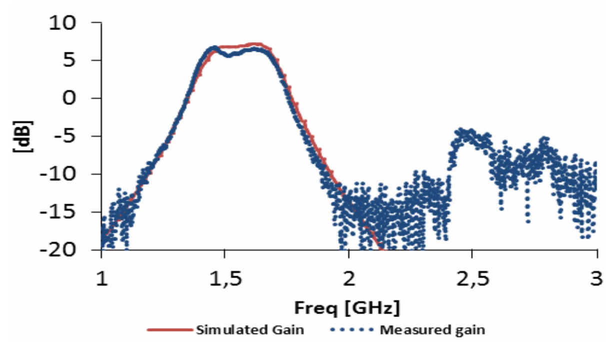


Figure 11: Stacked patch antenna with switch ON – Comparison between simulated and measured peak gain.

The difference are attributed to the hybrid power dividers magnitude and phase unbalances, which strongly affect the axial ratio measurement. The comparison between the measured and simulated gains are shown in Fig. 10 and Fig. 11. An excellent agreement is observed and the peak gains are about 7 dBi at the central frequencies.

IV. CONCLUSION

This paper presented frequency reconfigurable microstrip patch antennas. Different designs were realized obtaining a multi-band operation from around 1.5 GHz up to 3 GHz in circular polarization, making these antennas suitable for several different mobile services, such GPS, GSM, UMTS, WiMAX and WLAN applications. All the designs presented the same radiating structure composed by an internal circular patch and an external ring, properly separated and dimensioned to provide the desired resonant frequency. The frequency flexibility was achieved by short-circuiting some paths connecting the internal patch and the external ring. The presence or absence of some metallic ribbons mounted on the patch surfaces was used for miming electrically switched lumped components. The first part of the work aimed to the development of a single layer patch antenna. Afterwards, a dual-layer design was achieved, in order to enhance the working bandwidth of the antennas.In both cases prototypes were fabricated and measured, achieving an overall good result. The number of metallic ribbons and the manufacturing accuracy were identified to be critical parameters, which may lead to some difference between expected and measured results. Therefore, on the basis of the lessons learnt fabricating the single-layer antenna, the dual-layer prototype design and fabrication was modified obtaining excellent agreement.

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