

QUAD-FREQUENCY LINEARLY-POLARIZED AND DUAL-FREQUENCY CIRCULARLY-POLARIZED MICROSTRIP PATCH ANTENNAS WITH CRLH LOADING

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Abstract—In this paper, a novel technique to develop multifrequency microstrip patch antennas with polarization diversity or circular polarization is presented. The proposed approach consists of exciting modes with orthogonal polarizations in microstrip patches partially filled with Composite Right/Left-Handed (CRLH) cells. Two different kinds of quad-frequency single-layer patch antennas are proposed. The first one has two orthogonal ports with high isolation between them. The second kind of quad-frequency patch antennas consists of exciting the four modes with two orthogonal polarizations through only one port. Finally, the proposed approach is used to develop dual-frequency circularly-polarized (CP) patch antennas by exciting the modes with orthogonal polarizations in quadrature phase. Prototypes of all the designs are manufactured and measured, showing good performance.

1. INTRODUCTION

Microstrip patch antennas are very popular radiators due to their light weight, low profile, low cost, easiness of manufacturing and integrating with circuitry [1, 2]. Conventional microstrip patch antennas are usually operated at their fundamental frequency. For this reason, several approaches have been proposed to design multifrequency microstrip patch antennas [3–11]. These techniques to design

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multifrequency microstrip patch antennas are based on using several radiators [6, 7], fractal-based geometries [8], stubs [9, 10] and coupled resonators [11]. Recently, the authors have proposed the use of single-layer microstrip patch antennas partially filled with Composite Right/Left-Handed (CRLH) structures to increase the capabilities of these popular radiators. In [12] it was demonstrated that multifrequency performance could be achieved within a wide range of ratios between the working frequencies. This ratio was mainly controlled by the size of the patch and the filling CRLH structure. Two different designs were proposed in [12]. The first one was a dual-frequency patch antenna with patch-like radiation pattern at the two working frequencies. The other was a triple-frequency antenna by adding a monopolar mode between the two patch-like modes. In the present paper, the previous study is extended to develop quad-frequency patch antennas with polarization diversity and dual-frequency circularly polarized (CP) patch antennas.

The concept of polarization diversity has become popular during the last years. For example, this has been proposed to mitigate the effects of fading in communications [1]. Moreover, in many communication systems the uplink and downlink have assigned not only different frequencies, but also orthogonal polarizations to increase the isolation between them. (e.g., [13–20]). In these works, two-port patch antennas were proposed to provide two orthogonal polarizations. For this reason, great efforts have been made to achieve high isolation between both ports [13–16]. Furthermore, the works to obtain dual-frequency microstrip patch antennas with dual-polarization were based either on rectangular patches [13] or two-patch antennas with one small patch inside a slotted bigger one [16, 17]. The first approach is only valid for small frequency ratios, while the second one can be used only for large ratios (e.g., ≥ 2). As commented before, patch antennas partially filled with CRLH structures provides multifrequency performance within a wide range of frequency ratios (from small ratios to large ratios). Moreover, they provide additional capabilities in the design of patch antennas with dual-polarization. In Section 3 it is demonstrated that four different patch-like modes can be excited in the proposed antennas. These modes can be classified into two different pairs, each of them with a linear polarization orthogonal to the other. These capabilities are exploited in Section 4 to design two novel quad-frequency patch antennas with dual-polarization. Quad-frequency or penta-frequency patch antennas with patch-like radiation pattern at all the frequencies have been proposed in literature [7]. However, these patch antennas are based on multi-layer structures. In this paper, single-layer quad-frequency patch antennas are developed thanks to

the CRLH loading inside the patch structure.

The use of Circular Polarization is required for some applications such as satellite communications and radio-navigation systems, for example the well-known Global Positioning System (GPS). Moreover, a dual-frequency performance is also required for several of these applications; see for instance [21]. Previous works to achieve dual frequency CP [21–28] have been based on adding different kinds of parasitic elements (stacked patches, slots, etc). However, the stacked approach is multi-layered [21, 22]. On the other hand, the single-layer approaches are only valid for large (> 1.7) [23–25] or small ratios (< 1.3) [26–28]. Thus, there is no simple approach to achieve dual-frequency CP microstrip patch antenna with arbitrary ratios. On the other hand, in [12] it was demonstrated that the use of CRLH fillings provides enough degrees of freedom to achieve a broad range of frequency ratios. This technique is used in Section 5 to develop dual-frequency CP microstrip patch antennas in which a broad range of frequency ratios from small values (smaller than 1.2) to very large ratios (over 2.2).

2. TL MODEL OF MICROSTRIP PATCH ANTENNAS PARTIALLY FILLED WITH CLRH STRUCTURES

A conventional square microstrip patch antenna can be modeled as an open-ended TL. This element is a resonant structure, in which all the eigen-frequencies follow the resonant condition:

$$\beta_n L = n\pi \quad (1)$$

where β is the propagation constant along the TL, L is the equivalent length of the TL and n is the resonant index. In the case of a conventional TL, the phase constant is always positive and proportional to frequency ($\beta^{RH} = k_1 f$, where k_1 is a constant). This leads to positive resonant indices ($n = +1, +2, \dots$) and harmonic eigen-frequencies. It is well known that the fundamental mode ($n = +1$) of a microstrip patch presents half-wavelength electric field distribution ($\beta_{+1} L = +\pi$). For this reason the simplified model of the patch is based on a two-slot array with opposite phase placed $\lambda/2$ away. Then, the radiated field has a broadside radiation pattern

The simplified equivalent 1D-TL model of the proposed antenna is a *LH* section between two *RH* sections, as shown in Figure 1. It is important to note that in this simplified model the CRLH structure is modeled as a *LH* section because that is the dominant behavior at the working frequencies [12].

In this case, the resonant condition is given by

$$\beta_n L = \beta_n^{RH} d + \beta_n^{LH} \ell = n\pi \quad (2)$$

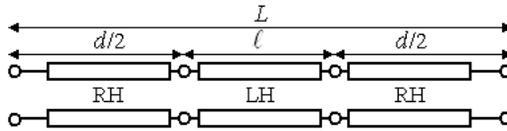


Figure 1. Simplified TL model of a microstrip patch antenna partially filled with a CRLH section.

where β^{RH} and β^{LH} are the phase constants along the *RH* and *LH* sections; d and ℓ are the lengths of the *RH* and *LH* sections, respectively. In the *LH* section, the phase constant is negative and proportional to the inverse of the frequency ($\beta^{LH} = -k_2/f$, where k_2 is a constant).

In this way, these resonant structures can be used to achieve multifrequency antennas. This fact is used to obtain two radiating modes with similar characteristics to the fundamental one in a conventional microstrip patch. The first of these modes ($n = -1$) is achieved when the resonant condition is $-\pi$:

$$\beta_{-1}L = k_1 f_{-1} d - \frac{k_2}{f_{-1}} \ell = -\pi \quad (3)$$

while the second is obtained when the whole structure fulfills the conventional condition ($n = +1$):

$$\beta_{+1}L = k_1 f_{+1} d - \frac{k_2}{f_{+1}} \ell = +\pi \quad (4)$$

The CRLH filling structures can be easily implemented by using distributed cells. An easy implementation in microstrip technology is based on Sievenpiper's mushroom structures [29]. The unit cell of the mushroom structure is composed of a microstrip metallic patch with a grounding via and there are gaps between adjacent cells. The *LH* behavior of these cells is provided by the metallic via (shunt inductor) and the gaps (series capacitors). The CRLH behavior of these structures was studied in [30].

3. POLARIZATION DIVERSITY

In the previous Section only modes with propagation along one main direction (TM_{n0} modes) were considered. Thus, all the patch-like modes were working with the same linear polarization. In this Section the possibility of exciting modes with orthogonal propagation with respect to the previous ones (TM_{0m} modes) is studied. This can be

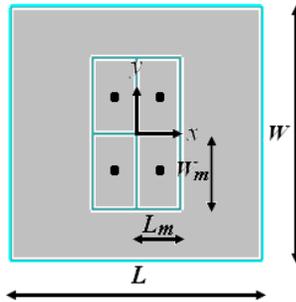


Figure 2. Sketch of the patch antenna partially filled with four CRLH cells, two in the x direction and two in the y direction.

used to increase the multifunctionality of the patch antennas filled with CRLH cells because antennas with simultaneous multifrequency and polarization diversity can be obtained.

The conventional technique to excite orthogonal modes in microstrip patch antennas consists of feeding the antenna through two orthogonal ports. Moreover, the dimensions of the two propagation directions in the patch antenna must be different when the objective is to achieve different resonance frequencies. This is the case of a rectangular patch fed through two orthogonal ports in which the TM_{10} and TM_{01} are obtained at different frequencies. On the other hand, when microstrip patch antennas partially filled with CRLH cells (Figure 2) are considered, two different approaches can be proposed to excite modes with orthogonal polarizations and different frequencies:

- Using square CRLH cells and a rectangular patch. In this way the dimensions L and W are different while L_m and W_m are equal. This is similar to the approach used for conventional patches, as commented before.

- Keeping the patch square and the CRLH cells rectangular so the dimensions of the CRLH cells (L_m and W_m) are different. This idea comes from the fact that rectangular mushroom CRLH cells have a different propagation constant along the two main directions [30].

In order to study the suitability of both approaches to develop multifrequency antennas with polarization diversity two studies have been made. The first one is a modal analysis of the structure to identify the modes which can be excited. The second analysis is a parametric study to compute the frequency ratio between the working modes which can be achieved by using each approach.

The result of the modal analysis is similar for both approaches. For example, the results for the second approach are presented. In that

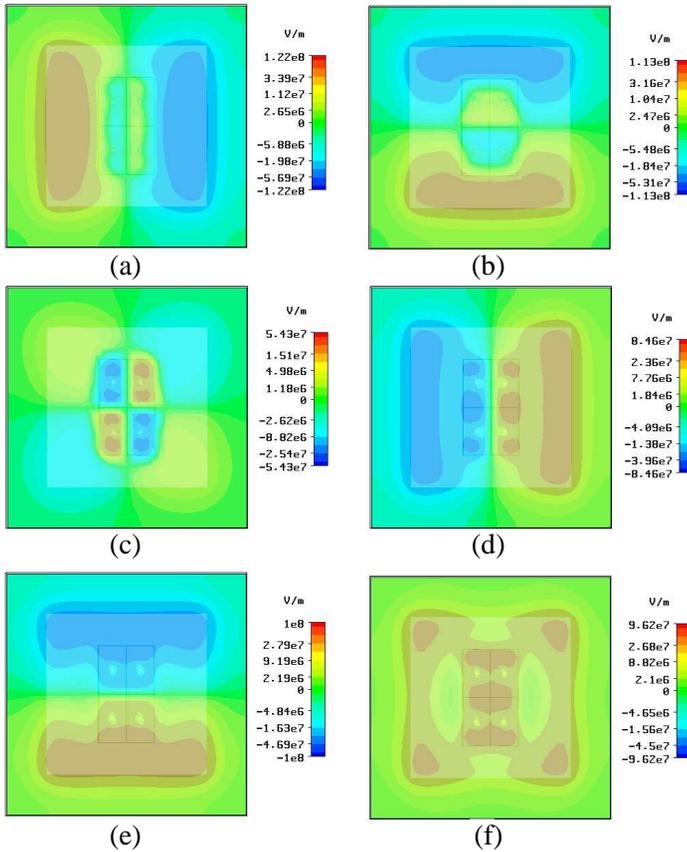


Figure 3. E_z field distributions for the different modes of the patch filled with a 2×2 array of CRLH cells. (a) $[-1, 0]$ at 1.78 GHz. (b) $[0, -1]$ at 1.89 GHz. (c) $[-1, -1]$ at 2.10 GHz. (d) $[+1, 0]$ at 2.56 GHz. (e) $[0, +1]$ at 2.73 GHz. (f) $[0, 0]$ at 2.97 GHz.

case the patch antenna of Figure 2 has been simulated with the modal solver of CST Microwave Studio [®]. The dimensions of the antenna are the following: $L = W = 40.00$ mm, $L_m = 7.00$ mm, $W_m = 12.00$ mm, the gaps have 0.20 mm width and the vias radius is 0.35 mm. The substrate is Polypropylene ($\epsilon_r = 2.20$) with height $h = 4.00$ mm.

Figure 3 shows the electric field distributions (E_z component) of the first six modes obtained in the modal analysis. The figure tries to represent the amplitude and phase of the corresponding E_z field. Figure 3(a) corresponds to a left-handed (LH) linearly polarized mode in the horizontal direction. In this way, it can be seen that, for instance,

paying attention to Figure 3(a), the field distribution in the left part of the patch corresponds to a positive phase while the field in the right part corresponds to the symmetric amplitude but with negative phase. The same can be applied to the other figures. For simplicity, the conventional notation TM_{nm} is substituted by the pair $[n, m]$. It is important to note that four of the modes have half-wavelength electric field distribution ($[-1, 0]$, $[0, -1]$, $[+1, 0]$ and $[0, +1]$) and one pair has propagation along the x direction ($[-1, 0]$ and $[+1, 0]$ modes) while the other pair has propagation along the orthogonal direction ($[0, -1]$ and $[0, +1]$ modes). This can be used to develop novel patch antennas with different polarizations:

- Quad-frequency linearly polarized antennas with polarization diversity when the four patch-like modes are simultaneously excited at different frequencies.

- Dual-frequency circularly polarized (CP) antennas when each pair of modes with the same sign (the pair of *LH* modes: $[-1, 0]$, $[0, -1]$ and the pair of *RH* modes: $[+1, 0]$, $[0, +1]$) is excited 90 degrees out-of-phase at the same frequency.

In order to make the parametric study, the previous antenna structure has been used but in this case the antenna is fed through two orthogonal coupled lines placed below the center of each patch side to excite the modes with orthogonal polarizations (Figure 4). The feeding lines are placed in the middle of the substrate height and they are shifted 15.00 mm away from the center of the patch. The port placed along the x direction is numbered as 1 while the orthogonal port

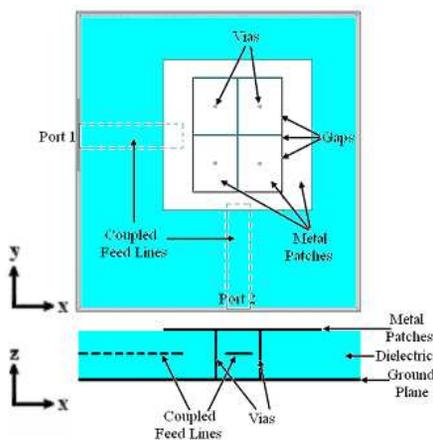


Figure 4. Quad-frequency patch antenna filled with CRLH cells and fed through two microstrip coupled lines.

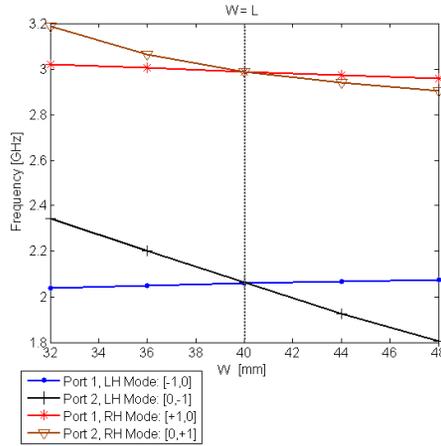


Figure 5. Resonance frequencies of the patch-like modes excited in the quad-frequency patch antenna when the CRLH cell dimensions (L_m , W_m) and the length of the patch (L) are set fixed while the width of the patch (W) is varied.

is numbered as 2. Other feeding schemes are possible (microstrip line or coaxial probes) but feeding through coupled lines has been chosen since it provides the best isolation between the ports.

The frequency variation obtained with the two proposed approaches has been studied. In the first approach the internal CRLH cells are kept square ($L_m = W_m = 7.00$ mm) while one of the patch dimension is varied. In this case, the vertical dimension of the patch, W , is varied while the horizontal one is maintained fixed, $L = 40.00$ mm, to obtain its parametric performance. Figure 5 shows the antenna resonance frequencies for the proposed situation. As the length of the patch is not varied, the resonant frequencies at port 1 are nearly constant. The frequency variation is only 1.78% for the *LH* mode $[-1, 0]$ and 1.98% for the *RH* mode $[+1, 0]$. This is logical since the only modification has been done along the orthogonal direction to port 1. On the other hand, as the vertical dimension is reduced, the resonant frequencies at port 2 are increased. It can also be seen that the slope for the *RH* mode ($[0, +1]$) is smaller than the one of the corresponding *LH* mode ($[0, -1]$) at this port. In particular, the frequency variation of the *RH* mode is 9.26% while it is 25.87% for the *LH* one. This makes that the resonant frequencies of the *RH* modes with orthogonal propagation constants ($[+1, 0]$ and $[0, +1]$) are very close independently of the patch dimensions (the maximum separation is only 5.41%).

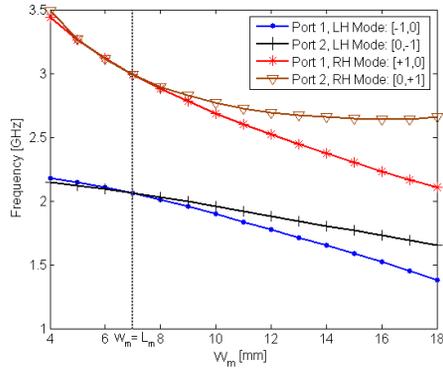


Figure 6. Resonant frequencies of the patch-like modes excited in the quad-frequency patch antenna when the dimensions of the patch (L , W) and the length of the CRLH cells (L_m) are set fixed while the width of the cells (W_m) is varied.

The effect of the second design procedure (variation of the vertical CRLH cell dimension W_m) can be seen in Figure 6. In order to obtain its parametric performance, only this cell dimension is varied while the horizontal one is maintained, $L_m = 7.00$ mm. The patch dimensions are kept fixed ($L = W = 40.00$ mm). As it can be seen, the frequencies of the *RH* modes ($[+1, 0]$ and $[0, +1]$) and the *LH* ones ($[-1, 0]$ and $[0, -1]$) are almost the same for small CRLH cells ($W_m < 8$ mm) although the frequencies of both pairs decreases with increasing W_m . However, as the y dimension of the cell gets larger and larger, the spacing between each pair of modes also increases. The maximum separation is 10.74% between the *RH* modes and 18.30% between the *LH* ones. It is important to note that the frequencies of the modes with propagation along x direction strongly depend on the y dimension of the cells W_m , which is not the case of the previous approach. In summary, the frequency variation of the different modes is: 27.14% for the $[0, +1]$ mode, 48.12% for the $[+1, 0]$ mode, 25.81% for the $[0, -1]$ mode and 45.17% for the $[-1, 0]$ mode.

In conclusion, with the second design procedure it is easier to achieve four sufficiently spaced resonant frequencies. For that reason this design strategy is more suitable for the design of quad-frequency antennas. Moreover, as the patch is square instead of rectangular, the total area of the antenna is smaller.

Finally, it is clear that when both the patch and the CRLH cells are square (dashed lines in Figure 5 and Figure 6), the resonance frequencies of each pair are the same. This situation can be used to develop CP antennas when the ports are 90° out-of phase fed.

4. QUAD-FREQUENCY MICROSTRIP PATCH ANTENNAS WITH POLARIZATION DIVERSITY

As it was concluded in the previous Section the best approach to design quad-frequency antennas with polarization diversity consists of using a square microstrip patch partially filled with a 2×2 mushroom structure composed of rectangular cells. Two different feeding techniques can be used and each of them is suitable for a different application. The first one consists of feeding the antenna with two orthogonal ports centered at each side of the patch, as in the parametric study of the previous Section (Figure 4). High isolation between both ports can be achieved. This approach can be used to develop antennas for transceivers working for two different wireless services. For most wireless services, the frequency bands for the uplink and the downlink are adjacent. Moreover, for some cases, the polarization of both links is orthogonal in order to increase the isolation. Hence, each port of the proposed antennas can be directly connected to a dual-service transmitter and a dual-service receiver taking advantage of the high isolation between them.

The second approach consists of feeding the patch with only one port placed close to the edge of one patch side. Thus, a one-port multifunction patch antenna with four different patch-like modes is achieved. The antenna has both frequency and polarization diversity which can be used for systems in which diversity is required (e.g., MIMO systems).

Prototypes of both approaches are designed, manufactured and measured in the present Section.

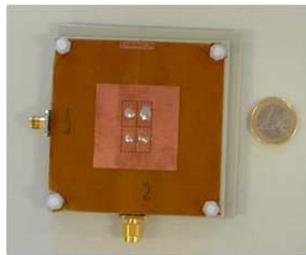


Figure 7. Picture of the manufactured two-port quad-frequency microstrip patch antenna with polarization diversity.

4.1. Two-port Quad-frequency Microstrip Patch Antenna with Polarization Diversity

As explained before, the first approach to achieve a quad-frequency microstrip patch antenna with polarization diversity consists of feeding a square microstrip patch filled with a 2×2 array of rectangular mushroom structures through two ports placed at the centre of each patch side, as shown in Figure 4. Proximity coupled lines have been used because they provide higher isolation than coaxial probes. A prototype of the two port quad-frequency patch antenna has been manufactured (Figure 7). The dimensions of the antenna are unchanged with respect to the example used for the modal analysis: $L = W = 40.00$ mm, $L_m = 7.00$ mm, $W_m = 12.00$ mm, the gaps have 0.20 mm width and the vias radius is 0.35 mm. The substrate is Polypropylene ($\epsilon_r = 2.20$) with $h = 4.00$ mm (implemented with two 2-mm-height boards). The coupled lines are printed on the lower Polypropylene board and they are shifted 15.00 mm away from the center of the patch in each direction.

Figure 8 shows the measured $[S]$ parameters. The reflection coefficient is -14 dB at $f_{[-1,0]} = 1.76$ GHz (port 1), -13 dB at $f_{[0,-1]} = 1.88$ GHz (port 2), -16 dB at $f_{[+1,0]} = 2.49$ GHz (port 1), and -14 dB at $f_{[-1,0]} = 2.64$ GHz (port 2). The ratio between the working frequencies of the LH ($[-1, 0]$ and $[0, -1]$) and RH ($[+1, 0]$ and $[0, +1]$) modes is approximately 1.41. A little dip can also be appreciated at 2.10 GHz (port 1). According to the modal analysis in Figure 3, this corresponds to a diagonal mode $[-1, -1]$. Finally, the isolation between the antenna ports is larger than 30 dB for frequencies

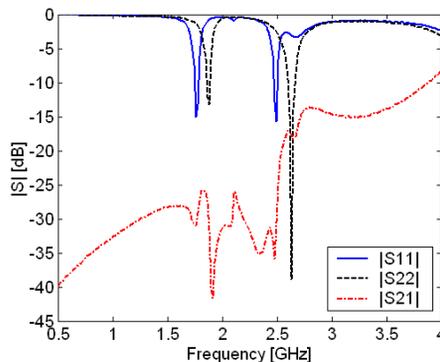


Figure 8. Measured $[S]$ parameters of the two-port quad-frequency microstrip patch antenna with polarization diversity.

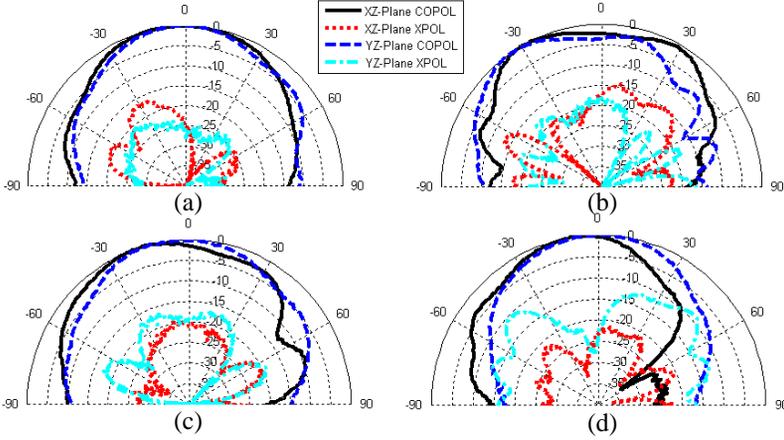


Figure 9. Measured radiation patterns of the two-port quad-frequency microstrip patch antenna with polarization diversity. (a) $f_{[-1,0]} = 1.76$ GHz (port 1, COPOL = x). (b) $f_{[+1,0]} = 2.49$ GHz (port 1, COPOL = x). (c) $f_{[0,-1]} = 1.88$ GHz (port 2, COPOL = y). (d) $f_{[0,+1]} = 2.64$ GHz (port 2, COPOL = y).

up to 2.5 GHz. However, the isolation between port 2 and port 1 at the last working frequency is decreased down to 18 dB. This is due to the fact that a spurious resonance at port 1 appears at 2.63 GHz. The patch length is $\lambda_0/4.26$ and $\lambda_0/4.00$ at the LH frequencies and $\lambda_0/3.01$ and $\lambda_0/2.86$ at the RH ones, achieving an important degree of miniaturization at the LH modes with respect to conventional patch antennas.

Figure 9 present the radiation patterns in the x - z and y - z planes at the four working frequencies. The antenna has a patch-like radiation pattern at the four working frequencies, as desired. For the first three modes ($[-1, 0]$, $[+1, 0]$ and $[0, -1]$ modes) the cross-polar component in both planes is lower than -20 dB (with respect to the normalized 0 dB co-polarization level) in most of the spatial directions. However the radiation pattern for the $[0, +1]$ mode at 2.64 GHz presents some distortion and higher cross-polarization due to the presence of the spurious mode seen at 2.63 GHz. It is important to note that the co-polar component is oriented along the x axis for the modes excited through the port 1 ($[-1, 0]$ and $[+1, 0]$), while it is oriented along the y axis for the modes excited through the port 2 ($[0, -1]$ and $[0, +1]$). Hence, polarization diversity is achieved. Measured gains at the broadside are 5.4 dB at $f_{[-1,0]}$ and $f_{[0,-1]}$, 6.2 dB at $f_{[+1,0]}$ and

Table 1. Two-port quad-frequency microstrip patch antenna measured characteristics.

Frequency	Gain (dB)	Co-Polarization	Length in terms of λ_0	$BW_{-10\text{ dB}}$	Isolation (dB)
1.76 GHz	5.4	x	$0.23 \lambda_0$	2.1%	32
1.88 GHz	5.4	y	$0.25 \lambda_0$	1.9%	42
2.49 GHz	6.2	x	$0.33\lambda_0$	1.5%	37
2.64 GHz	6.3	y	$0.35\lambda_0$	2.5%	18

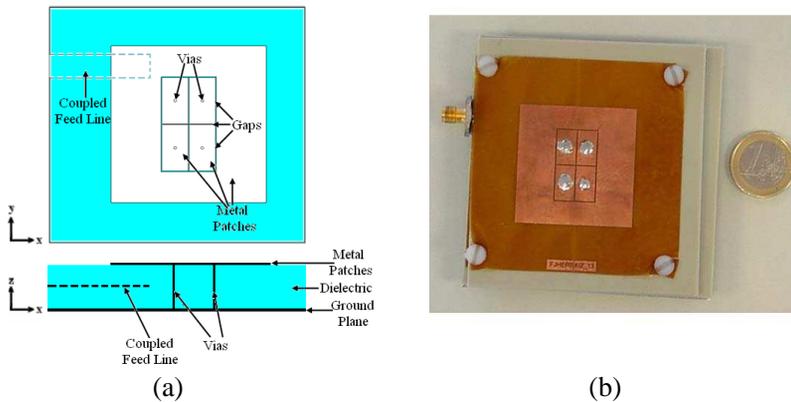


Figure 10. Single-port quad-frequency microstrip patch antenna with polarization diversity. (a) Sketch of the antenna. (b) Picture of the manufactured prototype.

6.3 dB at $f_{[0,+1]}$. The characteristics of the prototype are summarized in Table 1. The $|s_{11}| < -10$ dB criteria has been considered to measure the bandwidth of each band.

4.2. Single-port Quad-frequency Microstrip Patch Antenna with Polarization Diversity

Figure 10(a) shows the sketch of the single-port quad-frequency microstrip patch antenna with polarization diversity. The antenna structure is similar to the dual-port quad-frequency patch antenna but in this case only one coupled line is used to excite the four patch-like modes. This feeding line must be displaced along the y direction to excite the patch-like modes with y polarization ($[0, -1]$ and $[0, +1]$ modes). Moreover, the feeding line must be placed close to the vertical edge of the patch to achieve a proper matching at these

modes. A prototype with the same dimensions as the ones presented previously has been manufactured (Figure 10(b)). For this case, the patch antenna is fed through a coupled line displaced 15.00 mm from the centre of the patch in both directions.

The measured reflection coefficient of this antenna is shown in Figure 11. The reflection coefficient is -10 dB at $f_{[-1,0]} = 1.76$ GHz,

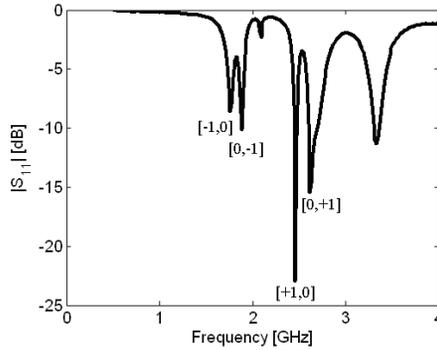


Figure 11. Measured reflection coefficient of the single-port quad-frequency microstrip patch antenna with polarization diversity.

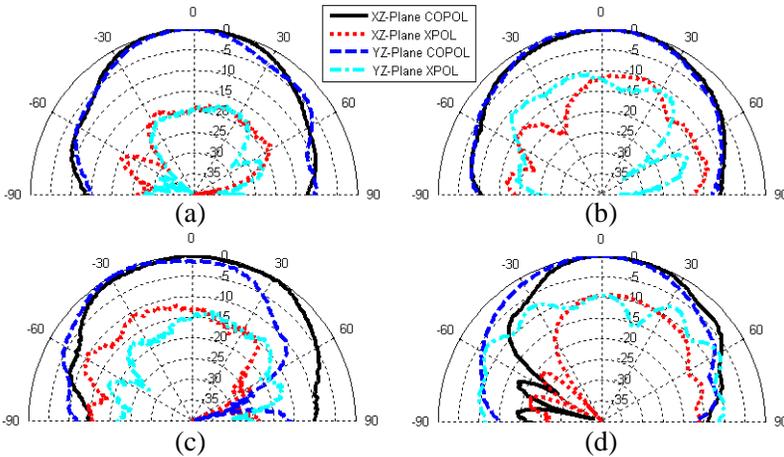


Figure 12. Measured radiation patterns of the single-port quad-frequency microstrip patch antenna with polarization diversity. (a) $f_{[-1,0]} = 1.76$ GHz (COPOL = x). (b) $f_{[+1,0]} = 2.49$ GHz (COPOL = x). (c) $f_{[0,-1]} = 1.83$ GHz (COPOL = y). (d) $f_{[0,+1]} = 2.62$ GHz (COPOL = y).

Table 2. Single-port quad-frequency microstrip patch antenna measured characteristics.

Frequency	Gain (dB)	Co-Polarization	Length in terms of λ_0	BW _{-6dB}
1.76 GHz	5.2	x	$0.23\lambda_0$	3.2%
1.83 GHz	5.2	y	$0.24\lambda_0$	2.6%
2.49 GHz	5.8	x	$0.33\lambda_0$	2.5%
2.62 GHz	5.9	y	$0.35\lambda_0$	7.2%

-11 dB at $f_{[0,-1]} = 1.88$ GHz, -24 dB at $f_{[+1,0]} = 2.46$ GHz and -17 dB at $f_{[0,+1]} = 2.62$ GHz. The little dip corresponding to the $[-1, -1]$ mode at 2.10 GHz can also be seen. Hence, the resonance frequencies are similar to the previous case and the reflection coefficient is very close to the superposition of the reflection coefficients of both ports in the dual feeding scheme. Thus, the degree of miniaturization achieved and the ratio between the working frequencies is the same as in the previous case.

Figure 12 shows the measured radiation patterns at the four working frequencies. The results are quite similar to the ones obtained with the two-port antenna, achieving four patch-like dipolar modes. The main difference with the two-port prototype is that the cross-polar component has increased. However, this was expected since the displacement of the feeding line makes this antenna asymmetric and the modes with two orthogonal polarizations are excited by the same port. It is important to note that four different patch-like modes and polarization diversity has been achieved with a single port. As in the previous prototype, the co-polarization at $f_{[-1,0]}$ and $f_{[+1,0]}$ is oriented along the x axis while it is oriented along the y axis at the other two working frequencies ($f_{[0,-1]}$ and $f_{[0,+1]}$). Measured gains at the broadside are 5.2 dB at $f_{[-1,0]}$ and $f_{[0,-1]}$, 5.8 dB at $f_{[+1,0]}$ and 5.9 dB at $f_{[0,+1]}$. The measured results are summarized in Table 2. For this case, as the matching levels are worse than in the previous case, the criteria for the impedance bandwidth has been chosen as -6 dB.

5. DUAL-FREQUENCY CP MICROSTRIP PATCH ANTENNAS

There are two main approaches to achieve CP microstrip patch antennas. The first one consists of exciting two orthogonal half-wavelength modes ($[+1, 0]$ and $[0, +1]$) with equal amplitude and

quadrature phase. This can be achieved with two-port patches in which each port is placed at the centre of one side of the patch and both ports are connected to external circuitry to achieve the 90° out-of-phase. The sign of the relative phase will determine the sense of the polarization (RHCP or LHCP).

The other approach to achieve CP is based on two orthogonal degenerated and quadrature phase modes. This can be developed with patches with some kind of asymmetry or geometrical modification, such as slots, slightly rectangular patches or elliptical geometries [1]. For all the cases, the dimensions of the antenna are modified such that the resonant frequencies of the two orthogonal modes ($[+1, 0]$ and $[0, +1]$) are close to each other. The antenna is excited at a frequency between both resonant frequencies, such that the amplitudes of the two excited modes are equal. Also, the feeding is placed in a diagonal to excite the two orthogonal quadrature-phase modes.

The main advantages of the first approach are the good axial ratio (AR) and its bandwidth. On the other hand, the total size and the complexity of the antenna are increased due to the use of external circuitry (e.g., hybrids) to achieve the required phase shift between the ports. This drawback is not present in the single-port CP antennas, but they provide limited bandwidths.

5.1. Dual-frequency CP Microstrip Patch Antenna with Two Ports and External Circuitry

This prototype is based on the first approach to achieve a CP patch antenna. Figure 13 shows the sketch of the proposed topology which is based on the dual-frequency patch fed through two orthogonal coaxial

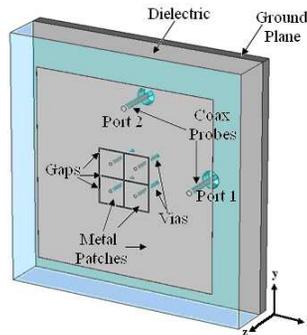


Figure 13. Sketch of the dual-frequency CP patch antenna with two orthogonal coaxial probes.

probes. If the phase difference between ports 1 and 2 is $+90^\circ$ then LHCP is obtained, while RHCP is obtained for a -90° phase shift. External circuitry is used to obtain the proper feeding at the two ports. It must be taken into account that the feeding circuitry must work correctly at both operating frequencies to achieve a good AR. Dual-band hybrids [31] are proposed to be used as feeding circuitry for large frequency ratios between the working frequencies and broad-band three-arm hybrids [32] is the optimal solution for small ratios.

An interesting feature of the patch antennas filled with CRLH cells is that the frequency ratio between the different modes can be set within a wide range of values, as it was demonstrated in [12]. This frequency ratio mainly depends on the patch and cells dimensions. This property can be used to design dual band CP patch antennas with very different frequency ratios, which cannot be achieved with other approaches, as it was commented in the Introduction. For this particular case, there is only one degree of freedom since the patch and the CRLH cells are square (Figure 13). In order to investigate the dependence of the frequency ratio with respect to the patch and mushrooms dimensions, a parametric study based on CST Microwave Studio® simulations has been made. The dimensions of the patch are fixed while the size of the cells is varied. The details of the simulations are as follows: the patch dimensions are $L = W = 46.00$ mm with $h = 10.00$ mm height, according to Figure 2. The substrate is Polypropylene ($\epsilon_r = 2.2$), the vias diameter is $d = 0.70$ mm and the gaps are $g = 0.20$ mm. Lastly, the side of the square cells changes

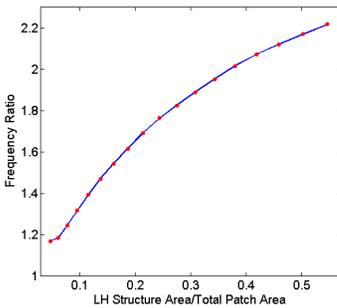


Figure 14. Dependence of the frequency ratio between the working frequencies of the dual-frequency CP patch antenna on the size of the patch and mushroom structures.

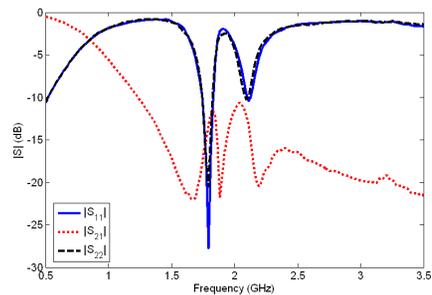


Figure 15. Measured $[S]$ parameters of the dual-frequency CP patch antenna with two orthogonal ports.

from $L_m = 5.00$ mm to $L_m = 17.00$ mm. The results of the simulations are shown in Figure 14. The range of values that can be obtained is very broad and it goes from very small values (smaller than 1.2) to large values such as 2.2. It is important to note that such small values cannot be achieved with other approaches.

As an example, a dual-frequency CP antenna working at the 1800 MHz and 2.1 GHz bands is designed, manufactured and measured. These two bands have been chosen due to the small frequency ratio between both bands. The dimensions of the patch antenna are chosen to achieve the working frequencies within the chosen bands. According to Figure 2, the patch side is $L = W = 46.00$ mm and the dimensions of the mushrooms are $L_m = W_m = 6.50$ mm. The other parameters are unchanged with respect to the previous simulations. The coaxial probes are placed at 16.50 mm from the centre.

A prototype of the proposed antenna has been manufactured and measured (Figure 15). The measured reflection coefficient at both ports is -20.5 dB at $f_{-1} = 1.80$ GHz and -10.25 dB at $f_{+1} = 2.11$ GHz. In both cases the reflection coefficient is below -10 dB. However, in the first situation it is better matched than in the second one. This is due to the fact that the only parameter to match both working bands is the distance from the probes to the centre of the patch, which is the same for both ports. Then, a trade-off in the matching between the two frequencies in the dual-band circularly polarized patch has to be made.

The isolation between both ports is higher than 12 dB at both

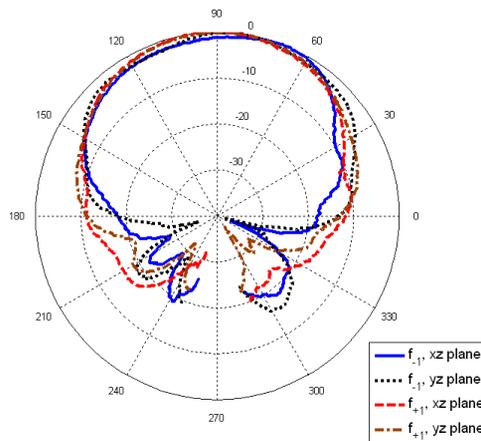


Figure 16. Measured radiation patterns of the dual-frequency CP patch antenna with the hybrid coupler connected.

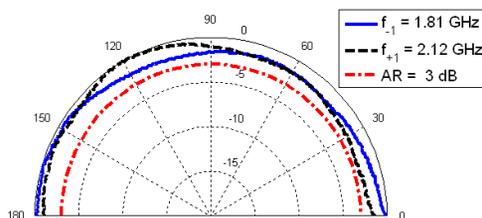


Figure 17. Measured roll diagram of the dual-frequency CP patch antenna fed by the hybrid coupler.

working frequencies. This isolation can be improved by using proximity coupling feeds, as shown in the previous Section. The electrical length of the patch is $\lambda_0/3.62$ at the first working frequency and $\lambda_0/3.09$ at the second working frequency. The ratio between the frequencies is only 1.17.

In this case, a broad-band hybrid coupler is chosen to feed the antenna to cover both working bands [32]. Figure 16 shows the measured radiation patterns at the two frequencies. The radiation patterns have not been measured in the full angular range due to the limitations of the measurement equipment. Both radiation patterns are similar to the fundamental mode of a conventional patch, as expected. Measured gains are 4.6 dB at f_{-1} and 5.8 dB at f_{+1} . In addition, a roll pattern measured with a linear polarization probe is presented in Figure 17. The roll pattern for both frequencies is always above than -3 dB giving a reasonable circularly polarized wave. The 3 dB AR beamwidth is 194° in the x - z plane and 167° in the y - z plane at the first frequency and 93° in the x - z plane and 72° in the y - z plane at the second one.

5.2. Single-port Dual-frequency CP Microstrip Patch Antennas

Two designs based on modified square patch antennas filled with CRLH structures are presented below (Figure 18). Hence, the second approach explained before to achieve CP patch antennas is used in both cases. The first design consists of a slightly rectangular microstrip patch with dimensions $L \times W$, being W slightly larger than L . When this patch is fed along one main diagonal, the two orthogonal modes corresponding to the main directions x ($[+1, 0]$ mode) and y ($[0, +1]$ mode) are excited at very close frequencies. The CP is obtained at a frequency, which lies between the resonance frequencies of these two modes, where the two orthogonal modes have equal magnitude

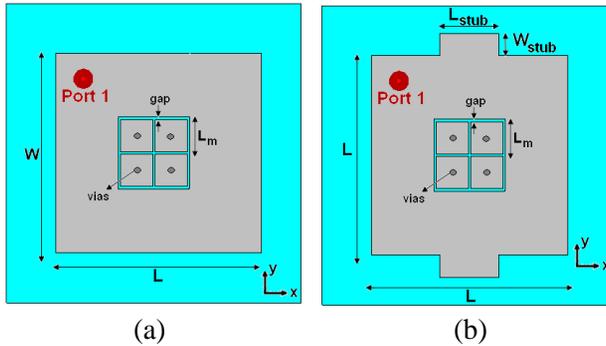


Figure 18. Single-port dual-frequency CP patch antennas. (a) Slightly rectangular patch antenna. (b) Square patch with stubs.

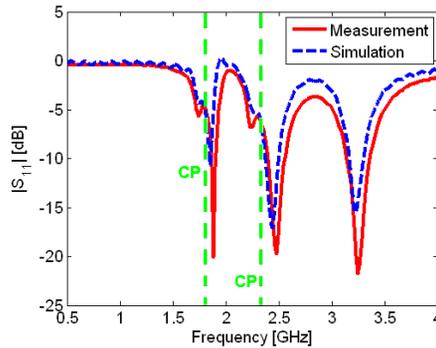


Figure 19. Measured radiation patterns of the single-port dual-frequency CP slightly rectangular patch antenna.

and are 90° out-of-phase. Additionally, dual-frequency performance is obtained by filling the patch antenna with a 2×2 array of mushroom structures. This CRLH filling allows exciting the *LH* modes $[-1, 0]$ and $[0, -1]$ in a similar way that is done for the *RH* ones $([+1, 0]$ and $[0, +1])$ and thus, CP is also achieved at an additional frequency. In this way, a single-port multifrequency antenna with circular polarization is achieved. As commented before, other modifications can be made in the square patch antenna to achieve CP. For example, the second design consists of adding stubs in one main dimension of the patch while maintaining the width of the patch equals to its length ($W = L$).

Prototypes of both designs have been manufactured and measured, achieving good results. The dimensions of the prototype based on the first design are $L = 40.00$ mm, $W = 45.00$ mm, $L_m = 6.80$ mm, the

gaps are $g = 0.20$ mm, and the vias diameter is $d = 0.70$ mm. The substrate is Polypropylene with $\epsilon_r = 2.2$ and $h = 8.00$ mm. The feeding approach is a coaxial probe placed in one main diagonal at a distance equals to 13.00 mm from the centre of the patch antenna. For the second design, the same substrate and dimensions are used,

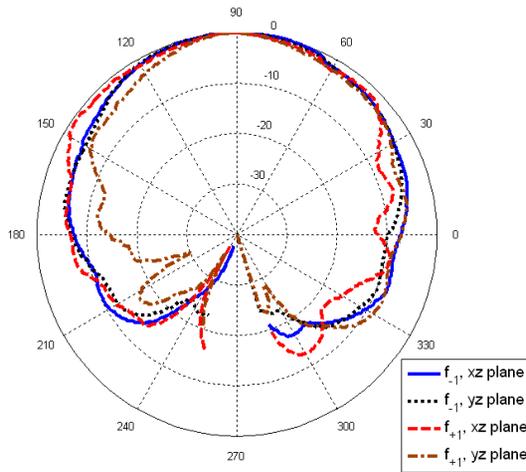


Figure 20. Measured radiation patterns of the single-port dual-frequency CP slightly rectangular patch antenna.

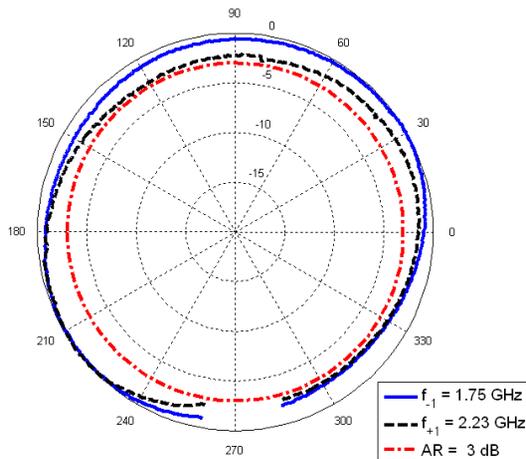


Figure 21. Measured roll diagram of the dual-frequency CP slightly rectangular patch antenna.

except the following ones: $L = W = 40.00$ mm, $L_{stub} = 12.00$ mm and $W_{stub} = 4.50$ mm. In this second prototype the feeding probe is placed in a main diagonal 14.00 mm away from the centre of the patch antenna.

Similar performance has been measured for both prototypes. The simulated and measured reflection coefficient is depicted in Figure 19. A high agreement between both results can be observed. CP is obtained at $f_{-1} = 1.75$ GHz and $f_{+1} = 2.23$ GHz. The measured radiation patterns in the x - z and y - z planes at the two working frequencies are depicted in Figure 20. The expected patch-like radiation pattern is obtained at both frequencies. Moreover, a roll diagram measured with a linear probe is plotted in Figure 21, showing a value below 3 dB at both working frequencies. In addition, the 3 dB AR beamwidths have been measured, obtaining 185° in the x - z plane and 220° in the y - z plane at f_{-1} and 43° in the x - z plane and 165° in the y - z plane at f_{+1} .

6. CONCLUSIONS

Multifrequency microstrip patch antennas can be developed by partially filling the patch with CRLH cells. In this paper, this approach has been considered along two dimensions in order to excite modes with orthogonal polarizations. Initially, these orthogonal modes have been used to develop quad-frequency single-layer patch antennas with polarization diversity. Two different kinds of quad-frequency patch antennas has been designed, manufactured and measured. The first one has two orthogonal ports with high isolation between them. This type of antenna is a good candidate as the radiating element of dual-band transceivers in which the uplink and downlink frequencies for each band are adjacent and the polarizations are orthogonal. Moreover, the high isolation between the ports can avoid the interferences between the transmitter and the receiver. The second kind of quad-frequency patch antennas consists of exciting the four modes with two orthogonal polarizations through only one port. A prototype has been manufactured, showing good performance. This approach is interesting for applications in which frequency and polarization diversity is required (e.g., MIMO systems).

Finally, dual-frequency CP patch antennas have been developed by exciting the modes with orthogonal polarizations in quadrature phase. Two different feeding approaches have been proposed. The first one is based on a square patch filled with square CRLH cells and two orthogonal ports connected to additional external circuitry (e.g., a branch-line coupler). A prototype of this antenna has been

manufactured and measured. The second feeding approach consists of making some modifications on a single-port square patch filled with CRLH cells. Two prototypes based on this approach have been designed, manufactured and measured. Axial ratios better than 3 dB have been measured at all the working bands for all the manufactured prototypes.

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