A Miniaturized Triple-Band and Dual-Polarized Monopole Antenna based on a CSRR perturbed Ground Plane

AHMED EL YOUSFI\textsuperscript{1}, ABDENASSER LAMKADDEM\textsuperscript{1}, KERLOS ATIA ABDALMALAK\textsuperscript{1,2}, (Member, IEEE), and DANIEL SEGOVIA-VARGAS.\textsuperscript{1}, (Member, IEEE)

\textsuperscript{1}Signal Theory and Communication Department, University Carlos III of Madrid, 28911 Madrid, Spain.
\textsuperscript{2}Electrical Engineering Department, Aswan University, Aswan 81542, Egypt.

Corresponding author: A. El Yousfi (aelyouf@ing.uc3m.es).

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\textbf{ABSTRACT} This paper proposes a new triple-band monopole antenna based on Complementary Split Ring Resonators (CSRR) perturbing the ground plane (GND). The antenna consists of an inverted-L-shaped monopole fed by a modified microstrip line with two CSRRs cut out of the ground plane. The operational bands are independently controlled by the CSRR unit cell parameters. In addition, the antenna presents a dual-polarization performance (vertical polarization at 2.4 GHz band and horizontal polarization at both 3.6 and 5.9 GHz bands). The designed antenna is fully planar and low profile avoiding the vias with the ground plane and covering the WLAN, WiMAX, and IEEE 801.11p bands at 2.45, 3.6, and 5.8 GHz. A compact prototype (0.32\(\lambda_0\) \times 0.32\(\lambda_0\) being \(\lambda_0\) is the wavelength corresponding to the lowest resonance frequency) has been fabricated and measured showing good agreement between simulations and measurements. The measured impedance bandwidths are 10\% (2.38-2.63 GHz), 2.5\% (3.54-3.63 GHz), and 20\% (5.83-7.12 GHz) whereas the measured gains are 1.34, 0.68, and 2.65 dBi at 2.4, 3.6, and 5.9 GHz respectively.

\textbf{INDEX TERMS} Complementary Split Ring Resonators (CSRR), Monopole antenna, Triple-Band, Dual-Polarization, Miniaturization.

I. INTRODUCTION

The increasing development of wireless communication systems such as WiMAX and WLAN requires the design of multiband antennas able to operate in different frequency bands. In addition to low profile and wide bandwidth, the antennas should be compact to facilitate their integration with other system components. Printed antennas are a good solution that could fulfill the previous requirements.

Different approaches have been developed in the literature to achieve multi-band property. The most conventional one consists of only acting on the radiating element by inserting conducting strips or etching slots to generate different resonant frequencies \cite{1}-\cite{6}. However, the reported designs either have relatively large dimensions or possess complex structures that can make obtaining the desired frequency a very difficult task. In \cite{6} embedding a set of V slots and slits into an annular patch antenna helps to achieve a triple-band antenna with dual-polarized performance. Despite its compact size (0.35\(\lambda\) \times 0.35\(\lambda\)), the proposed antenna showed relatively narrow bandwidths. In \cite{7}, a T-shaped monopole is loaded with a horizontal conducting branch for dual-band radiation. But, the antenna has a large size in addition, the two bands are not independently controlled. In \cite{8}, by loading a main radiating patch with four sub patches a multiband performance is achieved with independent frequency control. However, the bands are narrow which is not suitable for applications that need more bandwidth. Parasitic elements have also been used in \cite{9}, where T-shaped and Inverted-L strips were placed on a microstrip antenna to achieve multi-band performance but at a cost of a large ground plane and relatively high profile. Another widely used approach \cite{10}-\cite{13} consists of loading the antenna with Split Ring Resonators (SRR). In \cite{10} and \cite{11}, a set of SRR cells were coupled to a slot antenna to obtain multi-band performance but with large dimensions and narrow bandwidth. The same idea was used in \cite{10} but with a dipole with a capacitive gap loaded with via-less composite right/left-handed (CRLH) unit cells to achieve multi-band operation. The CSRR has...
also been used in [15], [16] for multiband performance in microstrip antennas. However, etching the CSRR in the radiating element decreases both, gain and efficiency. The CSRRs can also be printed in the ground plane for multiband and broadband performances [17]. Additionally, SRRs and CSRRs have been widely used in the filtering antenna design in order to avoid interferences between adjacent bands [18]- [19].

The second approach consists of jointly acting on the ground plane, feeding line, and/or radiating element. In this way, the addition of composite right/left-handed (CRLH) unit cells to load the radiating elements has been proposed to achieve multi-frequency performance with compact size [20] - [22]. However, this structure needs bridges in the coplanar feeding line and vias to the ground plane what makes the manufacturing process much more complicated. In [23], a triple-band monopole antenna was achieved by loading the monopole with distributed CRLH lines. However, the resultant radiation pattern is not monopolar within all operating bands. Finally, in [24], a bulky 3-D miniaturized monopole antenna was achieved. It consists of a vertical monopole loaded with a CSRR plus multiple zeroth-order resonator (ZOR) unit cells over the ground plane to achieve multi-band performance with an independent tuning of the frequencies band. However, the profile of the antenna is relatively high (0.1λ) and the bandwidth is narrow.

In this paper, a fully planar multi-band monopole antenna is presented thanks to jointly working on the whole antenna: radiating element and ground plane. In this way, the inclusion of a pair of CSRRs in the microstrip feeding line will constitute a defected ground plane and provide additional horizontally polarized resonances. In comparison with previously stated works this antenna has a low profile and shows large compactness and is easier to manufacture due to its fully planar structure. The inclusion of the CSRRs in the ground plane perturbs the current distribution in a coherent way creating an in-phase current along the x-axis at 3.6 and 5.9 GHz what contributes to the radiation. Consequently, a triple-band independently controlled resonance can be achieved by modifying the dimensions of the CSRRs in the defected ground plane. Finally, the proposed antenna provides a dual-polarized performance: vertical polarization at 2.4 GHz associated with the vertical radiating element and dual-band horizontal polarization at 3.6 and 5.9 GHz associated with the perturbed GND.

The rest of the paper is organized as follows: Section II presents the operation principle of the antenna and its design process, current distribution, parametric study, and equivalent circuit. The experimental results that validate the simulations are shown in Section III. Section IV contains a conclusion.

II. ANTENNA DESIGN

A. ANTENNA DESIGN

The proposed triple-band antenna geometry is shown in Fig. 1. The antenna consists of two layers. The top layer contains an inverted L-shape monopole designed to resonate at 2.4 GHz. A forked-like microstrip feeding line has been added to also consider the ground plane. Secondly, in the bottom layer, two CSRRs cells with different sizes have been etched out from a partial ground plane to achieve multi-band performance. The two rings in the CSRRs keep the same slot’s width and the gap at the end of the slot. The only different dimensions are the external radius \( r_{ex} \) and \( r_{ex1} \) which belongs to the small and large CSRR respectively as shown in Fig. 1. It is important to emphasize that if it were not for the forked feeding line the two CSRRs would not be equally excited neither in amplitude nor in phase. This feeding strategy allows the triple-band performance. We note that such a microstrip feeding line is selected to solve the problem of the beam tilt and gain decrease. This has been shown in [17] where a meandered microstrip feeding line was used for exciting two CSRR to obtain dual broadband performance. Therefore, out-of-phase currents are excited at a higher frequency band, which led to a great decrease of the broadside gain. This feeding approach can be extended to other metamaterial unit cells such as rectangular CSRR where the same radiation performances are obtained.

A further explanation of the way that the antenna works can be given by splitting the design steps of the proposed antenna. This is illustrated in Fig. 2 where all the design steps are presented. Firstly, the single inverted L-shaped monopole antenna denoted as Ant 0 refers to the conventional basic antenna without CSRR loading. This inverted L-shaped monopole provides the lowest working frequency, in this case, 2.4 GHz, and is fed through a straight microstrip line. This resonance is calculated when the length of the monopole \((L_m+L_{m1})\) is approximately \(\lambda_g/4\) (\(\lambda_g\) guided wavelength at 2.4 GHz) which corresponds to the fundamental mode of a conventional monopole antenna. Secondly, the inclusion of the forked-like feeding line constitutes the so-called Ant1.
This structure is designed to allow the presence of a tiny resonance at the highest desired frequency, in this case in the 6 GHz band. Thirdly, the perturbed ground plane (GND) is achieved through etching out one CSRR in the GND. This structure is called Ant2 and the CSRR is designed to provide resonance at the intermediate WIMAX band, in this case, 3.6 GHz as shown in Fig. 3. Finally, in order to symmetrize the antenna and improve the performance at the highest frequency, another CSRR has been etched out at the other prong of the forked-like feeding line. This will constitute the so-called Prop Ant and is shown in Fig. 2. Moreover, it can be seen that not only does the inclusion of the CSRR in the GND preserve the performance of the base monopole but also improves the matching conditions and enlarges its impedance bandwidth.

The fundamental mode of the CSRR unit cell is excited when an axial electric field is applied [25]. Thus, two CSRR unit cells with two different radii have been simulated as shown in Fig. 4. From Fig. 4 (b), it can be seen that the two resonances agree well with the obtained results in Fig. 3 where the two CSRRs are inserted below the feeding line.

 Concerning the radiation mechanism, it can be seen that at this highest frequencies is not any longer due to the monopole effect but to the perturbed ground plane. Then, despite of providing vertical polarization the final triple frequency antenna will provide two horizontal polarizations associated with the perturbed GND and one vertical polarization associated with the folded monopole. The resulting antenna covers the standard IEEE 802.11p. It can also be noted that the fundamental and higher modes of the monopole have been slightly shifted down due to the capacitive effect between the monopole itself and the loaded CSRR.

To gain more insight into the radiation mechanism of the proposed antenna, the current distribution at each resonant frequency is being analyzed through a full-wave simulation with CST. The designed frequencies are 2.4 GHz, 3.6 GHz, and 5.9 GHz respectively. Fig. 5 (a)-(c) shows the current distribution at the previous frequencies. At 2.4 GHz, we can see that the current distribution on the inverted L shape is similar to that of the reference monopole antenna (Ant 0). For the sake of conciseness, the current distribution at 2.4 GHz of the reference antenna (Ant 0) is not presented. The presence of the CSRR in the perturbed GND causes to appear two out of phase currents along with the GND. These currents are then canceled out and do not contribute to the overall radiation resulting in a vertically polarized E field. At 3.6 GHz, the radiation mechanism is somewhat different since the currents on the vertical monopole are very small and are canceled out due to its out-of-phase distribution. Then, the large currents surrounding the left CSRR (the CSRR with large dimension) induce a net in-phase current distribution along the edge of the ground plane along the x-axis. This yields to somewhat dipole-like radiation oriented along the x-axis. This fact will be demonstrated in the next section by giving the radiation pattern. Finally, at the highest frequency band, the current distribution on the vertical monopole produces a notch just at the middle of the monopole what yields to a tiny higher-order vertical mode as can be appreciated around 7.8 GHz. In addition to that, the presence of the large current distribution surrounding the small CSRRs (the one on the right) induces a horizontal current along the x-axis resulting in a dipole-like radiation pattern. It is also seen that these currents along the horizontal edge of the ground plane contribute to the radiation since they are in phase as can be seen in Fig. 5 (c). One of the advantages of this proposed antenna is that it exhibits an independent control of the resonance frequencies. In order to demonstrate this characteristic, a parametric study of some key parameters will be shown in the next subsection.

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while the second resonance shifts up to higher frequencies. This provides the ability to achieve different working bands just by controlling the outer radius of the CSRRs. These results reveal that the two resonances could be separately tuned without affecting the first one that can be easily controlled by the inverted L monopole.

It is worth noting that other applications such as WLAN 2.4/5.2/5.8 GHz can be easily obtained by changing the CSRR parameters: outer radius \( r_{ex} \), strip width \( d \), and slot width \( w_c \) as shown in Fig. 7. We note that when one parameter is changed the others are kept at their optimized values. It is seen that when \( r_{ex} \) increases from 3.3 to 4.4 mm the frequency is shifted from 5.2 to 3.45 GHz (Fig. 7 (a)). This is due to the decrease of the equivalent capacitance of CSRR \( C_{csrr} \) since it can be modeled as an LC resonator tank as shown in Fig. 8. On the other hand, \( w_c \) and \( d \) have similar behavior over the frequency band but in an opposite way (Fig. 7(b)). Increasing \( d \) decreases the equivalent inductance of CSRR \( L_{csrr} \) while increasing \( w_c \) decreases the capacitance \( C_{csrr} \) leading to a shift of frequency to higher values. This is consistent with the theoretical analysis reported in [25].

In order to have a more accurate control on all the resonance frequencies of the triple-band antenna, an equivalent circuit based on lumped elements has been proposed. The equivalent circuit is composed of four resonant circuits and their corresponding couplings between them. According to [25] two CSRRs have been modeled as shown in Fig. 8. Therefore a CSRR unit cell can be modeled as two L and C parallel circuit. First, a capacitor and an inductor, \( C_f \) and \( L_f \), are needed to model the microstrip feeding line. Secondly, four resonant parallel circuits are placed to model the CSRRs in the ground plane and the two resonant frequencies of the monopole. Then, the resonance frequency of the CSRR at 3.6 GHz is modeled with \( C_{csrr2}, R_{csrr2}, L_{csrr2} \) elements for the lowest resonant frequency, and \( C_{csrr1}, R_{csrr1}, L_{csrr1} \) for the highest resonance frequency of the CSRR at 5.8 GHz. In addition to that, two other resonators associated to the monopole have been also modeled as \( C_{low}, L_{low}, R_{low} \) and \( C_{high}, L_{high}, R_{high} \) respectively. Finally, the coupling between CSRR cells with the feeding line is realized through \( C_{e1}, L_{e1}, C_{e2}, \) and \( L_{e2} \). Another two inductors, \( L_1 \) and \( L_2 \), have been added to take into account the joint between the feeding lines and the monopole for the lowest and highest frequencies respectively. It is important to note that the resonance frequencies associated with the two CSRRs are mainly affected by the capacitive coupling between the fork-like feeding line and CSRRs. Therefore, the resonance frequency is given by:

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{L_{csrrl}(C_{csrr} + C_e)}{}}
\]

This results in the following resonances of 5.6 and 3.9 GHz for CSRR1 and CSRR2 respectively, which are slightly shifted from the simulated results shown in Fig. 10 due to the effect of the rest of the circuit. The optimized parameters of the circuit model are given in table 2.
The results of the equivalent circuit, CST MW solver, and measurements are depicted in Fig. 10. A good agreement can be seen between all of them.

III. SIMULATED AND MEASURED RESULTS

To experimentally validate the performances of the proposed antenna, a prototype has been fabricated based on the optimized values given in Table 1. The manufactured prototype can be seen in Fig. 9. Fig. 10 shows the simulated and measured results of the return loss versus frequency of the proposed tri-band antenna. A good agreement is observed, the small discrepancy can be attributed to fabrication errors and measurement conditions. The measured -10 dB bandwidth is about 250 MHz (2.38-2.63 GHz) for the first resonance which covers 2.4/2.5 GHz WLAN and WiMAX operation bands, 90 MHz (3.54-3.63 GHz) for the middle resonance which covers part of the 3.5 GHz WiMAX band and 1.29 GHz (5.83-7.12 GHz) for the upper resonant frequency covering the requirement of IEEE 802.11p standard (5.850-5.925 GHz). The measurement setup of the radiation pattern is shown in Fig. 11 (a). The simulated and measured radiation patterns of the proposed antenna at each resonant frequency are given in Fig. 12. A good agreement has also been achieved except for some discrepancies that may be attributed to the measurement conditions. We note that the presence of the unavoidable metallic holder behind the antenna causes to appear some ripples in the radiation pattern. Thus, an absorbing material has been added between the antenna and the holder to isolate them and avoid such ripples. It is important to note that due to the presence of the absorber the measurements have only been taken in the range ±90° since the back radiations are absorbed and suppressed.

Figure 12 (a) and (b) present the radiation pattern of the proposed antenna at 2.4 GHz. As it was previously expected in Fig. 5 (a) the antenna exhibits omnidirectional and bidirectional radiations in XZ and YZ planes respectively which are consistent with the radiation of a conventional monopole antenna in which the y-directed currents are the main contributors to the radiation. The cross-polarization level at the broadside direction is lower than -15 dB. At 3.6 GHz the antenna provides an orthogonal polarization to

| Table 2. Optimized values of the proposed circuit |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| L₁ (nH) | L₀₁ (nH) | C₀₁ (pF) | L₀₂ (nH) | L₀₀₁ (pF) | R₀₀₁ (Ω) | C₀₀₁ (pF) |
| 0.3     | 0.09    | 1.017    | 6.4     | 2.32     | 50     | 0.41    |
| R₀₀₁ (kΩ) | L₁₀₂ (nH) | L₀₀₁ (pF) | R₀₀₁ (Ω) | C₀₀₁ (pF) | L₀₀₁ (nH) |
| 1.26    | 0.82    | 0.7      | 37.5    | 1.14     | 0.23    | 3.03    |
| C₀₀₁ (pF) | R₀₀₁ (kΩ) | L₀₀₁ (nH) | L₀₀₁ (nH) | L₀₀₁ (pF) | L₀₀₁ (nH) |
| 0.45    | 3.3     | 0.137    | 0.13    | 0.9      | 1.78    | 0.7     |
FIGURE 11. Measurement setup of (a) radiation pattern (b) radiation efficiency.

FIGURE 12. Simulated and measured radiation pattern in the planes (a) XZ and (b) YZ at 3.6 GHz (c) XZ (d) YZ at 3.6 GHz (e) XZ (f) YZ at 5.9 GHz.

FIGURE 13. Measured and simulated (a) radiation efficiency (b) broadside gain.

with dimensions $20 \times 20 \times 14 \text{ cm}^3$. With this size, the corresponding resonance frequency of the cap is 1.06 GHz which is below the operating frequency bands of our antenna. The position of the antenna inside the Wheeler cap is in the middle and is presented in Fig. 11 (b). The method consists of two main measures. The first one measures the $S_{11}$ of the proposed antenna in a free space environment. The second one measures the antenna when enclosed in the Wheeler cap so that any radiation can be eliminated. The measured and simulated radiation efficiency over the frequency is shown in Fig. 13 (a). The measurements show an efficiency of 90%, 64%, and 93% at 2.4, 3.6, and 5.9 GHz respectively which well agree with the simulated ones (98%, 75%, and 97%). The estimated measured gain based on the measured efficiency and the simulated directivity is calculated using equation 2

$$G_{estimated} = D_{simulated} \times \eta_{measured}$$

Based on that, the estimated measured gain and simulated gain as a function of frequency are shown in Fig. 13 (b). It is clearly seen that the estimated measured gain is 1.34, 0.68, and 2.65 dBi at 2.4, 3.6, and 5.9 GHz respectively which agree well with the simulated results 1.78, 1.28, and 4.13 dBi at the same operating frequencies.

A comparison between the proposed antenna and some recent works is given in Table 3. The designs in [26] and [27] present high gain at the operating frequencies but at the cost of large size and narrow bandwidths which may limit their application. References [7] and [29] are single structures only based on strip loading but with large size and single polarization. Finally, references [20] and [21] have dual LP with a small horizontal size but with vias and bridges that make its profile higher and more complex than the one presented here.

From this comparison, it is concluded that the proposed antenna presents the lowest and most simple profile with dual linear polarization characteristic (LP) and good bandwidth.

IV. CONCLUSION

A novel tri-band antenna based on CSRR loading is studied. By etching out two CSRRs in the ground plane of an inverted L-shaped monopole and modifying the geometry of the feeding line the antenna can cover three working bands for...
TABLE 3. Comparison with recent works

| Ref | Freq (GHz) | -10dB band (%) | Gain (dBd) | Polarization | Height (λ₀) | Size (λ₀)² | Technique |
|-----|------------|----------------|------------|--------------|-------------|-----------|-----------|
| [26] | 3.04 | 0.83 | 2.56 | Single LP | 0.019 | 0.4 × 0.4 | Shorting via with multiple U slots |
| [27] | 3.5 | 0.81 | 2.35 | Single LP | 0.023 | 0.6 × 0.4 | HMSIW |
| [20] | 2.7 | 78.5 | NA | Dual LP | 0.018 | 0.26 × 0.35 | NRI via with \( Z \)-open-ed zeroth-order resonating metamaterial antenna |
| [21] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |
| [24] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |
| [25] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |
| [26] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |
| [27] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |
| [28] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |
| [29] | 2.45 | 3.76 | 0.98 | Single LP | 0.012 | 0.32 × 0.2 | TL MIM with via and bridges |

WLAN, WiMAX, and IEEE 802.11p applications. Additionally, the CSRRs allow independent control of the obtained frequency bands. The simulated results have been verified through measurements of a fabricated antenna prototype. The proposed antenna exhibits good radiation performance in terms of gain, efficiency, and radiation patterns. Furthermore, having a low profile, compact size, and simple structure for ease of implementation with other devices. The proposed antenna could be suitable for modern wireless communication systems.

REFERENCES

[1] L. C. Tsai, “Design of triple-band T-U shaped CPW-fed slot antennas,” Microw. Opt. Technol. Lett., vol. 56, no. 4, pp. 844–848, Apr. 2014.
[2] J. Park, M. Jeong, N. Hussain, S. Rhee, P. Kim, and N. Kim, “Design and fabrication of triple-band folded dipole antenna for GPS/DCS/WLAN/WiMAX applications,” Microw. Opt. Technol. Lett., vol. 61, no. 5, pp. 1328–1332, Feb. 2019.
[3] P. Wang, G. J. Wen, Y. J. Huang, and Y. H. Sun, “Compact CPW fed planar monopole antenna with distinct triple bands for WiFi/WiMAX applications,” Electron. Lett., vol. 48, no. 7, pp. 357–359, 2012.
[4] Y. D. Wan, J. H. Lu, and H. M. Hsiao, “Novel design of a semi-circular slot antenna with triple-band operation for WLAN/WiMAX communication,” Microw. Opt. Technol. Lett., vol. 50, no. 6, pp. 1531–1534, 2008.
[5] R. Sonak, M. Ameen, and R. K. Chaudhary, “CPW-fed electrically small open-ended zeroth-order resonating metamaterial antenna with dual-band features for GPS/WiMAX/WLAN Applications,” AEU - International Journal of Electronics and Communications, vol. 104, pp. 99–107, May 2019.

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[26] A. Boukarkar, X. Q. Lin, Y. Jiang, and Y. Q. Yu, “Miniaturized single feed multi-band patch antennas,” *IEEE Trans. Antennas Propag*, vol.65, no. 2, pp. 850–854, Feb. 2017.

[27] X. Yang, L. Ge, Y. Ji, et al., “Design of low-profile multi-band half-mode substrate-integrated waveguide antennas,” *IEEE Trans. Antennas Propag*, vol.67, no. 10, pp. 6639–6649, Oct. 2019.

[28] W. E. McKinzie, III, “A modified wheeler cap method for measuring antenna efficiency,” in *Proc. IEEE Antennas and Propagation Society Int. Symp.*, pp. 542–545, Jul. 1997.

[29] A. Iqbal, A. Bouaziz, O. A. Saraereh, A. Basir, and R. K. Gangwar, “Design of Multiple Band, Meandered Strips Connected Patch Antenna,” *Progress In Electromagnetics Research Letters*, vol.79, pp. 51–57, 2018.

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