Analysis and Development of an Efficient Cross-Slot Loaded Compact Electromagnetic Band Gap Antenna

El Amjed Hajlaoui [1,2] and Ziyad M. Almohaimeed [2]

[1] Department of Electrical Engineering EL MANAR University, Tunis, 2092, Tunisia
hajlamjed@yahoo.fr

[2] Department of Electrical Engineering, College of Engineering, Qassim University, Buraydah,51452, KSA
z.mohaimeed@qu.edu.sa

Abstract **─** This paper is devoted to a novel Electromagnetic Band Gap (EBG) single-feed circularly polarized microstrip EBG antenna with compact size proposed for C-Band applications. The antenna structure will include eight slits introduced at the boundary and the corners in the radiating square patch with a cross-slot at the center.

The provided study will effectively approve the various proposed structures and interest occupied by these types of antennas in the enhancement of output parameters (gain, directivity, radiation efficiency, and bandwidth) without much affecting the operating bandwidth at C-band.

At first, the concept and the realization of a directive and circularly polarized antenna using an electromagnetic band gap material whose circular polarization is generated by the structure itself is discussed. The analysis and simulation results are presented for an antenna operating at 6.1 GHz using computer Simulation Technologies (CST). Furthermore, the new compact circular polarized EBG antenna, compared to experimental results, will confirm the pre-studied goal of these kinds of antennas such as radiation efficiency, polarization purity, radiation efficiency, high directivity, and gain.

Index Terms **─** Circularly polarized cross-slot square patch antenna, dimensional characterization, electromagnetic waves & propagation, Electromagnetic Band Gap (EBG) resonator.

I. INTRODUCTION

Microstrip antennas are devices of choice in high performance applications where size, weight, cost, and ease of installation are prior requirements for specific wireless connexion [1]. Tunability in an antenna system is a quickly evolving feature that aims to control multifunctional antenna designs. Compared to conventional antennas, electromagnetic band gap (EBG) antennas provide an adjustment of diverse antenna parameters, including operational bandwidth, radiation pattern, gain, and polarization [2]. From the fundamental limit of the classic antennas [3], applying antenna miniaturization techniques for the antennas comes at the expense of the antenna performance. Here, we propose a new approach to achieve the major goal of these designs, with a smaller form factor and better performance in terms of radiation efficiency, polarization purity, radiation pattern, directivity, and gain. Hence, a new single-feed circularly polarized microstrip antenna with compact size is presented where eight slits are introduced at the boundary and the corners in the radiating square patch with a cross-slot at the center. The resonance frequency of the proposed antenna is dependent on the length and width of the cross-slot and corner slit for the entire band of circular polarization. The whole structure is the deposit on the Arlon AD 250 substrate and fed by a single coaxial probe.

In order to perform the gain, the directivity, and the total radiation efficiency, a new concept of directive electromagnetic band gap (EBG) antenna will be analyzed [2]. Hence, the electromagnetic band gap structures are objects that prevent/assist the propagation of electromagnetic waves in a specified band of frequency for all incident angles and all polarization states [3], [4]. They have been used in several applications to improve the antenna's directivity [5] and permit a harmonic control [6].

The proposed antenna is achieved by cutting four equally spaced slits at the corner of the square patch where the dominant mode is TM11 mode. The operating frequency band can be controlled via the cross slits lengths in the center of the square patch and adjusting the length of square patch. An arrangement combining the single feed square cross-slot patch antenna design and feeding sources included is considered necessary. Due to the existing of a single feeding point, the Position of the feeding point will permit Right-hand and Left-hand circular polarization operations due to two orthogonal modes with equal amplitudes, which are in-phase quadrature with the sign determining the sense of left-

Submitted On: March 8, 2021
Accepted On: June 21, 2021

https://doi.org/10.47037/2020.ACES.J.360615

1054-4887 © ACES

hand circular polarization/right-hand circular polarization (LHCP/RHCP) [7]. CP is achieved here using a single feed and does not require an external polarizer [8]. The thickness of the substrate is chosen to reduce the spurious surface wave and width. Coaxial feeding techniques have been used as it is easier to implement. This technique will be used for the EBG circularly polarized cross-slot patch antenna and carry two benefits (such as improvement of bandwidth, beamforming, creating zero radiation beams) and filtering characteristics of the resonator (spatial filtering, increased directivity, misalignment) due to the resonant structure itself. The effect of EBG structures embedded over the patch is studied for enhancing the gain, directivity, and radiation efficiency. Simulation and experimental results at 6.1GHz are presented. Table 1 shows dimensions of the Proposed Structures

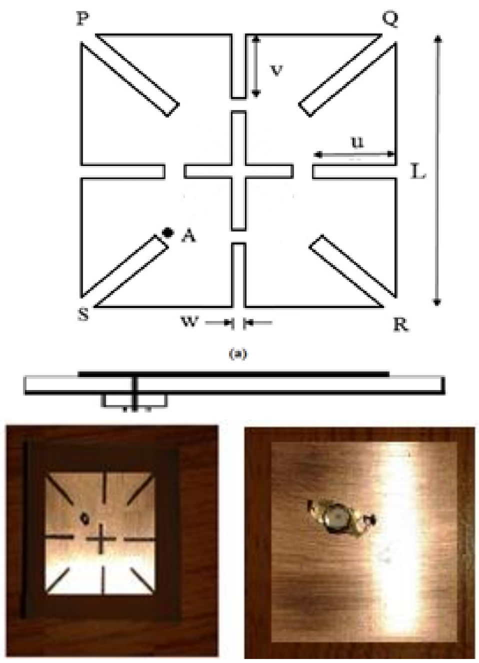


Fig. 1. Proposed cross-slot loaded compact antenna.

Table 1: Geometric parameters of the proposed compact cross-slot antenna

Antenna Parameters	Value (mm)
Length of square patch, L	30
Length of slit, u	10
Length of slit, v	9.2
Length of slit, w	1.0
Length of cross slot	10
Width of cross slot	1.0
Length of corner slit along diagonal PR	12.5
Length of corner slit along diagonal QS	10.5
Width of corner slits	1.0

II. PATCH-SLOT CIRCULAR ANTENNA DESIGN & DEVELOPMENT

The physical and geometric substrate material parameters have an important part in the design and conception of the microstrip patch antenna. Permittivity, conductivity, thermal expansion, and cost are fundamental factors to choose specific material. In this work, the substrate material have a dielectric constant of 2.5 and a dielectric loss tangent of 0.009 [9]. These materials have the ability to open localized electromagnetic modes inside the prohibited frequency band-gap by introducing defects into the periodic structures [10]. EBG structures have been used in several applications, such as Directive antennas [11], harmonic control [12]. Here, an innovative design of single & multilayered patch-slot circular microstrip EBG antenna having a displacement of the coaxial feeding source from the center of the circular patch is proposed and its simulated radiation performance in free space conditions have been presented in comparison with the experimental results.

The proposal considerations for this cross-slot loaded compact circularly microstrip patch antenna as shown in Fig. 1 on Arlon AD 250 substrate material with a relative dielectric constant of 2.5 with a thickness of 1mm and geometric parameters as shown in Table 1. Coaxial feedings are used to ensure the circular polarization in the presence of slots (cross and inserted in boundary). Hence, When the ratio of the total slit length in the slot in the x-direction (Lx) to that in the y-direction (Ly) is properly chosen, the two near-degenerate modes can be excited, using a single feed along the diameter at $\varphi=45^0$ planes, to be of equal amplitudes and 90^0 phase difference, which results in a CP radiation. When Lx is greater than Ly, the feed position at point A is for right-hand CP operation, while point B is for left-hand CP operation. The two slits on the *x*-axis have the same length L_x, and the two slits on the *y* axis have an equal length L_y. and ensure that $L_x > L_y$. Then, by varying x ($0 < x < y$).

An optimization of the structure thickness to give us best values of Return Loss, VSWR and 2-D Gain for the designed circular patch-slot antenna gave us a thickness 1.6mm

For a specific value of thickness h=1.6 and ε_r=2.5, and as shown in Fig. 2, the experimental return loss of the antenna S11 is -21.055 at 6.0155 GHz with a measured bandwidth of 247.81MHz. The reflection coefficient value suggests that there is good matching at the frequency point below the -10 dB region. It covers the C-frequency band for military requirements for land, airborne and naval radars applications. The radiation power shows the maximum peak value at the resonant frequency

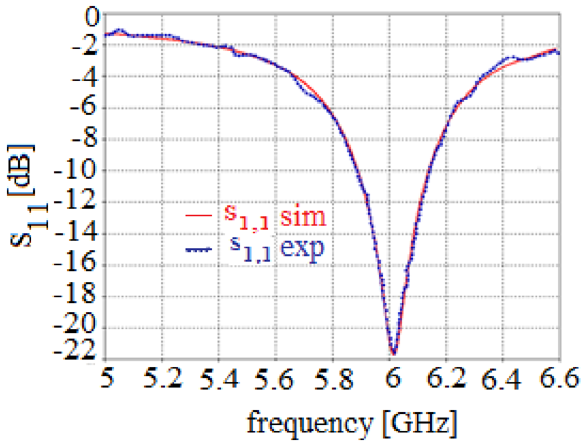


Fig. 2. Simulated versus measured reflection coefficient of the single-feed cross-slot loaded compact circularly polarized microstrip antenna.

In next Table 2, we present additional parameters given by the experimental approach versus the simulation ones. The far-zone electric field lies in the E-plane, and the far-zone magnetic field lies in the H plane. The patterns in these planes are referred to as the E and H plane patterns, respectively. These parameters concern the radiation power, total efficiency, and Return losses (dB).

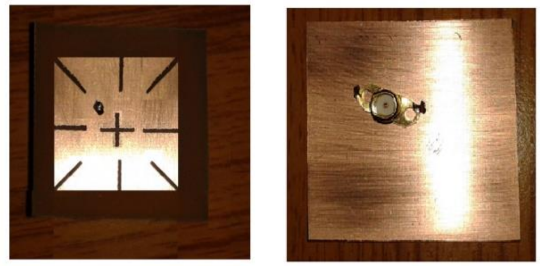
Table 2: Additional antenna parameters of the circular slot-patch antenna when the thickness is fixed as h=1.6 mm

		Experimental Results	Simulation Results
1	Directivity(dBi)	6.08	6.014
2	Peak realized gain(dB)	6.28	5.979
3	Radiation Efficiency	0.989	0.9919
4	Total radiation efficiency	0.564	0.5727

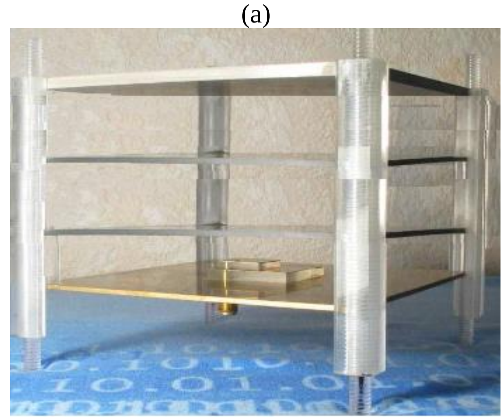
III. DEVELOPMENT OF THE SINGLE-FEED CROSS-SLOT LOADED COMPACT MICROSTRIP EBG ANTENNA.

In this section, the antenna prototype was carried out using the LPKF machine, which permits validation of the optimized structure. The measurement of return loss is obtained using Vectorial Network Analyzer (VNA) PNA-X from Agilent Technologies. Figure 3 gives the picture of the fabricated cross loaded antenna.

It shows the kit of calibration of 3.5 mm used to take into consideration the losses in the different transitions; this kit is composed from Open, Short, and Load components. The measured return loss for the achieved EBG antenna obtained after the calibration, along with the simulation results on CST is taken into account. No massive difference between simulation and experimental data is occurred due to the equipment well adapted to our work.



(a)



(b)

Fig. 3. (a) The proposed single-feed cross-slot loaded compact circularly polarized microstrip antenna, and (b) the antenna when included with the Plexiglass EBG layers.

The new Compact Circularly Polarized microstrip antenna geometry discussed above has been modified by the insertion of new EBG materials and understand the impact of the number of layers on the antenna performances while keeping the same dimensions as before concerning the patch and lateral conditions walls, as shown in figure 4, The distance between the patch and the first dielectric layer is λ_0 / 2 = 24.44 mm, and the layer thickness is λ_g / 4 =7.72mm.

Here, we add to our original patch, studied previously, new EBG structures and understand the impact of the number of layers on the performance of the antenna while keeping the same dimensions as before the patch and conditions power side (thickness of the substrate h=1.6mm, ε_r=3.6, Slot width=1mm, length of the square patch L=30 mm). However, the newly inserted dielectric layers will have dielectric permittivity fixed at ε_r = 2.5, and the only variation should include the number of layers. For only a one-layered EBG antenna, the return loss is about –46 dB

Figure 4 shows the measured and simulated return loss values at 6.135 GHz. The radiation patterns are well-predicted by the simulations. The beam width gets smaller as the number of EBG structures increases, implying the increasing directivity [12]. The next figure shows the measured 3 dB beam width of 33 degrees. Cross-polarization radiations could not be measured due to the limitation of the antenna measurement setup, but the simulation shows that they are suppressed by at least 25 dB in the broadside direction for both the E- and H-planes of the EBG antenna. Figure 4 will show the importance of EBG Layers in the improvement of the radiation pattern of the antenna

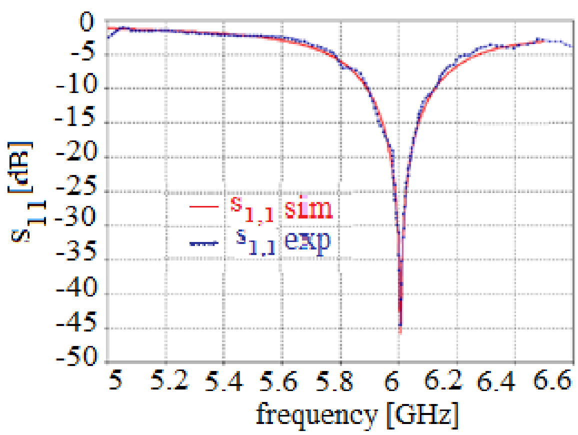


Fig. 4. Simulated versus measured reflection coefficient of the 1-layered single-feed cross-slot loaded compact circularly polarized microstrip EBG antenna.

The most important value for the reflection coefficient S11 (dB) = -45.5 dB is shown on a One-Layered Single-Feed Cross-slot compact EBG antenna, so layers of Plexiglas did not destabilize the matching of the antenna. If we search the impact of these layers on the radiation pattern of the antenna, the 3D radiation pattern, as shown in Fig. 5 and Fig. 6, shows that the radiation has a greater directivity equal to 8.150 dB, which is normal, since the parallel EBG materials increase directivity, gain; therefore, we get a longer range of transmission.

The opening angle decreased significantly. In fact, it passes from 80.4 deg to around 22.7 degrees with a preferred direction of propagation along the z-axis which confirms our studies on the effects of these materials defects. So we move from a unidirectional antenna to a directional antenna in the axis perpendicular to the patch. The side lobes pass from -16.5 dB to -0.5 dB, which means an excellent control of the transmission bandwidth.

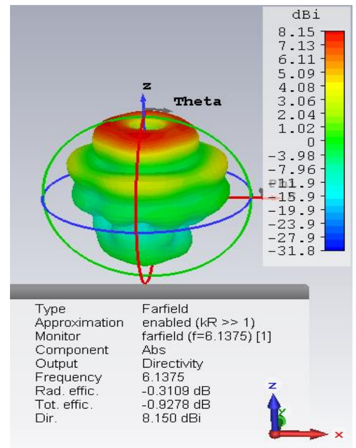


Fig. 5. 3D radiation pattern of a 4-layered circularly polarized slot-patch EBG antenna.

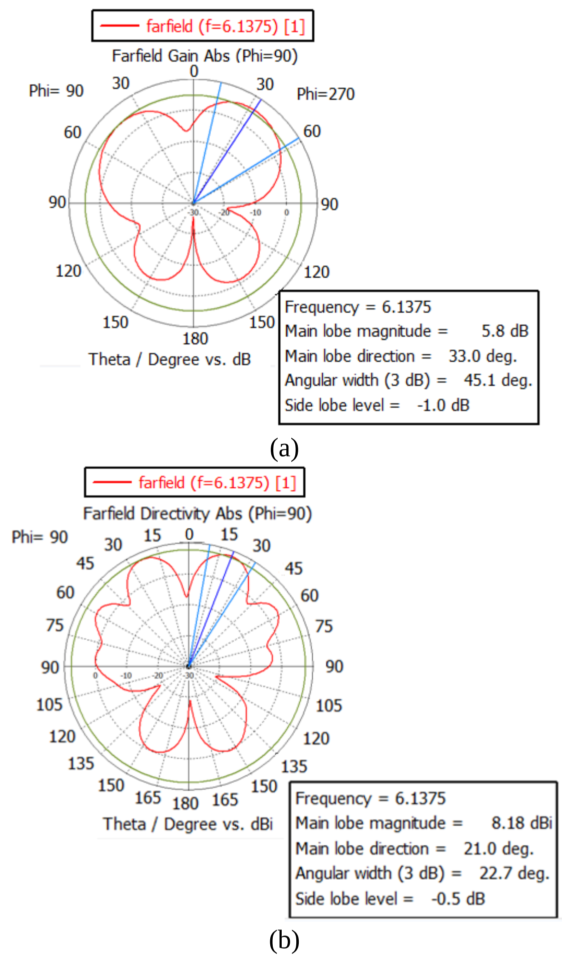


Fig. 6. Polar radiation pattern of the single-feed cross-slot loaded compact circularly polarized patch antenna: (a) without EBG structures and (b) 4-layered EBG structures.

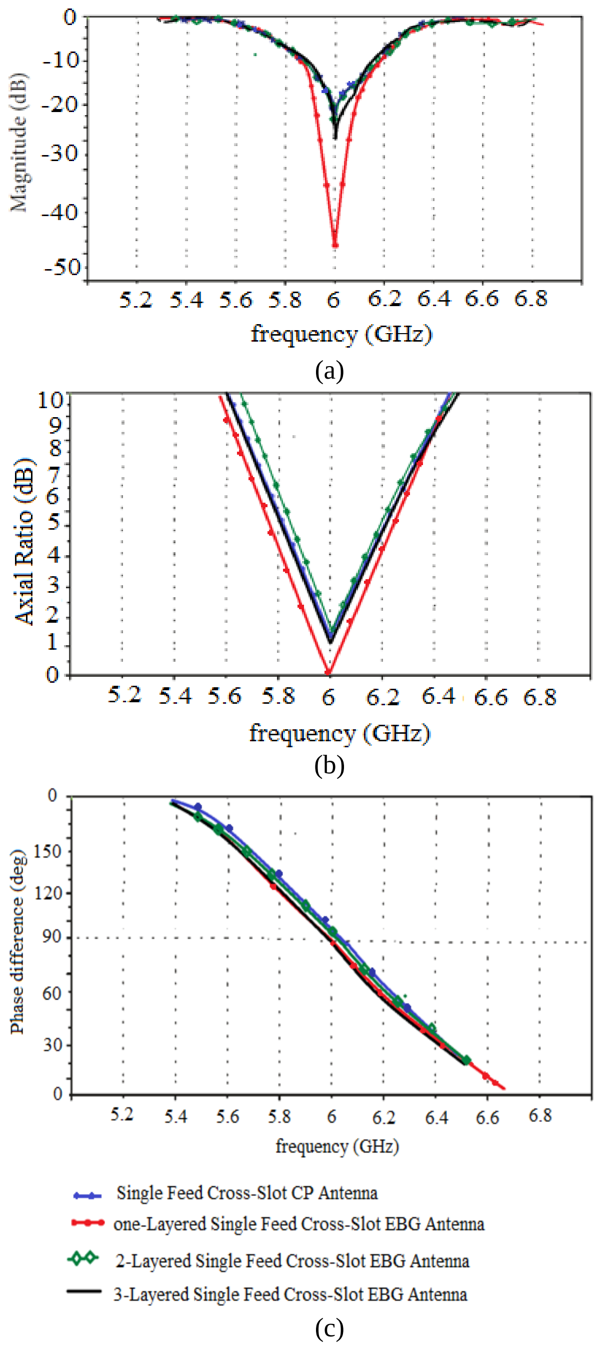


Fig. 7. Simulated results of the proposed cross-slot loaded compact electromagnetic band gap antenna with different Layers: (a) reflection coefficient, (b) AR, and (c) phase difference between two resonant frequencies.

Figure 7 shows the simulated results of the reflection coefficient, axial ratio (AR), and phase difference of the resonant frequency with respect to the number of the EBG structures (L). The remaining parameters are identical to those mentioned above. Here, all geometric parameters of the original antenna are identical. As *L* increases, the resonant frequency remains the same except the opening angle that will decrease significantly. In fact, it passes from 80.4 deg to around 22.7 degrees with a preferred direction of propagation along the z-axis, which confirms our studies on the effects of these materials defects.

In our proposed antenna, the number of EBG structures does not substantially reduce the resonant frequency. However, as EBG Structures (L) increase, the frequency of the minimum AR remains unchanged within a small margin of error, and only the minimum value of the AR becomes worse. As shown in Fig. 7, the frequency response of the phase difference changes negligibly with *L*. Therefore, the frequency at which the phase difference becomes 90° is nearly unchanged. Consequently, the minimum AR frequency is almost intact as well. Because the resonant frequency formed based on the reflection coefficient and the frequency at which the minimum point of AR should coincide, *L* is selected to get the best compromise between the directivity, gain, and reflection coefficient. From the simulated results, it is observed that *L* can be fixed at L=3 that number corresponding to S11=-26.5 and good impact on the total radiation efficiency

As shown in the previous figure and results of simulation and experimental parameters, the design procedure for implementing the EBG structures above the cross-slot loaded compact electromagnetic using the proposed technique can be summarized as follows: Apply identical EBG structures to the proposed patch. At this time, before the procedure begins, we should verify all required outputs (gain, directivity, AR …..) and stop to add new EBG structures if the AR value reduces to below 3 dB

The Table 3 will summarize the experimental results. The impact of EBG structures is evaluated on the antenna gain, directivity, reflection coefficient, and radiation efficiency. While increasing the number of EBG layers, the radiation efficiency will increase the same to the reflection coefficient. However, a slight variation in the directivity and gain will be shown when the number of layers will pass from one to three. After the third layer, the antenna output will decrease obviously. That is the reason why we have stopped our study to the third EBG layer

Table 3: Impact of the number of layer (L) with $\varepsilon_r = 2.5$

Number of EBG Layers (L)	L=1	L=2	L=3	L=4
f (GHz)	6.0065	6.0245	6.04	6.128
S11 (dB)	-45.86	-23.88	-26.5	-22.38
Gain (dB)	7.751	8.368	8.456	7.839
Directivity (dBi)	7.837	8.528	8.638	8.150
Linear radiation efficiency	0.5515	0.5661	0.8660	0.8076

As the number of layers' increases, the gain increases against the opening angle decreases, so the antenna is more directive. Note that the bandwidth decreases significantly with the number of EBG layers.

IV. CONCLUSION

A Cross-Slot Loaded Compact Circularly Polarized EBG Patch antenna is presented in this paper. The insertion of new EBG structures to the compact antenna as studied in the first section of our paper aims to perform the electromagnetic characteristics (Gain, Bandwidth, radiation efficiency…). Antenna radiation parameters are deeply changing as the number of EBG structures is increasing. In our case, ta make a compromise between all different parameters (Gain, bandwidth, directivity…), the best required EBG structures are limited to one layer. Either, the gain is increasing first when thickness increases from 0.8 mm to 1.6 mm and then decreased if the thickness is above 1.6 mm for the Cross-Slot Loaded Compact Circularly Polarized EBG Patch antenna. The same behavior is observed for the case of radiation efficiency, peak gain, and peak directivity.

Globally, we observe that the stability in the performance characteristics for the proposed Cross-Slot Loaded Compact Circularly Polarized EBG Patch antenna is showing better results compared to the same patch antenna without these EBG structures. The gain and directivity at C-band are enhanced from 8.368 dB and 8.528 dBi to 22.6 dB and 22.6 dBi without much affecting the operating bandwidth at C-band. Further enhancement of gain and directivity at the C-band does not affect the nature of broadside radiation characteristics.

REFERENCES

[1] A. K. Singh, M. P. Abegaonkar, and S. K. Koul, "High-gain and high-aperture-efficiency cavity resonator antenna using metamaterial superstrate," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2388-2391, 2017.

[2] M. J. Al-Hasan, T. A. Denidni, and A. R. Sebak, "Millimeter-wave compact EBG structure for mutual coupling reduction applications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 2, pp. 823-828, 2015.

[3] E. A. Hajlaoui, "New triple band electromagnetic band gap microstrip patch antenna with two shaped parasitic elements," *J. Comput. Electron.*, vol. 17, no. 1, pp. 452-457, 2018.

[4] E. Yassini, A. Aguni, L. Ibnyaich, S. Chabaa, and S. Zeroual, "A design of circular patch antenna with a high gain by using a novel artificial planar dual-layer metamaterial superstrate," *Int. J. RF Microw. Comput. Aided Eng.*, vol. 29, no. 11, 2019.

[5] S. S. Pawar, M. Shandilya, and V. Chaurasia, "Parametric evaluation of microstrip log periodic dipole array antenna using transmission line equivalent circuit," *Engineering Science and Technology an International Journal*, vol. 20, no. 4, pp. 1260-1274, 2017.

[6] L. Sun, G.-X. Zhang, and B.-H. Sun, "Slim planar composite antenna with two orthogonal polarizations for WLAN router applications," *Electronics Letters*, vol. 51, no. 18, pp. 1392-1394, 2015.

[7] T.-N. Chang, J.-M. Lin, and Y. G. Chen, "A circularly polarized ring-antenna fed by a serially coupled square slot-ring," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 1132-1135, 2012.

[8] Z. N. Chen and K.-M. Luk, *Antennas for Base Stations in Wireless Communications*, McGraw-Hill, New York, 2009.

[9] K. F.Lee and W. Chen, *Advances in Microstrip and Printed Antennas*, Wiley, New York, 1997.

[10] D. M. Pozar and D. H. Schaubert, *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*, Wiley, New York, 1995.

[11] R. Sauleau, "Fabry Perot resonators," *Encyclopedia of RF and Microwave Engineering*, vol. 2, pp. 1381-1401, 2005.

[12] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed., Wiley, New York, 2016.

El Amjed Hajlaoui received the M.Sc. degrees in Communications Systems from ELManar University-National Engineering School Tunis, Tunisia, the Ph.D degree in Electrical Engineering in 2009. His research interests the analysis and design of microwave circuits for use in communications, radar antenna topics, including design and measurement techniques.

Ziyad M. Almohaimeed received the M.Sc. and Ph.D degrees in Electrical and Computer Engineering from University of Victoria, Canada in 2013 and 2017, respectively. His research interests the design and optimization of electronic circuits and frequency dependence of their electrical parameters, including design and measurement techniques.