A compact multiband antenna based on metamaterial for L-band, WiMax, C-band, X-band, and Ku-band applications

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ABSTRACT

A novel multiband metamaterial (MTM) unit cell antenna loaded with split ring resonator (SRR) slots that resonates at seven bands, which are (1.91 GHz), (3.6 GHz), (6.25 GHz), and (8.69 GHz, 9.69 GHz, 10.70 GHz), and 12.33 GHz of the spectrum, making it suitable for L-band, worldwide interoperability for microwave access (WiMax), C-band, X-band downlink, and Ku-band applications, respectively, is proposed and discussed in this work. The proposed antenna has a very compact size of 14×15×1.6 mm^3 with an FR4 substrate. The simulation results show that the presented antenna attains a reflection coefficient of less than -10 dB (S11 -10 dB) and a radiation pattern across all operating bands. In addition, the suggested antenna provides good gains over the resonant frequency signals with an average of 6.75 db. The antenna simulations and parametric studies have been done using both computer simulation technology microwave studio (CST microwave studio) and high frequency structure simulator (HFSS) to confirm the obtained simulation results.

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1. INTRODUCTION

Nowadays, designing multiband antennas [1]–[3] is more demanding in wireless communication systems due to its multiple characteristics, but implementing these applications remains a major challenge for many researchers. In order to improve their characteristics, several methods can be applied, including the use of metamaterials (MTMs) [4], [5] that have piqued the interest of many researchers [6], [7]. Because of their advantageous properties, such as multi-band operation [8], [9]. Furthermore, they used to enhance the radiation characteristics [10], [11]. Moreover, MTMs are made up of unit cells [12] that are arranged in a regular pattern [13]. They exhibit various properties that are not available or not easily obtainable in nature. However, it is possible to construct it by modifying the material's permittivity and/or permeability properties [14].

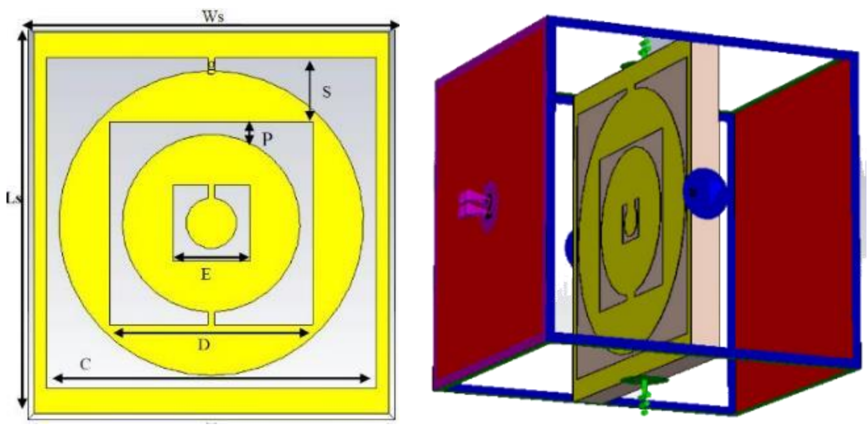
Different structures are used to create various types of MTMs which are split ring resonator (SRR) [15], [16] and the complementary split ring resonator (CSRR) [17]–[19]. There is a lot of research that has been published in the open literature which shows that these structures have also been used to obtain good performances [20], multiband in [21], [22]. Using CSRR to achieve a high gain in [23].

In this work, we propose the design of a MTM unit cell by using a complementary SRRs structure which covers seven frequency bands: L-band (1.91 GHz), worldwide interoperability for microwave access (WiMax) (3.6 GHz), C-band (6.25 GHz), X-band (8.69 GHz, 9.69 GHz, and 10.7 GHz), and Ku-band (12.33 GHz).

The proposed design has a relatively high gain of were -21.53 dB, -17.27 dB, -29.98 dB, -39.5 dB, -24.67 dB, -24.59 dB, and -22.44 dB respectively, and for the other parameters we will see them in the following sections. Computer simulation technology (CST) microwave is used to analyze the proposed antenna and optimize its geometrical parameters. and to confirm the obtained results we used Ansoft high frequency structure simulator (HFSS).

2. ANTENNA DESIGN AND CONFIGURATION

The design of the multiband frequencies unit cell MTM is illustrated in Figure 1(a). This MTM structure has been designed using FR-4 substrate with a thickness of 1.6 mm and a relative permittivity of 4.4. The top layer of this unit cell is comprised of a CSRR, which plays a crucial role in generating multiple resonance frequencies. The CSRR is morphologically divided into three similar rings, each obtained by cutting a circular shape out of a square. These rings are constructed from copper material with a thickness of 0.035 mm, and they each feature a gap on one of their horizontal sides. The rings are separated by a distance of $S = 5$ mm. The boundary conditions for this design involve perfect electric conductor (PEC) and perfect magnetic conductor (PMC) applied simultaneously along the Y and X axes, as indicated in Figure 1(b). Various design iterations and views have been considered to optimize the performance of the MTM unit cell, as depicted in Figure 2. Additionally, open boundary conditions are defined at the input and output ports along the Z axis. For a detailed overview of the structure's parameters, please refer to Table 1.



(a) (b)

Figure 1. The geometry of the proposed unit cell MTM: (a) front view and (b) the waveguide medium setup

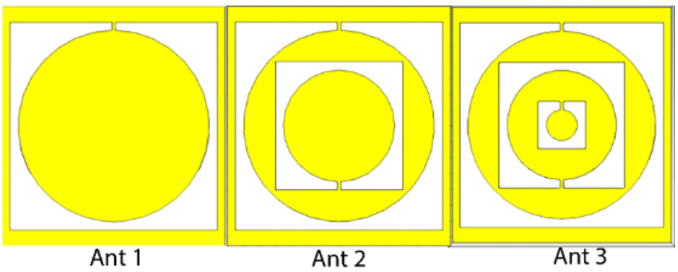


Figure 2. The steps of designing a structure proposed

Table 1. The parameters details of the structure

Parameter	Value (mm)	Parameter	Value (mm)
Ls	15	C	13
E	3	S	5
Ws	14	D	8
P	0.5	G	0.25

3. RESULTS AND DISCUSSION

To assess the unit cell's performance, we conducted simulations using CST software. We present the outcomes for the proposed MTM unit cell.

3.1. Coefficient reflection

Figure 3(a) depicts the simulated results of the coefficient reflection parameters. It can be observed that the unit cell is resonating at seven frequencies, which are suitable for L-band (1.91 GHz), WiMax (3.6 GHz), C-band (6.25 GHz), X-band (8.69 GHz, 9.69 GHz, and 10.7 GHz) and Ku-band (12.33 GHz) applications. The optimized reflection coefficients magnitudes were -21.53 dB, -17.27 dB, -29.98 dB, -39.5 dB, -24.67 dB, -24.59 dB, and -22.44dB respectively.

Concerning the S11 parameters for various structures shown in Figure 3(b). As we can see, the results of ant 1 indicate that the MTM unit cell operates in a quintuple band with resonant frequencies of around 2, 6.31, 8.69, 9.69, and 12.28 GHz. By adding the second SRR the Ant 2 almost covers the same bands of ant 1 and the two others appear which is 3.6 GHz and 10.7 GHz. When the third SRR introduced the Ant 3 (proposed) and Ant 2 are similar to but slightly different at level of the values of the reflection coefficients, gain.

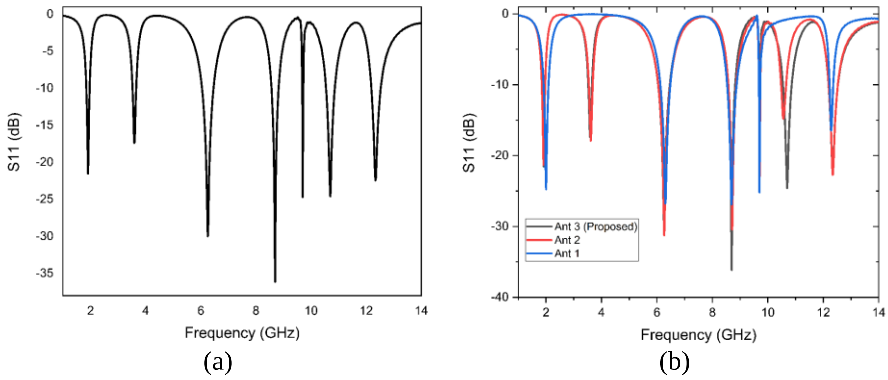


Figure 3. Unit cell reflection coefficient: (a) proposed and (b) various structures

3.2. Gain (IEEE) and radiation pattern

The Figure 4 shows that the MTM unit cell has a positive gain across all bands except the lower band which is 1.91 GHz, with a maximum gain of 13.22 dBi at 12.33 GHz. Figures 5(a)–(g) illustrate the simulated E-plane and H-plane radiation patterns in a two-dimensional (2D) geometric plane at specific frequencies: (a) 1.91 GHz, (b) 3.6 GHz, (c) 6.25 GHz, (d) 8.69 GHz, (e) 9.69 GHz, (f) 10.7 GHz, and (g) 12.33 GHz. These results highlight that the proposed MTM unit cell achieves an omnidirectional radiation pattern in the E-plane and maintains an acceptable bidirectional radiation pattern in the H-plane across all frequencies. The co-polarization pattern of the antenna remains stable, broadside, and directive, showing remarkable similarity.

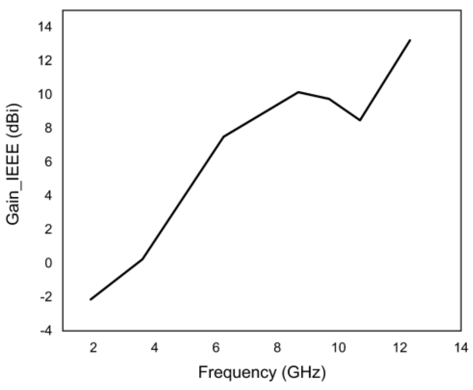


Figure 4. The characteristics of gain exhibited by the proposed antenna

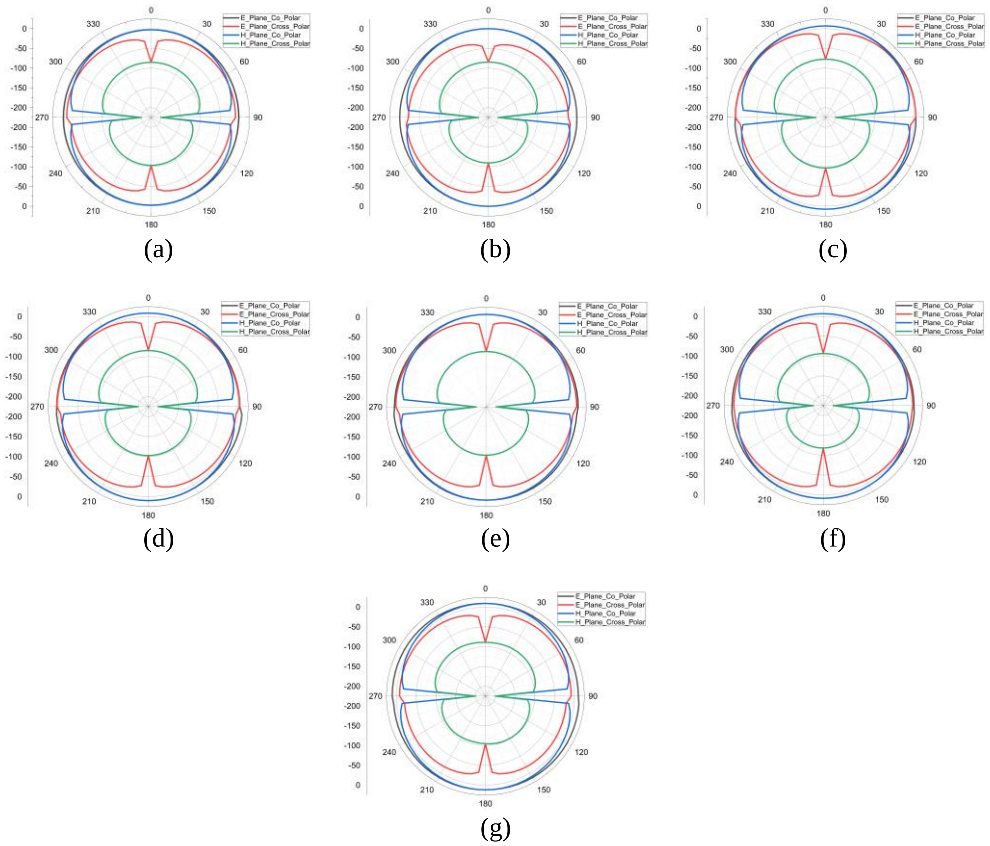


Figure 5. E-plane and H-plane radiation patterns: (a) 1.91 GHz, (b) 3.6 GHz, (c) 6.25 GHz, (d) 8.69 GHz, (e) 9.69 GHz, (f) 10.7 GHz, and (g) 12.33 GHz

3.3. Surface current density

In this section, the current distribution is studied and explained to provide an idea of the physical behavior of a radiated design. While in Figure 6(a), it can be seen that the current surface can be found in the gap of the first SRR as well as in these borders. Referring to Figure 6(b) at the 3.6 GHz resonance, it is apparent that the current density is concentrated more on the middle SRR, especially along the low sides where the gap is located. This implies that this SRR is responsible for the appearance of this band, suitable for WiMax application. Moving on to Figure 6(c), 6.25 GHz is observed as a resonant frequency with the current surface within the gap and borders of the first SRR. This makes it suitable for C-band applications. Figure 6(d) exhibits a resonant frequency of 8.69 GHz with the current surface found within the gap and borders of the first SRR. This resonance is suitable for X-band applications. Figure 6(e) demonstrates a resonant frequency of 9.69 GHz with the current surface within the gap and borders of the first SRR. This makes it suitable for X-band applications. Figure 6(f) shows a new resonant frequency of 10.7 GHz, resulting from the concentration of the current surface in the second and third SRRs of the unit cell. This creates a new resonance suitable for X-band. Lastly, Figure 6(g) presents a resonant frequency of 12.33 GHz, with the current surface within the gap and borders of the first SRR. This resonance is suitable for Ku-band applications.

3.4. Effect of varying the MTM unit cell dimension

The Figure 7(a) shows the curves of the reflection coefficient of different values of the length of the unit cell Ls as a function of frequency. On this graph we can see that the resonance frequencies below 8 GHz are almost unchanged, but the others are shifted to the right when we decrease the length Ls from 15 mm to 14 mm by a step of 0.5 mm and also, we allow to eliminate the fifth resonance frequency which is 9.69 GHz. So, on the other hand when we change the value of the width Ws as shown in Figure 7(b), we find out that the dimension Ws doesn't have a great influence on the results, but there is a small advantage to the value $Ws = 14$ mm.

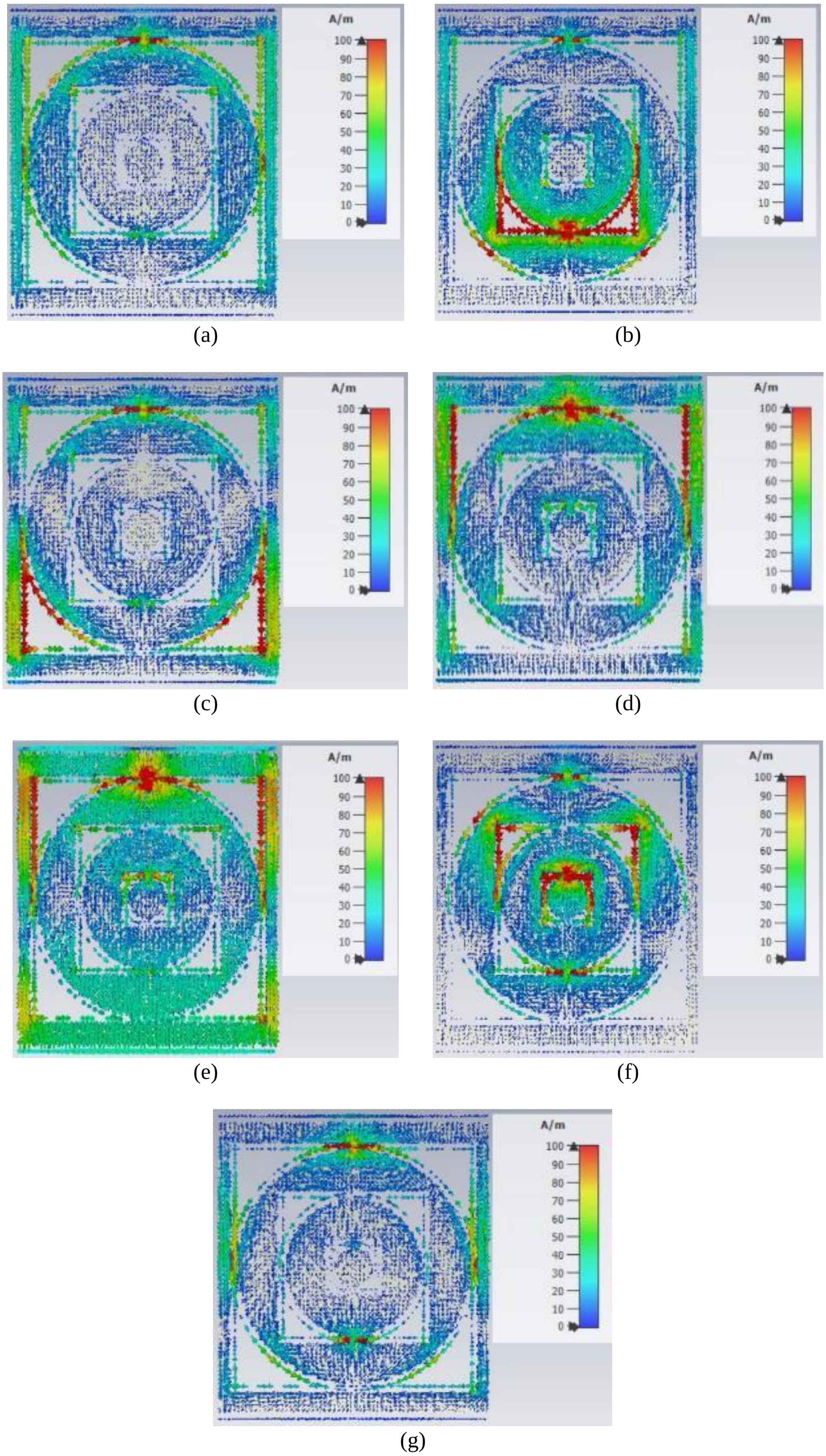
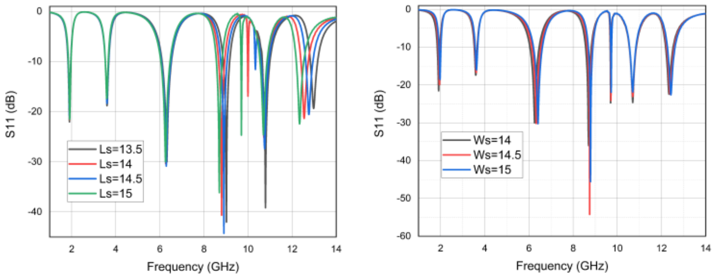


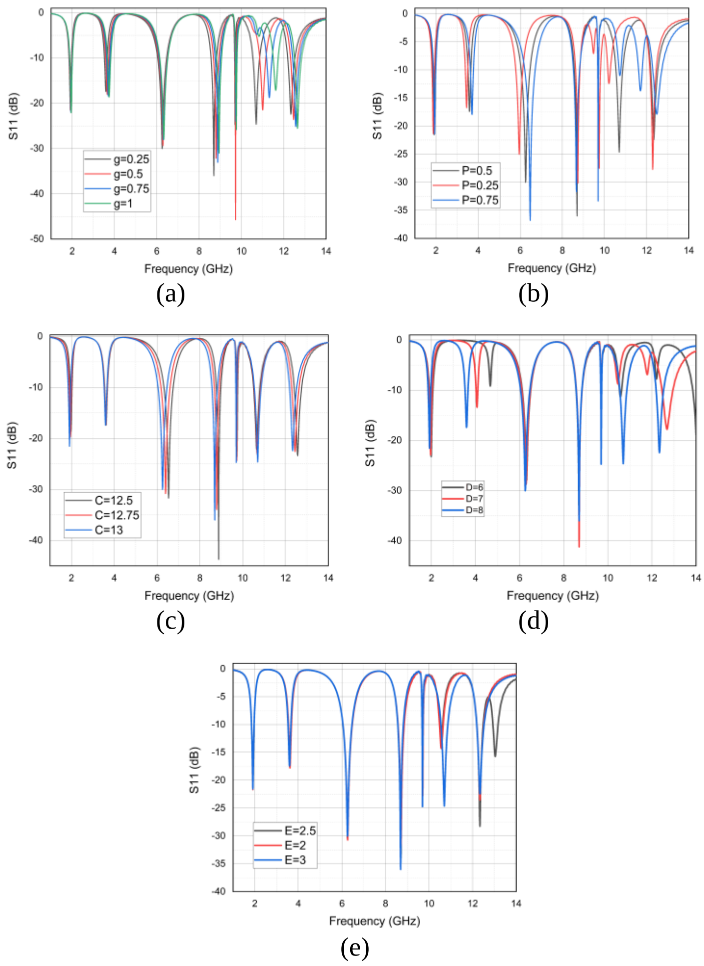
Figure 6. Current surface of the MTM unit cell proposed: (a) 1.91 GHz, (b) 3.6 GHz, (c) 6.25 GHz, (d) 8.69 GHz, (e) 9.69 GHz, (f) 10.7 GHz, and (g) 12.33 GHz

To investigate the effect of the gap g of each SRR we have changed it from 0.25 mm to 1 mm by a step of 0.25, see Figure 8(a). These results show that the increase in the g value serves to shift all frequencies to the right, furthermore serving to eliminate the sixth band, which is 10.7 GHz. Concerning the effect of the value P which represents the distance between the square and circle as depicted in the Figure 8(b). We can see that the case of $P = 0.5$ mm is the most suitable than the others. For the effect of the other dimensions C, D, and E, as shown in Figures 8(c)–(e), respectively, it can be seen that the decrease in the value of D allows us to eliminate the second and sixth resonance frequencies, which are 3.6 GHz and 10.7 GHz. As well as the results of the dimensions of C and E reaching the best results when we choose $C = 14$ mm and $E = 3$ mm, we also see the appearance of the eighth frequency of resonance in the case where $E = 2.5$ mm, but it is very weak compared to the other cases.



(a) (b)

Figure 7. S-parameters for various values of: (a) Ls and (b) Ws



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

Figure 8. S-parameters for various values of: (a) g, (b) P, (c) C, (d) D, and (e) E

3.5. Simulation results comparison

To validate the results, the proposed structure was simulated using the HFSS simulator. The Figure 9 compares these two simulators in terms of the reflection coefficient. As a result of the comparison, it is clear that the simulated results are in good agreement.

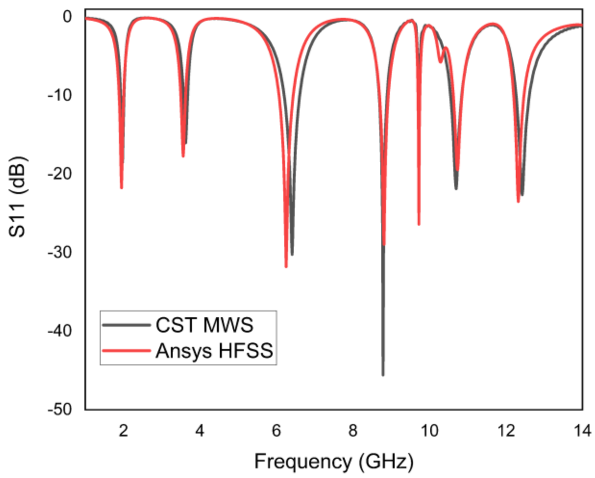


Figure 9. Comparison between the return loss obtained by both HFSS and CST software

3.6. A comparison between recently examined structures

Table 2 lists the study's parameters along with antennas found in the literature. The proposed MTM antenna demonstrates good impedance matching and satisfactory gain across a broad range of frequency band characteristics.

Table 2. Comparison between recently investigated structures

Ant	Fr. bands	Technique used	Applications	Avg gain (dB)
Ref. [8]	6	Fractal and resonator MTM	Bluetooth/wireless local area network (WLAN)/WiMax/ X-band	3.5
Ref. [4]	4	CRLH	WLAN/WiMax	2.8
Ref. [24]	3	SRR	WLAN/WiMax	3.34
Ref. [9]	3	SRR	WiMAX/WLAN/radio-frequency identification (RFID)	1
Ref. [15]	1	SRR	C-band	Not defined
Ref. [25]	3	CSRR	WLAN/WiMax/X-band	2
Ref. [19]	2	CSRR	WLAN/WiMax	Not defined
Ref. [1]	3	SRR	WLAN/WiMax/wireles access in the vehicular environment (WAVE)	Not defined
Ref. [22]	1	SRR	WLAN/Bluetooth/WiMax	Not defined
Ref. [16]	1	SRR	Ku band	Not defined
This work	7	CSRR	L-band/WiMax/C-band/X-band/Ku-band	6.75

4. CONCLUSION

In this work, a novel multiband MTM unit cell design is presented. The key element of this design is the incorporation of a CSRR, a component known for its unique electromagnetic properties. The MTM unit cell is engineered to resonate at seven distinct frequencies, showcasing a multiband behavior. These resonance frequencies span a broad spectrum from 1 to 14 GHz, making the MTM unit cell suitable for a wide range of applications requiring multiband antenna functionalities.

REFERENCES

[1] X. Pan, M. Li, S. Wang, Y. Zhou, C. Shen, and X. Li, "A compact multiband antenna based on metamaterial for WLAN/WiMAX/WAVE applications," in *2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP)*, Oct. 2017, pp. 1–3, doi: 10.1109/APCAP.2017.8420481.

[2] A. Boutejdar and B. I. Halim, "Design of Multiband Microstrip Antenna Using Two Parasitic Ring Resonators for WLAN/WiMAX and C/X/Ku-Band Applications," in *2019 IEEE International Electromagnetics and Antenna Conference (IEMANTENNA)*, Oct. 2019, pp. 046–050, doi: 10.1109/IEMANTENNA.2019.8928814.

[3] P. M. Paul, K. Kandasamy, and M. Sharawi, “SRR loaded slot antenna for multiband applications,” in *2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, Jul. 2017, pp. 2529–2530, doi: 10.1109/APUSNCURSINRSM.2017.8073307.

[4] N. Pouyanfar, J. Nourinia, C. Ghobadi, and K. Pedram, “A Compact Multiband Metamaterial-Based Antenna for WLAN and WiMAX Applications,” in *2019 5th Conference on Knowledge Based Engineering and Innovation (KBEI)*, Feb. 2019, pp. 250–255, doi: 10.1109/KBEI.2019.8734989.

[5] I. Aggarwal, M. R. Tripathy, and S. Pandey, “A Multiband Uniplanar Left Handed Metamaterial Unit Cell,” in *2018 2nd International Conference on Micro-Electronics and Telecommunication Engineering (ICMETE)*, Sep. 2018, pp. 292–294, doi: 10.1109/ICMETE.2018.00070.

[6] M. F. A. Sree, A. M. M. A. Allam, and H. A. Mohamed, “Design and Implementation of Multiband Metamaterial Antennas,” in *2020 International Applied Computational Electromagnetics Society Symposium (ACES)*, Jul. 2020, pp. 1–2, doi: 10.23919/ACES49320.2020.9196150.

[7] A. K. Singh and A. Raman, “Multiband Microstrip Patch Antenna Design for 5G Using Metamaterial Structure,” in *2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI)*, May 2018, pp. 909–914, doi: 10.1109/ICOEI.2018.8553773.

[8] M. Elhabchi, M. N. Srifi, and R. Touahni, “A Fractal Metamaterial Antenna for Bluetooth, WLAN, WiMAX and X-band Applications,” in *2020 International Conference on Intelligent Systems and Computer Vision (ISCV)*, Jun. 2020, pp. 1–5, doi: 10.1109/ISCV49265.2020.9204208.

[9] N. V. Rajasekhar and D. Sriramkumar, “A triple band compact asymmetric monopole-SRR based antenna for Wi-Max, WLAN and RFID applications,” in *2015 International Conference on Microwave, Optical and Communication Engineering (ICMOCE)*, Dec. 2015, pp. 96–99, doi: 10.1109/ICMOCE.2015.7489699.

[10] N. Sharma, R. P. S. Gangwar, and A. K. Arya, “Metamaterial Based Compact Super Wide Band Microstrip Antenna with DGS for Wireless Applications,” in *2018 International Conference on Advances in Computing, Communication Control and Networking (ICACCCN)*, Oct. 2018, pp. 1016–1021, doi: 10.1109/ICACCCN.2018.8748698.

[11] V. G. Sri, H. S. Shanoor, and S. Chilukuri, “A Wideband Dual-Band Metamaterial loaded antenna for Wireless Applications,” in *2018 IEEE Indian Conference on Antennas and Propogation (InCAP)*, Dec. 2018, pp. 1–5, doi: 10.1109/INCAP.2018.8770898.

[12] D. Pattar, P. Dongaokar, and N. S L, “Metamaterial for design of Compact Microstrip Patch Antenna,” in *2020 IEEE Bangalore Humanitarian Technology Conference (B-HTC)*, Oct. 2020, pp. 1–4, doi: 10.1109/B-HTC50970.2020.9297830.

[13] T. Ali, S. B.K., and R. C. Biradar, “Design and Analysis of Two Novel Metamaterial Unit Cell for Antenna Engineering,” in *2018 Second International Conference on Advances in Electronics, Computers and Communications (ICAECC)*, Feb. 2018, pp. 1–4, doi: 10.1109/ICAECC.2018.8479435.

[14] N. Abdullah, G. Bhardwaj, and Sunita, “Design of squared shape SRR metamaterial by using rectangular microstrip patch antenna at 2.85 GHz,” in *2017 4th International Conference on Signal Processing and Integrated Networks (SPIN)*, Feb. 2017, pp. 196–200, doi: 10.1109/SPIN.2017.8049943.

[15] M. Khombal, S. Bagchi, R. Harsh, and A. Chaudhari, “Metamaterial unit cell with negative Refractive Index at C band,” in *2018 2nd International Conference on Electronics, Materials Engineering & Nano-Technology (IEMENTech)*, May 2018, pp. 1–4, doi: 10.1109/IEMENTECH.2018.8465176.

[16] U. Farooq *et al.*, “Split Ring Resonator Based Metamaterial Absorber for Antenna Radar Cross Section Reduction Applications in Ku Band,” in *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, Jul. 2020, pp. 1283–1284, doi: 10.1109/IEEECONF35879.2020.9329704.

[17] A. F. Almutairi, M. S. Islam, M. Samsuzzaman, M. T. Islam, N. Misran, and M. T. Islam, “A complementary split ring resonator based metamaterial with effective medium ratio for C-band microwave applications,” *Results in Physics*, vol. 15, p. 102675, Dec. 2019, doi: 10.1016/j.rinp.2019.102675.

[18] S. P. J. Christydass and N. Gunavathi, “Design of CSRR loaded multiband slotted rectangular patch antenna,” in *2017 IEEE Applied Electromagnetics Conference (AEMC)*, Dec. 2017, pp. 1–2, doi: 10.1109/AEMC.2017.8325711.

[19] K. Yu, Y. Li, and Y. Wang, “Multi-band metamaterial-based microstrip antenna for WLAN and WiMAX applications,” in *2017 International Applied Computational Electromagnetics Society Symposium - Italy (ACES)*, Mar. 2017, pp. 1–2, doi: 10.23919/ROPACES.2017.7916032.

[20] L. Wen, S. Gao, Q. Yang, Q. Luo, X. Ren, and J. Wu, “A Compact Dual-Polarized Patch Antenna Loaded With Metamaterial Unit Cell for Broadband Wireless Communication,” in *2019 IEEE MTT-S International Wireless Symposium (IWS)*, May 2019, pp. 1–3, doi: 10.1109/IEEE-IWS.2019.8804152.

[21] V. Setia, K. K. Sharma, and S. Kishen Koul, “Triple-Band Metamaterial Inspired Microstrip Antenna using Split Ring Resonators for WLAN/WiMAX Applications,” in *2019 IEEE Indian Conference on Antennas and Propogation (InCAP)*, Dec. 2019, pp. 1–4, doi: 10.1109/InCAP47789.2019.9134602.

[22] S. Roy and U. Chakraborty, “Design of Dual Wideband Microstrip Antenna Loaded with SRR Metamaterial,” in *2017 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC)*, Dec. 2017, pp. 1–3, doi: 10.1109/ICCIC.2017.8524279.

[23] E. K. I. Hamad and M. Z. M. Hamdalla, “Design of a Compact Dual-Band Microstrip Antenna Enabled by Complementary Split Ring Resonators for X-Band Applications,” *Advanced Electromagnetics*, vol. 7, no. 3, pp. 82–86, Aug. 2018, doi: 10.7716/aem.v7i3.766.

[24] M. Ameen, R. Kumar, N. Mishra, and R. K. Chaudhary, “A compact triple band dual polarized metamaterial antenna loaded with double hexagonal SRR for WLAN/WiMAX applications,” in *2017 IEEE International Conference on Antenna Innovations & Modern Technologies for Ground, Aircraft and Satellite Applications (iAIM)*, Nov. 2017, pp. 1–4, doi: 10.1109/IAIM.2017.8402518.

[25] K. Ashish, D. Yeshaswini, B. K. Subhash, T. Ali, and R. C. Biradar, “A Metamaterial based Multiband Frequency Reconfigurable Antenna for Wireless Applications,” in *2018 Second International Conference on Advances in Electronics, Computers and Communications (ICAECC)*, Feb. 2018, pp. 1–6, doi: 10.1109/ICAECC.2018.8479498.

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