Analysis and Design of Metamaterial Antenna using the Theory of Characteristic Modes

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***Abstract*—In this paper, a Metamaterial unit cell is proposed for microwave applications. The structure is made up of an outer ring with four capacitive loads and two inside parts perpendicularly connected with a square in the center. A set of unit cells are associated with the bowtie antenna to improve their performances using the Theroy of Characteristic Modes. By adding the Metamaterial, the antenna performances are improved, such as the gain which increased by 3 dB, and the bandwidth that can reach 49 %.**

***Index Terms*—Antenna, Characteristic Mode Analysis (CMA), Metamaterial (MTM).**

I. Introduction

Metamaterials have become more and more popular in telecommunications fields in recent years. There are artificial electromagnetic materials with negative permeability, permittivity, and refractive index. Veselago created the MTM in 1968, proposing the possibility of having negative permittivity and negative permeability in materials [1], and in 2001, Smith completed the experimental confirmation of Negative Refraction [2]. Metamaterials are used to improve the performance of antennas, such as efficiency improvement [3], gain enhancement [4], and antenna miniaturization [5].

Antenna structures are often designed using 3D simulators. The problem with these simulators is that they don't provide a complete physics understanding of the structure's radiation. The physical understanding of the antenna's radiation mechanism can be simply investigated using CMA. It goes into great detail about the resonating frequency of specific modes, as well as radiation patterns and mode currents. Garbacz proposed the CMA in 1971 [6], and Harrington improved existing applications and suggested a simpler technique derivation [7]. The CMA can be found in a variety of applications, including MIMO applications [8] and antenna size reduction [9].

This paper will be divided as follows; Section 2 and Section 3 will present, respectively, the Metamaterial unit cell the MTM antenna analysis and design. Section 4 will illustrate the results of the simulations. After then, there will be a conclusion to the work.

II. Proposed Metamaterial Unit Cell

Fig. 1. presents the proposed Metamaterial unit cell, which is an evolved version of Split Ring Resonator used in [10].

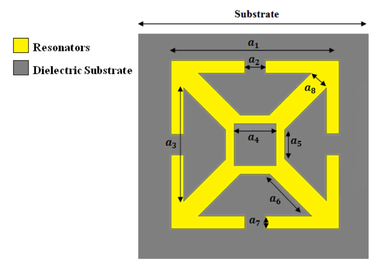

Fig. 1. MTM Geometry: Front View

The MTM produces a high capacity load thanks to the close spacing between the elements and gives a high inductive load due to their small thickness, and by that, the bandwidth of the antenna can be improved. We choose the Rogers RO4232 (TM) with a permittivity of 3.2 and a thickness of 1.5748 mm as a substrate. Table. 1 contains a list of all of the parameters. The MTM parameters dimensions are chosen in such a way that makes the MTM resonates at 28 GHz.

TABLE I
Metamaterial parameters

Parameters	Dimension (mm)
Substrate	3
a_1	2
a_2	0.25
a_3	1.34
a_4	0.5
a_5	0.34
a_6	0.5
a_7	0.15
a_8	0.18

Fig. 2 presents the S parameter of the MTM unit cell. While Fig. 3 and Fig. 4 illustrate, respectively, the permeability and the permittivity of the MTM. We notice from Fig. 2 that the MTM resonates at 28 GHz with a bandwidth of 12%. The MTM parameters are extracted using MATLAB. Both the permeability and permittivity are negative between 27 and 29 GHz. This is consistent with the transmission region determined by the magnitude of the S parameter, which verifies that the structure is indeed a MTM .

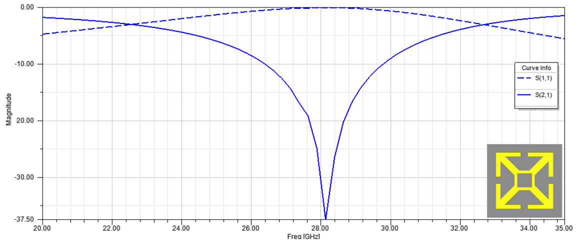

Fig. 2. The S parameter Magnitude of MTM.

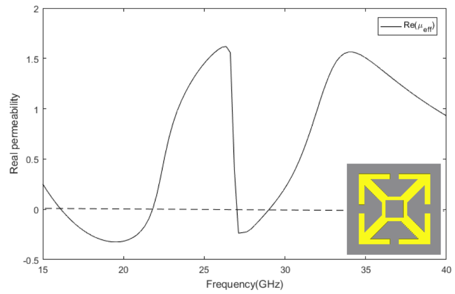

Fig. 3. The real values of MTM permeability.

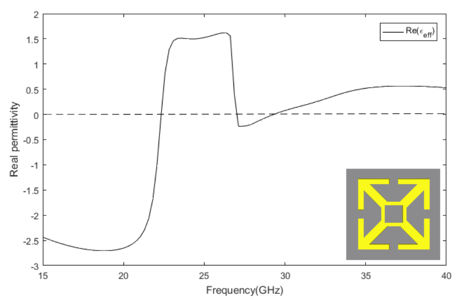

Fig. 4. The real values of MTM permittivity

Fig. 5 shows the equivalent circuit of the MTM unit cell extracted using the AWR simulator. The component values are chosen so that the MTM works with the resonant frequency as follows; inductors of 0.559 nH, capacitances of 0.0298 pF, and resistances of 6.76 ohm.

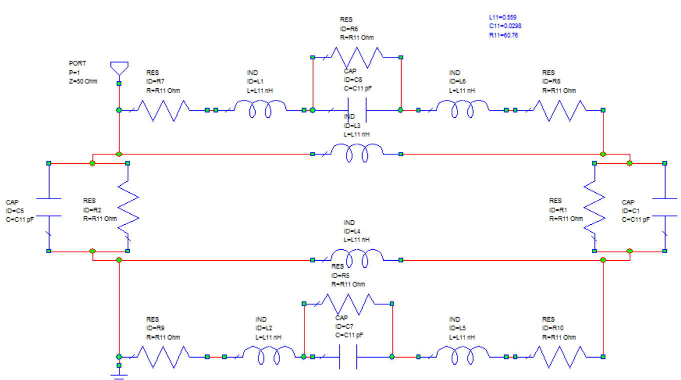

Fig. 5. Equivalent Circuit of the MTM Unit Cell.

III. Modelization of Metamaterial Based Antenna

A. Antenna without Metamaterial

1) Antenna Analysis: The CMA anlaysis is done with the commercial solver FEKO. We examined the antenna with CMA to know where to place exactly the MTM unit cell to ameliorate the gain and the bandwidth without influencing the antenna propagation. Fig. 6 and Fig. 7 show, respectively, the Modal Significance and the Current Distribution of the bowtie antenna.

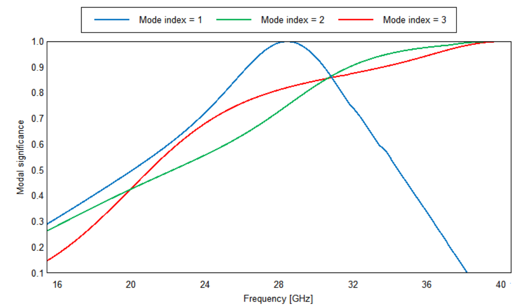

Fig. 6. Modal Significance of modes 1–2 of the bowtie antenna.

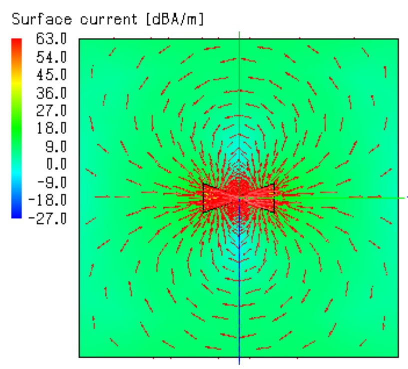

Fig. 7. Current Distribution of mode 1 of the bowtie antenna.

We notice from Fig. 6 that only Mode 1 contributes in the band of interest at 28 GHz (MS =1 at 28 GHz), and that Mode 2 and Mode 3 start contributing after 40 GHz. Thus Modes 2 and 3 will not be taken into consideration in the further work. We observe from Fig. 7 that Mode 1 has a double rotational mode with high loads concentrated in the middle of the antenna, while it is weak on the sides of the substrate, which allows us to add MTM unit cells to enhance the antenna performance without influencing its propagation.

2) Antenna Design: Fig. 8 shows the chosen bowtie antenna geometry and Table. 2 lists the antenna dimensions.The antenna parameter dimensions are chosen in such a way the bowtie resonates at 28 GHz. The reflection coefficient S(1,1) of the bowtie antenna created with ANSYS-HFSS is shown in Fig. 9. The antenna has a bandwidth of 25.32 % and resonates at 28 GHz (-36 dB).

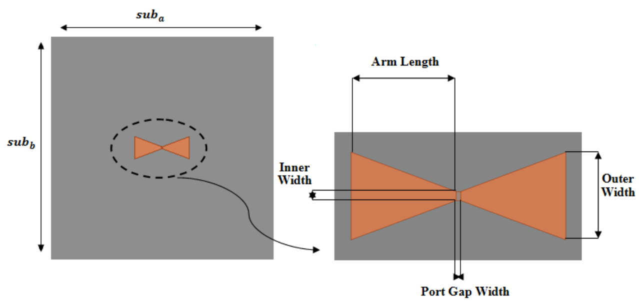

Fig. 8. Bowtie antenna Geometry

TABLE II
BOWTIE PARAMETERS

Parameters	**Dimensions (mm)**
Sub_a	10.5
Sub_b	10.5
Arm length	1.175
Outer Width	0.98
Inner Width	0.1
Port Gap Width	0.01

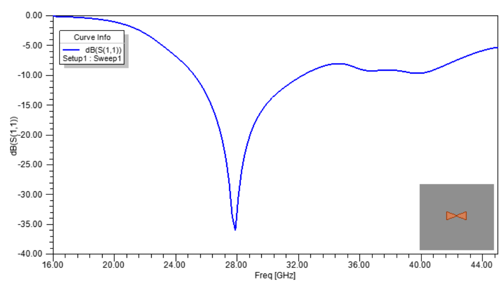

Fig. 9. The reflection coefficient S(1,1) of the antenna

B. Antenna with Metamaterial

1) MTM Antenna Analysis: Now we analyze the Antenna including MTM unit cells, to enhance gain and bandwidth. Fig. 10 presents the Modal Significance of the bowtie based on MTMs.

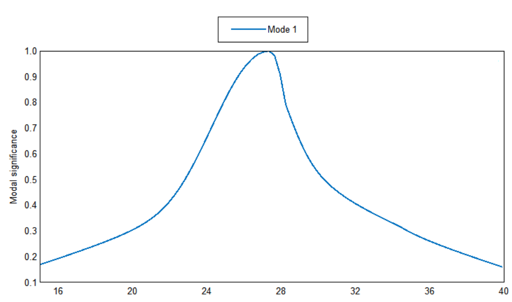

Fig. 10. Modal Significance of mode 1 of the MTM antenna.

As shown in Modal Significance curve, the antenna resonates efficiently at 28 GHz even with the addition of MTM unit cells. We added the MTM unit cells on the sides of antenna substrate to add a capacitve loads (due to the slots of the MTMs) to enhance the gain, and to add an inductive loads (due to the coupling between the MTMs) to improve the bandwidth. Fig. 11 illustrates the current distributions vectors of the antenna and the MTM unit cells.

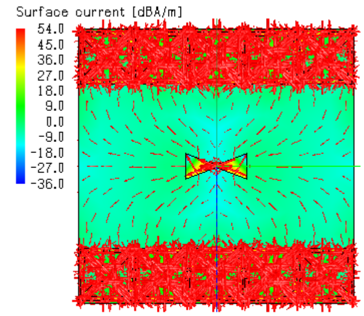

Fig. 11. Current Distribution of mode 1 of the MTM antenna.

We notice that the vectors save the same double rotational mode as the antenna without MTM, and the antenna propagates efficiently by adding the MTM on the substrate sides.

2) MTM Antenna Design: Metamaterials are mounted with the antenna, on the same substrate, as shown in Fig. 12. The distance between the elements is $d_1 = d_2 = 2.7mm$ and $d_3 = d_4 = 0.1mm$.

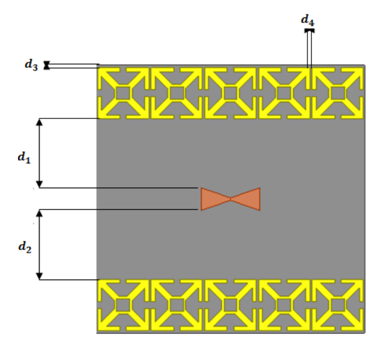

Fig. 12. Geometry of Metamaterial Antenna with High Frequency Structure Simulator, ANSYS-HFSS: Front View.

The reflection coefficient S(1,1) of the antenna with MTM is presented in Fig. 13. The antenna resonates at 28 GHz (-33 dB) with a bandwidth of 44.78%.

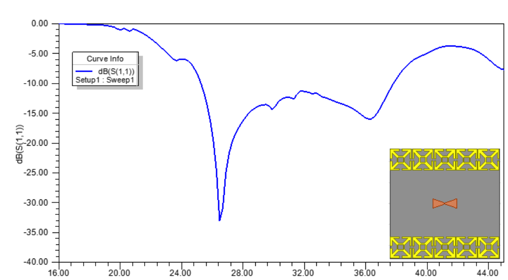

Fig. 13. The reflection coefficient S(1,1) of MTM Bowtie antenna

IV. Results and Discussion

The reflection coefficient S(1,1) and the gain of antennas with and without MTM are depicted in Fig. 14 and Fig. 15, respectively. The adding of MTMs improves the bandwidth, which can reach 45% compared to 25% for the antenna without MTMs. We notice from Fig. 15 that the gain ranges from 5.92 dB to 8.95 dB.

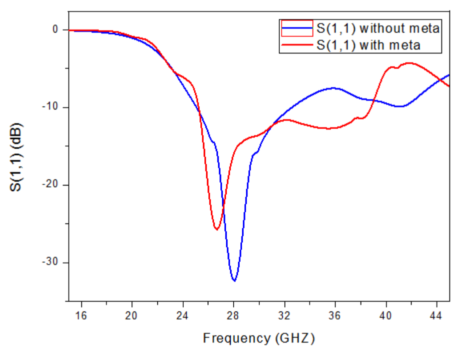

Fig. 14. The reflection coefficient S(1,1) of Bowtie antenna with and without Metamaterial.

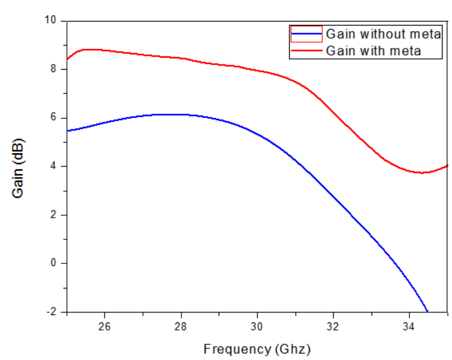

Fig. 15. Gain of Bowtie antenna with and without Metamaterials vs frequency.

Fig. 16 illustrates the radiation efficiency of the bowtie with and without MTM. We can notice here the improvement by adding the MTM on the band of interest.

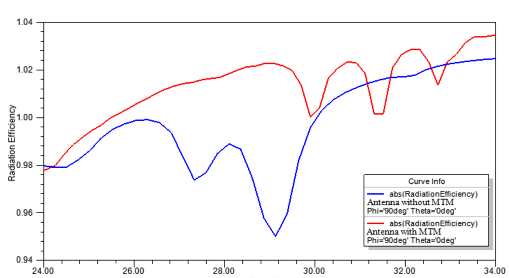

Fig. 16. Efficiency of Bowtie antenna with and without Metamaterials vs frequency.

Fig. 17 and Fig. 18 represent, respectively, the radiation pattern of the antenna with and without Metamaterial for E and H plane, depending on the total gain.

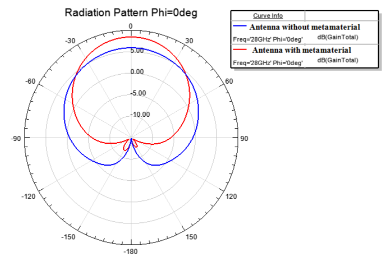

Fig. 17. Radiation pattern of the antenna with and without meta E plane.

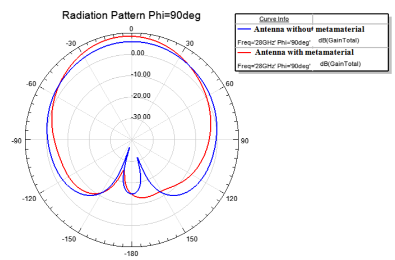

Fig. 18. Radiation pattern of the antenna with and without meta H plane.

Conclusion

In this paper a bowtie antenna based on Metamaterial was proposed for microwave applications. Characteristic Modes Analysis technique was used to analyze and design the structure. The adding of Metamaterial unit cells improved the gain and bandwidth of the bowtie antenna. The gain was enhanced from 6.25 dB to 8.65 dB and the bandwidth was extended from 25 % to 45 %.

References

[1] V. G. Veselago. The electrodynamics of substances with simultaneously negative values of and . *Phys. Usp.*, 10(4):509–514, 1968.

[2] RA Shelby, D R Smith, and S Schultz. Experimental verification of a negative index of refraction. *Science (New York, N.Y.)*, 292:77–79, 05 2001.

[3] KM Neeshu and Anjini Kumar Tiwary. Metamaterial loaded antenna with improved efficiency and gain for wideband application. *IETE Journal of Research*, 0(0):1–8, 2020.

[4] Imen Sansa, Abdelkhalek Nasri, and Hassen Zairi. A miniaturized metamaterial unit cell for 5g applications. In *IEEE 19th Mediterranean Microwave Symposium (MMS)*, pages 1–4, 2019.

[5] S. Ahdi Rezaeieh, Marco A. Antoniades, and Amin M. Abbosh. Miniaturization of planar yagi antennas using mu-negative metamaterial-loaded reflector. *IEEE Transactions on Antennas and Propagation*, 65(12):6827–6837, 2017.

[6] R. Garbacz and R. Turpin. A generalized expansion for radiated and scattered fields. *IEEE Transactions on Antennas and Propagation*, 19(3):348–358, 1971.

[7] R. Harrington and J. Mautz. Theory of characteristic modes for conducting bodies. *IEEE Transactions on Antennas and Propagation*, 19(5):622–628, 1971.

[8] Ali Araghi and Gholamreza Dadashzadeh. Oriented design of an antenna for mimo applications using theory of characteristic modes. *IEEE Antennas and Wireless Propagation Letters*, 11:1040–1043, 2012.

[9] Shizhe Zhao, Xiuping Li, Zihang Qi, and Yongxin Chen. A miniaturized microstrip patch antenna using characteristic mode analysis. In *International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, pages 1–3, 05 2021.

[10] Imen Sansa, Abdelkhalek Nasri, and Hassen Zairi. Metamaterial antenna analysis using wave concept iterative process. In *2021 International Symposium on Antennas and Propagation (ISAP)*, pages 1–2, 2021.