Multi-Band Metamaterial Absorber: Design, Experiment and Physical Interpretation

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Abstract **─** This paper presents the design, fabrication, characterization and experimental verification of a perfect Multi-Band Metamaterial (MTM) absorber (MA) based on a simple configuration of a rectangular resonator and strips operating in microwave frequency regime. The proposed multi-band MA provides perfect absorption with TE-incident angle independency. Maximum absorption rate is achieved as 99.43% at 5.19 GHz for simulation and 98.67% at 5.19 GHz for experiment, respectively. The measurement results of the fabricated prototype are in a good agreement with the numerical results. Furthermore, we introduce a numerical analysis in order to show physical interpretation of the MA mechanism in detail. Additionally, a sensor application of the proposed multi-band MA is presented to demonstrate an extra feature of the suggested structure. As a result, the proposed multi-band MA enables myriad potential application areas such as radar, stealth, shielding, communication, imaging and medical applications.

Index Terms – Absorber, metamaterial, microwave and multi-band.

I. INTRODUCTION

Since MTMs present unusual electric and magnetic features which are not commonly found in nature, such as negative refraction, MTM studies have gained a great attention in literature by the science community. In addition, these artificial materials have many potential applications like electromagnetic cloaking, filter, super lens, sensor, absorber and so on [1-7]. Moreover, because of their fabrication flexibility, MTMs can be artificially manufactured in desired frequency regimes of the electromagnetic spectrum from radio frequencies to optics [8-14].

Since MAs have wide potential application areas in these days, for example, radar and medical technologies; various MA studies have been proposed and realized in literature to achieve almost perfect absorption. There are some studies on MAs [15-20] such as bandwidth-enhanced microwave absorber [16], an extremely broad band absorber [18], tunable MA [19], a resonant microwave absorber based on a chiral MTM SRRs [20], etc. Unlike the conventional MA studies, this proposed model has several crucial advantages. One of them is to have properties of TE-incident angle independency for different angles. Another one is to exhibit a wide Fractional Bandwidth as (FBW) ≈ 4.62% at resonance frequency of 5.19 GHz. A third one is to have multi-band perfect absorption feature and the final one is that the suggested structure is very sensitive for sensor applications.

II.THEORETICAL ANALYSIS

Reflection and transmission waves have to be minimized ($R(\omega) \& T(\omega) \rightarrow 0$), in order to achieve a perfect absorption. The reason is that the absorption level of the MAs is calculated by: $A(\omega) = 1 - R(\omega) - T(\omega)$, where $A(\omega)$ is the absorption, $R(\omega) = |S_{11}|^2$ is the reflectance and $T(\omega) = |S_{21}|^2$ is the transmittance,

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correspondingly. To achieve perfect absorption with near-zero reflection, the effective permittivity and permeability should have the same value. If both incident electric and magnetic field responses can be properly tuned, it can provide perfect absorption. Moreover, to obtain perfect absorption, the reflection and transmission coefficients should be minimized by impedance matching at a certain resonance frequency range. In the resonance condition, the effective impedance can match to the free space impedance and therefore the reflection is minimized [15-17]. In this case, absorbed energy is constrained in the structure at the resonance frequency and this property of the proposed absorber can also be used on solar cell applications to improve their efficiency [21, 22].

III. SIMULATION AND EXPERIMENT

Proposed MA consists of a rectangular resonator, strips, a metal plate and a dielectric substrate. Top layer resonators and the bottom layer metal plate are separated by an FR4-substrate. While the resonators provide resonance at a certain resonance frequency regime, the metal plate provides zero transmission. Resonators and the metal layer are modeled as a copper sheet. It has electrical conductivity of 5.8×10^7 S/m and thickness of 0.035 mm. The thickness, loss tangent, relative permittivity and permeability values of the FR4 are 1.6, 0.02, 4.2 and 1 mm, respectively. Figure 1 (a) shows the dimensions of the resonators. Dimensions of the proposed model are tuned to increase the resonance and it can be seen that the gaps in the structure are created for this purpose. It is well known that at least one resonance (electric or magnetic) should be provided by the structure for the absorption. The magnetic resonance is generally provided by circulating and anti-parallel currents. The electric resonance is provided by the parallel currents. These resonances are directly related with dielectric thickness sandwiched between front and backside metallic layers. When the distance between the front and back side is increased, the mentioned resonances become weaker. Hence, the thickness of dielectric slab must be selected optimally to provide strong resonances. This issue is also mentioned in the following sections.

In addition, Fig. 1 (b) shows the MA sample fabricated by conventional printed circuit board techniques. The dimension of the sample contains 7x7 unit cells. The overall size of our sample is 70x55 mm^2. Designed MA structure is simulated by using a full-wave electromagnetic solver based on finite integration technique. The sample is then fabricated with PCB technique. To obtain experimental results, the reflection coefficient of the sample is measured by a Vector Network Analyzer (VNA) and two horn antennas, with the experimental setup shown in Fig. 1 (c). Firstly, free space measurement without the MNG structure is carried out and this measurement is used as the calibration data for the VNA. The structure is then inserted into the experimental measurement setup and *S*-parameter measurements are performed. Initially, the distance between the horn antennas and MTM sample is kept sufficiently large to eliminate near-field effects. The discrepancies between the experimental and simulation data as well as the minor noise in the data are imputed to fabrication tolerances related to the etching process and the dielectric dispersion of the substrate used. The misalignment during the experiment may also be considered as another source of error. In addition, the measurement results are normalized values with respect to the peak point to ignore undesired diffraction due to the limited array of the structure. The accuracy of the measurements can be clarified by the good agreement between the simulation and experimental results.

IV. NUMERICAL AND EXPERIMENTAL RESULTS

Simulated and measured reflection-absorption results are presented in Figs. 2 and 3, individually. It can be seen that the maximum absorption rate is 99.43% at 5.19 GHz for simulation and 98.67% at 5.19 GHz for experiment, respectively. In addition, we performed bandwidth calculations to show qualification of the proposed MA model. For this purpose, we carried out a Fractional Bandwidth (FBW) calculation of the negative region. FBW is the ratio between the bandwidth of the MA and the center frequency. It can be calculated as: FBW= $\Delta f / f_0$, where Δf is the half power bandwidth and f_0 is the center frequency. In this structure, these parameters are obtained as $\Delta f = 0.24$ GHz, $f_0 = 5.19$ GHz and FBW≈4.62%. Moreover, in order to show multi-band property of the suggested MA, we numerically analyzed the model for a high frequency range, as shown in Fig. 4. It can be seen that the designed resonators show perfect absorptions separately in various frequency points, in which they can be used for the places where multiband operations are needed.

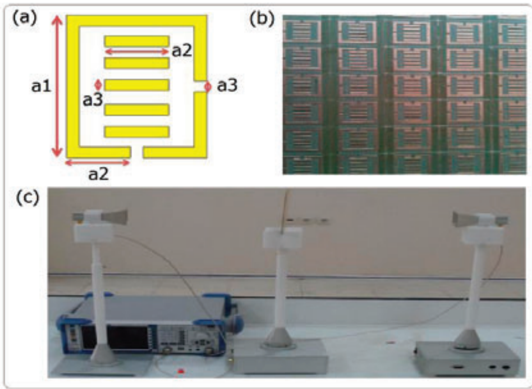

Fig. 1. Multi-band MA; (a) dimensions of the proposed structure with a1 = 13 mm, a2 = 5 mm and a3 = 2 mm, (b) a photograph of the front side of the fabricated sample and (c) a picture from the measurement setup.

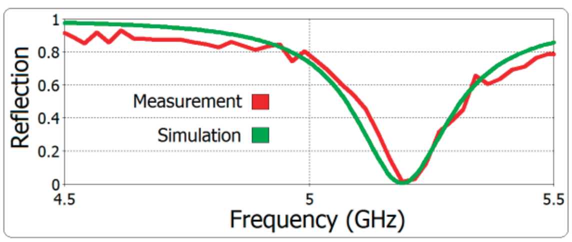

Fig. 2. Simulated and measured reflectivity of the MA as a function of frequency.

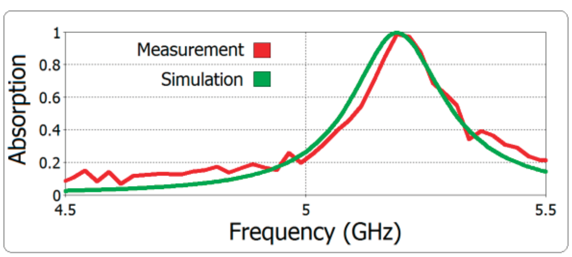

Fig. 3. Simulated and measured absorption of the MA as a function of frequency.

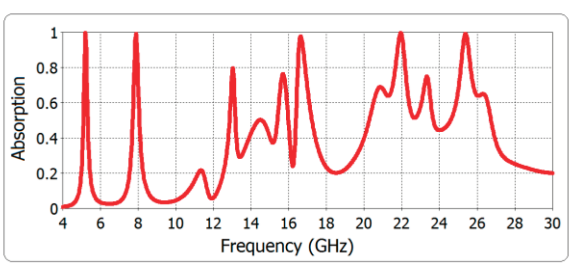

Fig. 4. Simulated absorption of the proposed multi-band MA.

Furthermore, the effects of TE-incident angle on multi-band MA are observed. For this purpose, TE-incident angle was rotated numerically from 0^0 to 90^0 with 15^0 steps, as shown in Fig. 5. The reference plane for the rotated angle is selected as the front face of the periodic structure. When the TE-incident angle is increased from 0^0 to 60^0, the absorption level also increases. Besides, when the value of polarization angle is 90^0, the absorption reaches the lowest level (85.56%). It means that the absorption slightly changes with TE-incident angles. However, all TE-incident angles show resonance at the same frequency level of 5.19 GHz. Note that similar observations are also scrutinized for TM polarization.

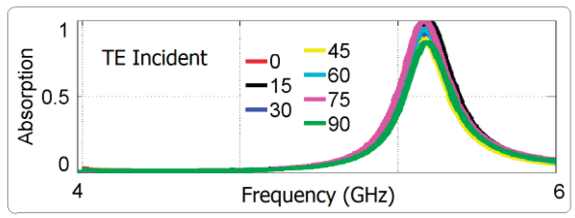

Fig. 5. Angular dependence of the absorption for TE incidence radiation.

We explored the electric field and surface current distributions to show the physical mechanism of the operation principle of the structure at the resonance frequency of 5.19 GHz (Figs. 6 and 7). A high density of the electric field around the rectangular resonator (except the gap area) and a low density around the strips inside are detected, as shown in Fig. 6. The electric field is strongly coupled on the rectangular resonator (except the gap area) and gives an electrical response at the resonance frequency. In addition, magnetic response due to surface charge inductions, leads also to have a magnetic resonance. As seen from the current distribution, parallel currents are responsible for the electric response; whereas the circulating and anti-parallel currents are related with the magnetic response. The configuration is designed as in the proposed form in order to have all mentioned current distributions (parallel, circulating and anti-parallel) for both electric and magnetic resonances together at the resonant frequency. It means that both electric and magnetic resonances occur at the resonance. These responses strongly couple with the electric and magnetic field components of the incident wave and produce strongly localized EM field at the resonance frequency. Hence, impedance matching condition is provided to confine the incident energy in the absorber that results in minimum reflection and maximum absorption.

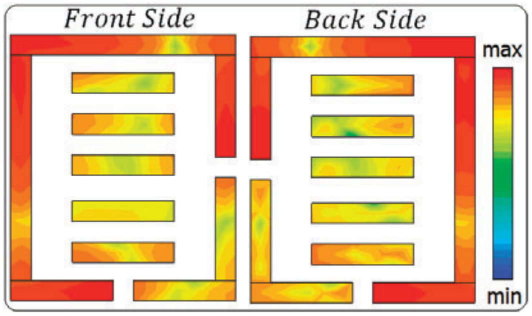

Fig. 6. Electric field distribution at the resonance frequency of 5.19 GHz.

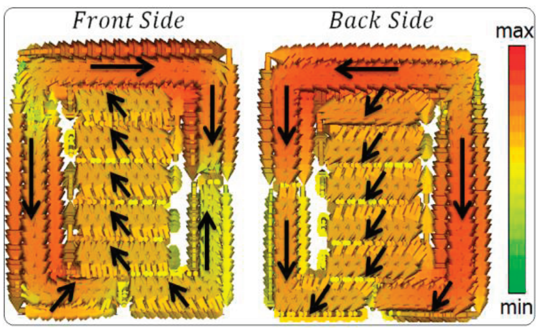

Fig. 7. Surface current distribution at the resonance frequency of 5.19 GHz.

V. SENSOR APPLICATION OF THE PROPOSED MA

The suggested multi-band MA structure can also be used for sensor applications, in the case when the dielectric thickness of the MA is changing. Therefore, in this part, the effect of a variation of the dielectric thickness on the reflection values is investigated for pressure sensor applications. The dielectric thickness is altered from 1.5 mm to 3.5 mm. The reflection data of the simulations for different dielectric thickness are shown in Fig. 8. It can be seen that the reflection values change with the variation of the dielectric thickness (i.e. $S_{11} = 0.02$ for 1.5 mm and $S_{11} = 0.60$ for 3.5 mm at the resonances). The resonance frequency shifts to lower frequencies when the thickness of the FR4-dielectric is increased. The reason of this downward shift can be explained by the variation of the pressure of the overall structure. Hence, the proposed structure can also be used as a pressure sensor in addition to its absorber applications. Besides, a sensor based on the suggested MA would have TE-incident angle independency and easily obtainable frequency range.

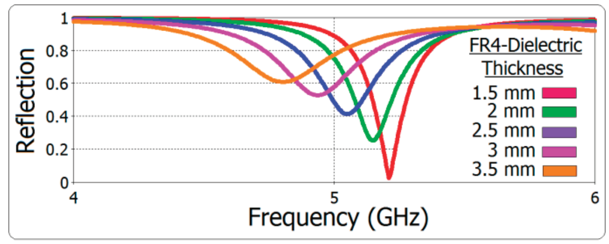

Fig. 8. Sensor application of the suggested multi-band MA.

VI. CONCLUSION

In conclusion, absorption properties of the proposed MA are numerically and experimentally investigated and evaluated. The proposed multi-band MA has simple geometry and shows efficient results for the studied microwave frequency range. Obtained results support our claim that the model can be used as a perfect absorber and is also suitable for absorber applications in a wide frequency range, due to the flexibility of the design. Moreover, the proposed model provides polarization and incident angle independencies and it can be designed for other frequency regimes, such as THz and optics by a simple rescale operation. Additionally, the proposed model can be used in long-distance radio telecommunications, many satellite communications transmissions, some Wi-Fi devices, some cordless telephones, some weather radar systems and so on.

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REFERENCES

[1] M. R. I. Faruque, M. T. Islam and N. Misran, "Evaluation of em absorption in human head with metamaterial attachment," *The Applied Computational Electromagnetics Society*, vol. 25, pp. 1097-1107, 2010.

[2] M. Veysi and A. Jafargholi, "Directivity and bandwidth enhancement of proximity-coupled microstrip antenna using metamaterial cover," *The Applied Computational Electromagnetics Society*, vol. 27, pp. 925, 2012.

[3] Y. Huang, G. Wen, T. Li and K. Xie, "Positive-negative-positive metamaterial consisting of ferrimagnetic host and wire array," *The Applied*

Computational Electromagnetics Society, vol. 25, pp. 696-702, 2010.

[4] N. Fang, H. Lee, C. Sun and X. Zhang, "Sub–diffraction-limited optical imaging with a silver superlens," *Science*, vol. 308, pp. 534-537, 2005.

[5] C. Sabah and H. G. Roskos, "Broadside-coupled triangular split-ring-resonators for terahertz sensing," *The European Physical Journal Applied Physics*, vol. 61, 30402, 2013.

[6] J. B. Pendry, D. Schurig and D. R. Smith, "Controlling electromagnetic fields," *Science*, vol. 312, pp. 1780-1782, 2006.

[7] F. Bilotti, L. Nucci and L. Vegni, "An SRR-based microwave absorber," *Microwave and Optical Technology Letter*s, vol. 48, pp. 2171-2175, 2006.

[8] M. C. K. Wiltshire, J. B. Pendry, I. R. Young, D. J. Larkman, D. J. Gilderdale and J. V. Hajnal, "Micro structured magnetic materials for RF flux guides in magnetic resonance imaging," *Science*, vol. 291, pp. 849-851, 2001.

[9] C. Sabah and S. Uckun, "Multilayer system of lorentz/drude type metamaterials with dielectric slabs and its application to electromagnetic filters," *Progress In Electromagnetics Research*, vol. 91, pp. 349-364, 2009.

[10] M. Gokkavas, K. Guven, I. Bulu, K. Aydin, R. S. Penciu, M. Kafesaki, C. M. Soukoulis and E. Ozbay, "Experimental demonstration of a left-handed metamaterial operating at 100 GHz," *Physical Review B*, vol. 73, 193103, 2006.

[11] T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov and X. Zhang, "Terahertz magnetic response from artificial materials," *Science*, vol. 303, pp. 1494-1496, 2004.

[12] S. Linden, C. Enkrich, M. Wegener, J. Zhou, T. Koschny and C. M. Soukoulis, "Magnetic response of metamaterials at 100 terahertz," *Science*, vol. 306, pp. 1351-1353, 2004.

[13] S. Zhang, W. Fan, N. C. Panoiu, K. J. Malloy, R. M. Osgood and S. R. J. Brueck, "Experimental demonstration of near-infrared negative-index metamaterials," *Physical Review Letters*, vol. 95, 137404, 2005.

[14] G. Dolling, M. Wegener, C. M. Soukoulis and S. Linden, "Negative-index metamaterial at 780 nm wavelength," *Optics Letters*, vol. 32, pp. 53-55, 2007.

[15] Y. J. Huang, G. J. Wen, J. Li, W. R. Zhu, P. Wang and Y. H. Sun, "Wide-angle and polarization-independent metamaterial absorber based on snowflake-shaped configuration," *Journal of Electromagnetic Waves and Applications*, vol. 27, pp. 552-559, 2013.

[16] J. Lee and S. Lim, "Bandwidth-enhanced and polarization-insensitive metamaterial absorber using double resonance," *Electronics Letters*, vol. 47, pp. 8-9, 2011.

[17] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith and W. J. Padilla, "Perfect metamaterial absorber," *Physical Review Letters*, vol. 100, 207402, 2008.

[18] J. Sun, L. Liu, G. Dong and J. Zhou, "An extremely broad band metamaterial absorber based on destructive interference," *Optics Express*, vol. 19, pp. 21155-21162, 2011.

[19] B. Zhu, Y. Feng, J. Zhao, C. Huang, Z. Wang and T. Jiang, "Polarization modulation by tunable electromagnetic metamaterial reflector/absorber," *Optics Express*, vol. 18, pp. 23196-23203, 2010.

[20] B. Wang, T. Koschny and C. M. Soukoulis, "Wide-angle and polarization-independent chiral metamaterial absorber," *Physical Review B*, vol. 80, 033108, 2009.

[21] F. Dincer, O. Akgol, M. Karaaslan, E. Unal and C. Sabah, "Polarization angle independent perfect metamaterial absorbers for solar cell applications in the microwave, infrared, and visible regime," *Progress In Electromagnetics Research*, vol. 144, pp. 93-101, 2014.

[22] Y. Liu, Y. Chen, J. Li, T. Hung and J. Li, "Study of energy absorption on solar cell using metamaterials," *Solar Energy*, vol. 86, pp. 1586-1599, 2012.

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