Novel Metamaterial Design for Electromagnetic Interference Mitigation between Transmission Lines

1st Mohammad Mohtasim Hamid Pial
Elect and Comp Engineering
Florida International University
Miami, USA
mpial001@fiu.edu

2nd Ghaleb Saleh Ghaleb Al-Duhni
Elect and Comp Engineering
Florida International University
Miami, USA
galdu001@fiu.edu

3rd Mudit Khasgiwala
RF System Architectures
Applied materials
Santa Clara, USA
Mudit_khasgiwala@amat.com

4th Pulugurtha Markondeya Raj
Biomedical Engineering
Florida International University
Miami, USA
mpulugur@fiu.edu

2023 IEEE Design Methodologies Conference (DMC) | 979-8-3503-1554-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/DMC58182.2023.10412596

Abstract—**Electromagnetic compatibility (EMC) is a key requirement for electronic system design. Meeting the EMC regulations becomes more challenging as the component density increases and operation frequencies spread to multiple bands. Coupling between transmission lines is a common manifestation of electromagnetic interference (EMI). In this work, we present a novel method to suppress the noise between two transmission lines by using a metamaterial (MTM) structure. This MTM design helps to mitigate the coupling between the two transmission lines where one acts as an aggressor and the other as the victim. This approach helps miniaturize the solutions such as shielding or filtering to mitigate the noise. MTM provides good protection in terms of EMI isolation, is inexpensive, and has a smaller footprint compared to traditional EMC solutions. The second part of this article studies the impact of the relative permittivity (ε_r) of the MTM structure. Changing the ε_r modifies the transmission and absorption bands. Thus, that can help in modulating the operation of the MTM through appropriate designs. The MTM designs used in this work enhanced the isolation between the victim and aggressor by 1-13.5 dB across 1-5 GHz.**

Keywords— Electromagnetic compatibility (EMC), Electromagnetic interference (EMI), Relative permittivity (εr), and Metamaterial (MTM).

I. INTRODUCTION

Electromagnetic compatibility (EMC) will impose key design constraints for future electronic systems with higher component densities and broadband functions. Any undesired coupling between the components, also referred to as electromagnetic interference (EMI), affects the component function and degrades the system's performance. The noise source that initiates the EMI is known as the aggressor. The component that is affected by the noise becomes the victim. When the EMI results through the electromagnetic coupling modes within the substrate, it is known as conducting EMI. EMC engineers address this through low-pass filters, common-mode choke filters, and differential-mode filters to eliminate the noise from the desired signal [1-4]. EMI can also occur through coupling from radiated fields. Depending on the wavelength of the interfering fields and the distance between the aggressor and victim, radiated noise coupling can be classified as near- or far-field coupling. EMI shielding is used to mitigate the coupling by using materials such as copper, magnetic alloys, materials composites, and graphene [5-14]. Such shields are usually used in all electronic components, both at the component level and module level. Metal cans are used from conductive commercial materials such as copper (Cu), and aluminum (Al) due to their higher electrical conductivity for shielding at the module level as package enclosures [1, 4, 13]. Magnetic materials such as nickel (Ni), iron alloys (Fe), ferrite, and cobalt (Co) are also a common way for shielding against magnetic fields at low frequencies usually at the component level [7-8,10]. Graphene also has the potential to replace all commercial materials due to its superiority in terms of thermal and electrical conductivity, lightweight, ability to be processed as thin- or thick-films with innovative approaches, as well as EMI shielding [5-6]. However, the previous two solutions require a large area for the implementation of the shield and filter. They also dramatically increase the thickness and resulting weight of components to achieve the required level of isolation.

In contrast to current shielding and filter options, this work aims to investigate low-profile metamaterial (MTM) solutions for noise isolation between two transmission lines. MTM structures are periodic electromagnetic structures with a unit cell that is much smaller than the guided wavelength. These structures can be designed to refractively couple with the waves and thus induce a variety of functions such as isolation, lensing, steering, filtering, and others. MTMs are typically employed to enhance the gain of the antenna and increase efficiency [15-18]. They are also used in beam steering devices [19-21] and frequency selective surfaces (FSS) applications [22-24]. They are often used to reduce coupling between antennae in multiple input multiple output components (MIMO) [25-28]. In addition, they are implemented in power electronics applications such as wireless power transfer (WPT) and energy harvesting [29-30].

In this work, we used MTM structures to suppress the coupling between electronic components. Two metamaterial (MTM) structures are designed to illustrate how they can be used to reduce the coupling between feeding lines. The second part of this paper studies the enhancements of the performance of MTM by tuning the permittivity of its dielectric medium. The third part of the paper demonstrates the reconfigurability of the MTM by tuning its dielectric substrate properties. Reconfigurability is shown in two aspects. Firstly, tuning the permittivity of the MTM helps to change the operation of the MTM over several bands of frequency. Secondly, this work illustrates that hard tuning of ε_r helps to reverse the operation of the MTM from acting as a way to block the EM waves to transmitting the EM waves. The operation of the MTM, thus, switches from acting as an EMI shield to acting as a Radome.

II. BACKGROUND

According to the EU guidance, an electronic system could be classified as electromagnetically compatible if it has the following attributes: 1) should not disturb other devices, 2) should not be susceptible to interference from other sources, and 3) should not interfere with itself. Further, EMC can be classified into two areas of concern: EMI and electromagnetic susceptibility (EMS). The major difference between EMI and EMS is the source of noise and the victim component to which the noise is coupled. In EMI studies, the source of the noise is inside the circuits, whereas for EMS, the source is external. Therefore, EMI is also related to emission requirements, whereas EMS is concerned with immunity requirements.

EMI suppression is critical for at least four reasons. First, EMI can act as an aggressor and disturb a neighboring victim component. In this case, the EMI source arises from the power or high-speed digital components in the electronic system with small rise times. For example, power components switch at speeds ranging from 1 to 100 MHz causing possible harmonics to interfere with the RF transceiver in the LTE bands. Also, components with steep signal edges such as switch-mode power supplies create EMI. Analog components, such as operational amplifiers, are typical victims because they require precise voltage or current margins. Thus, they are more sensitive to EMI. The major other sources of EMI arise from aggressor components associated with high-speed signals. Digital lines transmit timing clocks that switch from 100s of MHz to GHz and can generate electromagnetic noise. Also, CPUs that switch at higher frequencies could be EMI sources. Potential EMI sources or noise aggressors can be shielded with suitable metal encapsulation materials. The victim, typically an antenna, also needs to be shielded or blocked through RF filters. A secondary issue is that EMI can be captured by a hacker in proximity to deduce sensitive information. Third, shielding is essential to isolate the transmit and receive bands. Finally, electronics need to be regulated to ensure power levels are below the threshold for the required compatibility requirements.

Electronic component victims are coupled through four mechanisms: 1) galvanic coupling, 2) capacitive coupling, 3) magnetic coupling, and 4) far-field radiation coupling. Galvanic coupling is related to conductive coupling due to the common path impedance between components. Hence, it is typically associated with the parasitic inductance from components that are connected to the ground plane. Capacitive and magnetic coupling are related to the unintended antenna coupling in the near field. In this work, to represent the coupling between the aggressor and victim, two transmission lines are used, one of them is the aggressor and the other is the victim where all noise generated from the aggressor is coupled to the victim line caused interference. The mechanism of the coupling used in this article is illustrated in Fig. 1.

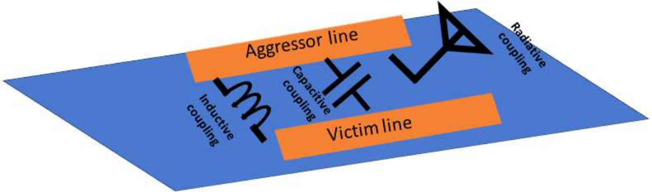
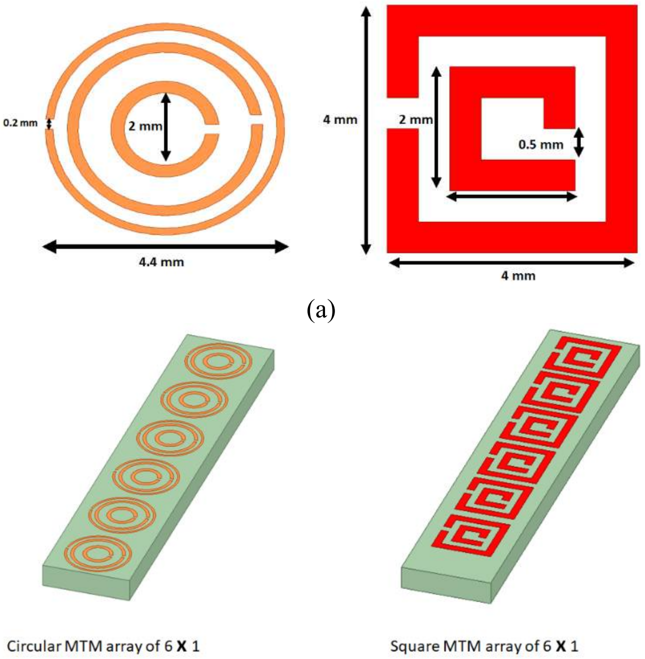


Fig. 1: Coupling mechanism between aggressor and victim lines.

III. MTM DESIGN

As mentioned previously, two MTM structures are studied in this work. The first structure is a circular shape of three concentrated circles, where the outer diameter is 4.4 mm, and the inner diameter is 2 mm. Each of those circles has a gap of 0.2 mm in width. The gap represents the opening of the split ring resonator in both shapes. The second MTM shape has two concentric squares. The length of the outer square is 4 mm, and that of the inner square is 2 mm. Every square has a gap of 0.5 mm. Both of the single MTM shapes are illustrated in Fig. 2a. In this work, we used an array of MTM of 1 × 6 as shown in Fig. 2b.



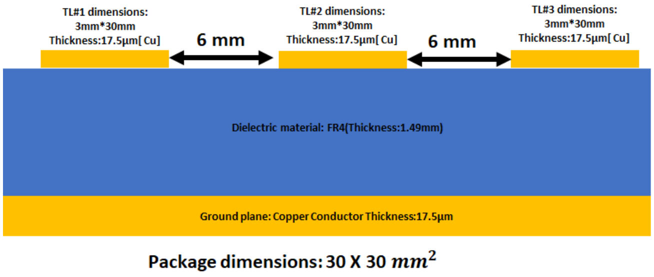
(a)

(b)

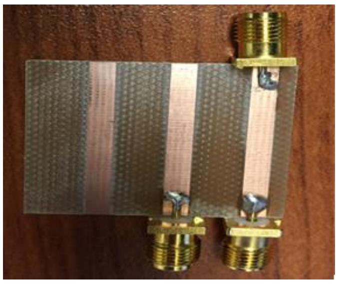
Fig. 2: MTM design and its key features: a) single circular and square MTM geometry, b) 6 × 1 circular and square MTM array.

IV. MTM TO MITIGATE THE NOISE

The prototype that is used in this work is illustrated in Fig. 3. The role of metamaterial (MTM) structures in enhancing the isolation between the feeding lines (TLs) is shown in Fig. 4. Two MTM structures were used, with two shapes of square and circular split rings. Both designs rely on the split ring resonator principle. The MTM structures were inserted between two strip lines; one of the strip lines represents the aggressor line, which is connected to the power source, and it is denoted by TL#1. The second strip line is denoted by TL#2, and it refers to the victim component, which is affected by the noise.

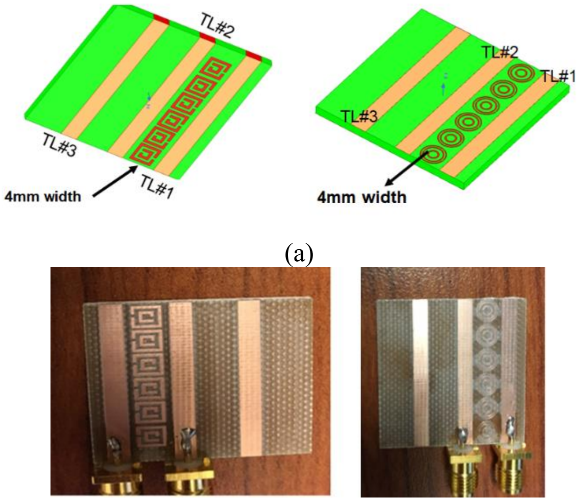


(a)



(b)

Fig. 3: Demonstration of the coupling between TLs: a) schematic of the prototype, b) fabricated circuit.

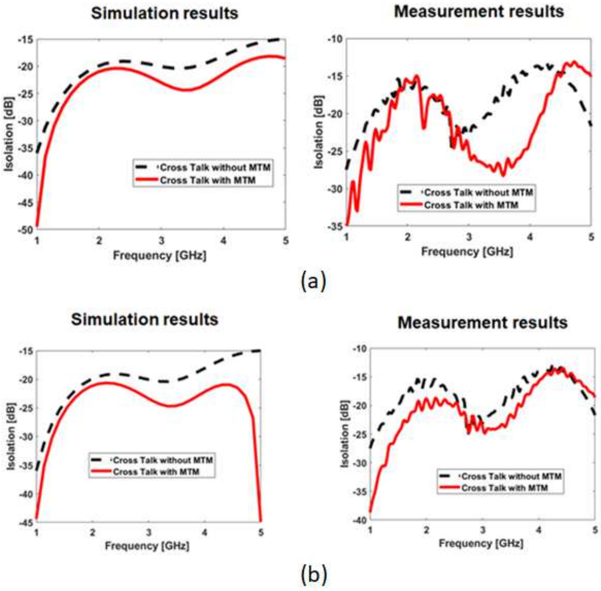


(a)

(b)

Fig. 4: a) simulated square and circular MTM b) fabricated square and circular MTM prototypes.

Square MTM structures help to enhance the isolation between the transmission lines, especially between TL# 1 and TL# 2; the isolation varies from 1-13.5 dB in the frequency range of 1-5 GHz. Circular MTM structures suppressed the coupling between the transmission lines, especially between TL#1 and TL# 2; the isolation varies from 1-13.5 dB in the frequency range of 1-5 GHz. Measurement and simulation demonstrate a good agreement for both MTM structures (see Fig. 5a and Fig. 5b). MTM designs show accepted performance in suppressing crosstalk between the lines.



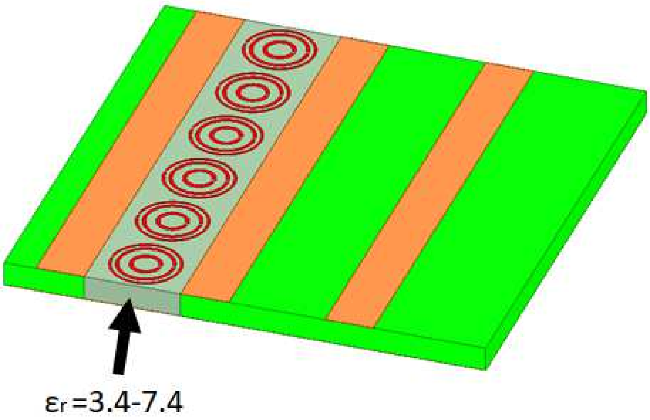
(a)

(b)

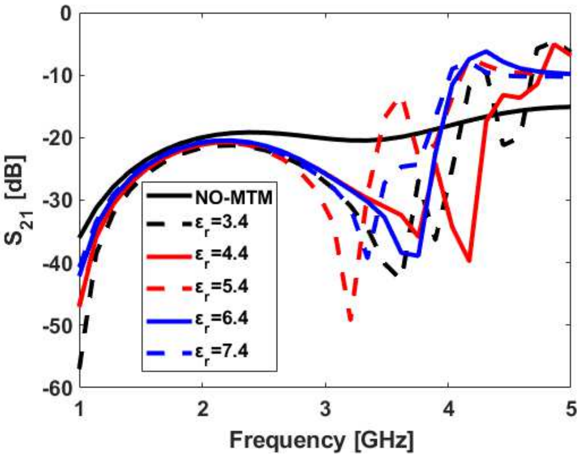
Fig. 5: Isolation measurements and simulation results using Square MTM (a) and Circular MTM (b).

V. TUNABLE METAMATERIAL

In the first part of the work, the permittivity of the MTM structure was fixed and equal to the permittivity of the medium between transmission lines. In this section, the shield performance is analyzed when the ε_r is varied across several values. Varying the permittivity of the dielectric materials can be accomplished through multiple approaches such as the application of electric field strength in ferroelectrics, magnetic field strength in case of multiferroics, mechanical sliding or shifting, and thermal stimulation in ferroelectrics or super paraelectrics. In this study, we are interested in assessing the impact of changing the electric permittivity in terms of enhancing or degrading the MTM performance. The ε_r was varied from 3.4 to 7.4 in the simulation models. The variation in the ε_r was applied specifically to the substrate where the MTM is printed. The substrate that holds the rest of the design including the TLs was kept the same in all trials (fixed at 4.4). As shown in Fig. 6, the changes in ε_r correspondingly shifted the S_{21} bands. This allows us to tune permittivity to control the behavior of the MTM. In addition, that leads to extra isolation of 20 dB at a certain operation frequency.



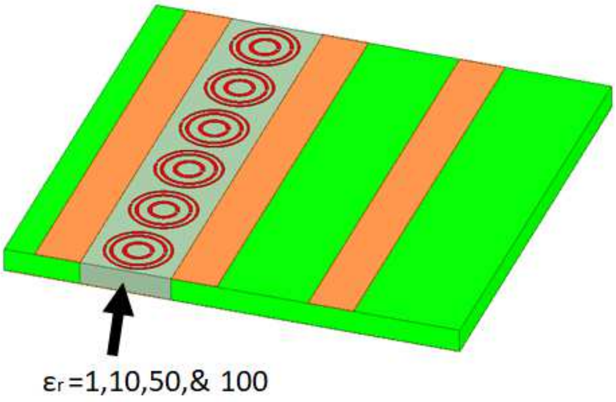
(a)



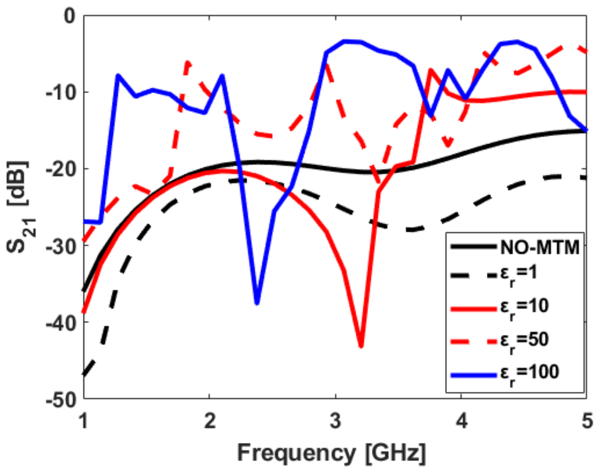
(b)

Fig. 6: (a) MTM structure with ε_r varying from 3.4 to 7.4. (b) transmission coefficient S_{21} for several ε_r.

On the other hand, increasing the ε_r to several tens will change the function of the MTM from blocking the EM waves to transmitting the EM waves, as illustrated in Fig. 7. When the ε_r equals 100, the operating frequency shifts to 2.4 GHz instead of 3.2 GHz at ε_r of 5.4. On the other hand, at $\varepsilon_r = 50$, the MTM depicted transmission characteristics over this band. The MTM also provides an additional enhancement of 5 dB towards the transmitted signal.



(a)



(b)

Fig. 7: (a) MTM structure with ε_r varying from 1, 10, 50, and 100. (b) transmission coefficient S_{21} for several ε_r.

VI. CONCLUSION

This work illustrates two MTM structures that show good performance in increasing the isolation between transmission lines and reducing the associated crosstalk coupling. This approach can be used as an alternative to traditional EMC solutions such as shielding and filters, especially in applications with some limitations in terms of volume and footprint. The MTM structures provide around 10 dB isolation across 1-5 GHz. After, applying the tunability approach to the dielectric materials, the MTM performance is enhanced by an additional 10 dB, achieving an isolation of 20 dB or more. Tuning the MTM can help to control the operation of the MTM. If the permittivity is tuned to lower values, the blocking will be shifted to another frequency band. In the second approach, the permittivity was increased by several tens compared to the original properties. The results showed that the MTM performance can be further controlled in terms of its operation frequency. In addition, it can completely change its performance to be a transmissive EMI shield instead of a reflective EMI shield. Moreover, if the tuning is towards higher values, the MTM can help to increase the power of the wave instead of attenuating it at a certain frequency band. Nonetheless, the design of the MTM needs to be optimized to enhance the isolation to an acceptable level.

REFERENCES

[1] H. W. Ott. “Electromagnetic Compatibility Engineering”, Hoboken, NJ, USA: Wiley, 2009.

[2] X. C. Wei. “Modeling and Design of Electromagnetic Compatibility for High-Speed Printed Circuit Boards and Packaging". Boca Raton, FL, USA: CRC Press, 2017.

[3] T. Williams. “EMC for Product Designers”. London, U.K.: Newnes, 2016.

[4] C. R. Paul. “Introduction to electromagnetic compatibility”. Hoboken, NJ: Wiley.2006

[5] G. A. Duhni, J. L. Volakis, and P. M. Raj, "EMI Shielding Performance of Thin and Thick Graphene Films Placed Within Integrated Power Modules," 2023 Fourth International Symposium on 3D Power Electronics Integration and Manufacturing (3D-PEIM), Miami, FL, USA, 2023, pp. 1-5, doi: 10.1109/3D-PEIM55914.2023.10052133.

[6] A. Nisar, G. A. Duhni, C. Zhang, P. M. Raj, and A. Agarwal, "Reticular Graphene Reinforced Copper for Electromagnetic Shielding Application," 2023 Fourth International Symposium on 3D Power Electronics Integration and Manufacturing (3D-PEIM), Miami, FL, USA, 2023, pp. 1-5, doi: 10.1109/3D-PEIM55914.2023.10052591.

[7] G. A. Duhni, M. Khasgiwala, J. L. Volakis, and P. Markondeya Raj, "Low-Frequency Shielding Effectiveness of Magnetic Alloys," SoutheastCon 2023, Orlando, FL, USA, 2023, pp. 49-52, doi: 10.1109/SoutheastCon51012.2023.10115097.

[8] G. A. Duhni, M. Khasgiwala and P. M. Raj, "Bi-Layered Magnetic Electromagnetic Interference Shields with Thinner Metals," 2023 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO), Winnipeg, MB, Canada, 2023, pp. 77-79, doi: 10.1109/NEMO56117.2023.10202292.

[9] G. A. Duhni, M. Khasgiwala, J. L. Volakis, and P. Markondeya Raj, "Component-Level Shielding with Assembled Copper Trenches in Package Slots," SoutheastCon 2023, Orlando, FL, USA, 2023, pp. 38-42, doi: 10.1109/SoutheastCon51012.2023.10115102.

[10] C. Chen, Y. Tseng, T. Wu, I. Lin, C. Fu and K. Liao, "Prediction of near-field shielding effectiveness for conformal-shielded SiP and measurement with magnetic probe," 2015 IEEE 24th Electrical Performance of Electronic Packaging and Systems (EPEPS), 2015, pp. 77-80, doi: 10.1109/EPEPS.2015.7347133

[11] A. O. Watanabe, P.M Raj, D. Wong, *et al.* “Multilayered Electromagnetic Interference Shielding Structures for Suppressing Magnetic Field Coupling”. *Journal of Elec Materi* **47,** 5243–5250 (2018). https://doi.org/10.1007/s11664-018-6387-2

[12] A. O. Watanabe et al., "Highly-Effective Integrated EMI Shields with Graphene and Nanomagnetic Multilayered Composites," 2016 IEEE

66th Electronic Components and Technology Conference (ECTC), 2016, pp. 206-210, doi: 10.1109/ECTC.2016.294.

[13] Tai, M. F., Kok, S. L., Mukai, K., Hotz, S., Brooks, P., & Cocina, D. R. “EMI Shielding Performance For Varies Frequency by Metal Plating on Mold Compound. Advances in Science”. Technology and Engineering Systems Journal, 2(3), 1159–1164.2017. https://doi.org/10.25046/aj0203146

[14] K. Song *et al.*, "Measurement, Simulation and Mathematical Estimation of Magnetic Field Shielding Effectiveness of Sputtered Shielding Materials using Spiral Coils," *2018 IEEE Symposium on Electromagnetic Compatibility, Signal Integrity and Power Integrity (EMC, SI & PI)*, 2018, pp. 47-51, doi: 10.1109/EMCSI.2018.8495438.

[15] R. H. Barroso and W. Malpica, "An Overview of Electromagnetic Metamaterials," in IEEE Latin America Transactions, vol. 18, no. 11, pp. 1862-1873, November 2020, doi: 10.1109/TLA.2020.9398627.

[16] M. Zhao et al., "Frequency-Diverse Transmission Metamaterial Aperture With a Bunching Random Beam," in IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 6, pp. 1029-1033, June 2018, doi: 10.1109/LAWP.2018.2829909.

[17] A.A. Althuwayb. “Enhanced radiation gain and efficiency of a metamaterial-inspired wideband microstrip antenna using substrate-integrated waveguide technology for sub-6 GHz wireless communication systems”. Microwave and Optical Technology Letters, 63(7), pp.1892-1898. .2021.

[18] G. Zhai et al., "Gain-Enhanced Planar Log-Periodic Dipole Array Antenna Using Nonresonant Metamaterial," in IEEE Transactions on Antennas and Propagation, vol. 67, no. 9, pp. 6193-6198, Sept. 2019, doi: 10.1109/TAP.2019.2924111.

[19] B. Orazbayev, M. Beruete, and I. Khromova, "Ultrafast beam steering based on graphene metamaterial," 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, France, 2017, pp. 3896-3899, doi: 10.23919/EuCAP.2017.7928528.

[20] B. Orazbayev, M. Beruete and I. Khromova, "Graphene-dielectric metamaterial for beam steering," 2016 10th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (METAMATERIALS), Chania, Greece, 2016, pp. 253-255, doi: 10.1109/MetaMaterials.2016.7746506.

[21] M. Sterner, D. Chicherin, A. V. Raisenen, G. Stemme and J. Oberhammer, "RF MEMS High-Impedance Tuneable Metamaterials for Millimeter-Wave Beam Steering," 2009 IEEE 22nd International Conference on Micro Electro Mechanical Systems, Sorrento, Italy, 2009, pp. 896-899, doi: 10.1109/MEMSYS.2009.4805528.

[22] A. Yelizarov and A. Kukharenko, "Metamaterial-based frequency selective surface with a band gap electronic adjustment," 2016 German Microwave Conference (GeMiC), Bochum, Germany, 2016, pp. 271-273, doi: 10.1109/GEMIC.2016.7461608.

[23] J. X. Zhang, Y. F. Fan, H. Z. Sun, Y. Z. Sun, X. M. Fan and H. R. Li, "All dielectric metamaterial frequency selective surface based on Y shaped barium strontium titanate ceramic resonator," 2019 12th UK-Europe-China Workshop on Millimeter Waves and Terahertz Technologies (UCMMT), London, UK, 2019, pp. 1-4, doi: 10.1109/UCMMT47867.2019.9008273.

[24] S. Narayan, R. Gopinath, R. U. Nair, and R. M. Jha, "EM performance analysis of multilayered metamaterial frequency selective surfaces," 2011 IEEE Applied Electromagnetics Conference (AEMC), Kolkata, India, 2011, pp. 1-4, doi: 10.1109/AEMC.2011.6256849.

[25] L. Duggani, U. Naik and V. Rayar, "Review of Mutual Coupling Reduction in Microstrip Patch Antenna Array for MIMO Applications," 2020 3rd International Conference on Intelligent Sustainable Systems (ICISS), Thoothukudi, India, 2020, pp. 1227-1231, doi: 10.1109/ICISS49785.2020.9316130.

[26] M. Farahani, J. Pourahmadazar, M. Akbari, M. Nedil, A. R. Sebak and T. A. Denidni, "Mutual Coupling Reduction in Millimeter-Wave MIMO Antenna Array Using a Metamaterial Polarization-Rotator Wall," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2324-2327, 2017, doi: 10.1109/LAWP.2017.2717404.

[27] M. Farahani, J. Zaid, T. A. Denidni, M. Akbari, A. R. Sebak and M. Nedil, "Mutual coupling reduction in millimeter-wave MIMO dielectric resonator antenna using metamaterial polarization rotator wall," 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, USA, 2017, pp. 1261-1262, doi: 10.1109/APUSNCURSINRSM.2017.8072673.

[28] A. Dadgarpour, B. Zarghooni and T. A. Denidni, "Mutual-coupling suppression for 60 GHz MIMO antenna using metamaterials," 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, BC, Canada, 2015, pp. 422-423, doi: 10.1109/APS.2015.7304597.

[29] A. S. M. Alqadami, N. Nguyen-Trong, K. Bialkowski, and A. Abbosh, "Mutual Coupling Reduction in Wideband Electromagnetic Medical Imaging Antenna Array Using Compact Electromagnetic Band Gap," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 2019, pp. 999-1000, doi: 10.1109/APUSNCURSINRSM.2019.8889175.

[30] Z. Ding and F. Liu, "A Metamaterial Design for Suppression of Cross Interference in Multi-Frequency Multi-Load MCR WPT System," 2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia), Nanjing, China, 2020, pp. 90-95, doi: 10.1109/IPEMC-ECCEAsia48364.2020.9368118.