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Mathematical Modeling of a Sub-6 GHz Metamaterial-Inspired Absorber for Miniaturized 5G IoMT Microwave Sensors

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Abstract

The rapid deployment of fifth-generation (5G) wireless communication in Internet of Medical Things (IoMT) environments has increased the demand for compact, efficient, and highly sensitive microwave sensing technologies capable of operating within the sub-6 GHz spectrum. This study presents the design and performance evaluation of a metamaterial-inspired electromagnetic absorber intended for miniaturized 5G IoMT microwave sensor applications. The proposed absorber employs a subwavelength patterned metallic resonator, dielectric substrate, and continuous metallic ground plane to achieve strong electromagnetic confinement and enhanced absorption. An equivalent inductor–capacitor (LC) circuit model is developed to establish the relationship between geometrical parameters and resonance frequency, while full-wave electromagnetic analysis is considered for evaluating the reflection coefficient, absorption, impedance matching, electric-field enhancement, and surface-current distributions. Parametric optimization is performed by varying resonator dimensions, slot gap, substrate thickness, and periodicity to obtain a compact sub-6 GHz response. The sensing mechanism is established through dielectric loading, where variations in the permittivity of the target material produce measurable resonance frequency shifts. Sensitivity, bandwidth, quality factor, and figure of merit are subsequently considered as principal performance indicators. The proposed architecture provides a promising foundation for compact, low-profile, and highly responsive microwave sensors for wireless biomedical monitoring and next-generation IoMT healthcare applications for future healthcare systems.

Keywords: Metamaterial absorber, sub-6 GHz, 5G, Internet of Medical Things (IoMT), microwave sensor, electromagnetic absorption, impedance matching, miniaturized resonator

INTRODUCTION

The integration of 5G communication with the Internet of Medical Things (IoMT) is enabling increasingly connected healthcare environments in which medical sensors, wearable devices, monitoring systems, and intelligent diagnostic platforms exchange information with low latency and improved network reliability. Within this technological transition, sub-6 GHz frequencies remain important because they provide favorable propagation characteristics, practical coverage, and comparatively manageable hardware requirements for healthcare environments. However, the miniaturization of microwave sensors operating in these frequency bands remains challenging because conventional resonant structures generally require dimensions related to a significant fraction of the operating wavelength. Metamaterial-inspired structures provide an attractive approach for overcoming this limitation through artificial

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electromagnetic loading and subwavelength resonances. Carefully engineered metallic patterns can introduce enhanced inductive and capacitive effects, allowing the resonance frequency to be reduced without proportionally increasing the physical dimensions. In absorber configurations, a patterned metallic resonator, dielectric substrate, and conductive ground plane can provide impedance matching, suppressed transmission, and strong electromagnetic energy confinement. For IoMT applications, these characteristics are particularly useful because localized electromagnetic fields can interact strongly with biological materials and sensing layers. Changes in dielectric properties can consequently modify the effective capacitance and produce detectable resonance shifts. Therefore, this study investigates a compact metamaterial-inspired absorber designed for sub-6 GHz 5G IoMT microwave sensing, emphasizing electromagnetic absorption, miniaturization, sensitivity, bandwidth, and sensing performance. Recent research on metamaterial absorbers has demonstrated their strong potential for electromagnetic absorption, miniaturized microwave structures, and sensing applications relevant to next-generation wireless and IoMT systems.

Figure 1 presents a systematic three-phase workflow adopted for developing and validating the proposed sub-6 GHz metamaterial-inspired absorber for 5G IoMT microwave sensing applications. Phase I—Design and Optimization begin with the selection and development of the metamaterial unit cell geometry, including split-ring resonator configurations. Computer simulation technology (CST) or high-frequency structure simulator (HFSS) full-wave simulations are then employed to optimize the geometrical parameters, substrate properties, boundary conditions, and equivalent-circuit characteristics. The absorption response is evaluated under normal and oblique electromagnetic incidence to achieve strong resonance and impedance matching. Phase II—Fabrication and Measurement convert the optimized numerical design into a physical prototype using printed circuit board (PCB) fabrication or photolithographic techniques. Experimental characterization is performed using a vector network analyzer, horn antennas, and an anechoic chamber, where reflection and transmission coefficients, $S_{11}$and S_{21}, are measured. These parameters are subsequently used to calculate absorptivity. Phase III—Performance Evaluation and Sensing Validation assesses polarization independence, angular stability from 0°to 60°, fractional bandwidth, and structural miniaturization. Finally, the absorber is integrated into a representative 5G IoMT sensing environment to evaluate resonance shifts caused by target analytes and demonstrate sensitive dielectric-material detection.

To harness the benefits of engineered coding elements to control electromagnetic absorption while maintaining compact resonances, broadband microwave coding metamaterial absorbers have been developed [1]. A resistor-loaded meander-wire structure to achieve a compact low-frequency broadband

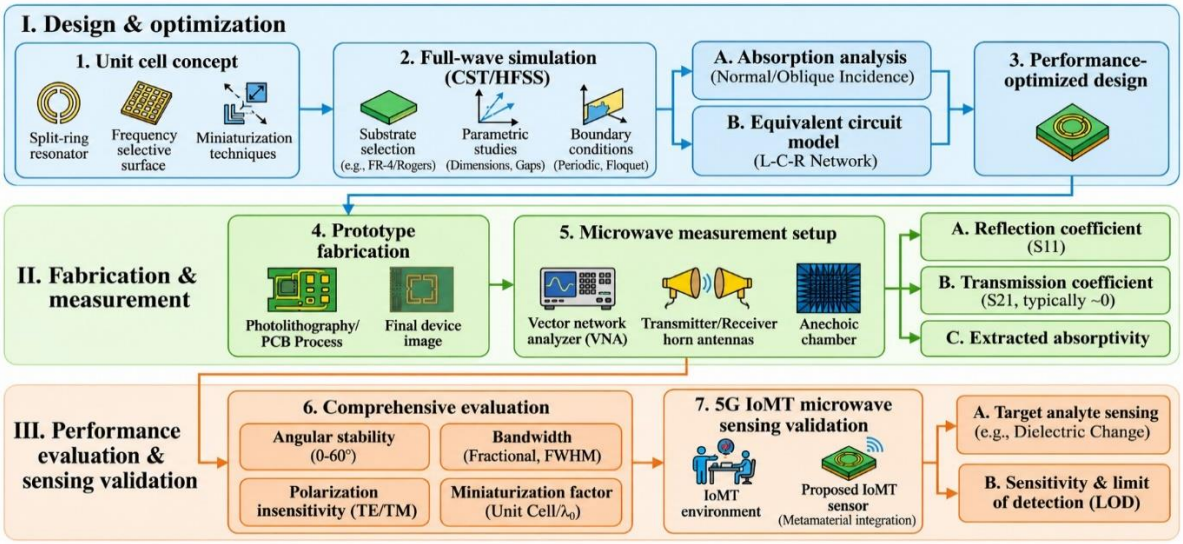


Figure 1. Systematic research workflow for the design, fabrication, and validation of the sub-6 GHz metamaterial-inspired absorber for 5G IoMT microwave sensors.

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microwave absorber was proposed [2], where both the extended current paths and resistive loading contribute to reducing the operating frequency and providing broadband absorption. A wideband metamaterial absorber with angle- and polarization independence was studied, and its electromagnetic stability was enhanced under different incidence angles and polarizations [3]. The SNG/DNG metamaterial absorber was designed to obtain better interaction between the incident waves and the sensing material, and it was shown that a negative-permeability and negative-permittivity response can enhance this interaction [4]. The combination of plasmonic and Mie resonances was also explored, and dual-band metamaterial absorption was demonstrated; multiple resonance mechanisms can be added to a compact absorber structure [5].

Finally, a single negative metamaterial absorber was designed using a modified split-ring-resonator configuration that spans four band gaps in the S, C, X, and Ku microwave frequency bands, highlighting the power of resonator design for multiband microwave absorption [6]. A further development of the aforementioned angle-insensitive metamaterial absorber was carried out using equivalent-circuit analysis, and it was demonstrated that the behavior of the resonant absorber can be described and optimized using circuit-based modeling [7]. An ultrawideband electromagnetic metamaterial absorber comprising double-layer carbon metapatterns was proposed that can be formed to absorb wideband electromagnetic energy using coherent absorption and surface-plasmon-polariton effects [8]. A strong metamaterial-based microfluidic sensor for low-dielectric-constant liquids was created, which shows that the microwave response changes significantly under different sensing conditions, such that the localized resonant fields can induce sensitive changes [9]. Furthermore, highly sensitive microwave metamaterial-inspired sensors were also explored for metal detection, where resonator-based frequency responses were found to be successful for effective metal identification [10]. A multiband metamaterial-based microwave sensor for mercury contamination sensing was developed, which illustrates the possibility of using engineered resonators for environmental and chemical-sensing applications of metamaterials [11].

A thin, flexible, and sensitive microwave sensor based on a flexible metamaterial was designed to measure the complex permittivity, and the advantages of such a thin, flexible, and sensitive structure for material characterization were discussed [12]. An asymmetric metamaterial structure with high microwave sensing sensitivity was also proposed, such that structural asymmetry can be used to boost the electromagnetic interaction in the structure, which leads to high sensing sensitivity [13]. Further review studies showed that metamaterial absorbers can be considered multifunctional platforms of electromagnetic fields for sensing, shielding, imaging, and reducing the radar cross-section [14]. There has also been significant progress in research on RF/microwave absorbers, with miniaturization, bandwidth improvement, polarization independence, and tunability being key research areas [15]. A systematic broadband metamaterial absorber review revealed important design principles such as engineered resonances, impedance matching, tunability, and multifunction integration [16]. A narrow-band metamaterial microwave sensor with an ultrahigh quality factor was developed, revealing the ability of sharp absorption resonances to enhance frequency-resolution-based sensing [17]. Compact geometry and polarization stability are critical characteristics in the practical design of a sensor, with the polarization-insensitive absorbers proposed in the above-mentioned work [18] being shaped as Archimedean spirals of ultrathin width for use in microwave sensing. To have multiple microwave sensing bands, a modified circular-ring-resonator-based metamaterial absorber was presented for S-, X-, and Ku-band sensing [19].

The review of resonator-loaded microwave sensors, which are based on metamaterials, has pinpointed the applications of dielectric characterization, resonance frequency tracking, and compact integration of metamaterial-based sensors [20]. In recent years, the sub-6 GHz spectrum of 5G, especially the 3.5 GHz band, has garnered more research interest, as is the case with absorber designs around this 5G spectrum, especially in the context of compact wireless healthcare and IoMT systems. Despite the successful progress in increasing the absorption efficiency, multiband operation, polarization independence, and sensing sensitivity, a path forward is still needed to integrate high-absorption miniaturized sub-6 GHz metamaterial absorbers with the 5G-enabled IoMT microwave

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sensing platform. To this end, the present study aims to develop a compact absorber architecture that solves the issues of resonance miniaturization, impedance matching, electromagnetic confinement, sensing sensitivity, and practical integration aspects for 5G IoT applications.

MATHEMATICAL FORMULATION OF THE METAMATERIAL-INSPIRED ABSORBER

Electromagnetic and Geometrical Modeling

The proposed absorber is modeled as a periodic subwavelength unit cell consisting of a patterned metallic resonator, dielectric substrate, and metallic ground plane. The fundamental resonance is governed by the effective inductive and capacitive loading of the resonator.

$$\lambda_0 = \frac{c}{f_r} \tag{1}$$

where $\lambda_0$is the free-space wavelength at resonance, $c$is the speed of light in free space, and $f_r$is the resonant frequency. For sub-6 GHz operation, the unit cell dimensions must remain substantially smaller than λ_0.

The normalized electrical size of the unit cell is expressed as

$$\eta_p = \frac{p}{\lambda_0} = \frac{pf_r}{c}, \eta_p \ll 1 \tag{2}$$

where $p$denotes the periodicity of the unit cell. A small $\eta_p$confirms that the absorber behaves as an electrically compact metamaterial surface.

For a resonator with an effective current path l_{eff}, the equivalent inductance can be approximately represented as

$$L_{\text{eff}} = \mu_0 l_{\text{eff}} \left[\ln\left(\frac{2l_{\text{eff}}}{r_{\text{eff}}}\right) - \frac{3}{4}\right] + L_{\text{geo}}, \tag{3}$$

where $\mu_0$is the permeability of free space, $r_{\text{eff}}$is the equivalent conductor radius, and L_{geo}accounts for the additional geometric loading produced by bends, slots, and folded current paths.

The capacitive loading generated by the resonator gap is approximated by

$$C_{\text{eff}} = \varepsilon_0 \varepsilon_{\text{eff}} \frac{A_g}{g} + C_{\text{fr}}, \tag{4}$$

where $A_g$is the effective gap area, $g$is the slot/gap width, $\varepsilon_{\text{eff}}$is the effective dielectric constant surrounding the gap, and C_{fr}represents the fringing capacitance. Equation (4) shows that decreasing the gap increases the capacitive loading and consequently lowers the resonance frequency.

The effective dielectric constant for a microstrip-like resonator can be approximated by

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{w_r}\right)^{-1/2} \tag{5}$$

where $\varepsilon_r$is the relative permittivity of the substrate, $h$is its thickness, and $w_r$is the effective resonator width.

The equivalent LC resonance is consequently obtained as

$$f_r = \frac{1}{2\pi\sqrt{L_{\text{eff}} C_{\text{eff}}}} \tag{6}$$

which provides the principal design relationship between resonator geometry, substrate properties, and operating frequency.

Equivalent-Circuit and Impedance Derivation

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The impedance of the resonant branch is modeled by

$$Z_{\mathrm{LC}}(\omega) = R_{\mathrm{eff}} + j\omega L_{\mathrm{eff}} + \frac{1}{j\omega C_{\mathrm{eff}}}, \quad (7)$$

where R_{eff}represents the combined metallic and dielectric loss resistance, and $\omega = 2\pi f$is the angular frequency.

At resonance, the reactive components cancel according to

$$\omega_r L_{\mathrm{eff}} = \frac{1}{\omega_r C_{\mathrm{eff}}}, \quad (8)$$

Yielding

$$\omega_r = \frac{1}{\sqrt{L_{\mathrm{eff}} C_{\mathrm{eff}}}} \quad (9)$$

The absorber input impedance can be expressed using its equivalent series/parallel resonant network as

$$Z_{\mathrm{in}}(\omega) = R_{\mathrm{eff}} + jX_{\mathrm{eff}}(\omega), \quad (10)$$

where X_{eff}denotes the net reactive impedance of the resonator-substrate configuration.

For an absorber backed by a continuous metallic ground plane, the transmission coefficient is ideally negligible:

$$| S_{21}(f) | \to 0. \quad (11)$$

The reflection coefficient at the absorber interface is therefore

$$\Gamma(f) = S_{11}(f) = \frac{Z_{\mathrm{in}}(f) - Z_0}{Z_{\mathrm{in}}(f) + Z_0} \quad , \quad (12)$$

where $Z_0 \approx 377\ \Omega$is the free-space impedance.

Maximum absorption is achieved when the real and imaginary parts simultaneously satisfy

$$\mathrm{Re}\{Z_{\mathrm{in}}(f_r)\} \approx Z_0, \mathrm{Im}\{Z_{\mathrm{in}}(f_r)\} \approx 0 \quad . \quad (13)$$

Under this impedance-matching condition,

$$\Gamma(f_r) \approx 0, \quad (14)$$

and the incident wave is minimally reflected.

Absorption and Electromagnetic Energy

The reflection, transmission, and absorption coefficients satisfy the power-conservation relation

$$A(f) + R(f) + T(f) = 1 \quad , \quad (15)$$

Where,

$$R(f) = | S_{11}(f) |^2, T(f) = | S_{21}(f) |^2 \quad . \quad (16)$$

Consequently, the general absorption coefficient is

$$A(f) = 1 - | S_{11}(f) |^2 - | S_{21}(f) |^2 \quad (17)$$

and, for the ground-backed configuration,

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$$A(f) \approx 1 - |\, S_{11}(f)\,|^2 \tag{18}$$

The maximum theoretical absorption at resonance is therefore obtained from

$$A_{\max} = 1 - \left|\frac{Z_{\text{in}}(f_r) - Z_0}{Z_{\text{in}}(f_r) + Z_0}\right|^2 . \tag{19}$$

Equation (19) directly demonstrates the importance of impedance matching for high-performance absorption.

The electromagnetic energy density within the dielectric region is approximately

$$W_e = \frac{1}{4}\varepsilon_0 \varepsilon_r \,|\, E \,|^2, \tag{20}$$

where E is the local electric-field intensity. Strong electric-field confinement around the resonator gap increases W_e, thereby enhancing the interaction with the sensing material.

Similarly, the magnetic energy density is

$$W_m = \frac{1}{4}\mu_0 \mu_r \,|\, H \,|^2, \tag{21}$$

where $H$is the magnetic-field intensity and $\mu_r$is the relative permeability.

The total stored electromagnetic energy can consequently be represented as

$$W_{\text{stored}} = \int_V \left(\frac{1}{4}\varepsilon_0 \varepsilon_r \,|\, E \,|^2 + \frac{1}{4}\mu_0 \mu_r \,|\, H \,|^2\right) dV. \tag{22}$$

Loss and Quality Factor Formulation

The absorbed power associated with dielectric and conductor losses is

$$P_{\text{loss}} = \frac{1}{2}\int_V [\sigma \,|\, E \,|^2 + \omega \varepsilon_0 \varepsilon_r \tan\delta \,|\, E \,|^2]\, dV, \tag{23}$$

where $\sigma$is the effective conductivity and $\tan\delta$is the dielectric loss tangent.

The resonance quality factor is then expressed as

$$Q = \frac{\omega_r W_{\text{stored}}}{P_{\text{loss}}}. \tag{24}$$

For practical characterization, the quality factor can also be determined from the -3dB bandwidth:

$$Q = \frac{f_r}{\Delta f_{3\text{dB}}}, \tag{25}$$

where $\Delta f_{3\text{dB}} = f_2 - f_1$represents the resonance bandwidth between the lower and upper half-power frequencies.

IoMT Sensing Formulation

When a sensing material with relative permittivity ε_s is placed over the resonator, the effective capacitance changes according to

$$C'_{\text{eff}} = C_{\text{eff}} + \Delta C_s(\varepsilon_s, t_s), \tag{26}$$

where $t_s$is the sensing-layer thickness and ΔC_srepresents the additional capacitive loading produced by the sensing material.

The corresponding shifted resonance is

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$$f_r' = \frac{1}{2\pi\sqrt{L'_{\text{eff}}C'_{\text{eff}}}}, \tag{27}$$

where $L'_{\text{eff}}$and C'_{eff}denote the effective inductance and capacitance after sensor loading.

The resonance frequency shift is therefore

$$\Delta f_r = f_r' - f_r, \tag{28}$$

and the dielectric sensitivity is defined as

$$S_f = \frac{\Delta f_r}{\Delta \varepsilon_s}\ [\text{GHz/RIU}] \tag{29}$$

where RIU denotes the refractive index unit when the refractive index is used as the sensing variable.

Finally, a normalized sensor figure of merit combining sensitivity and resonance sharpness can be defined as

$$\text{FOM} = \frac{|S_f|}{\Delta f_{3\text{dB}}} = \frac{|\Delta f_r|}{\Delta \varepsilon_s\, \Delta f_{3\text{dB}}} \tag{30}$$

where FOM represents the overall sensing effectiveness, S_f is the frequency sensitivity, and $\Delta f_{3\text{dB}}$is the resonance bandwidth.

Equations (1)–(6) establish the miniaturization and resonance conditions, showing how the physical dimensions, substrate, inductance, and capacitance determine the sub-6 GHz operating frequency. Equations (7)–(19) establish the impedance-matching and absorption mechanism, demonstrating that maximum absorption occurs when the absorber impedance approaches the free-space impedance while transmission remains suppressed by the ground plane. Equations (20)–(25) quantify the electric/magnetic energy confinement, losses, and resonance quality. Finally, Equations (26)–(30) establish the IoMT sensing mechanism, where the interaction with a dielectric sensing material modifies the effective capacitance and shifts the resonance. Thus, the final FOM in Equation (30) provides a unified metric connecting the resonance shift, sensitivity, and bandwidth for evaluating the proposed miniaturized 5G-IoMT microwave absorber.

CONCLUSION

The proposed study presents a compact metamaterial-inspired absorber for sub-6 GHz 5G-enabled Internet of Things (IoMT) microwave sensing, addressing the growing requirement for miniaturized, sensitive, and electromagnetically efficient healthcare sensing platforms. The developed concept combines a patterned resonator, dielectric substrate, and conducting ground plane to establish strong inductive-capacitive loading, impedance matching, suppressed transmission, and localized electromagnetic-field enhancement. The mathematical formulation demonstrates that resonance can be controlled through effective inductance and capacitance, while absorption is governed primarily by impedance matching between the absorber and free space. The proposed sensing mechanism exploits dielectric loading to produce measurable resonance frequency shifts, enabling the characterization of target materials and potentially biological parameters. The performance can be assessed through the absorption coefficient, resonance frequency, bandwidth, quality factor, sensitivity, and figure of merit. Overall, the proposed architecture provides a promising foundation for compact, low-profile, high-sensitivity microwave sensors integrated with future 5G IoMT healthcare systems, with experimental fabrication and measurement representing important next steps for practical validation.

REFERENCES

1. Tran MC, Pham VH, Ho TH, Nguyen TT, Do HT, Bui XK, et al. Broadband microwave coding metamaterial absorbers. Sci Rep. 2020;10(1):1810. doi:10.1038/s41598-020-58774-1. PMID:32020003.
2. Wang Q, Cheng Y. Compact and low-frequency broadband microwave metamaterial absorber based on meander wire structure loaded resistors. AEU Int J Electron Commun. 2020;120:153198. doi:10.1016/j.aeue.2020.153198.

© STM Journals 2026. All Rights Reserved

3. Hannan S, Islam MT, Almutairi AF, Faruque MRI. Wide bandwidth angle- and polarization-insensitive symmetric metamaterial absorber for X and Ku band applications. Sci Rep. 2020;10(1):10338. doi:10.1038/s41598-020-67262-5. PMID:32587313.
4. Hoque A, Islam MT, Almutairi AF, Chowdhury MEH, Samsuzzaman M. SNG and DNG meta-absorber with fractional absorption band for sensing application. Sci Rep. 2020;10:13086. doi:10.1038/s41598-020-69792-4. PMID:32753600.
5. Wang C, Huang M, Zhang Z, Xu W. Dual band metamaterial absorber: combination of plasmon and Mie resonances. J Mater Sci Technol. 2020;53:37–40. doi:10.1016/j.jmst.2020.02.058.
6. Islam MR, Islam MT, Moniruzzaman M, Samsuzzaman M, Arshad H. Penta band single negative meta-atom absorber designed on square enclosed star-shaped modified split ring resonator for S-, C-, X- and Ku-band microwave applications. Sci Rep. 2021;11(1):8784. doi:10.1038/s41598-021-87958-6. PMID:33888759.
7. Hannan S, Islam MT, Faruque MRI, Chowdhury MEH, Musharavati F. Angle-insensitive co-polarized metamaterial absorber based on equivalent circuit analysis for dual band WiFi applications. Sci Rep. 2021;11(1):13791. doi:10.1038/s41598-021-93322-5. PMID:34215833.
8. Kim Y, Park P, Jo J, Lee J, Jeong L, Shin J, et al. Ultrawideband electromagnetic metamaterial absorber utilizing coherent absorptions and surface plasmon polaritons based on double layer carbon metapatterns. Sci Rep. 2021;11(1):23045. doi:10.1038/s41598-021-02303-1. PMID:34845258.
9. Cao Y, Chen K, Ruan C, Zhang X. Robust and sensitive metamaterial-inspired microfluidic sensor for liquids with low dielectric constants. Sens Actuators A Phys. 2021;331:112869. doi:10.1016/j.sna.2021.112869.
10. Al-Duhni G, Wongkasem N. Metal discovery by highly sensitive microwave multi-band metamaterial-inspired sensors. Prog Electromagn Res B. 2021;93:1–22. doi:10.2528/PIERB21051606.
11. Hassan KMZ, Wongkasem N. Development of microwave metamaterial-inspired sensors with multiple-band reactivity for mercury contamination detection. J Electromagn Waves Appl. 2022;36(4):520–541. doi:10.1080/09205071.2021.1973914.
12. Bagci F, Gulsu MS, Akaoglu B. Dual-band measurement of complex permittivity in a microwave waveguide with a flexible, thin and sensitive metamaterial-based sensor. Sens Actuators A Phys. 2022;338:113480. doi:10.1016/j.sna.2022.113480.
13. Cao Y, Ruan C, Chen K, Zhang X. Research on a high-sensitivity asymmetric metamaterial structure and its application as microwave sensor. Sci Rep. 2022;12(1):1255. doi:10.1038/s41598-022-05255-2. PMID:35075165.
14. Garg P, Jain P. A review of metamaterial absorbers and their application in sensors and radar cross-section reduction. Microw Opt Technol Lett. 2023;65(2):387–411. doi:10.1002/mop.33496.
15. Jorwal S, Dubey A, Gupta R, Agarwal S. A review: advancement in metamaterial based RF and microwave absorbers. Sens Actuators A Phys. 2023;354:114283. doi:10.1016/j.sna.2023.114283.
16. Wang BX, Xu C, Duan G, Xu W, Pi F. Review of broadband metamaterial absorbers: from principles, design strategies, and tunable properties to functional applications. Adv Funct Mater. 2023;33(14):2213818. doi:10.1002/adfm.202213818.
17. Liang J, Ding F, Fu Y, Huang X, Jin J, Yang H. Metamaterial microwave sensor with ultrahigh Q-factor based on narrow-band absorption. Sens Actuators A Phys. 2023;364:114779. doi:10.1016/j.sna.2023.114779.
18. Lateef OS, Al-Badri M, Al-Badri KSL, Mohammed SA. Polarization-insensitive Archimedes'-spiral-shaped ultrathin metamaterial absorbers for microwave sensing application. Sci Rep. 2023;13(1):19445. doi:10.1038/s41598-023-46363-x. PMID:37945627.
19. Rabbani MG, Islam MT, Moniruzzaman M, Alamri S, Rahman AAM, Moubark AM, et al. Dumbbell shaped structure loaded modified circular ring resonator based perfect metamaterial absorber for S, X and Ku band microwave sensing applications. Sci Rep. 2024;14(1):5588. doi:10.1038/s41598-024-56251-7. PMID:38454118.
20. Sim MS, You KY, Dewan R, Esa F, Salim MR, Khe CS, et al. Microwave sensors loaded with metamaterial-inspired resonators for dielectric material characterization: a review. Sens Actuators A Phys. 2024;372:115322. doi:10.1016/j.sna.2024.115322.

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