Extended Abstract

Polarization-Independent High-Q Metamaterial Perfect Absorber for Microwave Refractive Index Sensing and Chemical Identification

Mehdi Askari*[,1], Sohrab Mohammadi Pouyan[2], Ehsan Menbari[1]

[1]Department of Physics, Faculty of Basic Science, Salman Farsi University of Kazerun, Kazerun, Iran
[2]Department of Electrical Engineering, Faculty of Engineering, Salman Farsi University of Kazerun, Kazerun, Iran

Received: 06.01.2026 Final revised: 27.07.2026 Accepted: 19.09.2026 Published On-Line: 06.10.2026

Doi: 10.22055/jrmbs.2026.21019

Abstract

Abstract In this study, a high-performance, polarization-independent metamaterial perfect absorber operating in the microwave regime is introduced and numerically investigated for refractive-index-based sensing applications. The proposed structure is based on a metal–dielectric–metal configuration and incorporates a concentric double-square double-layered resonator, enabling near-unity absorption at the resonance frequency of 5.489 GHz. This perfect absorption originates from strong electromagnetic field confinement and the excitation of surface plasmon modes at the metal–dielectric interfaces. Simulation results demonstrate that the proposed sensor exhibits high sensitivity, a large quality factor, and a considerable figure of merit. The maximum sensitivity, quality factor, and figure of merit are found to be 2.3 GHz/RIU, 166, and 48.9, respectively, exceeding those reported for many previously published microwave sensors. It is also shown that the device maintains stable performance under varying angles of incidence, with optimal sensing characteristics achieved at normal incidence. By appropriately scaling the structure, the resonance frequency is shifted to 8 GHz, enabling accurate discrimination among edible oils, brake fluids, and selected industrial solvents. These characteristics make the proposed metamaterial perfect absorber a promising platform for rapid, precise, and non-destructive chemical identification in industrial and environmental applications.

Keywords: Metamaterial perfect absorber, microwave sensor, refractive-index-based sensing, quality factor, figure of merit, plasmonic resonance, edible oils.

*Corresponding Author: mehdiaskari@kazerunsfu.ac.ir

This work is licensed under a Creative Commons Attribution 4.0 International License

1. Introduction

Metamaterial perfect absorbers provide engineered resonances that can strongly confine electromagnetic energy and approach unity absorption [1,2]. Their resonance frequency is highly sensitive to the dielectric environment, making them attractive for sensing applications. Microwave implementations are particularly suitable for non-contact and non-destructive characterization of materials such as oil and chemical liquids [3–5]. In this study, a simple polarization-independent high-Q MPA was investigated for refractive-index sensing and chemical identification. The study focused on the absorption mechanism, sensing performance, angular response, and a scaled demonstration for material discrimination.

2. Structure and Numerical Method

The unit cell consists of a copper–FR408–copper stack. The lower copper layer is a continuous ground plane, while the upper layer contains two concentric square cut-outs that form the resonant metallic element. The dielectric substrate is Isola FR408 with relative permittivity εr = 2.53. Copper is modeled as a lossy conductor with constant microwave conductivity. Full-wave simulations are performed in CST Microwave Studio using periodic boundaries and plane-wave excitation. The lateral symmetry of the unit cell gives a polarization-independent response. The calculated spectra show near-unity absorption at 5.489 GHz. Because the continuous ground plane suppresses transmission, high absorption is obtained primarily by reducing reflection at resonance.

3. Absorption Mechanism

The physical origin of the absorption peak was analyzed from the surface-current and field distributions.



Fig. 1. Unit-cell geometry, periodic arrangement, and excitation configuration of the proposed absorber.

4. Refractive-Index Sensing

The sensing mechanism is based on the electric field concentrated in the resonator gaps and between the metallic layers. Simulations were performed for n = 1.02, 1.04, 1.06, 1.08, and 1.10, and a systematic red shift was obtained.

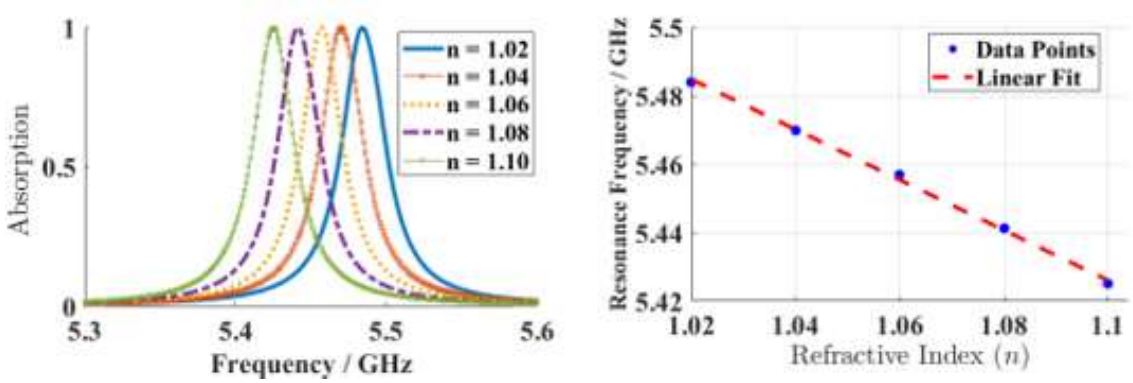


Fig. 2. Simulated absorption spectra for different refractive indices and the corresponding resonance-frequency shift.

The sensitivity was defined as $S = \Delta f/\Delta n$, while the figure of merit was obtained from the sensitivity and resonance linewidth. For the principal normal-incidence condition, the reported values are S = 1.25 GHz/RIU, FOM = 37.87 RIU^{-1}, and Q = 166. Over the investigated sensing conditions, the maximum reported values reached S = 2.3 GHz/RIU and FOM = 48.9 RIU^{-1}. These results combined a narrow resonance with a measurable frequency response to changes in the dielectric environment.

5. Angular Response

The response was also examined for oblique incidence. Increasing the incidence angle reduces the peak absorption and shifts the resonance, while the quality factor can increase. For the air-filled structure, Q reaches about 223.7 at 60°, with a resonance near 5.502 GHz. In the corresponding sensing simulations, the reported maximum FOM and Q are 33.64 RIU^{-1} and 172.4, respectively. The persistence of the resonance over the investigated angular range is associated with the subwavelength unit cell and localized LC response.

6. Geometrical Dependence and Performance.

A parametric study of the main geometrical dimensions was used to identify a suitable balance among sensitivity, FOM, and Q. Changes in the resonator dimensions modify the effective inductance and capacitance and consequently alter the resonance frequency and linewidth. The proposed design combines polarization-independent operation with Q = 166 and a normal-incidence sensitivity of 1.25 GHz/RIU. The comparison supports the relevance of the design for microwave sensing, while the present study remains numerical and does not include experimental validation [6–8].

7. Chemical Identification

To demonstrate a practical application, the geometry was scaled so that the resonance moved from 5.489 GHz to approximately 8 GHz. This frequency was selected because dielectric-constant data for several liquids were available at 8 GHz [5]. The test set includes edible oils, brake fluids, and carbon tetrachloride. The reported resonance frequencies for olive oil and corn oil are approximately 8.009 and 7.763 GHz, respectively, giving a separation of about 246 MHz. The distinct spectral positions obtained for the other materials also demonstrate the potential of resonance tracking for material identification.

8. Conclusions

A polarization-independent microwave metamaterial perfect absorber based on a copper–dielectric–copper configuration and a concentric double-square resonator was numerically demonstrated. Near-unity absorption occurred at 5.489 GHz through coupled electric and magnetic resonances and free-space impedance matching. The proposed structure provided Q = 166, while the maximum reported sensitivity and FOM reached 2.3 GHz/RIU and 48.9 RIU^{-1}. Its response remains useful under oblique incidence and preserves polarization independence. Following scaling to approximately 8 GHz, distinct resonance shifts were obtained for several oils, brake fluids, and carbon tetrachloride, indicating potential for non-contact material identification. The main limitation is the absence of experimental fabrication and measurement. Future studies should investigate fabrication tolerances, material losses, conductor roughness, and experimental measurement conditions. Experimental validation is therefore required before practical performance can be established.

References

[1] J.B. Pendry, D. Schurig, D.R. Smith, Controlling electromagnetic fields, Science, 312 (2006) 1780–1782. https://doi.org/10.1126/science.1125907

[2] M. Askari, A scheme for increasing the sensitivity of metal–insulator–metal perfect absorber sensors, Optik, 338 (2025) 172477.
https://doi.org/10.1016/j.ijleo.2025.172477

[3] N. Kazemi, M. Abdolrazzaghi, P. Musilek, E. Baladi, A Planar Compact Absorber for Microwave Sensing Based on Transmission-Line Metamaterials, IEEE Sens. J. 24 (2024) 41864–41874.
DOI: 10.1109/JSEN.2024.3484585

[4] Y. Yao, Z. Liao, Z. Liu, X. Liu, J. Zhou, G. Liu, Z. Yi, J. Wang, Recent progresses on metamaterials for optical absorption and sensing: A review, J. Phys. D: Appl. Phys. 54 (2021) 113002.
DOI: 10.1088/1361-6463/abccf0

[5] M.R. Islam, M.T. Islam, M.M. Salaheldeen, B. Bais, S.H.A. Almalki, H. Alsaif, M.S. Islam, Metamaterial sensor based on rectangular enclosed adjacent triple circle split ring resonator with good quality factor for microwave sensing application, Sci. Rep. 12 (2022) 6792.
https://doi.org/10.1038/s41598-022-10729-4

[6] H. Zhu, Y. Zhang, L. Ye, Y. Li, Z. Dang, R. Xu, B. Yan, A high Q-factor metamaterial absorber and its refractive index sensing characteristics, IEEE Trans. Microw. Theory Tech. 70 (2022) 5383–5391. https://doi.org/10.1109/TMTT.2022.3218041

[7]] J. Liang, F. Ding, S. Li, H. Cheng, X. Zhou, C. Wang, H. Yang, J. Jin, Microwave metamaterial sensor with a high Q factor to measure complex permittivity based on cross-polarization conversion, Opt. Express, 33 (2025) 20918–20928.
https://doi.org/10.1364/OE.561277

[8] M.A. Khalil, Y. Wong Hin, T. Batool, A. Hoque, L.Y. Chiong, H.H. Goh, T.A. Kurniawan, M.S. Soliman, M.T. Islam, Highly sensitive split ring resonator-based sensor for quality monitoring of edible oils, Sci. Rep. 15 (2025) 2283.
https://doi.org/10.1038/s41598-025-85800-x

[9] K.P. Kaur, T. Upadhyaya, K. Pandya, U. Patel, Ultrathin high Q-factor perfect metamaterial absorber for sensing applications, IEEE Wireless Antenna and Microwave Symposium (WAMS), 2023.
https://ieeexplore.ieee.org/document/10242878