Original Article

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TMU Journal of Basic & Applied Chemistry
Vol.5
Jan-December, 2025: P.56-59

Infrared Metamaterial Absorbers: A Comprehensive Review of Design Strategies, Mechanisms, and Applications

Abstract

Copper Oxide nanoparticles were synthesized by a simple synthetic route involving hydrothermal method at 120 °C, and it is effectively characterized by various techniques, such as XRD, FESEM, and UV-vis DRS. UV-vis DRS and showed a reflection edge with corresponding energy at 2.2 eV. The photocatalytic degradation activity of the Copper Oxide nanoparticles was investigated against the degradation of methylene blue under natural sunlight irradiation. About 65% degradation of methylene blue is observed in 150 min.

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Received on: 16.10.2025

Revised on: 24.10.2025

Accepted on: 31.10.2025

Keywords: IMAs, LWIR, MWIR, Dielectric spacer, Plasmon resonance,

Introduction

Metamaterials are artificially engineered materials composed of subwavelength unit cells that exhibit electromagnetic properties not found in natural substances[1]. Infrared metamaterial absorbers (IMAs) are designed to achieve high absorption efficiency within the infrared region by controlling wave-matter interactions through tailored resonances. These absorbers have become crucial in defense, thermal regulation, sensing, and energy applications due to their unique ability to manipulate light at the nanoscale.[2]

Conventional infrared absorbers often rely on bulk materials, which limit spectral tunability and efficiency. Metamaterials overcome this limitation by introducing resonant effects that enable selective and efficient absorption[3]. The performance of IMAs depends on the interaction between their structural design and material properties, which determine resonance behavior and spectral response.

Design Approaches and Structural Configurations

A typical IMA follows a metal–dielectric–metal (MDM) configuration comprising three primary layers: (1) a patterned top metallic resonator, (2) a dielectric spacer layer, and

(3) a continuous metallic ground plane[4]. The resonator defines spectral selectivity, while the spacer controls impedance matching and field confinement. The ground plane blocks transmission, ensuring all incident radiation is either absorbed or reflected.

Materials such as tungsten (W), titanium nitride (TiN), and indium tin oxide (ITO) serve as excellent conductors with high-temperature stability. Dielectrics like zinc selenide (ZnSe), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3) provide low-loss behavior in the mid- to far-infrared regime. The design parameters—including disk radius, periodicity, and spacer thickness—critically affect the resonance wavelength and absorption amplitude.

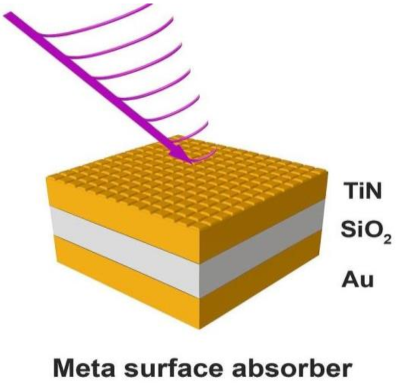

Figure 1. 3D schematic of a generalized MDM metamaterial absorber composed of a titanium nitride (TiN) top layer, a silicon dioxide (SiO_2) dielectric spacer, and a gold (Au) substrate. The structure demonstrates selective absorption of incident infrared radiation.

Absorption Mechanisms

The absorption characteristics of IMAs arise primarily from localized surface plasmon resonance (LSPR), magnetic dipole resonance, and Fabry–Perot interference. When electromagnetic waves interact with metallic nanostructures, collective oscillations of free electrons are induced at specific resonance frequencies, resulting in LSPR. This produces enhanced electric fields at the metal–dielectric interface, facilitating high absorption. Meanwhile, Fabry–Perot resonance occurs when multiple reflections within the dielectric cavity lead to constructive interference, maximizing the electric field intensity[3].

These mechanisms can coexist, leading to dual-band or multi-band absorption behavior. Adjusting resonator geometry allows precise tuning of the resonance peaks to match specific infrared regions. The combination of impedance matching and energy dissipation ensures minimal reflection and transmission, leading to near-unity absorption.

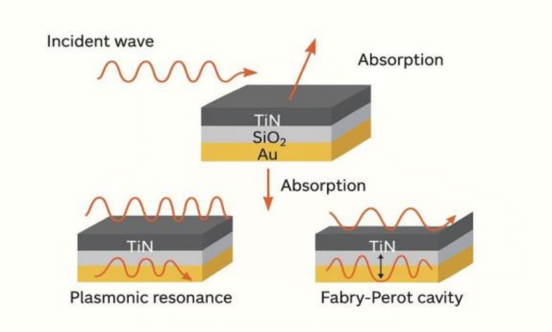

Figure 2. Schematic illustration of the absorption mechanisms in an MDM metamaterial absorber, highlighting the roles of plasmonic resonance and Fabry–Perot cavity effects. The incident electromagnetic wave interacts with the TiN–SiO_2–Au layered structure, where surface plasmon resonance at the metal–dielectric interface and multiple reflections within the cavity lead to enhanced field confinement and strong absorption.

Comparative Study of Reported Designs (2019–2025)

Ref	**Material System**	**Mechanism**	**Wavelength Range**	**Absorption (%)**	**Application**
[5]	Au/SiO2/Au	Plasmonic + FP	3–8 µm	98	Stealth
[6]	Au/Al2O3/Si	LSPR + FP	3–10µm	97	Thermal Control
[7]	$\mathrm{Cr/Si_3N_4}$	Magnetic Dipole	5–10 µm	95	Energy Harvesting
[8]	Ag/ITO/ZnO	LSPR	4–9 µm	99	Sensing
[9]	$\mathrm{W/Al_2O_3/W}$	Impedance Matched	2–20 µm	96	Stealth

Applications of Infrared Metamaterial Absorbers

Infrared metamaterial absorbers serve in diverse technological domains such as stealth, infrared camouflage, photothermal energy conversion, and environmental sensing. Their ability to suppress reflection in specific IR bands makes them ideal for reducing thermal signatures in defense applications. In sensing and detection, their high field confinement enables precise detection of minute changes in refractive index or temperature[10].

IMAs are also increasingly explored for thermophotovoltaic devices and radiative cooling applications. Their capacity to control emissivity and thermal radiation directionality offers significant promise in energy and aerospace engineering.

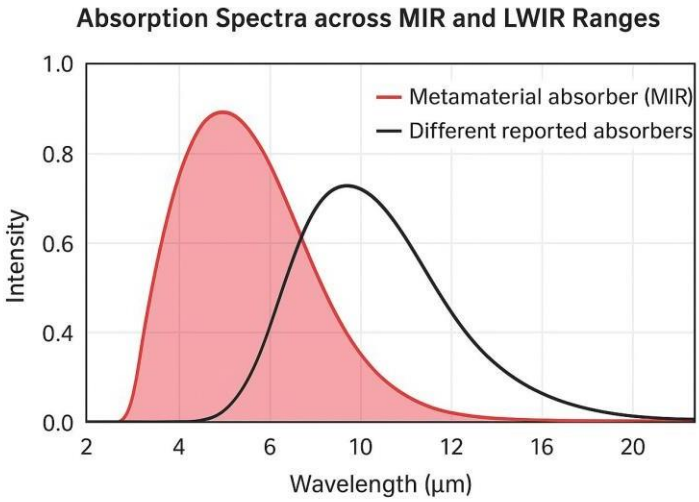

Figure 3. Absorption spectra comparison across mid-wave infrared (MWIR) and long-wave infrared (LWIR) ranges for various reported absorbers. The metamaterial absorber demonstrates strong absorption in the MWIR region, while other absorbers show peak response in the LWIR range, highlighting the tunable nature of metamaterial-based infrared absorbers[11].

Challenges and Future Perspectives

Despite extensive research, certain limitations remain. The scalability of fabrication techniques, material losses at higher frequencies, and environmental stability pose challenges for large-scale applications. To address these issues, future work may focus on adaptive metamaterials based on phase-change materials (e.g., VO_2, GST) or two- dimensional conductors (e.g., graphene). Machine-learning-based optimization of geometric parameters also presents opportunities for accelerating absorber design.

Conclusion

Infrared metamaterial absorbers represent a vital class of engineered materials with tunable spectral responses and near-unity absorption. Through precise design of resonator geometry and dielectric thickness, dual-band and broadband absorption can be achieved across MWIR and LWIR regions. Advancements in fabrication and material innovation will continue to expand their applications in stealth, thermal management, and sensing.

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