

Metamaterial Absorbers: Review

A PROJECT REPORT
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF SCIENCE IN PHYSICS

Submitted by:
DEVANSHI SEN (23/MSCPHY/17)

Under the supervision of

DR. KAMAL KISHOR



DEPARTMENT OF APPLIED PHYSICS
DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

JUNE, 2025

DEPARTMENT OF APPLIED PHYSICS
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, DEVANSHI SEN(2k23/PHY/17) hereby certify that the work which is presented in the Major Project-II/Research Work entitled in fulfillment of the requirement for the award of the Degree of Master of Science in Physics, and submitted to the Department of Applied Physics, Delhi Technological University, Delhi, is an authentic record of my/our own, carried out during a period from September 2024 to June 2025 under the supervision of Dr. Kamal Kishor. The matter presented in this report/thesis has not been submitted by us/me for the award of any other degree of this or any other Institute/University.

Place: Delhi

Date: dd.mm.yyyy

DEVANSHI SEN

CERTIFICATE

To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I, further certify that the publication and indexing information given by the students is correct.

Place: New Delhi

Date: dd.mm.yyyy

DR. KAMAL KISHOR

(SUPERVISOR)

ABSTRACT

Metamaterials are man-made structures that exhibit extraordinary electromagnetic properties not typically found in natural materials. These unique materials hold great promise for a variety of advanced applications, one of the most prominent being metamaterial absorbers. The design of such absorbers relies on the simultaneous excitation of electric and magnetic dipole resonances. A standard metamaterial absorber consists of a three-layer structure: a top layer featuring metallic patterns at subwavelength scales, a metallic ground plane at the bottom, and a dielectric (insulating) layer sandwiched in between. The top patterned layer acts as an electric resonator, interacting with the electric field of incoming electromagnetic waves.

Meanwhile, the magnetic response arises from the interplay between the two metallic layers and the intervening dielectric. To block wave transmission, the ground layer must be thicker than the skin depth. By adjusting the geometry of these structural components, one can tune the effective permittivity and permeability, allowing the structure to match the impedance of free space, which results in perfect absorption at specific wavelengths. In recent years, the need for chemical and biological sensing has driven the development of mid-infrared perfect metamaterial absorbers. This thesis focuses on literature review of various metamaterial absorbers and its other application.

DEPARTMENT OF APPLIED PHYSICS
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

ACKNOWLEDGEMENT

I wish to express our sincerest gratitude to Dr. Kamal Kishor for his continuous guidance and mentorship that he provided us during the project. He showed us the path to achieve our targets by explaining all the tasks to be done and explained to us the importance of this project as well as its industrial relevance. He was always ready to help us and clear our doubts regarding any hurdles in this project. Without his constant support and motivation, this project would not have been successful.

Place: Delhi

DATE: dd.mm.yyyy

DEVANSHI SEN

(23/MSCPHY/17)

CONTENTS

Candidate's Declaration

Certificate

Abstract

Acknowledgement

Contents

List of figures

List of Symbols, abbreviations

1. Introduction

- 1.1 Introduction of Metamaterials
- 1.2 Types of Metamaterials
- 1.2 Metamaterial Absorber

2. Metamaterial Overview

- 2.1 Metamaterial background
- 2.2 Electromagnetic Theory and Wave Propagation
- 2.2 Absorption equation and impedance matching
- 2.3 Absorption Mechanisms and Perfect Absorption Conditions
- 2.4 Computational Design and Simulation Methods
- 2.5 Multi-Resonance and Broadband Design Strategies
- 2.6 Polarization Independence and Angular Stability

3. Literature Review

- 3.1 Plasmonic Metamaterial
- 3.2 Broadband metamaterial absorber at midinfrared using multiplexed cross resonators'
- 3.3 Design of Tunable Perfect Absorbers in the Mid-IR Spectrum Using Graphene-Based Multilayer Structures: Emerging Applications in Atmospheric Window Matching
- 3.4 Broadband and Polarization-Insensitive Absorption Based on a Set of Multisized Fabry–Perot-like Resonators
- 3.5 Highly Transparent Broadband and Polarization-Insensitive Absorber Based on Metasurface

4. Conclusion

5. References

6. Appendix

- 6.1 Plagiarism Report

List of Figures

1. **Figure 1.1.1:** Metamaterial absorbers
2. **Figure 3.1.1:** Response curve of SRR made up from silver metal
3. **Figure 3.1.2** SRR curve for materials
4. **Figure 3.2.1** Schematic diagrams of the unit cells for (a) sample A, (b) sample B, and (c) sample C are shown. The ground plane consists of a 100 nm thick gold layer, while the metallic patterns are made of 60 nm thick gold. All samples include a 190 nm thick SiO₂ dielectric layer.
5. **Fig. 3.3.1.** Proposed PA: graphene-dielectric stack between PbSe layers on a gold substrate (~2 μm thick)..
6. **Fig. 3.3.2.** GOA enhances absorption at 4 μm in Structure 1 vs. non-optimized variants with varying layer thicknesses
7. **Figure 3.4.1.** Illustration of the fabrication steps and an SEM image of the truncated-cone-shaped metamaterial. a) Deposition of stacked Au–ZnO multilayers using magnetron sputtering. (b) Patterning of a hole array in PMMA through lithography. c) Formation of an aluminum tapered plate array on the Au–ZnO multilayers via electron beam evaporation followed by a lift-off process. (d) Use of ion beam etching to produce the multilayer nanostructures with a truncated cone shape. (e) SEM image taken at a 52° tilt, showing the truncated-cone-type metamaterial with a period (P) of 1.5 μm and a structure consisting of five Au–ZnO pairs
8. **Figure 3.4.2** Measured vs. simulated absorption for TCMA with five Au–ZnO pairs, varying geometry; SEM insets show sample structure
9. **Figure 3.5.1.** Illustration of the absorber design and its corresponding CST MWS simulation setup. (a) Physical structure of the absorber, (b) simulation model created in CST MWS.
10. **Figure 3.5.2.** Properties of the designed absorber

List of Symbols, abbreviations

1. $\epsilon(\omega)$; permittivity
2. $\mu(\omega)$; permeability
3. **MDM**: metal-dielectric-metal
4. σ : electrical conductivity
5. **EM**: electromagnetic
6. **PMA**: perfect metamaterial absorber
7. **PML**: perfectly matched layers
8. **n**: refractive index
9. **Z(ω)**: Impedance
10. **MGA**: micro-genetic algorithm

Introduction

1.1 WHAT ARE METAMATERIALS?

Metamaterials are a class of artificial materials engineered to exhibit electromagnetic properties not typically found in nature. These materials derive their unique behavior not from their chemical composition but from their precisely designed internal micro- or nano- scale structure. By arranging subwavelength-scale building blocks in periodic or quasi- periodic patterns, metamaterials can manipulate electromagnetic waves in highly unusual and often counterintuitive ways. One of the earliest and most significant theoretical milestones in the study of metamaterials came in 1968 when Russian physicist Victor Veselago proposed the existence of materials with simultaneously negative electric permittivity (ϵ) and magnetic permeability (μ). He theorized that such materials would exhibit a negative index of refraction, leading to phenomena such as reverse Snell's law, reverse Doppler effect, and backward wave propagation. While Veselago's ideas were groundbreaking, they remained speculative until technological advancements in the late 20th century enabled the fabrication of materials with subwavelength structural elements that could realize these theoretical predictions. In the early 2000s, the first experimental realization of a negative-index metamaterial was achieved by Smith et al., who used split-ring resonators and conducting wires to fabricate a composite structure that exhibited negative refractive index behavior at microwave frequencies. This landmark achievement confirmed that metamaterials could be constructed to produce tailored electromagnetic responses and spurred a wave of research across the fields of optics, materials science, and applied physics.

Metamaterials can be characterized by their effective medium parameters: effective permittivity $\epsilon(\omega)$ and effective permeability $\mu(\omega)$, which are typically complex-valued and frequency-dependent. These parameters describe how the material responds to electric and magnetic fields and determine its interaction with electromagnetic radiation. By tuning the geometry, size, orientation, and composition of the unit cells, researchers can design materials with highly specific and controllable electromagnetic responses. One of the most impactful applications of metamaterials is in the development of metamaterial absorbers. These devices are designed to achieve near-perfect absorption of incident electromagnetic waves over specific frequency bands. A perfect metamaterial absorber (PMA) functions by simultaneously eliminating reflection and transmission, thereby converting all incoming electromagnetic energy into heat or other forms of energy. This is typically accomplished through a three-layer metal-dielectric-metal (MDM) structure, where electric and magnetic resonances are engineered to overlap at the same frequency. The top layer often contains a patterned metallic resonator, the middle layer serves as a dielectric spacer, and the bottom layer is a continuous metallic ground plane that prevents transmission. The unique ability of metamaterials to control and localize electromagnetic fields has led to a diverse range of applications. These include super-resolution imaging (or "superlensing"), cloaking devices that render objects invisible to certain frequencies, antennas with improved performance, and sensors with enhanced sensitivity. In the terahertz and infrared regions, metamaterials have shown great promise in areas such as chemical and biological sensing, thermal emission control, and energy harvesting. The field has also seen significant development in the design of broadband and multiband metamaterials. These structures are capable of interacting with electromagnetic waves over a wide range of frequencies, which is crucial for applications

like broadband absorbers, multifunctional sensors, and adaptive camouflage. Techniques to achieve broadband response include the use of multiple resonator geometries, stacked layers, graded-index profiles, and non-resonant absorptive materials.

Despite their many advantages, metamaterials also pose certain challenges. The fabrication of complex nanostructures, particularly for applications in the visible and near-infrared ranges, requires advanced lithography and nanomanufacturing techniques. Additionally, the inherent losses in metallic components at high frequencies can limit the efficiency of metamaterial-based devices. Nonetheless, ongoing advancements in material science, computational modeling, and fabrication technologies continue to push the boundaries of what is possible with metamaterials. In conclusion, metamaterials represent a transformative concept in material design, enabling unprecedented control over electromagnetic phenomena. From theoretical origins to practical devices, they have opened new frontiers in science and engineering. As research continues, metamaterials are poised to play a pivotal role in the next generation of photonic, electronic, and sensing technologies. Metamaterials are capable of producing unconventional electromagnetic responses because they are made up of subwavelength-scale resonant structures. These unique behaviors result from the resonance phenomena of these tiny elements. The way waves propagate in a material is governed by its inherent properties—namely, dielectric permittivity (ϵ), magnetic permeability (μ), and electrical conductivity (σ). In 1968, Victor Veselago theoretically analyzed the behavior of electromagnetic waves in materials with both negative permittivity and negative permeability. He discovered that, in such materials, the group velocity moves in the opposite direction of the Poynting vector, a phenomenon not seen in traditional materials. This work laid the theoretical foundation for negative-index materials. In 1999, Smith et al. provided the first experimental demonstration of a material exhibiting both negative ϵ and μ . Shortly after, Pendry further explained how these properties give rise to a negative refractive index. These breakthroughs triggered a surge of research across various frequency ranges, from microwave to optical regions. Metamaterials are often described using effective complex parameters: permittivity $\epsilon(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$ and permeability $\mu(\omega) = \mu_1(\omega) + i\mu_2(\omega)$. By fine-tuning these parameters, scientists can create materials with properties that do not occur in nature, such as a negative refractive index or reverse wave propagation. Typically, metamaterials are made from periodic metallic structures that are engineered to resonate at selected frequencies. Unlike traditional materials, whose electromagnetic behavior depends largely on their chemical makeup, metamaterials derive their properties from their physical structure and layout.

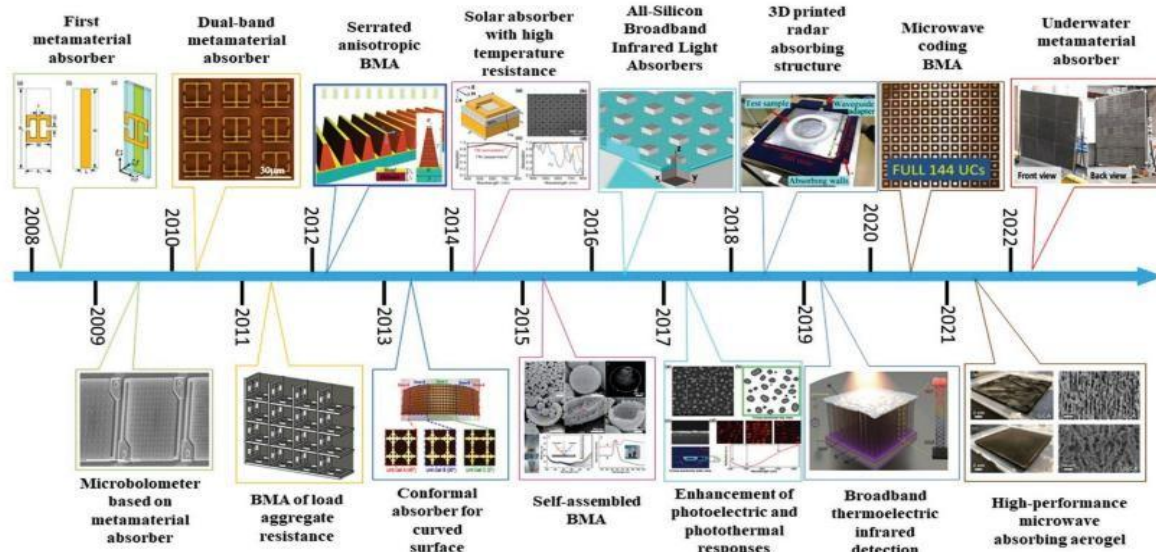


Figure 1.1.1: Metamaterial absorbers. [6]

1.2 Metamaterial Absorbers

Metamaterial absorbers are artificially engineered structures designed to achieve high or even near-perfect absorption of incident electromagnetic (EM) waves over specific frequency ranges. Unlike traditional absorptive materials, where absorption primarily arises from intrinsic material losses, metamaterial absorbers rely on the geometry and arrangement of subwavelength resonators to manipulate electromagnetic responses such as permittivity (ϵ) and permeability (μ). These structures can be tailored to exhibit resonances at desired frequencies, allowing for highly controlled interaction with incident waves.

The first perfect metamaterial absorber (PMA) was proposed by Landy et al. in 2008, which demonstrated 88% absorption at 11.5 GHz using a design that included a split-ring resonator, a dielectric spacer, and a cut wire on a ground plane. The absorption mechanism in this configuration arises from the impedance matching to free space and the generation of anti-parallel currents that result in strong magnetic coupling within the dielectric layer. Since then, this concept has been significantly refined through variations in unit cell geometry, materials, and structural layering.

Subsequent research extended these absorbers to the terahertz and infrared ranges. Multi-layer and multi-resonator designs enabled the development of multi-band and broadband absorbers, where multiple absorption peaks are achieved either by stacking resonators of different sizes or through structural designs like sawtooth and fractal geometries. Such broadband absorbers can maintain high absorption over a wide frequency range and for various incident angles and polarizations.

Applications of metamaterial absorbers are vast, including thermal emitters, sensors, radar cross-section reduction, solar energy harvesting, and imaging systems. However, challenges remain in fabricating complex multilayer structures, particularly at shorter wavelengths such as the mid-infrared and visible regions, where precise nano-fabrication is required. Continued

advancements in design optimization, material choice, and fabrication techniques are essential to realizing practical, broadband, polarization-independent, and angle-insensitive metamaterial absorbers across the electromagnetic spectrum. By exploiting dielectric loss within metamaterials, strong electromagnetic (EM) wave absorption can be achieved, leading to what is known as perfect absorption. The concept of a perfect metamaterial absorber (PMA) was first introduced by Landy et al. in 2008. Their structure included a metallic split-ring resonator, a dielectric layer, and a copper cut wire, reaching 88% absorption at 11.5 GHz. This configuration allows coupling between electric and magnetic fields through anti-parallel currents, influenced by the dielectric material thickness and the resonator dimensions. Later developments showed that altering the dielectric thickness or the size of the resonant unit cell can shift the frequency response. To simplify fabrication, researchers replaced the cut wire with a continuous metal ground plane. Due to their high absorption and tunability, PMAs have been applied in areas like solar energy collection, sensors, imaging systems, and thermal emitters.

Building on Landy's design, Tao et al. demonstrated a flexible terahertz PMA that maintained over 99% absorption across a wide range of angles and both TE and TM polarizations. In 2010, they also developed a dual-band absorber using two electric-field-coupled resonators, achieving absorption peaks at 1.4 and 3.0 THz. Ma et al. extended this by designing a symmetric, polarization-insensitive structure with concentric square rings, yielding two peaks at 2.7 and 5.2 THz.

Broadband absorbers have been achieved by stacking resonators of different sizes. For example, Abul et al. created a metasurface absorber with multiple gold nano-resonators, offering wide-angle and polarization-independent performance. Cui et al. proposed a sawtooth multi-layer absorber for infrared use, capturing various frequencies at different structural depths. Although multi-layered PMAs perform well in microwave and terahertz ranges, fabricating them for the infrared spectrum is challenging due to micro-scale lithography limits. Alternative geometries, such as square, circular, or cross-shaped resonators, have been explored—however, broadband absorbers using raindrop-shaped resonators are still rarely reported.

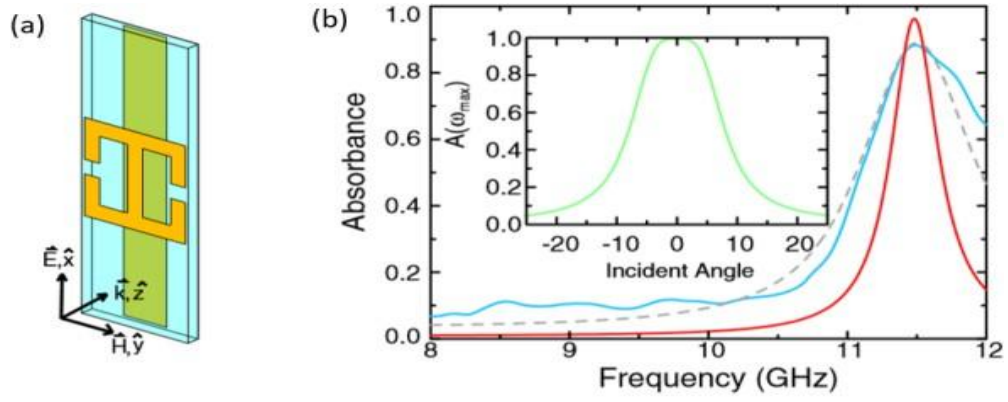


Figure 1.1: Absorber structure and its absorption spectra [1].

Metamaterial Overview

2.1 METAMATERIAL BACKGROUND

The conceptual foundation of metamaterial absorbers traces back to Victor Veselago's pioneering theoretical work in 1968, when he first suggested that materials might possess negative values for both permittivity and permeability. Veselago's groundbreaking analysis demonstrated that such materials would exhibit extraordinary electromagnetic properties, including negative refractive indices and reversed electromagnetic wave propagation characteristics. However, the practical realization of these concepts remained elusive for over three decades due to the absence of suitable materials and insufficient computational capabilities to design and analyze complex metamaterial structures.

The renaissance of metamaterial research occurred at the turn of the millennium when John Pendry of Imperial College London developed theoretical frameworks for creating artificial magnetic materials using structured copper elements. This work provided the essential bridge between Veselago's theoretical predictions and practical implementation possibilities.

Subsequently, David Smith and colleagues at the University of California San Diego achieved the first experimental demonstration of left-handed metamaterials operating at microwave frequencies, thereby validating the fundamental concepts and opening new avenues for electromagnetic device development.

2.2 Electromagnetic Theory and Wave Propagation

Contemporary metamaterial absorber design relies on sophisticated understanding of electromagnetic wave interactions with structured materials. The fundamental governing equations for electromagnetic wave propagation in metamaterial structures are derived from Maxwell's equations, which describe the relationships between electric and magnetic fields in the presence of material discontinuities and sub-wavelength structural elements. In metamaterial absorbers, the periodic arrangement of metallic and dielectric components creates effective medium properties that can be characterized by equivalent permittivity and permeability parameters.

The wave equation for electromagnetic propagation in metamaterial structures takes the form of coupled differential equations that account for both spatial field variations and frequency-dependent material responses. For time-harmonic electromagnetic fields, the complex permittivity $\epsilon(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$ and permeability $\mu(\omega) = \mu_1(\omega) + i\mu_2(\omega)$ determine the material's electromagnetic response characteristics. The refractive index $n = \sqrt{\epsilon_r \mu_r}$ and wave impedance $Z = \sqrt{\mu/\epsilon}$ provide critical parameters for characterizing metamaterial absorber performance and optimizing impedance matching conditions.

2.3 Absorption Mechanisms and Perfect Absorption Conditions

Perfect electromagnetic absorption in metamaterial structures occurs when incident electromagnetic waves are completely converted to other forms of energy, typically heat, without reflection or transmission. The fundamental condition for perfect absorption requires simultaneous achievement of zero reflection and zero transmission, which can be expressed mathematically as $A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$. In practical metamaterial absorber designs with metallic ground planes, transmission is inherently suppressed ($S_{21} = 0$), simplifying the design requirement to minimizing reflection through impedance matching.

The impedance matching condition for perfect absorption requires that the surface impedance of the metamaterial structure equals the free space impedance $Z_0 = 377\Omega$ [1]. This condition can be achieved through careful optimization of the metamaterial geometry, material selection, and structural parameters to satisfy $|S_{11}(\omega)| = |(Z(\omega) - Z_0)/(Z(\omega) + Z_0)| = 0$. Modern metamaterial absorber designs employ various physical mechanisms to achieve this impedance matching, including electric and magnetic resonances, surface plasmon effects, and interference phenomena.

2.4 Computational Design and Simulation Methods

Modern metamaterial absorber development relies heavily on advanced computational electromagnetics techniques to model complex electromagnetic interactions and optimize design parameters. The finite element method (FEM) has emerged as the predominant computational approach for metamaterial simulation due to its ability to handle complex geometries, material discontinuities, and multiphysics coupling effects. Commercial simulation platforms such as COMSOL Multiphysics provide comprehensive capabilities for three-dimensional electromagnetic modeling, including frequency-domain and time-domain analysis methods.

The FEM approach for metamaterial absorber simulation involves discretizing the computational domain into small finite elements, with electromagnetic field quantities determined at element nodes through variational formulations of Maxwell's equations. Advanced meshing strategies are essential for accurately capturing electromagnetic field distributions near metallic structures and material interfaces, where field enhancement and rapid spatial variations occur. Perfectly matched layers (PML) are commonly employed as absorbing boundary conditions to simulate infinite domain electromagnetic wave propagation without spurious reflections.

Recent developments in metamaterial simulation have incorporated artificial intelligence and machine learning techniques to accelerate design optimization and parameter exploration. Generative Adversarial Networks (GANs) and Multi-Layer Perceptron (MLP) networks are being employed to predict electromagnetic responses and generate optimized metamaterial geometries with reduced computational requirements. These AI-driven approaches enable rapid exploration of design spaces that would be computationally prohibitive using traditional optimization methods.

2.5 Multi-Resonance and Broadband Design Strategies

Achieving broadband electromagnetic absorption represents one of the most significant challenges in metamaterial absorber design, as individual resonant elements typically produce narrow absorption bandwidths. Contemporary design approaches employ multiple resonance mechanisms to extend absorption bandwidth through careful orchestration of overlapping resonant responses. Multi-resonator configurations incorporate structural elements of different sizes and shapes within single unit cells to generate multiple absorption peaks that can be merged into continuous broadband responses.

The theoretical framework for multi-resonance metamaterial design involves analyzing coupling interactions between adjacent resonant modes and optimizing their frequency separation to achieve desired bandwidth characteristics. Genetic algorithms and particle swarm optimization techniques are commonly employed to determine optimal geometric parameters for multi-resonant structures. These optimization approaches can achieve absorption bandwidths exceeding 200% improvement over single-resonance designs through systematic bandgap merging strategies. Alternative broadband design strategies include multilayer metamaterial configurations with vertically stacked resonant elements separated by dielectric spacers. While these approaches can achieve impressive bandwidth performance, they require more complex fabrication processes and increased overall thickness compared to single-layer designs. Hybrid approaches combining multi-resonance and multilayer strategies offer potential for achieving ultra-broadband absorption while maintaining practical fabrication constraints.

2.6 Polarization Independence and Angular Stability

Polarization-insensitive operation represents a critical requirement for many metamaterial absorber applications, particularly in communication systems and sensing applications where incident wave polarization cannot be controlled. Achieving polarization independence requires metamaterial unit cell designs with rotational symmetry or symmetric response characteristics for both transverse electric (TE) and transverse magnetic (TM) polarization modes. Four-fold rotational symmetry is commonly employed in metamaterial absorber designs to ensure equivalent electromagnetic responses for arbitrary linear polarization orientations. Angular stability extends the operational capabilities of metamaterial absorbers to accommodate oblique incidence conditions commonly encountered in practical applications. Maintaining high absorption efficiency across wide angular ranges requires careful consideration of impedance matching conditions as functions of incident angle and polarization. Advanced metamaterial designs incorporate structural modifications such as vertical metallic through-holes and three-dimensional geometries to enhance angular stability performance.

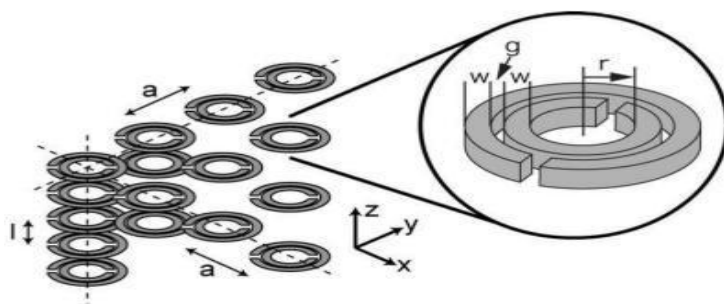
Recent research has demonstrated metamaterial absorbers maintaining over 85% absorption efficiency for incident angles up to 70° for both TE and TM polarization modes. These achievements represent significant advances in developing practical metamaterial absorber systems suitable for real-world deployment scenarios where precise alignment and polarization control may not be feasible.

LITERATURE REVIEW

3.1 Plasmonic Metamaterials

Takuo Tanaka (2012)

The author starts by discussing basics of metamaterial and then discussed a split ring resonators (SRR). The author discusses it's geometry and then calculates impedance, reactance and permeability of SRR.



Then the response curve of SRR is studied

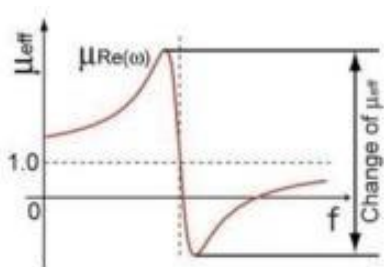


Figure 3.1.1: Response curve of SRR made up from silver metal [1]

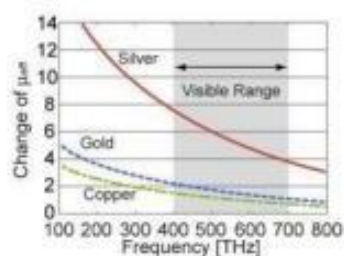


Figure3.1.2 SRR curve for materials [1]

3.2 Broadband metamaterial absorber at mid infrared using multiplexed cross resonators

Wei Ma et al.(2013)

Metamaterial absorbers (MAs) have drawn significant attention due to their ultra-thin form factor, light weight, and strong resonant absorption characteristics. Unlike traditional bulky absorbers, which rely on quarter-wavelength thickness for effective absorption, metamaterial absorbers can achieve near-perfect absorption with subwavelength thicknesses. This makes them highly suitable for applications requiring compact and efficient absorption of electromagnetic (EM) waves.

Evolution from Single- to Broadband Absorbers

Initially, most metamaterial absorbers were designed for single-band absorption, which limited their practical applications. To overcome these constraints, researchers developed multi-band metamaterial absorbers, capable of absorbing multiple discrete frequencies. However, multi-band absorbers still suffered from spectral discontinuity, making them unsuitable for applications like radar stealth, IR detection, or broadband energy harvesting.

This motivated the emergence of Broadband Metamaterial Absorbers (BMAs), designed to exhibit high absorption over a continuous frequency range. Various strategies have been employed to broaden the absorption bandwidth, including geometric tailoring, multi-resonator superposition, and slow-light waveguide effects.

Key Mechanisms in BMAs

The review outlines four key physical mechanisms used in broadband design:

1. **Resonance Peak Superposition:** Combining multiple resonant elements of varying sizes to overlap their individual peaks, effectively expanding the absorption band.
2. **Slow Light Waveguide Effect:** Employing structured dielectric-metal interfaces to reduce group velocity, increasing interaction time and enabling broadband absorption.
3. **Quality Factor (Q-Factor) Reduction:** Integrating resistive or lossy elements to flatten and broaden the absorption profile.

4. Hybrid Material Light Capture: Utilizing material combinations (e.g., graphene, metal-organic frameworks) with intrinsic broadband light absorption capabilities.

Design Strategies

BMA s are fabricated through several approaches:

- Top-down lithography: Precise control over resonator shape and periodicity using techniques like electron beam lithography. Variants include planar, vertical, and coded patterning.
- Bottom-up self-assembly: Leveraging material properties and deposition techniques to form structured absorbers without traditional lithographic steps.
- 3D printing: An emerging technique allowing multi-scale, complex absorber geometries.

Dynamic Tunability

Recent studies also introduce actively tunable BMAs, where absorption can be modified in real time using external stimuli such as:

- Temperature
- Electric/magnetic fields
- Optical pumping
- Mechanical strain

Materials like VO₂, graphene, and phase-change compounds have been integrated into BMAs to realize such dynamic behavior.

Application Fields

BMA s have found promising applications in a wide range of areas, including:

- Photodetectors and thermal imaging
- Solar energy harvesting
- Radar and IR stealth technologies
- Sensing and spectroscopy
- Wearable and flexible devices

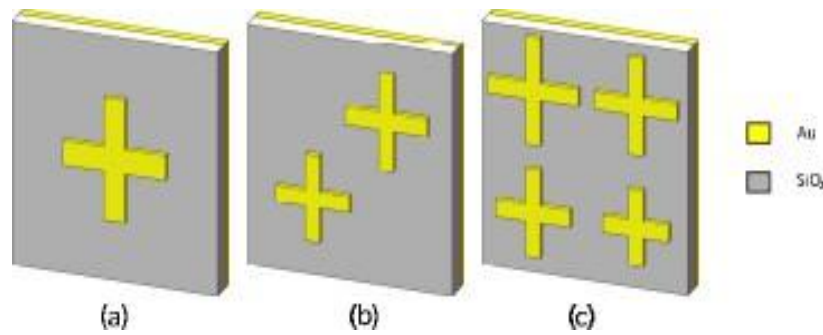


Figure 3.2.1 Schematic diagrams of the unit cells for
 (a) sample A,
 (b) sample B, and
 (c) sample C are shown. The ground plane consists of a 100 nm thick gold layer, while the metallic patterns are made of 60 nm thick gold. All samples include a 190 nm thick SiO_2 dielectric layer [2]

3.3 Design of Tunable Perfect Absorbers in the Mid-IR Spectrum Using Graphene-Based Multilayer Structures: Emerging Applications in Atmospheric Window Matching

Masoumeh Nazari et al.(2024)

The field of perfect electromagnetic absorbers (PAs) has seen considerable progress due to their critical applications in thermal emitters, gas sensing, infrared detection, and energy harvesting. These structures are engineered to exhibit near-unity absorption at specific wavelengths by eliminating both reflection and transmission, typically via careful material selection and resonator design. Their effectiveness across different spectral ranges—from microwave to visible light—has been demonstrated, with the mid-infrared (mid-IR) region (3–5 μm) garnering special attention due to its minimal atmospheric absorption and relevance to greenhouse gas detection.

Key Contributions in Mid-IR Absorber Design

Several researchers have pioneered innovations in mid-IR absorbers:

- Fang et al. (2023) designed a broadband absorber using layers of Al_2O_3 and Si, combined with an embedded Ti ring, achieving robust absorption performance across the 3–5 μm range.
- Bossard et al. (2014) proposed a genetically optimized metamaterial absorber with a broadband and polarization-insensitive design. Their single-screen metallic structure supports multiple resonant modes, improving spectral coverage.
- Wang et al. (2017) demonstrated a near-perfect dual-channel mid-IR absorber, fully constructed using semiconductor materials, which opens opportunities for all-semiconductor absorptive platforms.

- Chen et al. (2019) presented an ultra-narrowband absorber based on a hybrid dielectric metasurface, relying on super-cavity effects and plasmonic resonance for tight spectral confinement.

These studies underline the variety of structural approaches in absorber development—from metal-dielectric composites to purely semiconductor-based systems—all aiming to achieve high-efficiency spectral control.

Toward Tunability and Switchability

A major limitation in traditional PAs is the fixed nature of their absorption spectra, which is dictated by static structural parameters. Earlier tunability efforts depended on altering physical geometries, which required complete redesign and re-fabrication. This challenge has led to growing interest in tunable and switchable absorbers, capable of spectral adjustment without structural changes.

Dynamic tunability has been achieved through integration of phase-change materials (PCMs) such as VO₂ and GST, enabling real-time control over absorptive properties via thermal, electrical, or optical stimuli. These materials, however, often require high switching power, limiting their application in low-power photonic systems.

Recent advancements in graphene-based absorbers have shown promise for efficient tunability. Owing to graphene's adjustable conductivity (via chemical potential), it is well-suited for electrically tunable PA designs. Structures incorporating graphene multilayers enable dynamic modulation of absorption peaks through low-energy DC bias, making them suitable for applications in infrared modulation, thermal emission control, **and** adaptive sensing.

Graphene-Driven Absorber Innovations

Nazari et al.'s study proposes aperiodic multilayer graphene-dielectric structures, optimized using a micro-genetic algorithm (GOA) and the Transfer Matrix Method (TMM). This hybrid inverse design framework allows:

- Precise absorption peak positioning across the 3–5 μm range with 0.25 μm resolution.
- Total absorber thicknesses under 2 μm , suitable for compact devices.
- High absorption (>90%) across wide incident angles (up to 60° in TM polarization).
- Dynamic spectral tunability through electrical biasing, shifting peaks without redesign.
- Switchability, enabling toggling between high and low absorption states by modulating chemical potential.

Their results demonstrate the ability to precisely control mid-IR absorption properties, offering new avenues for space-based sensors, thermal photovoltaics, and stealth applications.

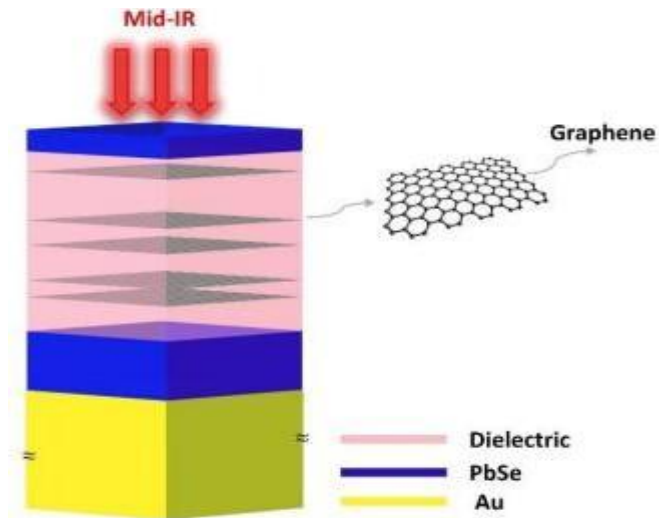


Fig. 3.3.1. Proposed PA: graphene-dielectric stack between PbSe layers on a gold substrate ($\sim 2 \mu\text{m}$ thick) [3]

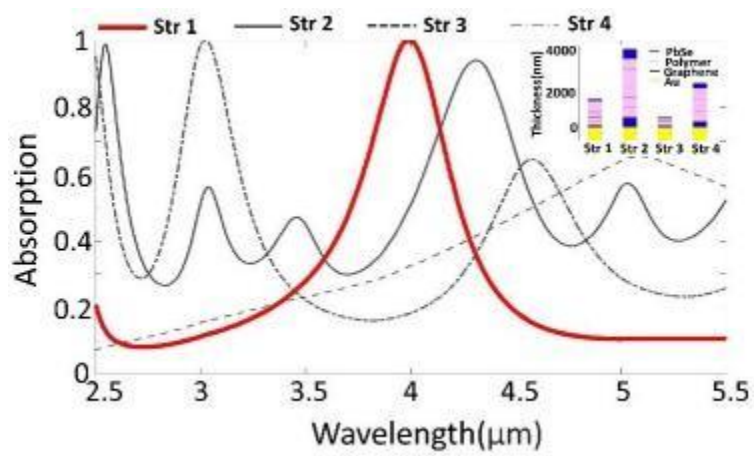


Fig. 3.3.2. GOA enhances absorption at $4 \mu\text{m}$ in Structure 1 vs. non-optimized variants with varying layer thicknesses [3]

3.4 Broadband and Polarization-Insensitive Absorption Based on a Set of Multisized Fabry–Perot-like Resonators

Sha Hu et al.(2019)

The advancement of metamaterial absorbers has brought transformative innovations in electromagnetic wave management, particularly in achieving high-efficiency, subwavelength-thickness structures for light absorption. Metamaterials, made from engineered subwavelength resonators, can exhibit electromagnetic properties such as negative refraction, superlensing, and plasmon-induced transparency—features absent in naturally occurring materials.

Evolution of Perfect Absorbers and Bandwidth Limitations

The idea of perfect metamaterial absorbers was first presented by Landy et al. in 2008, leading to widespread interest in applications like solar energy harvesting, thermal sensing, and plasmonic detection. These early designs typically featured a metal-dielectric-metal (MIM) layered structure, supporting perfect absorption at a specific frequency.

To expand functionality, multi-band absorbers were introduced by incorporating multiple resonators of varying geometries within a single unit cell. Although effective, these designs often led to spectrally discrete absorption peaks, limiting their performance in broadband applications.

To overcome this, stacked multilayer architectures with slightly varying geometric parameters were explored to broaden the absorption range. For example, microwave absorbers using such stacking techniques have demonstrated improved performance, but scaling them to nanoscale for infrared absorption remains challenging.

Tapered and Hyperbolic Multilayer Structures

Recent efforts have focused on tapered and hyperbolic metamaterial absorbers (HMMs). These structures enable gradual impedance matching and support complex resonant modes, including slow-light effects and gap surface plasmon–polariton (G-SPP) modes. While fabrication methods such as focused ion beam (FIB) and self-mask deposition have been used, they often suffer from low throughput and limited design flexibility.

Multisized Fabry–Perot-Like Resonators: A New Strategy

The authors propose a truncated-cone-type multilayer absorber fabricated using a hybrid process of lithography and ion beam etching (IBE). This method offers both nanoscale resolution and mass-production capability, addressing the limitations of prior fabrication approaches. Their structure is based on the concept of Fabry–Perot-like resonators, where G-SPP modes are confined within the dielectric layers of stacked metal-dielectric films (e.g., Au-ZnO). These resonators reflect G-SPP waves at their ends, forming standing waves and enhancing both electric and magnetic field localization.

Moreover, by varying resonator sizes vertically in a tapered fashion, multiple wavelengths can be trapped simultaneously—leading to broadband absorption. Reducing the gap between adjacent structures further enhances coupling of leakage fields, strengthening absorption via field localization in the air gaps.

Contribution of This Work

This work introduces an efficient design and fabrication strategy for broadband, polarization-insensitive, and wide-angle absorbers. By using multisized Fabry–Perot-like G-SPP resonators, the structure achieves:

- Tunable absorption from near-IR to mid-IR by adjusting geometric parameters.
- Absorption higher than 90% across a broad spectral range.
- Angular tolerance up to 60° incidence.
- Scalable and flexible fabrication using standard nanofabrication techniques.

This approach represents a significant step forward in the realization of practical metamaterial absorbers for applications in thermal emission, photovoltaics, sensing, and photodetection.

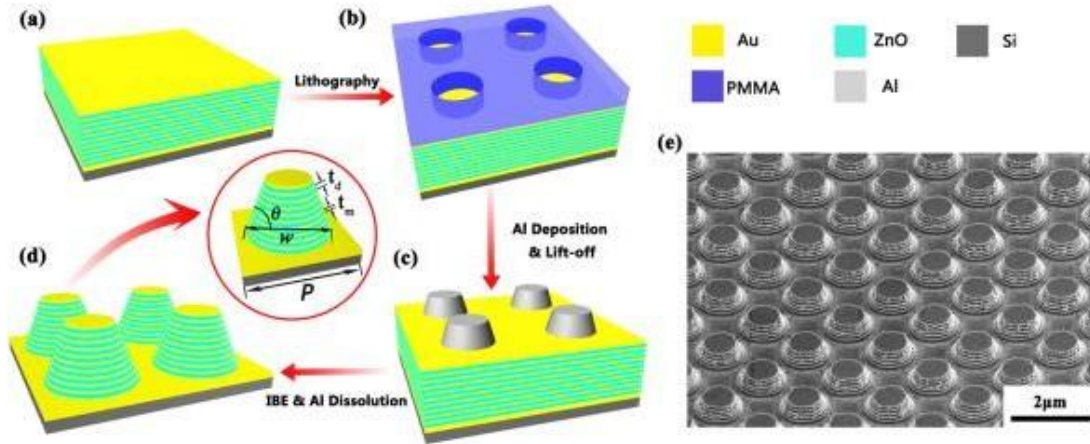


Figure 3.4.1. Illustration of the fabrication steps and an SEM image of the truncated-cone-shaped metamaterial. (a) Deposition of stacked Au–ZnO multilayers using magnetron sputtering. (b) Patterning of a hole array in PMMA through lithography. (c) Formation of an aluminum tapered plate array on the Au–ZnO multilayers via electron beam evaporation followed by a lift-off process. (d) Use of ion beam etching to produce the multilayer nanostructures with a truncated cone shape. (e) SEM image taken at a 52° tilt, showing the truncated-cone-type metamaterial with a period (P) of 1.5 μm and a structure consisting of five Au–ZnO pairs [4]

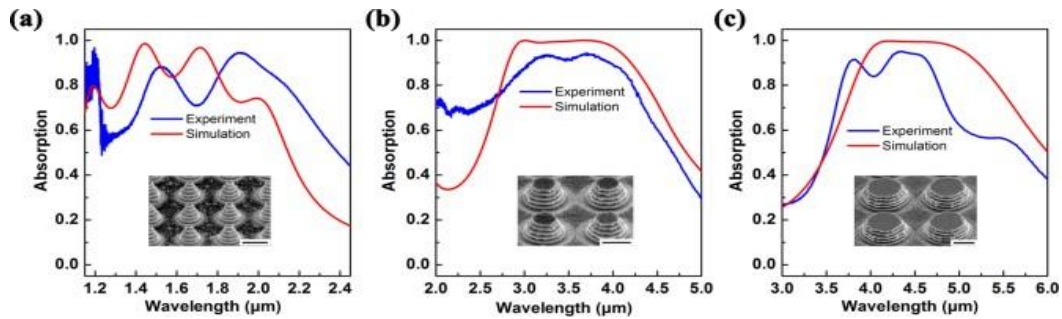


Figure 3.4.2 Measured vs. simulated absorption for TCMA with five Au–ZnO pairs, varying geometry; SEM insets show sample structure [4]

3.5 Highly Transparent Broadband and Polarization-Insensitive Absorber Based on Metasurface

Houdi Xiao et al (2020)

The pursuit of efficient electromagnetic (EM) wave absorption has led to significant advancements in metamaterial absorbers (Mas), which offer superior design flexibility and performance compared to traditional absorbers such as Salisbury screens and Jaumann absorbers. These classical absorbers operate on resonant principles but are often limited by their thickness (approximately a quarter of the operational wavelength). Metamaterials, by contrast, can achieve subwavelength absorption with enhanced tunability and functionality.

Evolution of Metamaterial Absorbers

Since the introduction of the perfect metamaterial absorber (PMA) by Landy et al. (2008), the field has progressed from single-frequency to multi-band and ultimately broadband absorption. This evolution has also been accompanied by improvements in polarization insensitivity and angular stability, enabling absorbers to function effectively under diverse incidence conditions.

Metamaterial absorbers have been extended across a broad frequency range—from radio and microwave bands to terahertz, infrared, and visible light regions. Such extensions have facilitated applications in stealth technology, electromagnetic shielding, thermal imaging, and RFID systems.

Development of Transparent Broadband Absorbers

A major research focus has been on the development of transparent broadband absorbers that combine high microwave absorption with significant visible light transmittance. This dual-functionality is crucial for use cases such as stealth windows, transparent shielding, and optical communication systems.

Several efforts have been made in this direction:

- Min et al. designed a transparent absorber achieving >90% absorption between 4.3–18.7 GHz. However, it had limited visible transmittance (~65%).
- Guan et al. used standing closed-ring resonators with ~82% transmittance and 90% absorption from 5.5–19.7 GHz, although polarization sensitivity remained an issue.

These limitations—including pattern visibility, structural complexity, and limited durability—highlighted the need for designs with simple fabrication, mechanical robustness, and environmental adaptability.

CONCLUSION

This thesis has presented an in-depth overview of metamaterials, covering their core concepts, structural design approaches, and wide-ranging technological applications—particularly in manipulating electromagnetic (EM) waves. Through careful engineering of subwavelength-scale features, metamaterials exhibit unique electromagnetic behaviours such as negative refraction, complete absorption, and super-resolution imaging, which are not achievable with naturally occurring materials.

Special attention has been given to the progression of metamaterial absorbers (MAs), which have evolved from narrowband and polarization-sensitive architectures to advanced designs that support broadband absorption, polarization independence, and wide-angle performance. Breakthroughs involving multiple resonant structures, layered configurations, slow-light mechanisms, and graphene-based tuneable surfaces have greatly improved the efficiency and versatility of these devices across various frequency domains, including microwave, infrared, and visible light.

Moreover, current research points to the growing capability of actively tuneable and reconfigurable metamaterials, enabling real-time adjustments of electromagnetic properties like absorption, reflection, and transmission. This advancement unlocks potential in several emerging fields, such as infrared detection, adaptive photonic systems, stealth applications, renewable energy conversion, and smart sensing technologies.

However, despite significant progress, several challenges remain unresolved. These include the difficulty of scaling up fabrication, minimizing material losses at high frequencies, and reducing manufacturing costs for broader commercial adoption. Nevertheless, continued progress in nanofabrication methods, computational modelling, and material engineering is steadily addressing these obstacles.

In summary, metamaterials stand at the forefront of innovation in electromagnetic wave control. As interdisciplinary research and development efforts grow, these materials are expected to become essential in shaping future technologies in optics, electronics, energy systems, and beyond.

REFERENCES

- 1) Plasmonic metamaterials. Takuo Tanaka, 2012
- 2) Broadband metamaterial absorber at mid infrared using multiplexed cross resonators
Wei Ma, Yongzheng Wen and Xiaomei Yu*. (2013)
- 3) Design of Tunable Perfect Absorbers in the Mid-IR Spectrum Using Graphene-Based Multilayer Structures: Emerging Applications in Atmospheric Window Matching, Masoumeh Nazari, Mike Banad, and Sarah Sharif, 2024
- 4) Broadband and Polarization-Insensitive Absorption Based on a Set of Multisized Fabry–Perot-like Resonators, Sha Hu,[†] Shengyan Yang,^{†,‡} Zhe Liu,^{†,§} Baogang Quan,[†] Junjie Li, and Changzhi Gu*, 2019
- 5) Highly Transparent Broadband and Polarization-Insensitive Absorber Based on Metasurface, Houdi Xiao, Ruiru Qin, Mingyun Lv and Chuanzhi Wang, 2020
- 6) Review of Broadband Metamaterial Absorbers: From Principles, Design Strategies, and Tunable Properties to Functional Applications Ben-Xin Wang, Chongyang Xu, Guiyuan Duan, Wei Xu, Fuwei Pi, 2023
- 7) Landy, N. I.; Sajuyigbe, S.; Mock, J. J.; Smith, D. R.; Padilla, W. J. A Perfect Metamaterial Absorber. *Phys. Rev. Lett.* 2008, 100, 207402.
- 8) Wan, B.; Koschny, T.; Soukoulis, C. M. Wide-Angle and Polarization-Independent Chiral Metamaterial Absorber. *Phys. Rev. B* 2009,
- 9) Cheng, Q.; Cui, T. J.; Jiang, W. X.; Cai, B. G. An Omnidirectional Electromagnetic Absorber Made of Metamaterials. *New J. Phys.* 2010,
- 10) Hutley, M. C.; Maystre, D. The Total Absorption of Light by a Diffraction Grating. *Opt. Commun.* 1976,
- 11) Bonod, N.; Tayeb, G.; Maystre, D.; Enoch, S.; Popov, E. Total Absorption of Light by Lamellar Metallic Gratings. *Opt. Express* 2008
- 12) Le Perchec, J.; Quémenerais, P.; Barbara, A.; López-Ríos, T. Why Metallic Surfaces with Grooves a Few Nanometers Deep and Wide May Strongly Absorb Visible Light. *Phys. Rev. Lett.* 2008,
- 13) Narimanov, E. E.; Kildishev, A. V. Optical Black Hole: Broadband Omnidirectional Light Absorber. *Appl. Phys. Lett.*
- 14) Tao, H.; Bingham, C. M.; Strikwerda, A. C.; Pilon, D.; Shrekenhamer, D.; Landy, N. I.; Fan, K.; Zhang, X.; Padilla, W. J.; Averitt, R. D. Highly Flexible Wide Angle of Incidence Terahertz Metamaterial Absorbers: Design, Fabrication, and Characterization. *Phys. Rev. B* 2008,
- 15) Zhu, W.; Zhao, X. Metamaterial Absorber with Dendritic Cells at Infrared Frequencies. *J. Opt. Soc. Am. B* 2009, 26, 2382–2385. 11. Wang, C.; Yu, S.; Chen, W.; Sun, C. Highly Efficient Light Trapping Structure Design Inspired by Natural Evolution. *Sci. Rep.* 2013.
- 16) Teperik, T. V.; García de Abajo, F. J.; Borisov, A. G.; Abdelsalam, M.; Bartlett, P. N.; Sugawara, Y.; Boumberg, J. J. Omnidirectional Absorption in Nanostructured Metal Surfaces. *Nat. Photonics* 2008,
- 17) Landy, N. I.; Bingham, C. M.; Tyler, T.; Jokerst, N.; Smith, D. R.; Padilla, W. J. Design, Theory, and Measurement of Polarization-Insensitive Absorber for Terahertz Imaging. *Phys. Rev. B* 2009 (18). Diem, M.; Koschny, T.; Soukoulis, C. M. Wide-Angle Perfect Absorber/Thermal Emitter in the Terahertz Regime. *Phys. Rev. B* 2009,
- 18) Hibbins, A. P.; Murray, W. A.; Tyler, J.; Wedge, S.; Barnes, W. L.; Sambles, J. R. Resonant Absorption of Electromagnetic Fields by Surface Plasmons Buried in a Multilayered Plasmonic Nanostructure. *Phys. Rev. B* 2006
- 19) Bossard, J. A.; Werner, D. H. Metamaterials with Angle Selective Emissivity in the Near-Infrared. *Opt. Express* 2013, 21
- 20) Bossard, J. A.; Werner, D. H. Metamaterials with Custom Emissivity Polarization in the Near-

Infrared. Opt. Express 2013

- 21) Liu, X.; Tyler, T.; Starr, T.; Starr, A. F.; Jokerst, N. M.; Padilla, W. J. Taming the Blackbody with Infrared Metamaterials as Selective Thermal Emitters. Phys. Rev. Lett. 2011,
- 22) Zhang, B.; Zhao, Y.; Hao, Q.; Kiraly, B.; Khoo, I.-C.; Chen, n, S.; Huang, T. J. Polarization-Independent Dual-Band Infrared Perfect Absorber Based on a Metal-Dielectric-Metal Elliptical Nanodisk Array. Opt. Express 2011
- 23) Liu, N.; Mesh, M.; Weiss, T.; Hentschel, M.; Giessen, H. Infrared Perfect Absorber and Its Application as Plasmonic Sensor. Nano Lett. 2010
- 24) Cai, W.; Shalaev, V. Optical Metamaterials; Springer: New York, USA, 2010. (2) Sihvola, A. Metamaterials in electromagnetics. Metamaterials 2007
- 25) Smith, D. R.; Pendry, J. B.; Wiltshire, M. C. Metamaterials and negative refractive index. Science 2004
- 26) Pendry, J. B. Negative refraction makes a perfect lens. Phys. Rev. Lett. 2000
- 27) Yang, S.; Xia, X.; Liu, Z.; Yiwen, E.; Wang, Y.; Tang, C.; Li, W.; Li, J.; Wang, L.; Gu, C. Multispectral plasmon-induced transparency in hyperfine terahertz meta-molecules. J. Phys.: Condens. Matter 2016
- 28) Hu, S.; Yang, S.; Liu, Z.; Li, J.; Gu, C. Broadband crosspolarization conversion by symmetry-breaking ultrathin metasurfaces. Appl. Phys. Lett. 2017
- 29) Landy, N. I.; Sajuyigbe, S.; Mock, J. J.; Smith, D. R.; Padilla, W. J. Perfect metamaterial absorber. Phys. Rev. Lett. 2008
- 30) Wang, Y.; Sun, T.; Paudel, T.; Zhang, Y.; Ren, Z.; Kempa, K. Metamaterial-plasmonic absorber structure for high efficiency amorphous silicon solar cells. Nano Lett. 2012
- 31) Chen, J.-D.; Li, Y.-Q.; Zhu, J.; Zhang, Q.; Xu, R.-P.; Li, C.; Zhang, Y.-X.; Huang, J.-S.; Zhan, X.; You, W.; Tang, J.-X. Polymer solar cells with 90% external quantum efficiency featuring an ideal light-and charge-manipulation layer. Adv. Mater. 2018
- 32) Rephaeli, E.; Fan, S. Absorber and emitter for solar thermophotovoltaic systems to achieve efficiency exceeding the ShockleyQueisser limit. Opt. Express 2009
- 33) Liu, N.; Mesch, M.; Weiss, T.; Hentschel, M.; Giessen, H. Infrared perfect absorber and its application as plasmonic sensor. Nano Lett. 2010
- 34) Hu, X.; Xu, G.; Wen, L.; Wang, H.; Zhao, Y.; Zhang, Y.; Cumming, D. R. S.; Chen, Q. Metamaterial absorber integrated microfluidic terahertz sensors. Laser Photonics Rev. 2016
- 35) Cong, L.; Tan, S.; Yahiaoui, R.; Yan, F.; Zhang, W.; Singh, R. Experimental demonstration of ultrasensitive sensing with terahertz metamaterial absorbers: A comparison with the metasurfaces. Appl. Phys. Lett. 2015
- 36) Wu, P. C.; Liao, C. Y.; Chen, J.-W.; Tsai, D. P. Isotropic absorption and sensor of vertical split-ring resonator. Adv. Opt. Mater. 2017
- 37) P. Yu, F. Zhang, Z. Li, Z. Zhong, A. Govorov, L. Fu, H. Tan, C. Jagadish, and Z. Wang, "Giant optical pathlength enhancement in plasmonic thin film solar cells using core-shell nanoparticles," J. Phy D: Appl Phys. (2018)

NEW THES.docx

 Delhi Technological University

Document Details

Submission ID

trn:oid:::27535:100786379

Submission Date

Jun 13, 2025, 10:58 PM GMT+5:30

Download Date

Jun 13, 2025, 11:00 PM GMT+5:30

File Name

NEW THES.docx

File Size

1.3 MB

35 Pages

5,835 Words

39,247 Characters

8% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Small Matches (less than 10 words)

Exclusions

- 9 Excluded Matches

Match Groups

-  **32** Not Cited or Quoted 8%
Matches with neither in-text citation nor quotation marks
-  **1** Missing Quotations 0%
Matches that are still very similar to source material
-  **0** Missing Citation 0%
Matches that have quotation marks, but no in-text citation
-  **0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

- 5%  Internet sources
- 5%  Publications
- 5%  Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

- 32** Not Cited or Quoted 8%
Matches with neither in-text citation nor quotation marks
- 1** Missing Quotations 0%
Matches that are still very similar to source material
- 0** Missing Citation 0%
Matches that have quotation marks, but no in-text citation
- 0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

- 5% Internet sources
- 5% Publications
- 5% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Internet		
in.iphy.ac.cn			<1%
2	Submitted works		
Jaipuria Institute of Management on 2025-04-09			<1%
3	Internet		
arxiv.org			<1%
4	Internet		
ds.inflibnet.ac.in			<1%
5	Submitted works		
University of Bradford on 2025-04-22			<1%
6	Publication		
P. Gornert, P. Payer, O. Surzhenko, L. Michalowsky, H. Heegn, E. Madai, M. Langer...			<1%
7	Submitted works		
Universiti Tun Abdul Razak on 2025-06-08			<1%
8	Publication		
Ayman Ayd R. Saad. "Miniaturized multi-band polarization-insensitive microwave ...			<1%
9	Submitted works		
South Bank University on 2024-08-30			<1%
10	Internet		
www.mdpi.com			<1%

11	Internet	ebin.pub	<1%
12	Internet	elibrary.stipram.ac.id	<1%
13	Submitted works	The University of Manchester on 2025-04-18	<1%
14	Submitted works	VIT University on 2019-04-15	<1%
15	Submitted works	Higher Education Commission Pakistan on 2011-02-25	<1%
16	Submitted works	Vilnius Gediminas Technical University on 2020-11-25	<1%
17	Internet	core.ac.uk	<1%
18	Internet	d.docksci.com	<1%
19	Publication	R. S. Nilotpal, Somak Bhattacharyya. "Chapter 2-1 Metamaterial-based High-Perfo...	<1%
20	Submitted works	University Politehnica of Bucharest on 2024-06-26	<1%
21	Internet	discovery.researcher.life	<1%
22	Internet	www.researching.cn	<1%
23	Publication	A. Goswami, S. Aravindan, P.V. Rao, M. Yoshino. "Structured Surfaces for Generati...	<1%
24	Publication	Guilin Liu, Menhui Qian, Binbin Xi, Zhongliang Ma, Hong Jiang, Tingting Cao, Ben...	<1%

25

Submitted works

National University of Singapore on 2023-03-05

<1%

26

Submitted works

University of Nottingham on 2010-04-09

<1%

27

Publication

Yanxia Cui, Kin Hung Fung, Jun Xu, Hyungjin Ma, Yi Jin, Sailing He, Nicholas X. Fan...

<1%