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Implementation of Metamaterial Based Electromagnetic Absorbers

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Abstract

The goal is to develop a new type of metamaterial absorber that operates within the infrared spectrum with a single absorption band. This innovative design utilizes a basic circular-shaped resonator, which has not been proposed previously. By incorporating raindrop-shaped resonators of varying sizes on the top layer, we can achieve single-band absorption specifically tuned for the infrared regime. Additionally, we propose a structure capable of generating a single absorption band in the terahertz spectrum. This design aims to create a versatile metamaterial absorber with adjustable high-absorption characteristics across multiple bands. Such a device would find applications in various engineering fields, including terahertz imaging and detection. The MIM (Metal-Insulator-Metal) construction features a configuration comprising a cross and four circular rings with quarter-sections surrounded by square rings on the top layer. By modifying these structural parameters, we can adjust the overall number of resonance bands produced by the metamaterial. This research focuses on exploring and designing narrow-band metamaterial absorbers specifically optimized for infrared and terahertz frequencies, with the goal of enhancing their absorption properties and applicability in advanced technological applications.

Keywords: Absorber, Metamaterial,Terahertz

Introduction

Electromagnetic metamaterials are artificially engineered materials consisting of subwavelength-scale arrays of resonant structures that do not occur naturally [9]. The electromagnetic properties of these materials are determined by the geometric configuration of their individual unit cells. By carefully designing these structures, metamaterials can exhibit resonances in both electric and magnetic fields at specific frequencies, which has garnered significant interest. Materials capable of converting incident electromagnetic waves into other forms of energy, such as heat or electrical currents, are known as electromagnetic wave absorbers. These absorbers achieve minimal reflection, transmission, and scattering of incident waves through either high inherent loss or engineered optical properties. Depending on the spectral band where peak absorption occurs within the electromagnetic spectrum, absorbers are categorized into various wavelength regions. Previously, electromagnetic absorbers primarily focused on the RF regime (3 kHz to 300 GHz) due to extensive applications in fields like communication and military defense. Terahertz (THz) absorbers operate in a higher frequency range (0.3 to 3 THz), finding use in medical applications such as non-invasive imaging and in security applications for detecting concealed weapons. In the visible spectrum, research on cloaking devices and visible electromagnetic absorbers for camouflage technologies has attracted significant scientific interest.

This thesis concentrates on infrared (IR) regime applications and current technologies. Infrared radiation absorbers (0.3 to 400 THz) have diverse applications including thermal imaging, chemical spectroscopy, and energy harvesting. Designing IR absorbers requires careful consideration of the specific spectral region of operation for each application. The thesis delves into a specific type of IR absorber known as metal-insulator-metal (MIM) IR absorbers, which exhibit exceptional absorption capabilities for mid-wave infrared (MWIR) wavelengths with high spectral resolution and near-unity absorption. Furthermore, the thesis explores applications such as miniaturized IR spectroscopy and zero-power micromechanical IR digitizers enabled by the unique absorption properties of

MIM IR absorbers.

METAMATERIALS FOR EM ABSORBERS

Metamaterials constitute a burgeoning field of research aimed at creating materials with exceptional optical properties not found in natural substances. These materials are meticulously engineered with patterns arranged in a periodic fashion, typically much smaller than the wavelengths they interact with. This precise design allows metamaterials to manipulate electromagnetic waves in diverse ways, including steering, redirecting, focusing, absorbing, and reflecting them. Such control over electromagnetic waves has enabled breakthroughs in technologies like electromagnetic cloaking, perfect absorbers, energy harvesting, and imaging beyond the diffraction limit. A notable example within metamaterials is the concept of negative refractive index materials, also known as left-handed metamaterials. These exploit artificial electric and magnetic resonances (where electric permittivity, ε, and magnetic permeability, μ, can be less than zero) to achieve a negative refractive index [3, 4]. This discovery has led to innovations such as flat lenses, invisibility cloaks, and imaging capabilities that surpass traditional diffraction limits. Another significant type is high impedance surfaces, composed of stacked layers of metallic and dielectric films whose precise geometries and dimensions enable specific properties such as phase shifting and frequency-selective responses [5]. These surfaces can achieve complete absorption at targeted wavelengths, particularly when their effective surface impedance matches that of free space [6]. Known as metamaterial perfect absorbers, they have proven effective across a wide range of the electromagnetic spectrum, from microwaves to optical frequencies. Metamaterials exhibit remarkable electromagnetic phenomena due to their subwavelength constituents, where resonances of these small-scale structures define their unique properties. This contrasts with conventional materials, whose electromagnetic characteristics are primarily determined by their chemical composition, dielectric permittivity, magnetic permeability, and conductivity. Veselago's pioneering theoretical work in 1968 on materials with negative ε and μ paved the way for exploring backward wave propagation and negative refraction [10]. Smith et al. demonstrated the first experimental realization of such materials in 1999 [11], and Pendry subsequently provided theoretical insights into negative refractive indices [12]. Since then, extensive research has extended from microwave to optical wavelengths in the electromagnetic spectrum [13]. Metamaterials can be characterized by effective complex permittivity $\varepsilon\ (w) = \varepsilon 1\ (w) + i\varepsilon 2\ (w)$ and effective complex permeability $\mu\ (w) = \mu\ (w)+i\mu 2\ (w)$[2]. By carefully adjusting ε (w) and μ (w), it is feasible to construct metamaterials that exhibit properties that do not exist in nature, such as negative index of refraction and backward wave propagation [14]. Typically constructed from periodic arrays of metallic elements, metamaterials derive their electromagnetic properties predominantly from their structural design rather than material composition alone. The presence of a ground plane beneath these structures, with a thickness greater than the skin depth, effectively suppresses transmission, resulting in minimal $S_{21}(\omega)$ transmission and allowing absorption calculations to be expressed as

$$A\ (\omega) = 1 - R\ (\omega)$$

IMPLEMENTED WORK

The aim is to develop a novel metamaterial absorber operating within the infrared spectrum with a single absorption band. This innovative design utilizes circular-shaped resonators, a configuration not previously proposed. By integrating raindrop-shaped resonators of varying sizes on the top layer, we achieve a targeted single-band absorption in the infrared range. Furthermore, we propose a structure capable of generating a single absorption band within the terahertz regime. This design aims to create a versatile metamaterial absorber with adjustable high-absorption capabilities across multiple bands, beneficial for applications such as terahertz imaging and detection. The proposed metamaterial is based on a MIM (Metal-Insulator-Metal) configuration featuring a cross and four quarter-sectioned circular rings surrounded by square rings on the top layer. The number of resonance bands can be modified by adjusting the structural parameters. This study focuses on investigating and designing narrow-band metamaterial absorbers specifically tailored for the infrared frequency spectrum. Our analysis explores the impact of these narrow-band absorbers on infrared frequencies. To achieve this, we advocate for a fresh and straightforward approach for the top layer design, centered around the commonly used circular shape. Through theoretical investigations into the symmetry and uniformity of micron-sized metallic circular discs on the top layer, we aim to further narrow down the absorption band characteristics.

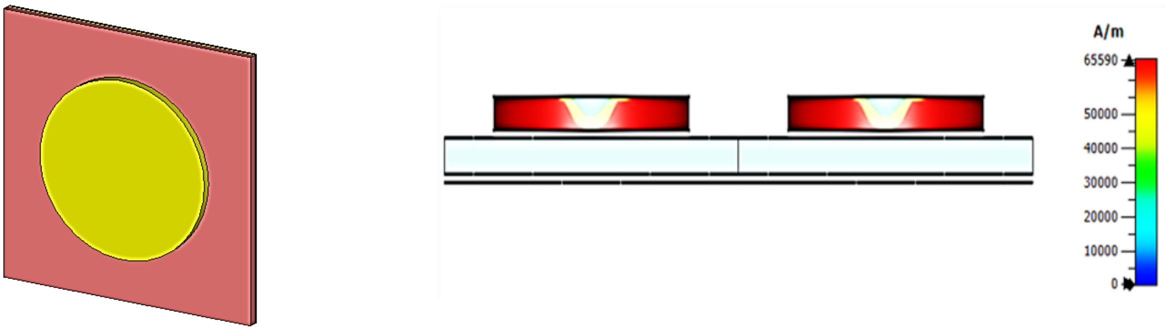

Figure-1: (a) Unit-cell structure of the implemented absorber (b) Magnetic Field Distribution at the Interface of Top Gold Layer and the Dielectric Layer for the Designed Absorber at Different Frequencies

IMPLEMENTATION

Absorber Structure Design

Figure 1 illustrates a single-unit cell depicting the construction of a suggested single-band absorber. The absorber consists of three functional layers: periodic arrays of gold on the top, a gold ground plane at the bottom, and a dielectric spacer made of SiO2 between them, which has a constant refractive index of 1.45 and is considered to be lossless [8]. The gold arrays on the top layer are 45 nm thick, while the gold ground plane beneath is 100 nm thick. The period length p1p1p1 of each cell is set to 1.5 µm. For modeling the gold material, a Lorentz-Drude model [6] was utilized. The incident electromagnetic wave was plane waves oriented parallel to the X-Z plane with TE polarization along the Y direction. Periodic boundary conditions were applied on the vertical sides of the structure, and a port boundary condition was used between the perfectly matched layer (PML) and the air layer. Because of the presence of the bottom ground layer, which exceeds the skin depth at the desired wavelength range, the overall transmission through the structure is nearly zero. The symmetric nature of the absorber ensures it is insensitive to both TE and TM polarizations due to its four-fold symmetry. The wavelength-dependent reflection parameter R (λ) was obtained from the S-parameter of the port and the absorption of the structure was calculated by A (λ) = 1 - R (λ). Due to the existence of the bottom ground layer, which is thicker than the skin depth at the desired wavelength range, the total transmission is close to zero. The symmetric absorber is not sensitive to TE and TM polarizations because of the four-fold.

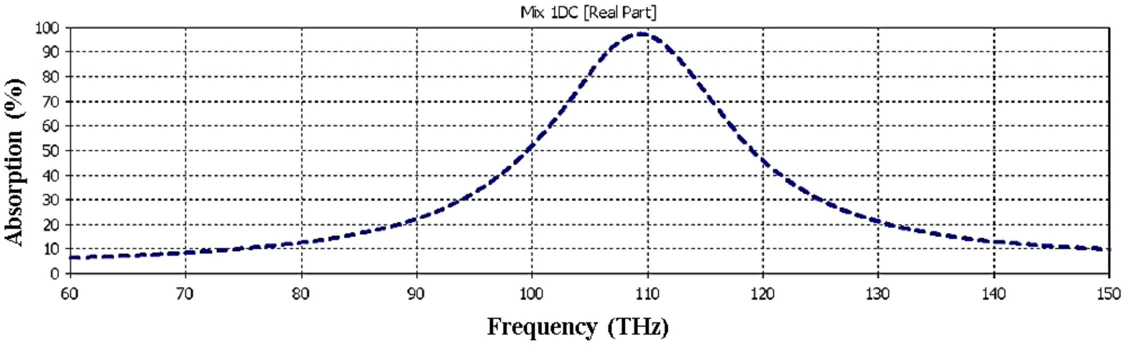

Figure-2: Near-perfect absorption response of the implemented absorber

Result Analysis

Research investigations also explored the impact of varying parameters on the performance of the proposed absorber. Using simulations in the CST program, different parametric adjustments were analyzed to evaluate absorber efficiency. Each simulation focused on altering one parameter while keeping all others constant. One crucial finding was that increasing the substrate height from 0.07 to 2 micrometers led to a significant decrease in absorptivity. It was determined that a substrate height of 0.07 micrometers optimally achieves near unity absorption. The radius of the graphite disc also proved influential. Absorption levels increased notably as the radius expanded from 0.1 to 0.6 micrometers, as depicted in Figure 3.9. Conversely, smaller radii resulted in considerably lower absorptivity. This disparity arises because smaller discs relative to the unit cell cause impedance mismatches, resulting in minimal absorption and significant reflection from the device's top surface. Larger radii, on the other hand, widened the absorption bandwidth. After achieving absorptivity exceeding 90% at resonant frequencies, a radius of r = 0.6 micrometers was identified as optimal for the final structure. This size not only meets the bandwidth requirements for sensing applications but also demonstrates closely aligned absorption values as predicted by the modeling.

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