

Polarization Insensitive and Ultra-Broadband Ni-PTFE Metamaterial Absorber with High Angular Stability for Optical Applications

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This study presents a polarization insensitive, ultra-broadband metamaterial absorber designed for stability under oblique incident angles. The proposed metamaterial absorber consists of nickel resonator disks on a polytetrafluoroethylene substrate with a ground plane made of nickel. Numerical simulations performed using CST Studio Suite[®] confirm the performance of the absorber across a broad spectral range of 300–3000 nm, achieving an average absorption rate of 97.96% and a peak absorption of 99.72%. The proposed structure presents insensitivity to both transverse electric and transverse magnetic modes due to the symmetry of the unit cell geometry. The proposed absorber demonstrates stability under oblique incidence angles of up to 60°, offering high absorption efficiency, cost-effectiveness, and a thinner, simplified design.

Index Terms—Metamaterial absorber, polarization-insensitive, oblique incident stability, optical wavelength.

I. INTRODUCTION

RESEARCH on electromagnetic absorbers has advanced significantly, particularly with the emergence of metamaterials in the optical frequency spectrum. Since their introduction by [1], metamaterial absorbers (MAs) have attracted considerable attention due to their wide range of applications. Scientific advancements in this field depend on the availability and use of suitable materials, as well as the development of simpler and more practical fabrication processes [2], [3]. Enhancing electromagnetic absorption demands meticulous consideration of material selection, geometric dimensions, and design to enable precise tuning of electromagnetic properties and optimize performance.

Various materials have been used as substrates in the design of MAs. One material commonly used, with interesting results in the optical regime, is silicon dioxide (SiO₂) [2], [4], [5]. However, polytetrafluoroethylene (PTFE) has emerged as a promising and relatively under-explored alternative. PTFE is recognized for its low refractive index, resistance to oxidation, and excellent long-term stability. These properties make PTFE highly desirable for applications requiring durability and performance in the visible electromagnetic spectrum [6], [7]. Recent research has highlighted potential of PTFE in the fabrication of MAs using 3D printing, a technique that combines flexibility, speed, and cost-effectiveness, enabling greater design versatility in MAs [6].

This study introduces a novel, thinner, polarization- and angle-insensitive ultra-broadband MA composed of nickel resonator disks on a PTFE substrate, combined with a continuous nickel ground plane. Numerical simulations and an optimization process were conducted using CST Studio Suite[®] to achieve high absorption efficiency and stability across the spectral range of 300–3000 nm, even under varying incidence angles. The proposed simplified and thin design, free of noble metals, is cost-effective and easier to fabricate. It demonstrates significant potential for a wide range of applications, including sensing, coatings and thermal devices, owing to the high absorption values achieved.

II. METAMATERIAL ABSORBER DESIGN AND MODELING

The geometry of the three-layered MA proposed, composed of Ni-PTFE-Ni, is shown in Fig. 1. The absorption performance was simulated using the Finite Element Method (FEM) in CST Microwave Studio[®]. A default tetrahedral meshing approach was selected, with the number of mesh cells set to 20 cells per maximum model box edge. Unit cell boundary conditions were applied along the *x*- and *y*-axes, representing an infinite array structure of the proposed MA.

The electromagnetic (EM) wave was applied to the MA along the *z*-axis, propagating from the positive to the negative direction, using a Floquet port. This configuration supports both transverse electric (TE) and transverse magnetic (TM) polarized incident waves. The ports were positioned at a distance 10 times the unit cell width from the reference plane to minimize near-field interactions between the wave and the MA.

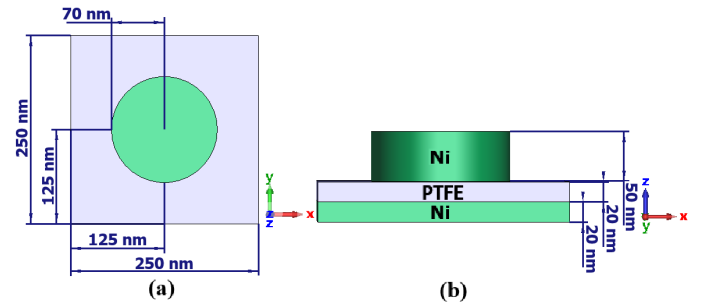


Fig. 1. Proposed MA unit cell geometry (a) Top view and (b) Side view.

The geometric parameters of the proposed MA were determined through multiple simulations and an optimization process using the genetic algorithm (GA) available in CST Microwave Studio[®] software. The absorption index of electromagnetic (EM) waves is defined by the scattering parameters, given as $A = 1 - R - T$, where R represents the reflection coefficient, and T represents the transmission coefficient. The objective function was defined with a target absorption condition of $A > 0.99$, aiming to minimize reflection and maximize

absorption of the MA unit cell, thus achieving maximum absorption within the 300–3000 nm wavelength range. A total of 697 iterations were performed with a population size of 12 samples. Additionally, a sensitivity analysis regarding the angle of incidence was conducted to verify the stability of absorption for different incident angles of electromagnetic waves.

III. RESULTS

To assess the trade-off between simulation accuracy and computational cost in computing the electromagnetic wave absorption, three configurations of the proposed Ni-PTFE MA were analyzed: a single unit cell (1x1), an array of 4 unit cells in a 2x2 pattern, and an array of 16 unit cells in a 4x4 pattern. The absorption results for these configurations are compared in Fig. 2.

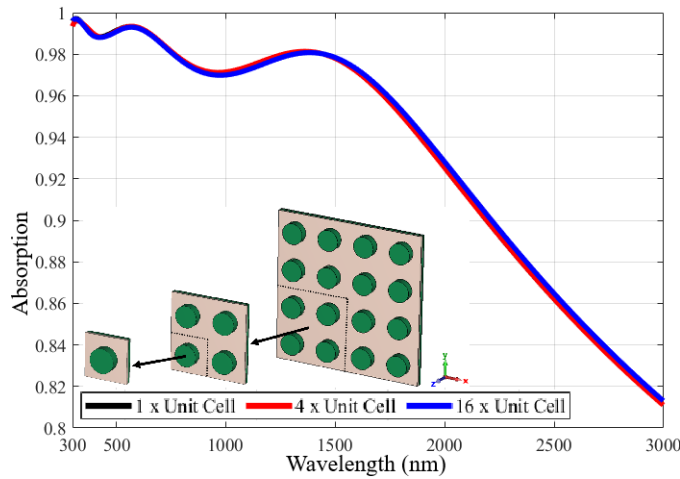


Fig. 2. Absorption index for 1x1, 2x2 and 4x4 unit cells.

The absorption index result for the 4x4, 2x2, and 1x1 unit cells configurations showed no significant differences, with the maximum absorption value reaching 99.72% and an average of 97.96%. The difference in average absorption between the configurations was minimal, only 0.005%. However, the computational time required for each configuration decreased significantly as the discretized area of the MA was reduced. The simulation time for the 1x1 unit cell was 219 s, compared to 1585 s for the 2x2 configuration and 9604 s for the 4x4 configuration, making the simulation of the 1x1 unit cell 97.72% faster than that of the 4x4 unit cells.

Since the results obtained for a single unit cell, applying appropriate periodic boundary conditions, are equivalent to those obtained for a complete structure but with significantly lower computational cost, this configuration was used to analyze the response of the proposed MA structure under oblique incidence of the electromagnetic wave. The obtained results are presented in Fig.3.

For incidence angles (θ) greater than 60° , the MA unit cell achieved absorption rates exceeding 80% across the entire evaluated spectral range. For incidence angles (θ) below 40° , the maximum absorption of incident energy exceeded 99.10%, with minimum absorption values remaining above 88.66% throughout the range, demonstrating the excellent performance

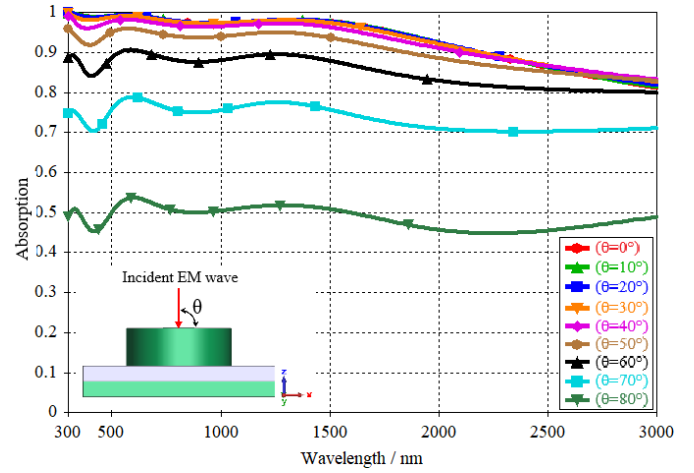


Fig. 3. Absorption index of 1x1 unit cell varying the angle of incidence.

of the proposed MA. Additionally, the MA is polarization insensitive due to its symmetrical and periodic structure along both the x - and y -axes.

The proposed PTFE-Ni MA demonstrates broadband performance and angle-insensitive absorption for incidence angles up to 60° . The use of PTFE and nickel offers several advantages, including low cost, high-temperature tolerance, oxidation resistance, and hydrophobicity. The dynamic electromagnetic behavior, combined with the thinner and simplified design of the MA unit cell, provides a cost-effective solution with significant potential for a wide range of optical broad-spectrum applications.

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