Design and Analysis of Some Broadband Metamaterial Absorbers in Visible and Near-Infrared Regions

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Award of Degree

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by

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Sincerely

(Raj Kumar)

Dedicated

To

My Beloved

Family

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NOMENCLATURE

MTM	Metamaterials
μ	Magnetic permeability
ε	Electric permittivity
n	Index of refraction
$\vec{D}$	Electric flux density or electric displacement ($C.m^{-2}$)
$\vec{B}$	Magnetic flux density (T)
$\vec{E}$	Electric field ($V.m^{-1}$)
$\vec{H}$	Magnetic field ($A.m^{-1}$)
ω	Angular frequency
$\vec{k}$	Wave number
K	Extinction coefficient
c	Speed of light ($m\ s^{-1}$)
$\vec{S}$	Poynting vector
EM	Electromagnetic
e	Charge of electron ($1.60217657 \times 10^{-19}$ C)
Γ	Damping Constant
ω_p	Plasma frequency
ε_0	Permittivity free space (8.85×10^{-12} F/m)
R (ω)	Frequency-dependent reflection coefficient
A (ω)	Frequency-dependent absorption coefficient
T (ω)	Frequency-dependent transmission coefficient
Z (ω)	Frequency-dependent impedance
MPA	Metamaterial perfect absorber
SRR	Split Ring Resonator
TE	Transverse Electric
TM	Transverse Magnetic

FIT	Finite Integration Technique
CST	Computer Simulation Technology
FEM	Finite Element Method
FDTD	Finite Difference Time Domain
PDEs	Partial Differential Equations
$\boldsymbol{\delta}$	Skin depth (m)
GaAs	Gallium Arsenide
SiO_2	Silicon dioxide
Al	Aluminium
W	Tungsten
UV	Ultraviolet
IR	Infrared Au Gold
TL	Transmission line
$\boldsymbol{\beta}$	Debye temperature (K)
T	Absolute temperature (K)
$\boldsymbol{\sigma}$	Electric conductivity (s m^{-1})
$\boldsymbol{\rho}$	Electric resistivity
$\boldsymbol{h}$	Plank's constant (6.62606957 × $10^{-34} m^2 kg\ s^{-1}$)
$\boldsymbol{k_B}$	Boltzmann's constant (1.3806 × $10^{-23}\ m^2 kg\ s^{-2} K^{-1}$)
$\boldsymbol{\tau}$	Electron relaxation time (s)
PBC	Periodic boundary condition

Preface

Metamaterials have seen increased development and progress over the years, as they are composite arrays in the sub-wavelength region that exhibit incredible electromagnetic properties such as negative permittivity, negative permeability, and negative refractive index. A metamaterial array's fundamental unit cell, or unit cell, is capable of being designed to exhibit electrical and magnetic resonance at specific frequencies. The study and design of metamaterial components to handle several issues with small bandwidth, bulkiness, and accuracy levels are covered in this thesis. The structures are thoroughly examined, and issues are suggested as potential remedies.

This research work deals with metamaterials in visible and near-infrared frequency regions. The main objective of this thesis is to investigate broadband perfect metamaterial absorbers that show near-unity absorption of electromagnetic waves for the application of solar energy harvesting. A larger part of this work is focused on the engineering of metamaterial wideband absorbers.

The research work presented in this thesis has been divided into **six** chapters.

Chapter 1 introduces metamaterials, and describes the historical milestones to achieving metamaterial realization and implementation phase with a glimpse of some important innovations in the field of metamaterials via electromagnetics. This chapter discusses the fundamentals of metamaterial structures that obey the necessary conditions for wave propagation because their unique properties make these materials more stimulating to explore. It reflects the accumulated work in the field of metamaterials suited for many applications of interest and the revolutionary development of metamaterials incorporated into components such as antennas, sensors, absorbers, and clocks. This chapter is devoted to exploring in detail the different mechanisms of resonance that underlie the selective absorption possible with metamaterials. The characteristics required for absorbing materials are discussed, and traditional methods of designing such materials are included. Next comes a review of recent studies in the area of absorbing materials. In this chapter, we have also introduced various software tools and methods. We have used one of them software for the design, simulation, and characterization of metamaterial absorbers. It focuses on the use of finite integration techniques as a tool for the design of metamaterial absorbers and in particular the CST software.

Chapter 2 presents a new design of metamaterial perfect absorbers consisting of three layers of metal-dielectric-metal (Al-GaAs-Al) in which a special type of square patch is decorated at various locations on the top layer of the unit cell. The proposed absorber exhibits impedance matching conditions with free space due to which it provides large bandwidth absorption (112.86 nm) in the visible region. Moreover, the parametric study of the resonators, dielectric layer, and multi-band topology has also been investigated. We have also investigated the absorption performance for polarization and incidence angles that may help to increase the conversion efficiency for solar energy harvesting applications.

Chapter 3 presents an efficient broadband metamaterial solar spectrum absorber with a wide incidence angle and polarization-insensitive absorption in visible regions. The proposed absorber consists of a three-layer as metal-dielectric-metal (resonator). The top and bottom layers are made of tungsten (W) metal and the intermediate layer is silicon dioxide (SiO_2). Compared to the previous chapter, we have increased absorption in the visible regions. The absorber achieves an average absorption of about 99% from 400 nm to 750 nm. For both the transverse magnetic (TM) and transverse electric (TE) modes, this design demonstrates the wide-angle absorption of up to 60°. We also analyze the weighted absorption under AM1.5 solar luminosity by changing the thickness parameter of the SiO_2

layer. We have also enumerated other important results that may be helpful for solar cell-related applications.

Chapter 4 demonstrates the broadband metamaterial absorber in the visible to the near-infrared region (375-1100 nm) with a three-layer (W-GaAs-W) structure. This absorber achieved an average absorbance of more than 90% and the maximum absorbance (>99%) was found to be in the range of 422 to 962 nm. The polarization-insensitive-based proposed absorber bears a large incidence for both transverse magnetic (TM) and transverse electric (TE) modes. In addition, optimization of the geometrical parameters of the unit cell is investigated to obtain the best absorption results. The improved conversion efficiency under solar irradiation ($A_{AM1.5}$) has been investigated and the short circuit density has also been calculated. The proposed broadband absorber may have more potential to be used in various applications of optoelectronic devices.

. **Chapter 5** presents an efficient ultrathin broadband metamaterial (MTM) solar absorber design for increasing the efficiency of solar energy harvesting devices. The proposed absorber consists of only two layers of gallium arsenide and tungsten. The dielectric layer of gallium arsenide is used as a top layer (resonator) over a ground layer of tungsten. The proposed absorber shows a good absorption of 96.57% in the 375 nm to 1200 nm region. The simulated absorber exhibits polarization-independent behaviors for a wide range of incident angles for transverse electric and transverse magnetic modes. The proposed absorber can be utilized as an ultrathin compact solar energy absorber device with efficient solar radiation absorptivity.

The conclusions of overall studies have been summarized in the last **chapter 6**. This Chapter also comprises further future research plans on this topic.