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Short Communication

# Designing Aspects for Performance Optimization of Dual-Band Metamaterial Absorbers Useful for IR Camouflaging in Aeronautics

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## ABSTRACT

This paper deals with the analytical treatment and unique characteristics of artificial dielectrics in the form of Dual-band metamaterial absorbers. The advantages of the metamaterials designed as Absorbers over the conventional absorbers have been discussed. The usefulness of such absorbers in various opto-electronic devices including Spatial light modulators and Infrared camouflaging in Aeronautics; and especially in Research areas has been highlighted. An attempt has been made to suggest a new approach for the fabrication of such absorbers by discussing the experimental aspects of the designing and coating techniques required in such work, which can be very useful for the optical engineers engaged in making these absorbers. The paper is expected to be useful for the researchers and optical and coating designers engaged in this novel evolving field of aeronautics and aeronautical engineering.

**Keywords:** Dielectrics; Dual-band metamaterial absorbers; Impedance matching; Dual ion beam sputtering deposition

## INTRODUCTION

It has now been clearly understood that the artificial dielectrics are increasingly been used for various novel applications, including photonic crystal cavity with resonance in dirac leaky-wave antennas, and dual-band metamaterial absorbers. Artificial dielectric molecule consists of four atoms of two different sizes with two absorption bands with nearly unit absorption. In addition, it has been established by the numerical and experimental absorptivity values that the dual-band metamaterial absorber is polarization insensitive, and capable of operating in wide-angle incidence. It is important to note that a metamaterial absorber is just a metamaterial having property of efficiently absorbing electromagnetic radiation like light. Theoretecal and, experimental studies have confirmed that the metamaterials belong to advanced materials science. This is why that the metamaterials designed to be absorbers have various benefits over the conventional absorbers including more miniaturization, wider adaptability, and also increased effectiveness; which make them useful for applications for the metamaterial absorbers: like emitters, photodetectors, sensors, spatial light modulators, infrared camouflaging, wireless communication, and solar photovoltaics and thermos-photo voltaics. From applications point of view, the metamaterial absorbers may be divided into two types: narrow band and broadband. Interestingly, metamaterial absorbers have been found useful both for improving the performance of photodetectors, and also for enhancing the absorption in solar photovoltaic and thermo-photovoltaic devices.

## METHODOLOGY

### Important breakthroughs in dual-band metamaterial absorbers

It is important to note that the Skin depth engineering may be used in metamaterial absorbers, photovoltaic applications, and other optoelectronic devices, in which optimization of the device performance requires minimizing resistive losses and power consumption, as in photodetectors, laser diodes, and light emitting diodes. In addition, the advent of metamaterial absorbers has helped the researchers for better understanding the theory of metamaterials, derived from the classical electromagnetic wave theory. Most importantly, this has led to understanding the material's unique capabilities and also the main reasons for the limitations being faced at present [1].

For this to be useful, more research efforts are needed to be made

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in this evolving field, since it is still quite difficult to achieve broadband absorption, especially for the higher frequencies in the THz region. The intrinsically narrow bandwidth of surface plasmon polaritons (SPPs) or localized surface plasmon resonances (LSPRs) generated on metallic surfaces at the nanoscale, are exploited for use as a mechanism for achieving perfect absorption. An electromagnetic absorber has no reflection or transmission to the incident radiation. Therefore, the power of the impinging wave is mostly absorbed in the absorber materials. As is expected, the performance of an absorber depends on its thickness and morphology, and also the materials used to fabricate it.

An absorber of unit absorption is a device in which all the incident radiation is absorbed in the operating frequency region, i.e., no transmission, reflection or scattering loss are observed. Electromagnetic (EM) wave absorbers are of two types: resonant absorbers and broadband absorbers. Many investigations have recently been carried out on perfect metamaterial absorbers (PMAs) with high fractional bandwidth (FBW) and have been found useful for solar energy harvesting, since solar cells based on perfect metamaterials provide a great increase in the efficiency of Solar systems by intensifying the solar electromagnetic wave, incident on the device. The designers synthesize the structure generally in the visible spectral range in order to use the solar energy efficiently. The designer has to satisfy parametric investigations corresponding to the measurements of the structure for characterizing the absorber. It has been observed that the finite-difference time-domain (FDTD) method-based CST simulator is very useful for absorptance analysis, and also for optimizing the pattern parameters. The metamaterial devices with more than 99.5% absorption at 523.84 THz and 674.12 THz resonance frequencies, with absorption's FBW at 39.22% FBW have already been reported.

Wang, et al. [2] have presented a new type of dual-band terahertz metamaterial absorber formed by a patterned metallic strip and a dielectric layer on top of a metallic ground plane. It has been found that besides a strong absorption in the fundamental resonance, a prominent high-order resonance with near-unity absorption is also observed. It has been emphasized that (i) the origin of the induced dual-band absorption was elucidated; and (ii) the quality factor (Q) and the figure of merit (FOM) of the high-order resonance are 8.4 and 22.7 times larger than that of the fundamental resonance, respectively were obtained, and hence makes this absorber to have significant potential in biological monitoring and sensing. Interestingly, a dual-band and insensitive for two orthogonal polarizations terahertz absorber based on a metallic cross and a metallic ground plane separated by a dielectric layer has been demonstrated and put in use in various research centers astound the world. Finally, it has been stated that the Q and FOM of the high-order resonance are still larger than that of the fundamental resonance; and the this type of absorbers appear to be very promising for solar cells, detection, and imaging applications, and also in research areas.

Kaur and Upadhyaya [3] have studied, a novel dual-layer wide-angle metamaterial absorber with polarization independence, and have presented at three distinct frequencies. Their suggested structure consists of dual stacked metal-dielectric layers which are terminated by the metal ground panel, the unit cell of the presented structure being consisting of three concentric 8-point star rings on the top surface of both dielectric layers exhibiting three absorption peaks of 98.96%, 98.7% and 99.43% under normal incidence at 1.8 GHz, 2.14 GHz and 2.57 GHz, respectively. The polarization independence of the design has been validated by numerical simulation and practically verified using waveguide measurement technique, which qualifies it as a very useful device.

Hoa, et al. [4] have reported a facile design of an ultra-thin broadband metamaterial absorber (MA) for C-band applications by utilizing a single layer of a metal-dielectric-metal structure of FR-4 substrate, and have characterized absorption performances by using a numerical method. They have found that their proposed MA exhibits the broadband absorption response over the entire C-band spectrum range from 4.0 GHz to 8.0 GHz with absorptivity above 90% and the high absorptivity over 80% for a large incident angle up to 40° under both transverse electric (TE) and transverse magnetic (TM) polarizations over the band. In addition, the origin of absorption mechanism has been explained by the electric and surface current distributions, which is also supported by the retrieved constitutive electromagnetic parameters, significantly affected by magnetic resonance. Interestingly, as compared with the previous reports, their proposed MA presents a greater practical feasibility in term of low-profile and wide incident angle insensitivity, which makes the proposed absorber, is a promising candidate for C-band applications.

Other useful contributions in this topic have been reported by Hossain, et al. [5,6] have studied Perfect metamaterial absorber with high fractional bandwidth for solar energy harvesting. Liu, et al. [6] have numerically designed and then experimentally verified a metamaterial perfect absorber based on artificial dielectric composed of dielectric ceramic material (SrTiO<sub>3</sub>) "atoms" embedded in a background matrix on a metal plate. It has been observed that (i) the dielectric "atoms" couple strongly to the incident electric and magnetic fields at the Mie resonance mode, resulting in the narrow perfect absorption band with simulated and experimental absorptivity of 99% and 98.5% at 8.96 GHz, respectively; and (ii) the designed metamaterial perfect absorber is polarization insensitive and can operate in wide angle incidence. This feature makes it very useful, as it makes use of all part of the incident light in various polarizations.

## Designing aspects of synthesis of such absorbers

There are various approaches for making this structure:

(i) For obtaining a multi-resonant response, the design of MA is mainly focused on the top layer patch by utilizing a multi-shaped/sized architecture. Then, the different resonance frequencies, in the form of narrow peaks, resulting from the different-sized patch resonators are combined together to form the final overall broadband absorption response.

(ii) By using an elongated shape, in which the elongation of the geometry in one direction results in extending the light absorption toward the lower frequencies.

(iii) This approach is based on utilizing the combination of both (i and ii) the approaches to design an efficient broadband absorber. This MA structure is composed of the combination of two different sized and shaped patch resonators, in which one resonator is an elongated shape e.g., a copper top layer patch periodic array, formed by an elongated shape based on a double-sided axe (DSA) and two interior circles (ICRs), over a copper bottom layer separated by an FR-4 dielectric substrate. The designer has to optimize various Parameters for the FR-4 substrate (FR-4 glass epoxy is a popular and versatile high-pressure thermo set plastic laminate grade with good strength to weight ratios. With near zero water absorption, FR-4 is most commonly used as an electrical insulator possessing considerable mechanical strength) like it's dielectric constant around 4.5, loss tangent around 0.03, and the copper layers with thickness (t) of about 0.03- 0.04 mm and the electric conductivity (σ) of 5.96 × 107 S/m.

### Absorbance of the absorber

The absorbance of the absorber can be defined by:

$$A(\omega) = 1 - R(\omega) = 1 - \left| Z_{in}(\omega) - Z_o Z_{in}(\omega) + Z_o \right|^2 \qquad (1),$$

where $Z_o$ is the characteristic impedance of free space with

$$1Z_{um}(\omega) = 1 - 1Z_{iin}(\omega) - 1Z_d(\omega) 1Z_{in}(\omega) = 1Z_m(\omega) Z_o + 1Z_d(\omega)$$

$$1Z_{in}(\omega) = \{1R1 + j\omega L1 + 1j\omega C1 + 1R2 + j\omega L2 + 1j\omega C2 + 1R3 + j\omega L3 + 1j\omega C3 + 1Z_{in}(\omega)\} \qquad (2),$$

$$= \{1R1 + j\omega L1 + 1j\omega C1 + 1R2 + j\omega L2 + 1j\omega C2 + 1R3 + j\omega L3 + 1j\omega C3\} \qquad (3),$$

$$Z_d(\omega) = j\omega_r \omega_o \varepsilon_r \varepsilon_o \tan(kh) \qquad (4),$$

and

$$k = (k_o / \varepsilon_r \omega_r) \qquad (5).$$

In these Equations, R, C, and L are resistance, capacitance, and inductance respectively; in the Equivalent Circuit, the numbers are the various layers in the multi- layer system; εr, ωr, k are relative permittivity, permeability, and wavenumber of the dielectric substrate respectively; and ε0, ω0, and k0 are permittivity, permeability, and wavenumber of the free space, respectively. Clearly, the perfect broadband absorber can be achieved only when the input characteristic impedance (Zin) is made exactly equal to the characteristic impedance of free space (Z0).

This is a complicated job, and the designer has to achieve it by tuning the input impedance of MA by varying and adjusting the size of the copper top layer and the height of the FR-4 substrate. The designing and verification of this type of MA is implemented by the designer using the full-wave EM simulation based on CST-Microwave Studio software. In addition, the designer has to optimize the thickness of the FR-4 substrate and the size of resonator shapes for obtaining the higher absorbance in entire C-band.

The absorption spectra of the proposed MA are simulated at different thickness (h) of FR4 substrate in range of 3.4–5.0 nm. There is mostly difference between the theoretically designed values and the experimentally achieved values; and hence correction has to be applied. In most of the cases, 3-4 iterations are required to get the optimum results.

Bamanc, et al. [7] have done the numerical analysis for showing TE, TM, and TEM mode absorption characteristics for different polarizations and angles.

### Experimental aspects of synthesis of MA absorbers

The impedance and reflection matching can be done by coating of dielectric materials [8]. The results of many studies on Synthesis of MA Absorbers, have confirmed that the designed PMA can attain very high absorption peak at both the modes: transverse electric (TE) and transverse magnetic (TM) mode, besides being polarization angle insensitive. Also, highly reflective coatings have to be designed, and deposited, so that the radiation is stopped from escaping through the device. The multilayer coating can be designed to have high reflection in broad band under consideration [9-11]. The coating design is of various alternate layers of high and low refractive indices as:

Substrate/(HLHL - - - HLH)(raised to power) (2n+1) (6)

where H and L are the quarter wave optical thicknesses (OTs) of high and low refractive index at the desired wave length, n being the number of L layers; (n+1) the number of H layers, (2n+1) about 27, and (Optical thickness) OT is given by:

OT=Product of Refractive index and geometrical thickness (7)

Another point to be taken care of, is that the dual Ion beam sputtering coating technique (one beam for sputtering, and the other for assisting/cleaning while the coating is going on) has to be used for keeping the scattering loss to nearly zero values for ideal matching, which also helps in increasing the damage threshold of the device. The sputtering materials useful for this purpose are Ta2O5/SiO2, and TiO2/SiO2. The thicknesses of the various layers in the design have to be very carefully controlled and optimized, which is done by using In-situ film thickness monitor (quartz or optical). For better results, the substrates should be having very smooth and polished surfaces (polished with copper turning machine or float polishing, the choice depending on the material of substrate) with very low values of root mean square value of the roughness of the surface.

## DISCUSSION AND CONCLUSION

The analytical treatment and unique characteristics of artificial dielectrics in the form of dual-band metamaterial absorbers are very important for designing the opto-electronic devices. The advantages of the metamaterials designed as Absorbers over the conventional absorbers have now been well understood by the scientists. The usefulness of such absorbers in various opto-electronic devices including Spatial light modulators and Infrared camouflaging in Aeronautics ; and especially in Research areas has been well realized by the engineers in these fields. An attempt has been made to suggest a new approach for the fabrication of such absorbers by discussing the experimental aspects of the designing and coating techniques required in such work, which can be very useful for the optical engineers engaged in making these absorbers. The paper is expected to be very informative for the Researchers and optical and coating designers engaged in this novel evolving field of air surveillance and radars connected with aeronautics and aeronautical engineering.

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