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Prof Kehar Singh

Formerly Professor of Physics

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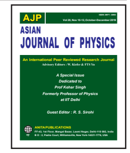

Broadband infrared emissivity engineering in optically transparent metamaterials by regulation of electromagnetic resonances

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This article is dedicated to Prof Kehar Singh for his significant contributions to Optics and Photonics

We present designs of optically transparent metamaterial structures with customizable emissivity response across the technologically important Long Wave Infrared (LWIR) window. The proposed designs have explicitly been conceived in a manner that separates the micro-structuring and thin film deposition steps leading to substantial fabrication process simplification, making them suitable for mass production over large areas. These emissivity engineered structures may be employed for digital spatial modulation of inherent thermal radiation from an object, thereby making them useful in encoding information for security applications. Furthermore, based on the finite element simulations, we have characterized the electromagnetic resonances of the structure and briefly explained the underlying physical mechanisms for the band-selective absorptivity.

Keywords: Emissivity, Metamaterial, Optical Transparency, Resonance.

1 Introduction

Thermal radiation is ubiquitous, and every object at finite temperature becomes a source of infrared radiation. This inherent emission from the objects can be used as a crucial input to the process of detection and identification of adversary troops or objects. Thereby, thermal imagers have gained much traction among the armed forces, and they are used in a widespread manner, particularly to defy the limitations of low ambient light or scattering conditions in the visible domain. Simultaneously significant efforts have also been made to develop countermeasures aimed at suppressing thermal emission from objects by making the outer surface more and more metallic in composition [1-3]. The strategy relies on using metals to reduce the infrared (IR) emissivity of the object, thereby making it difficult for the enemy to detect it. However, such a strategy may not be very useful since the resulting high gloss value leaves the object vulnerable to detection in the visible domain. Therefore, there exists a need for the development of IR structures which can provide IR stealth without the characteristic sheen of the metals. For this purpose, we propose the use of Indium Tin Oxide (ITO) in the metamaterial structures, which provides the properties of an electric plasma in the IR range along with sufficient visible transparency.

Going one step further, we envisage using thermal radiation as a carrier of information through spatial modulation of the emitted intensity. This is done by designing thermal pixels with specified emissivity, an ordered arrangement of which can embed a certain amount of information, provided the depth of modulation is sufficient. However, exhibiting precise control on the characteristic features like emissivity is a non-trivial task. In this context, thermal metamaterial structures can play a pivotal role as they do not solely rely on the

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natural properties of substances, but derive the requisite functionality from the underlying resonances of the subwavelength structures [4]. The metamaterial, upon homogenization, can mimic the bulk properties of the hypothesized material. Precisely, this is the strategy employed in this work to generate customized emissivity responses from the same underlying template by optimizing a few geometrical dimensions of the metamaterial for each design. One peculiar aspect of this work is the due consideration that has been paid to come up with a metamaterial design that is conducive for large-area fabrication. This feature reflects in the fact that micro structuring in the proposed design can be introduced without the need for complex lift-off or etching processes [5].

In perspective, we propose the design of an optically transparent thermal metamaterial that can provide a customized value of the band averaged emissivity across the LWIR wavelengths. These customized emissivity metamaterials can serve as materials for individual pixels that can be used for digital spatial modulation of the IR emission from the surface. This way, we can convert the seemingly undesirable thermal emission into a carrier of information. The proposal can prove to be vital for security applications such as IR tagging for friend or foe identification, as now one can encrypt information or signals in the metamaterial structures that can only be deciphered by a thermal imager.

The paper has been organized as follows; first of all, the structural details of the metamaterial unit cell have been provided, followed by the details of the finite element simulations to ascertain their response. After that, the identification and analysis of the underlying resonances based on the field profiles is presented.

2 Design and Structural Details

The unit cell design of the proposed metamaterial structure has been depicted in Fig 1. It consists of a polymer disk of varying dimensions on the Polyethylene Terephthalate (PET) substrate, which is being coated with three optical thin films in the sequence of ITO-ZnS-ITO. We will see later that the deposited films on the polymer disk generates magnetic resonances, giving rise to high absorption. The structured polymer disks can be fabricated by various lithography techniques, particularly soft lithography where a Polydimethylsiloxane (PDMS) stamp of a master pattern is used for imprinting the structure over a large area using a UV curable polymer. Successively, large area thin films of ZnS and ITO can be grown by thermal evaporation and sputtering respectively to result in deposition on the structured surface in a snowfall-like manner. Unlike the usual lithographic processing techniques for micro/nano structures, we have been able to introduce micro structuring in the sample without involving the complex and expensive processes of lift-off and etching [6]. Such a simplification is not possible in the conventional tri-layered designs of metamaterials [7].

Fig 1. Schematic of the metamaterial unit cell

The periodicity of the unit cell structure, the diameter of the polymer disks and the height of the disks are assumed as the design parameters. Based on FEM simulations; these parameters have been optimized for four different designs of metamaterial unit cells that provide four sufficiently distant values of the band averaged emissivity over the LWIR domain. Indium doped Tin Oxide (ITO) is selected as the plasmonic material in this work since it provides the functionality of a good electrical conductor at IR wavelengths at the same time it behaves like a dielectric in the visible region, which is of immense utility for maintaining the optical transparency in visible domain. The reason being that the plasma frequency of this doped semiconductor material usually corresponds to a wavelength between 1200-1500nm. Since the first demonstration of ITO based IR metamaterials by Dayal *et al* [8], it has been employed as a substitute of noble metals for many of the metamaterial designs.

3 Simulations and calculated performance

The proposed metamaterial structure has been simulated as a square periodic array in the FEM based commercial software package COMSOL Multiphysics® and analyzed for its performance. While simulating the structure in the Radio Frequency module of COMSOL, periodic boundary conditions have been implemented in the X-Y plane; this makes the structure infinitely periodic along the X-Y plane without actually increasing the size of the computational domain. Perfectly matched layers have been employed along the propagation direction to remove the artificial reflections along the z-direction, arising from the termination of the simulation domain. All the materials have assumed to be non-magnetic in the simulations. The electromagnetic properties of ITO are defined in terms of the Drude model $\varepsilon(\omega) = 3.95 - [\omega_p^2/(\omega^2 + i\omega\gamma)]$, with plasma frequency, $\omega_p = 3.074 \times 10^4$ THz and damping frequency $\gamma = 29.01$ THz [9]. For ZnS, the experimental values of refractive index and extinction coefficient have been taken from [10], while the material constants of polymer and PET substrate have been defined in terms of constant RI values of 1.58 and 1.63, respectively.

The spectral performance of the structure has been calculated in terms of the Reflectance and the Transmittance (zeroth order remittances for the sub-wavelength structure) using port boundary conditions along the direction of wave propagation; while the absorption is calculated by invoking energy conservation. For calculating the emissivity of the structure, we have made use of Kirchoff's law, according to which, the emissivity and absorptivity of an object in thermal equilibrium, are identical. The simulations were carried out by taking the unit cell periodicity, the diameter of the polymer disk and the height of the polymer disk as design parameters. Based on the simulations four optimized designs of the metamaterial unit cells have been selected, details of which are provided in Table 1. On account of practical considerations, the thicknesses of the ZnS layer, bottom ITO layer and top ITO layer have been kept constant at 0.4µm, 0.01 µm and 0.4 µm, respectively in all the four designs so that large area thin film deposition methods can be utilized.

Table 1. Structural details of the four optimized designs of metamaterial structures

	Periodicity (µm)	**Polymer Disk Diameter (µm)**	**Polymer Disk Height (µm)**
Design 1	4.40	1.30	0.70
Design 2	4.40	4.00	0.60
Design 3	4.20	2.40	1.00
Design 4	4.20	3.20	0.80

The calculated spectral performance curves for the four designs in the 5-12µm range have been depicted in Fig 2. We can observe the occurrence of absorption resonances, the peak of which can reach as high as 90%.

For thermal imaging in the LWIR window; however, the quantity of interest is the integrated thermal emission captured across the LWIR domain, which can be characterized by the band-averaged emissivity parameter, defined as,

$$\varepsilon_{\text{avg}} = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda) d\lambda$$

Taking cognizance of this fact, we have categorized the performance of the four designs in terms of the band averaged emissivity and it is summarized in Table 2. It can be seen that the average values of the thermal emissivity for these designs span a wide range from 9.4% to 65.3%. Higher emissivity values can easily be obtained using conventional materials.

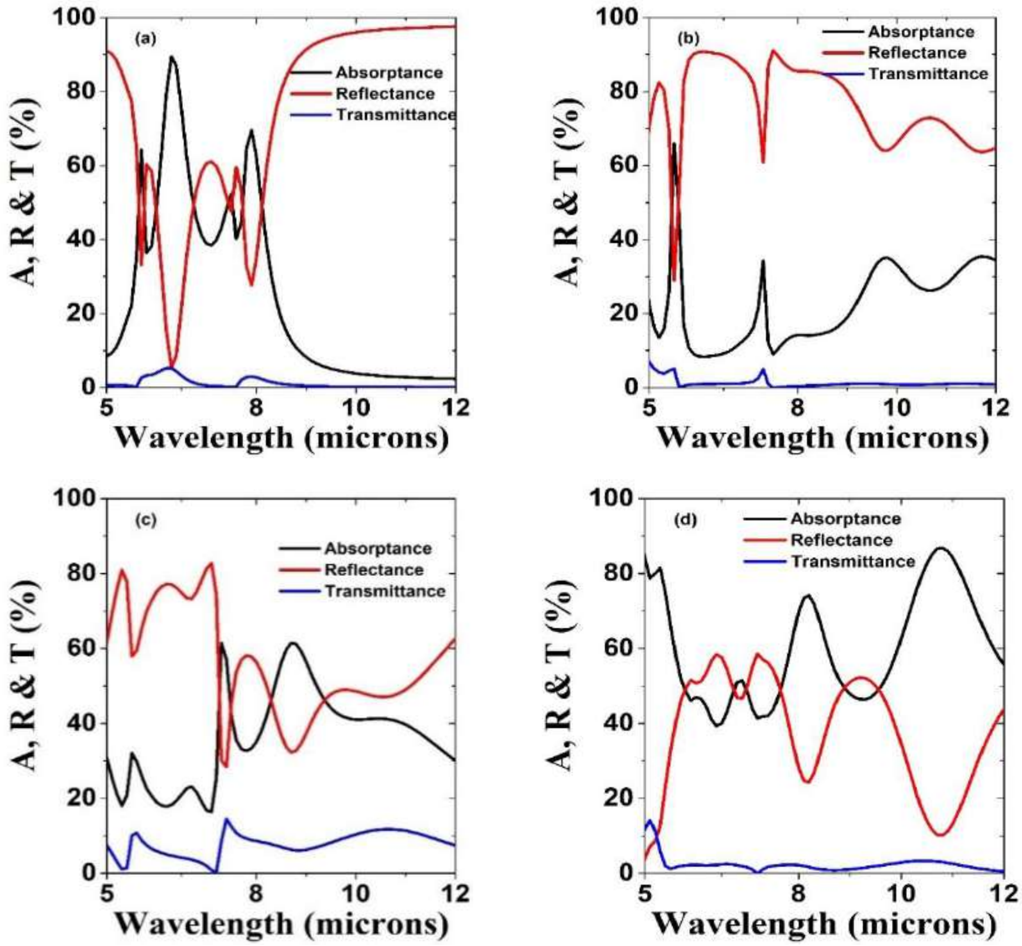


Fig 2. Calculated spectral performances of the four metamaterial designs with designation (a) Design 1, (b) Design 2, (c) Design 3 and (d) Design 4.

Table 2. Calculated spectral performance for the four metamaterial designs, averaged over 8-12µm.

	Band Averaged Emissivity (%)	Reflectivity (%)	Transmissivity (%)
Design 1	9.4	90.1	0.4
Design 2	26.4	72.7	0.9
Design 3	43.2	47.8	9.0
Design 4	65.3	32.8	1.9

4 Characterization of the resonances

The spectral performance of the proposed metamaterial can be analyzed in terms of the underlying electromagnetic resonances, the genesis and the behavior of which depend on the dimensional parameters. In the present work, we will resort to the FEM simulations to elucidate the underlying resonances. The calculated spectral performances can be understood by analyzing the spatial profiles of the electric fields, magnetic fields as well as time-averaged Poynting vector at the resonant wavelengths. Since all the four designs are obtained with the same underlying structure, so a detailed analysis with one of the designs will suffice; and the same analysis can be extended to explain the spectral performance of the rest of the designs as well. For the purpose of analysis, we pick the highest emissivity Design 4 and analyze its resonant behavior. In order to fully characterize the behavior of Design 4, first of all, we present its spectral performance in an extended range of 2.8μm -19.5μm in Fig 3.

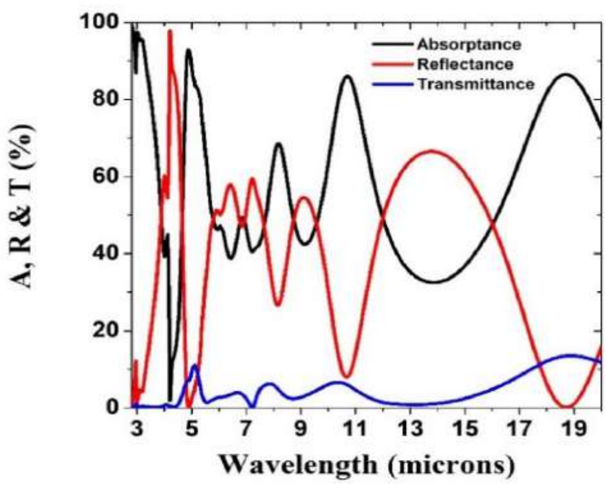
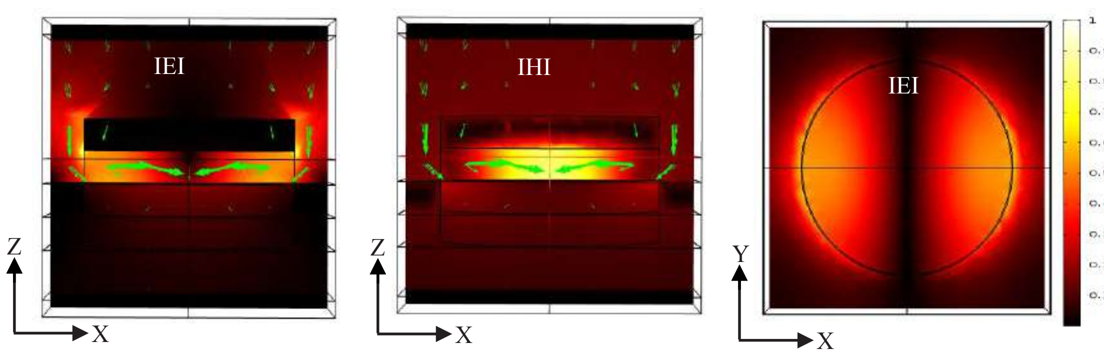
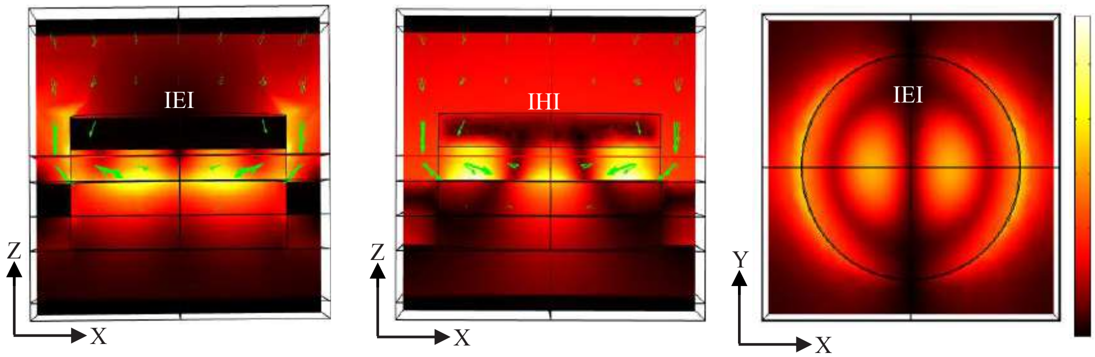


Fig 3. Calculated performance of Design 4 in the extended spectral range.

We can see multiple resonant peaks in its absorption spectrum corresponding to the excitation of fundamental and higher-order magnetic resonances. In Fig 4, we have plotted the spatial profiles of electric and magnetic field magnitudes at two of the higher wavelength absorption peaks (i.e. 18.76 μm and 10.56 μm in Fig 3). The green arrows in these plots represent the spatial profile of the time-averaged Poynting vector.



(a)



(b)

Fig 4. Spatial profiles of the electric field and magnetic field magnitudes for Design 4, in X-Z and X-Y planes, corresponding to resonant peaks at (a) 18.76 µm and (b) 10.56 µm.

All the field profile plots have been normalized with respect to the peak electric and magnetic field magnitudes corresponding to the fundamental magnetic resonance at 18.76 µm. In Fig 4 (a), we can observe the existence of an electric dipole in both X-Y and X-Z planes. This electric dipole forms its image in the bottom ITO layer with opposite polarity since the thickness of the spacer is much less than the wavelength. These give rise to oppositely directing conduction currents while significant displacement currents also arise in the ZnS spacer layer on account of the intense electric field. Therefore, an artificial current loop is generated, which gives rise to a net magnetic dipole moment directed along Y-axis. We can observe in the spatial profile of the magnetic field magnitude that it is highly localized in the ZnS spacer layer, between the top and bottom ITO layers. This confirms the existence of the fundamental magnetic resonance at 18.76 µm. In Fig 4 (b), we show the occurrence of a higher-order magnetic resonance at 10.56 µm. This magnetic resonance corresponds to the third order as we can observe the existence of three antinodes in the spatial profiles of the magnetic field and three nodes in the spatial profile of the electric field. It is to be noticed here that we do not observe any resonant peak corresponding to the second-order magnetic resonance. This is because the structure is symmetric and the even order resonances cannot be excited at normal incidence. Similarly, the absorption peak at 2.92 µm corresponds to the excitation of fifth-order magnetic resonance in the structure. The green arrows in the plots, which define the local direction of energy flow in the structure, also suggest that energy is being channeled inside the space between the top and bottom ITO layers, where the inherent ohmic losses in the ITO layers lead to absorption of energy.

5 Discussion

Figure 4 establishes the existence of magnetic resonances in the proposed metamaterial structure, which leads to field localization and hence high absorption in the structure. The absorption performance of these structures is tunable by variation of geometrical parameters, as described in Tables 1 & 2. From Table 2, it can be deduced that Designs 1 & 4 exhibit the largest contrast of emissivity, and hence can be considered as the suitable candidates for the realization of Logical Boolean units of 1 and 0 which we are referring here as *thermal bits*. These thermal bits, when maintained at the same temperature, will radiate substantially different amounts of heat flux in the atmosphere, owing to their large emissivity contrast. Therefore, when being looked at from a thermal imager, high and low emissivity structures will appear as bright and dark pixels, respectively. Multi-level encoding can also be achieved by using pixels with multiple levels of emissivties. With the help of these pixels, information can be encoded in a two-dimensional binary thermal pattern. Since the metamaterial structure is optically transparent, the information will remain encrypted in the visible domain. This novel capability can be employed to design IR tags for friend or foe identification purposes as well as in security applications such as in paper currency, security documents or credit cards. These can also be used for creating encrypted signals in low ambient light conditions.

6 Conclusion

In this work, we have proposed a novel design of optically transparent thermal metamaterial whose emissivity values can be customized as per the requirements by changing the geometrical parameters of the unit cell. Four such designs have been proposed in the present work with emissivity values ranging from 9.4 % to 65.3% over the 8-12µm IR band. Higher values of emissivities are obtained by conventional materials while similar emissivities as here can usually only be obtained by metalizing the surfaces, resulting in high values of optical gloss. The underlying mechanisms for the observed absorption resonances can be attributed to the excitation of simultaneous electric and magnetic resonances and strong localization of the magnetic field within the ZnS spacer layer, sandwiched between two ITO layers. These designs can be the potential candidates for creating thermal pixels, the ordered arrangement of which can be used for information encryption.

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