2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/USNC-URSI) | 978-1-6654-9658-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/AP-S/USNC-URSI47032.2022.9886421

A Transmissive All-Dielectric Metasurface-Based Nanoantenna Array for Selectively Manipulation of Thermal Radiation

Bahram Khalichi*†, Zahra Rahimian Omam*, Ataollah Kalantari Osgouei*‡, Amir Ghobadi*†, and Ekmel Özbay*†‡§
* NANOTAM-Nanotechnology Research Center, Bilkent University, 06800 Ankara, Turkey
† Department of Electrical and Electronics Engineering, Bilkent University, 06800 Ankara, Turkey
‡Department of Physics, Bilkent University, 06800 Ankara, Turkey
§UNAM-Institute of Materials Science and Nanotechnology, Bilkent University, 06800 Ankara, Turkey
Emails: bahram@ee.bilkent.edu.tr, ozbay@bilkent.edu.tr

***Abstract*—In this study, a wavelength-selective thermal nanoantenna emitter based on metamaterial design with heat radiation signature management and radiative cooling property is proposed. The design can be considered as a multifunctional window by reducing the heat signature and releasing the heat energy within the non-atmospheric window. The approach relies on the indium tin oxide cubic-shaped unit cell coated on a flexible and transparent substrate (polystyrene). The spectral behaviors of the proposed structure are obtained using the finite difference time domain method, where the power calculation model is utilized to demonstrate the radiative cooling efficiency and low power detection on infrared cameras.**

***Index Terms*—Metametarial, nanoantenna array, thermal signature management, polarization insensitivity.**

I. Introduction

Thermal emission process [1], and the ability to control thermal radiation from a hot object mainly in the infrared (IR) range has attracted growing attention due to various applications ranging from environmental monitoring to thermophotovoltaics. From this perspective, two common approaches to control the thermal radiation of an object are *i*) decreasing surface temperature and *ii*) modifying surface emissivity [2]–[5]. Although simultaneous reducing the IR emittance and the temperature is of great significance, the poor efficiency of the thermal radiation contributes to a sharp increase in the actual temperature of the object, enhancing the radiation of thermal energy. In particular, thermal emission from surfaces of targets occurs in the two main IR atmosphere transparent windows: mid-wave IR (MWIR, $3-5$ μm) and the long-wave IR (LWIR, $8-12$ μm) ranges. In these spectrum ranges, most thermal radiation propagates through the atmosphere with near-zero absorption. In contrast, due to attenuation and absorption phenomena in the atmosphere, the thermal radiation can be absorbed with near-unity absorption outside the IR transparency windows. Therefore, reducing the emitted waves from the surfaces of targets within atmospheric windows and permitting high emission within non-atmospheric window ($5-8$ μm) is a robust approach to overcome the high temperature/less radiation paradox and to balance the thermal emission utilized in the IR camouflage and radiative cooling applications. As a result, wavelength-selective metamaterial-based designs [5]–[8] are proposed in which the optical absorption response of a structure is engineered due to the connection to the surface emissivity of that structure at thermodynamic equilibrium based on Kirchhoff's radiation law [1]–[4]. Having a perfect absorption resonance within the non-atmospheric window helps to reduce coated targets' temperature, which causes thermal balance and radiative heat exchange between the targets and low-temperature surroundings. However, most of the designs are based on the reflective mode response of the target within MWIR and LWIR ranges detected by the IR cameras. Thereby, we propose a wavelength-selective nanoantenna emitter that acts as an optically transparent multifunctional window, hides the main indoor targets, and cools the surrounding medium by characterizing wavelength-selective emission and transmission spectra within the non-atmospheric window.

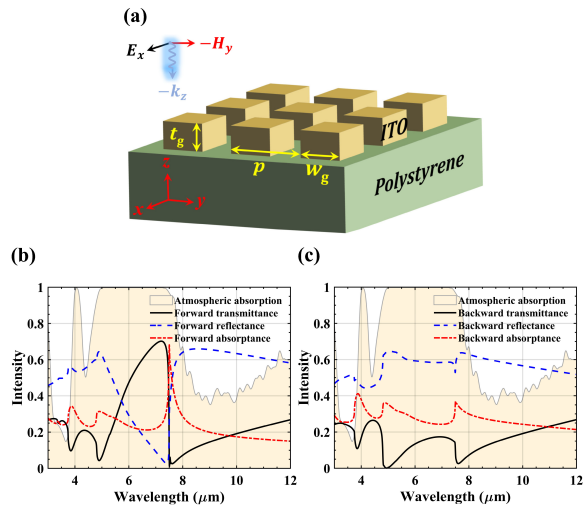

Fig. 1. (a) Schematic representation of the proposed metasurface-based emitter. (b) Forward and (c) backward illuminations spectra when the structure is illuminated with an $x-$polarized uniform plane wave propagating along the $\mp z$ directions, respectively.

II. Design Procedure and Simulation Results

Fig. 1(a) shows a schematic illustration of the proposed metasurface-based emitter, including cubic-shaped nanoantennas made of indium tin oxide (ITO), a visible light-transparent material, on top of polystyrene (PS) substrate. The structure can be illuminated by an $x-$ or a $y-$polarized uniform plane wave propagating along the $\pm z$ directions since the symmetry makes the emitter insensitive to polarization. The optical property of the ITO material as a dispersive medium has been taken from the ellipsometry, and the relative permittivity of PS substrate is considered as 2.4346. The geometrical parameters of each unit cell, namely the period (p), width (w_g), and thickness (t_g) of the grating, are optimized using finite-difference time-domain (FDTD) software package to achieve the desired goal in the reflection, transmission, and absorption spectra. The wavelength-dependent surface emissivity is obtained as $\varepsilon_\lambda = 1 - R_\lambda - T_\lambda$ according to Kirchhoff's law where R_λ and T_λ are the reflectivity and the transmissivity of the

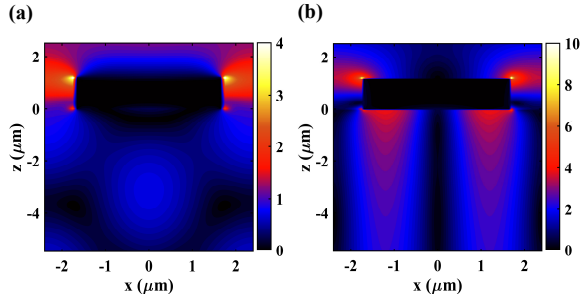

Fig. 2. Absolute value of total electric field distributions on the $x-z$ plane at the resonance wavelength of (a) 7.2 μm and (b) 7.5 μm when the structure is normally illuminated by an $x-$polarized uniform plane wave.

design, respectively. As a result, the width of the unit cell is set $w_{\mathrm{g}} = 3.4$ μm where the periodicity of the grating is fixed as $p = 4.8$ μm, and the grating thickness is tuned to be $t_{\mathrm{g}} = 1.2$ μm to obtain the desired surface transmissivity and emissivity within the non-atmospheric window. The spectral responses of the designed nanoantenna emitter are plotted in Fig. 1(b) and Fig. 1(c) for the forward $(-z)$ and backward $(+z)$ illuminations, respectively. For the forward illumination (indoor environment), two distinct resonances are placed in the non-atmospheric region belonging to the transmissivity and absorptivity at 7.2 μm and 7.5 μm, respectively. Therefore, a partial amount of the blackbody radiation can pass or can be absorbed by the wavelength-selective nanoantenna emitter within the non-atmospheric region, which results in cooling of the indoor environment as well as hiding the object. Additionally, the backward spectra (outdoor environment) demonstrate high reflection and low emissivity in the whole region, helping the inner object be hidden to IR detectors. The physical behavior of nanoantenna emitter at the resonance wavelengths of transmission and absorption spectra is analyzed to determine the types of supported modes by the structure. Therefore, the corresponding total electric field on the $x-z$ plane is presented in Fig. 2. At the resonance wavelength of the transmission spectrum (7.2 μm), the incident waves interact with the unit cell, and it is partially transmitted through the slits. In this case, the electric field distribution is strongly enhanced and confined within the gratings and experiences a large discontinuity with high amplitude in the low-index side for satisfying the continuity of the normal component of electric flux density. Meanwhile, At the resonance wavelength of the absorption spectrum (7.5 μm), the diffraction of electric fields results in satisfying the phase-matching condition and excitation of surface plasmons (SPs) at the upper and lower interfaces of ITO grating as seen from the electric field given in Fig. 2(b). This is due to the fact that ITO is an alternative plasmonic material in the IR range due to its metallic behavior.

The proposed multifunctional window can elegantly cool the indoor environment without letting the indoor targets be detected by the outdoor IR cameras. Emitted power from the indoor blackbody radiation is calculated using thermal emission modeling to verify this capability. The total thermal emission $TE\left(T,\lambda\right)$ by a blackbody radiator at the indoor environment passing through the multifunctional window can be obtained by

$$TE\left(T,\lambda\right) = BB\left(T,\lambda\right)\times\left[T_{\mathrm{forward}}\left(\lambda\right)+\varepsilon_{\mathrm{backward}}\left(\lambda\right)\right], \quad (1)$$

where $T_{\mathrm{backward}}\left(\lambda\right)$ and $\varepsilon_{\mathrm{backward}}\left(\lambda\right)$ are the forward transmittance and backward absorptance of the proposed structure, respectively, dependent on the operating wavelength,

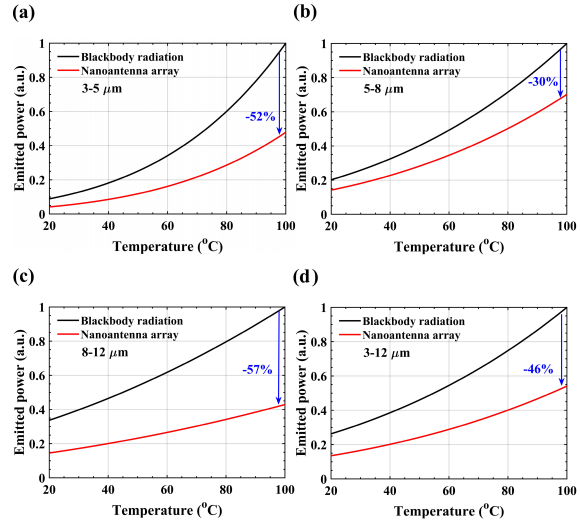

Fig. 3. Detected emitted powers versus temperature at different intervals (a) 3−5 μm, (b) 5−8 μm, (c) 8−12 μm, (d) 3−12 μm. The calculations are done without considering the effect of atmospheric absorption spectrum.

λ. The blackbody radiation spectrum is expressed by $BB\left(T,\lambda\right)$. As shown in Fig. 3, taking an integral with respect to the wavelength over the region of interest without considering the effect of atmospheric absorption spectrum will give the normalized optical power versus temperature (T) detected by the IR cameras. As expected, the heat signature should be low enough within the 3−5 μm and 8−12 μm regions (i.e., 52% and 57% reductions) and the power should be as close as to the blackbody radiation in 5−8 μm (30% reduction) for satisfying camouflage and cooling properties simultaneously.

III. Conclusion

We proposed a wavelength-selective transmissive nanoantenna emitter acting as a multifunctional window with thermal camouflage and radiative cooling properties. The design releases the heat energy into the atmosphere through the non-atmospheric window. The suppression of thermal power without considering the atmospheric absorption effect is verified by calculating the received power by the IR cameras where 52% and 57% reductions are obtained at 100 °C, respectively within the MWIR and LWIR regions in comparison to the blackbody radiation. This number is 30% within the non-atmospheric window, which is equivalent to cooling of the indoor environment.

References

[1] M. Planck, *The theory of heat radiation*. Blakiston, 1914.
[2] E. Buhara and et al., "Mid-infrared adaptive thermal camouflage using a phase-change material coupled dielectric nanoantenna," *J. Phys. D. Appl. Phys.*, vol. 54, no. 26, p. 265105, 2021.
[3] B. Khalichi and et al., "A transparent all-dielectric multifunctional nanoantenna emitter compatible with thermal infrared and cooling scenarios," *IEEE Access*, vol. 9, pp. 98590–98602, 2021.
[4] A. K. Osgouei and et al., "A spectrally selective gap surface-plasmon-based nanoantenna emitter compatible with multiple thermal infrared applications," *J. Optics*, vol. 23, no. 8, p. 085001, 2021.
[5] Q. Kang and et al., "Multiband tunable thermal camouflage compatible with laser camouflage based on GST plasmonic metamaterial," *J. Phys. D. Appl. Phys.*, vol. 55, no. 6, p. 065103, 2021.
[6] B. Khalichi, A. Ghobadi, A. K. Osgouei, and E. Özbay, "Diode like high-contrast asymmetric transmission of linearly polarized waves based on plasmon-tunneling effect coupling to electromagnetic radiation modes," *J. Phys. D. Appl. Phys.*, vol. 54, no. 36, p. 365102, 2021.
[7] H. Kocer and et al., "Nano shell impact on huygens' metasurface dipolar resonances and optical response," *J. Opt, Soc. Am. B*, vol. 38, no. 9, pp. C127–C135, 2021.
[8] A. K. Osgouei and et al., "Active tuning from narrowband to broadband absorbers using a sub-wavelength VO_2 embedded layer," *Plasmonics*, pp. 1–9, 2021.