A Wavelength-Selective Multilayer Absorber for Heat Signature Control

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

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***Abstract*—Engineering the thermal radiation using wavelength-selective thermal emitters is of great importance in the field of thermophotovoltaics, radiative cooling, and heat signature control. In this paper, a wavelength-selective Vanadium/Germanium (V/Ge) multilayer absorber is demonstrated. The proposed design realizes a perfect absorption at the resonance wavelength of 5870 nm, placed within the nonatmospheric window (5-8 μm) while maintaining low absorptivity within the atmospheric windows. It is verified that the proposed emitter represents angle insensitive feature for oblique incidence up to 60° for both transverse magnetic (TM) and transverse electric (TE) polarizations.**

***Index Terms*—Thermal radiation, heat signature control, multilayer absorber, polarization insensitive**

I. Introduction

The ability to control thermal radiation is of great importance in a wide range of applications, including radiative cooling [1], thermophotovoltaics (TPVs) [2], and heat signature control [3]. In general, the thermal radiation energy per unit area emitted from an object depends not only on the surface emissivity but also on the fourth power of the absolute temperature according to the Steven-Boltzmann equation $P = \epsilon\sigma T^4$, where σ is the Steven-Boltzmann constant and ϵ and T are the emissivity and absolute temperature of the surface, respectively [4]. It is also known that for an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity. Therefore, reducing both the emissivity/absorptivity and the temperature of the surface are the two means to control the object's thermal radiation. The temperature control represents a direct solution of achieving the thermal radiation, but it requires additional cooling and heating systems [5]. On the other hand, controlling the surface emissivity is an easier task than the temperature, as covering a low emissivity material on the surface can effectively suppress the thermal radiation. Unfortunately, the poor efficiency in thermal radiation, caused by a low emissivity, contributes to a sharp increase in the absolute temperature of the object. Therefore, wavelength-selective thermal emitters with appropriate optical properties are highly desirable. As wavelength-selective absorbers are equivalent to the wavelength-selective emitters at the thermal equilibrium $\alpha(T,\lambda) = \epsilon(T,\lambda)$ according to Kirchhoff's law of thermal radiation, therefore, metamaterial-based perfect absorbers (MPAs) can be a suitable candidate for achieving wavelength-selective thermal radiations [6], [7]. In general, MPAs are artificially engineered materials for achieving near-perfect absorptions by employing a series of periodic arrayed unit cells. By adequately choosing geometrical structures and materials, the resonances can reach near unity at specific wavelengths, enabling realizing near unity wavelength-selective properties [8], [9]. Thereby,

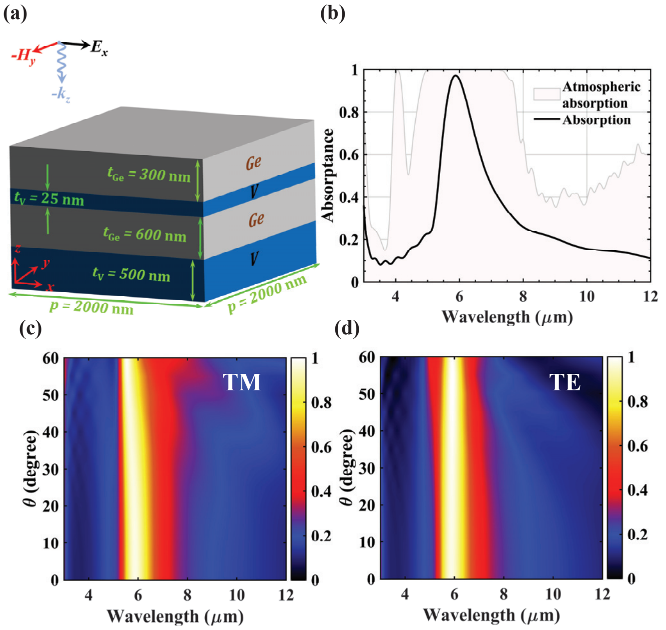

Fig. 1. (a) Schematic diagram of the proposed multilayer absorber. (b) The simulated absorptance of the proposed structure versus wavelength. The atmospheric absorption band [shown as the light area] is modeled by the US standard atmosphere compositions at the vertical distance of 5 km [12]. Numerically calculated the dependence of the absorption performance of the structure on the incident angle for (c) TM and (d) TE polarizations.

the wavelength-selective metamaterial absorbers/emitters are widely exploited in heat signature control. In particular, a wavelength-selective metamaterial absorber/emitter demands the suppression of the thermal radiation within the mid-wave infrared (MWIR: 3-5 μm) and the long-wave infrared (LWIR: 8-12 μm) ranges representing the main transmission channels for the electromagnetic waves in the atmosphere, while the thermal radiation is allowed to be enhanced in the nonatmospheric window (5-8 μm). In other words, the desired emitter should have a low emissivity in the specific atmospheric windows to be hidden in the background and high emissivity outside the atmospheric window due to attenuation and absorption phenomena in the atmosphere to offer heat signature control for thermal camouflage scenarios. In this paper, a planarized wavelength-selective thermal absorber based on using a multi-layer film of Vanadium/Germanium (V/Ge) configuration, with the possible advantages of structural simplicity and large-scale fabrication, is proposed. The proposed design shows a perfect absorption at the resonance wavelength of 5870 nm placed in the nonatmospheric window while maintaining low emissivity within the atmospheric window. Moreover, it is shown that the proposed emitter is angle insensitive for oblique incidence up to 60° for both transverse electric (TE) and transverse magnetic (TM) polarizations.

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II. Design Procedure and Simulation Results

The schematic of the proposed wavelength-selective emitter working in the 3-12 μm wavelength range is shown in Fig. 1(a). The proposed structure is consisting of a four-layered structure of a thin V layer, two Ge insulator spacers, and the bottom metallic V layer. Surfaces of an object can be coated with the proposed structure to be hidden from MWIR and LWIR mode cameras that detect blackbody photons emitted from the object. Therefore, numerical simulations based on the FDTD method with a commercial software package (Lumerical Solutions, Inc.) are utilized to optimize the geometrical parameters so that a low emittance within the atmospheric windows and a high emittance in the nonatmospheric window are achieved [10]. In the simulations, the frequency-dependent refractive index of V is taken into account from the CRC Handbook of Chemistry and Physics [11]. Furthermore, the refractive index of Ge is assumed to be the constant value of 16. Therefore, based on the utilized simulations approaches, the geometrical parameters are explicitly shown in Fig. 1(a). The optimal thicknesses of the bottom and middle V layers are 500 nm (thick enough to suppress the transmission) and 25 nm, respectively, while top and middle Ge layers are 300 nm and 600 nm, respectively. The absorptance of the proposed structure with respect to the wavelength is shown in Fig. 1(b). The result shows a perfect absorption at the resonance wavelength of 5870 nm, which is in very good agreement with the atmospheric absorption spectrum [shown as the light area in Fig. 1(b)], while showing low emissivity in the two atmospheric windows. Therefore, the thermal radiation of the proposed multi-layer film emitter can be efficiently absorbed by the atmosphere, which makes the coated object blind to infrared cameras. Due to the symmetrical design, the proposed emitter is polarization insensitive. Furthermore, Figs. 1(c) and (d) shows that the absorptivity remains independent versus incident angle ranging from 0° to 60° for both TM and TE polarizations, respectively. In order to introduce the working mechanism of the V/Ge multilayer wavelength-selective emitter in details, the calculated total electric- and magnetic-field distributions at the resonance wavelength of 5870 nm are presented in Fig. 2(a) and 2(b), respectively. The calculated electric and magnetic field distributions are mainly localized within the middle Ge space layer due to the excitation of the Fabry-Perot (FP) cavity resonance. In other words, the incident light penetrates through the thin V layer and bounces back at the bottom reflector, leading to a absorption thanks to the lossy behavior of V in the NIR region. Additionally, as shown in Fig. 2(c), the absolute value of the absorbed-power density at the resonance wavelength of 5870 nm indicates that the energy of the incident light is mainly absorbed within the thin V layer. This result supports the idea that thermal radiation management or the heat signature control is accomplished thanks to the thin V layer, while the bottom V layer contributes less in the absorption and behaves as an infrared reflective layer.

III. Conclusion

In conclusion, a wavelength-selective V/Ge multilayer absorber with the possible advantages of simple structure and large-scale fabrication is proposed and investigated for heat signature control application. Through numerical simulations, the emissivity of the proposed emitter realizes a perfect absorption at the resonance wavelength of 5870 nm while

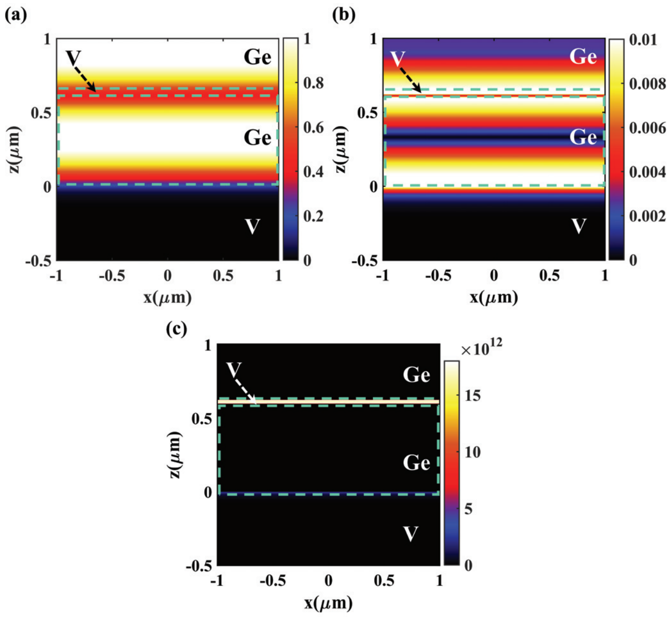

Fig. 2. Absolute values of the total electric- (a) and magnetic-field (b) distributions of the proposed structure at the resonance wavelength of 5870 nm. (c) Absolute value of the absorbed-power density at the same resonance wavelength.

showing low emissivity within the atmospheric windows. Moreover, the physical mechanisms of the proposed design indicate that the FP resonance is excited within the middle Ge space layer at the resonance wavelength. Finally, the proposed emitter represents an angle-independent feature for oblique incidents up to 60° for TM and TE polarizations.

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