A spectrally selective gap surface-plasmon-based nanoantenna emitter compatible with multiple thermal infrared applications

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Abstract

Wavelength-selective nanoantenna emitters have attracted considerable attention due to their widespread applications ranging from thermal radiation management to thermophotovoltaics. In this paper, we design a wavelength-selective nanoantenna emitter based on the excitation of gap-surface plasmon modes using a metal–insulator–metal configuration (silicon dioxide (SiO₂) sandwiched between silver (Ag) layers) for satisfying multiple infrared applications. The proposed design, which is called design I, realizes triple narrowband perfect absorptions at the resonance wavelengths of 1524 nm, 2279 nm, and 6000 nm, which perfectly match the atmospheric absorption bands while maintaining relatively low emissivity in the atmospheric transparency windows of 3–5 μm and 8–12 μm . Later, the functionality of design I is extended, which is called design II, to include a broadband absorption at the near-infrared region to minimize the solar irradiation reflection from the nanoantenna emitter. Finally, single- and three-layer graphene are introduced to provide a real-time tuning of the infrared signature of the proposed nanoantenna emitter (design II). It is also demonstrated that the three-layer graphene structure can suppress an undesired absorption resonance wavelength related to the intrinsic vibrational modes (optical phonons) of the SiO₂ layer by 53.19% compared to 25.53% for the single-layer one. The spectral analysis of design I is validated using both analytical and numerical approaches where the numerical simulation domain is extended for the analysis of design II. The thermal characteristic analyses of design I and design II (without/with graphene layers) reveal that infrared signatures of the blackbody radiation are significantly reduced for the whole wavelength spectrum at least by 96% and 91% within a wide temperature ranging from room temperature to 500 K, respectively.

Keywords: nanoantenna emitter, wavelength selectivity, plasmonic structure, gap surface plasmon, thermal radiation management, solar absorber

(Some figures may appear in colour only in the online journal)

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1. Introduction

Total emissive power per unit area from a hot surface is defined by the Stefan–Boltzmann law $P = \varepsilon \sigma T^4$ [1, 2], where σ is the Stefan–Boltzmann constant, ε and T are the emissivity and absolute temperature of the object, respectively. At the thermal equilibrium, Kirchhoff's radiation law [1, 2] states that the wavelength-dependent thermal radiation of a surface is equal to the optical absorption of that surface defined as $\varepsilon(T, \lambda) = \alpha(T, \lambda)$. Therefore, suppressing the thermal radiation can be achieved by reducing the emissivity/absorptivity (ε) or the real temperature of the object (T). However, the poor efficiency of the thermal radiation contributes to a sharp increase in the real temperature of the object. Accordingly, wavelength-selective thermal emitters are widely used to overcome this problem. In particular, a wavelength-selective material-based shield should have a low emissivity to reduce the object's thermal radiation within specific atmospheric windows as well as have a high emission outside of those atmospheric windows for the radiative cooling applications. In other words, the thermal radiation should dominantly be suppressed within the mid-wave infrared (MWIR: 3–5 μm) and the long-wave infrared (LWIR: 8–12 μm) ranges representing the transmission channels for electromagnetic waves in the atmosphere, while the thermal radiation is allowed to pass in the non-transmissive (absorption) windows, including 1.5–1.61 μm , 2.15–3 μm , 4–4.2 μm , and 5–8 μm , due to the fact that the absorption phenomenon quench the propagation of emitted photons in these ranges [3]. This wavelength-selective characteristic makes the object blend into the background and offers thermal radiation management for multiple thermal camouflage scenarios. Moreover, to have a comprehensive infrared characteristic, the design should absorb (solar) photons in the range of 0.9–1.7 μm to hide from short-wave infrared (SWIR) and laser tracking cameras (typically operating at 1064 nm).

Since the design of wavelength-selective thermal nanoantenna emitter is equivalent to the design of wavelength-selective thermal nanoantenna absorber (Kirchhoff's law), metamaterial-based perfect absorbers with wavelength selectivity characteristic have attracted considerable attention due to their potential applications in radiative cooling [4, 5] and thermophotovoltaics [6, 7]. In addition, plasmonic metamaterials [8–10] and photonic crystals [11, 12] are widely exploited in thermal radiation management [13–18] as an ability to hide or disguise an object from infrared (IR) detection equipment and thermal imaging systems. Although photonic crystals can be designed to realize high emissivity with a special structure [11, 12], the configuration complexity makes photonic crystals less suitable in high-temperature environments due to the thermal stress [17]. On the other hand, plasmonic metamaterials as a periodic array of subwavelength structures can be artificially engineered to achieve exotic properties in terms of perfect absorptions and wavelength selectivity. The absorption can reach near unity at specific wavelengths, enabling the realization of perfect absorptions. Generally, metal–insulator–metal (MIM) plasmonic-based cavity designs are considered as one of the typical configurations for designing near unity wavelength-selective

absorbers [19–23]. Properly choosing selective emissive materials for an MIM cavity design and its extensions to composite unit cell [24, 25] or multi-layer [26, 27] structures can lead to wavelength-selective metamaterial-based nanoantenna emitters/absorbers satisfying the requirements of multiple thermal infrared applications. Overall, in an ideal architecture, a wavelength-selective thermal nanoantenna emitter should radiatively cool the surface within specific atmospheric absorption windows without being detected by infrared cameras.

In the first part of this paper, a wavelength-selective nanoantenna emitter based on the excitation of gap surface plasmon modes using an MIM configuration (silicon dioxide (SiO_2) sandwiched between silver (Ag) layers) is proposed. The proposed structure, called design I, shows triple narrowband perfect absorptions at the resonance wavelengths of 1524 nm, 2279 nm, and 6000 nm that perfectly match the atmospheric absorption bands. Meanwhile, the emissivity of the structure in the wavelength ranges of 3–5 μm and 8–12 μm (atmospheric windows) is suppressed considering the average amount of absorption occurred below 0.10. Later, we extend the functionality of design I to cover the possible threats in the SWIR range (design II). The results indicate that a near perfect absorption is acquired in a broadband spectrum spanning from 929 nm to 1472 nm (SWIR range), together with a narrowband absorption peak at 5750 nm (atmospheric absorption window). Finally, a real-time tuning of the infrared response using external electrostatic bias is added to the system by embedding graphene layers. It is also shown that an undesired resonance wavelength at the absorption spectrum related to the intrinsic vibrational modes (optical phonons) of the SiO_2 layer within the LWIR range is reduced by adding a single-layer graphene. Moreover, the amount of reduction is significantly enhanced in the case of embedding a three-layer graphene. In other words, the amount of absorption of the LWIR response for the three-layer graphene device is decreased by 53.19%, compared to 25.53% for the single-layer graphene one. The performances of the proposed structures are validated using rigorous coupled-wave analysis (RCWA) as an analytical method [28], besides a finite-differences time domain solver (FDTD) as a numerical method [29]. In addition, the thermal characteristic performances of design I and design II (without/with graphene layers) are validated by calculating spectral radiant emittance at different temperatures.

2. Design I

2.1. Results and discussions

The schematic diagram of the proposed nanoantenna emitter (design I) is shown in figure 1(a). The unit cell consists of two metallic silver (Ag) layers: a bottom reflector (optically thick with no transmission in our analysis range) and a top grating array, with an insulator layer of SiO_2 (silicon dioxide) sandwiched in between. The Ag film is selected as the primary thermal radiation layer because of its unique radiation

Figure 1. (a) Schematic unit cell of the proposed wavelength-selective nanoantenna emitter (design I). (b) Spectral absorption responses of design I obtained by considering constant and frequency-dependent values for the permittivity of the SiO₂ layer. The atmospheric absorption band [shown as the light blue area] is modeled by the US standard atmosphere compositions at the vertical distance of 5 km.

properties [17], while the SiO₂ spacer layer is added to match the selective emissions to the impedance of the air. The analytical (RCWA) and numerical (FDTD) approaches are utilized to investigate the optical properties of the proposed nanoantenna emitter, when the structure is normally illuminated by an x -polarized (p -polarization) uniform plane-wave propagating along the $-z$ direction. In the simulations, the frequency-dependent refractive indices of Ag and SiO₂ are taken into account from the CRC Handbook of Chemistry and Physics [30] and the Palik model database [31], respectively. Then, based on the utilized simulation approaches, the geometrical parameters as explicitly presented in figure 1(a) are optimized in such a way that the excited resonances in the absorption spectrum match the atmospheric absorption windows. As a result, the thickness of the top nanograting Ag layer is

$t_{Ag} = 160$ nm while its width is considered $w_{Ag} = 1220$ nm, and the thickness of the SiO₂ layer is set to be $t_{SiO_2} = 20$ nm. The period of the unit cell is considered to be $p = 1365$ nm along the x direction. The absorptivity of design I with respect to the wavelength is presented in figure 1(b), where the analytical and numerical approaches are in good agreement with each other. The results unveil that the fourth resonance (λ_4 in figure 1(b)) is due to intrinsic vibrational modes (optical phonons) of the SiO₂ layer in the LWIR range [32] since the resonance is suppressed by considering a constant relative permittivity ($\epsilon_{SiO_2} \simeq 2.15$) valid below the wavelength of 8 μ m, as shown in figure 1(b). The other triple narrowband perfect absorptions are successfully achieved at the resonant peaks of $\lambda_1 = 1524$ nm, $\lambda_2 = 2279$ nm, and $\lambda_3 = 6000$ nm (see figure 1(b)). These resonances are in very good agreement with the atmospheric spectrum (shown as the light blue area in figure 1(b)), while showing remarkable low average emissivity in the atmospheric windows (i.e. $\epsilon_{3-5 \mu m}$ and $\epsilon_{8-12 \mu m} \leq 0.10$). Therefore, the thermal radiation of the wavelength-selective design can be greatly absorbed by the atmosphere, which makes the coated object hidden to infrared detectors. The atmospheric spectrum is obtained from [33] where the atmospheric absorption is modeled by considering the US standard atmosphere compositions at the vertical distance of 5 km.

2.2. Physical mechanism

The physical behavior of design I is analyzed at the resonance wavelengths to determine the types of supported modes by the structure. Therefore, the calculated total electric- and magnetic-field distributions are presented in figures 2(a)–(f). At the resonance wavelengths of λ_1 , λ_2 , and λ_3 shown in figures 2(a)–(f), the presented electric and magnetic mode profiles are mostly concentrated within the thin spacer layer, due to the formation of gap surface plasmon (GSP) resonances [34–39]. The GSP resonator, being composed of a thin SiO₂ layer sandwiched between the top Ag grating array and bottom Ag substrate, experiences multiple reflections from the termination of the MIM structure. This results in a lateral standing-wave type resonance between the metallic terminations and oscillating antiparallel electric currents in the two metallic layers [34]. Therefore, GSP resonances can be described by a simple Fabry–Perot (FP) resonator formula [36, 37]

$$w_{Ag} \frac{2\pi}{\lambda_0} n_{GSP} + \varphi = m\pi, \quad (1)$$

where w_{Ag} as mentioned before denotes the width of the top nanograting array, λ_0 is the wavelength of the free space, n_{GSP} is the real part of the effective mode index, φ is the additional phase acquired upon its reflection at the termination of the structure, and m is an integer showing the order of the GSP mode. According to figure 2, the electric field distribution at the resonance wavelength of λ_1 demonstrates the excitation of fifth-order mode ($m = 5$) within the spacer layer, while the electric-field mode profiles at the

Figure 2. Absolute values of the total electric- and magnetic-field distributions on the $x-z$ plane obtained for a two-unit cell of design I at the resonance wavelengths of (a), (d) $\lambda_1 = 1524$ nm, (b), (e) $\lambda_2 = 2279$ nm, and (c), (f) $\lambda_3 = 6000$ nm, respectively. In all the figures, dashed white lines represent the Ag area.

resonance wavelengths of λ_2 , and λ_3 correspond to the excitation of the third-order ($m = 3$) and first-order ($m = 1$) modes, respectively [34].

The calculated total magnetic-field distributions depicted in figures 2(d)–(f) also validate the type of the GSP-based resonances. In the fifth mode, anti-parallel currents in the top Ag nanograting and the bottom metallic layer create five anti-nodes of the magnetic fields inside the thin spacer layer. Accordingly, the third and first modes are due to the formation of three and first anti-nodes of the magnetic fields in the spacer layer, respectively. From the electric- and magnetic-field distributions given in figures 2(a) and (d), it is observed that surface plasmons (SPs) are also excited between the air and the top Ag nanograting, and localized around the grating corners between the adjacent unit cells, creating an SP-induced light absorption at λ_1 . Therefore, the origin of λ_1 is due to the formation of both SP and GSP resonances. While λ_2 and λ_3 are due to the excitations of GSP resonances. These facts can also be illustrated by calculating the absorbed-power densities given in figure 3. Figure 3(a) demonstrates that a small amount of absorption within the groove and the absorption between the top and bottom Ag layers are attributed to the combinations of both SP and GSP resonances at the resonance wavelength of λ_1 . Furthermore, the absorbed power densities, given in figures 3(b) and (c), demonstrate that the most amount of absorption occurred between the top and bottom Ag layers (both interfaces of the dielectric layer), confirming the types of the resonance wavelengths of λ_2 and λ_3 are due to the excitation of GSPs.

2.3. Geometric parameters effects

The impact of changes of t_{SiO_2} , w_{Ag} , and p on the overall absorption spectrum of design I is examined. Figure 3(d) represents the contour plot of absorptivity versus the wavelength for the different thicknesses of the spacer (t_{SiO_2}), while the other parameters of the structure are kept at their optimal values ($10 \text{ nm} \leq t_{\text{SiO}_2} \leq 200 \text{ nm}$ when $w_{\text{Ag}} = 1220 \text{ nm}$, $t_{\text{Ag}} = 160 \text{ nm}$ and $p = 1365 \text{ nm}$). The results illustrate triple narrowband perfect absorptions that are sensitive to the variation of the thickness of the spacer as it increases from 10 nm to 200 nm. Increasing and getting far away from the optimized thickness value of the spacer (i.e. $t_{\text{SiO}_2} = 20 \text{ nm}$, by considering the fact that the perfect absorption threshold is above 0.9) leads to a reduction in the amount of absorption, while the fourth resonance at longer wavelengths is efficiently excited by moving from a thinner to a thicker spacer. It is evident from figure 3(d) that all the resonances are a function of the thickness of the spacer. In other words, by changing the thickness of SiO_2 from 50 nm to 10 nm, the resonance wavelengths are red-shifted toward the longer wavelength regions. This behavior of the resonances is in good agreement with the concept of GSP modes [38]. Therefore, according to the electric- and magnetic-field confinements within the spacer as shown in figures 2(a)–(f), all resonances more or less are affected by the thickness variation of the SiO_2 layer. The normalized contour plot absorptivity response of the design I for different widths of the top Ag nanograting layer is shown in figure 3(e). The Ag width is swept from 1150 nm

Figure 3. Absolute values of the absorbed-power densities on the $x-z$ plane obtained for a two-unit cell of design I at the resonance wavelengths of (a) $\lambda_1 = 1524$ nm, (b) $\lambda_2 = 2279$ nm, and (c) $\lambda_3 = 6000$ nm. In all the figures, dashed green lines represent the SiO_2 area. (d) Simulated contour plot of absorptivity as a function of wavelength for different thicknesses of the spacer (t_{SiO_2}) ($10 \text{ nm} \leq t_{\text{SiO}_2} \leq 200 \text{ nm}$ when $t_{\text{Ag}} = 160 \text{ nm}$, $w_{\text{Ag}} = 1220 \text{ nm}$, and $p = 1365 \text{ nm}$). (e) Simulated contour plot of absorptivity versus wavelength for different widths (w_{Ag}) of the top Ag nanograting layer ($1150 \text{ nm} \leq w_{\text{Ag}} \leq 1350 \text{ nm}$ when $t_{\text{SiO}_2} = 20 \text{ nm}$, $t_{\text{Ag}} = 160 \text{ nm}$, and $p = 1365 \text{ nm}$). (f) Simulated contour plot of absorptivity versus wavelength for different periodicities (p) of the structure ($1300 \text{ nm} \leq p \leq 1450 \text{ nm}$ when $t_{\text{SiO}_2} = 20 \text{ nm}$, $t_{\text{Ag}} = 160 \text{ nm}$, and $w_{\text{Ag}} = 1220 \text{ nm}$). The intersection points of the dashed green lines correspond to the resonance wavelengths of $\lambda_1 = 1524$ nm, $\lambda_2 = 2279$ nm, $\lambda_3 = 6000$ nm, and $\lambda_4 = 10450$ nm.

to 1350 nm, while the thickness of SiO_2 is kept at its optimal value ($t_{\text{SiO}_2} = 20 \text{ nm}$). The resonance wavelengths of λ_2 and λ_3 are smoothly red-shifted by moving toward a wider grating. The red-shifted behavior of the resonances obtained by increasing the width of the top Ag nanograting are in complete agreement with the FP formula given in equation (1) [39]. As a result, it is almost possible to linearly tune the resonances of the nanoantenna emitter by changing the width of Ag nanograting. However, the resonance position of λ_1 is almost unaffected by increasing the width of the top Ag nanograting, confirming that the first resonance is excited by the combination of GSP and SP resonances. Figure 3(f) shows the variation of absorptivity versus wavelength at different values of the nanograting periodicity, while the other parameters are kept at their optimized values ($1300 \text{ nm} \leq p \leq 1450 \text{ nm}$ when $t_{\text{SiO}_2} = 20 \text{ nm}$, $w_{\text{Ag}} = 1220 \text{ nm}$, and $t_{\text{Ag}} = 160 \text{ nm}$). As expected, the periodicity does not affect the position of the GSP-based resonances as explained in [40, 41].

All in all, it is concluded that at specific dimensions ($20 \text{ nm}/1220 \text{ nm}/1365 \text{ nm}$ for $t_{\text{SiO}_2}/w_{\text{Ag}}/p$), the incident electromagnetic waves can dominantly couple to GSP modes which lead to a high amount of absorption at the resonance wavelengths of λ_1 , λ_2 , and λ_3 .

2.4. Power analysis

To evaluate the thermal performance of the proposed nanoantenna emitter (design I), we calculate the spectral radiant emittance of a blackbody, a conventional surface, and the selective nanoantenna emitter at different temperatures. Planck's law which describes the spectral radiance emitted by a blackbody in thermal equilibrium is given by

$$P(\lambda, T) = 2\pi hc^2 / \lambda^5 \left(\exp\left(\frac{hc}{\lambda k_B T}\right) - 1 \right)^{-1}, \quad (2)$$

where k_B is Boltzmann's constant, c is the speed of light in vacuum, and λ is the wavelength of the incident light. The IR signatures of the conventional surface $[\text{CS}(\lambda, T) = P(\lambda, T) \times (1 - \varepsilon_{\text{atmosphere}}(\lambda, T))]$ and the selective nanoantenna emitter $[\text{NE}(\lambda, T) = P(\lambda, T) \times (1 - \varepsilon_{\text{atmosphere}}(\lambda, T)) \times \varepsilon_{\text{structure}}(\lambda)]$ can be obtained from the data of the atmospheric absorption $[\varepsilon_{\text{atmosphere}}(\lambda, T)]$ and the calculated emissivity of design I $[\varepsilon_{\text{structure}}(\lambda)]$, respectively. Figure 4(a) compares the calculated IR signatures of the conventional surface and the selective nanoantenna emitter with the spectral radiant emittance of the blackbody radiation at 300 K by considering the radiation energy emitted

Figure 4. IR signatures of a blackbody, a conventional surface, and the selective nanoantenna emitter (design I) at different temperatures of (a) 300 K, (b) 400 K, and (c) 500 K.

Table 1. The reduction rates of the selective nanoantenna emitter (design I).

	3–5 μm	8–12 μm	0.9–12 μm
$T = 300\text{ K}$	99.71%	94.76%	96.09%
$T = 400\text{ K}$	99.61%	95.23%	97.71%
$T = 500\text{ K}$	99.53%	95.55%	98.68%

from the normal direction. The IR signatures of the selective nanoantenna emitter at the room temperature in the MWIR and LWIR ranges are reduced by 99.71%, and 94.76% compared to the blackbody radiation, respectively. While the selective nanoantenna emitter can reduce the radiant energy by 96.09% throughout the entire wavelength band. As the temperature increases to 400 K and 500 K, as shown in figures 4(b) and (c), the reduction rates of IR signatures for the selective nanoantenna emitter in the MWIR and LWIR ranges decrease but are still higher than 95%. Notably, the reduction rate of the selective nanoantenna emitter is greater than 96% across a wide temperature varying from room temperature to 500 K for the entire wavelength range. Using the relation

$$\text{Reduction rates} = \sqrt{\frac{\sum_{i=1}^n |P(\lambda_i, T) - NE(\lambda_i, T)|^2}{\sum_{i=1}^n |P(\lambda_i, T)|^2}}, \quad (3)$$

the reduction rates of the selective nanoantenna emitter (design I) in the wavelength ranges of 3–5 μm , 8–12 μm , and the entire band for different temperatures are calculated and shown in table 1.

3. Design II

3.1. Results and discussions

In the next section of this study, we extend the functionality of design I to provide multifunctional operations including different thermal camouflage scenarios. The extended structure is called design II. The overall detection scenario of a hot object is schematically explained in figure 5(a). To hide from these surveillance devices, the surface of the object should be

decorated with the proposed GSP-based nanoantenna emitters. Unlike MWIR and LWIR mode cameras that detect blackbody photons emitted from the object, SWIR mode cameras detect solar reflectance from the surface. Therefore, in an ideal scheme, the camouflage design should also perform as a broadband absorber in the 900–1700 nm range. To achieve a broadband absorption within the near-infrared (NIR) region and the main atmospheric absorption window, design I is modified with a highly lossy titanium (Ti) layer [42] embedded on an SiO_2 layer and extended to design II with a multi-layer grating as presented in figure 5(a). The thickness of each layer of grating is optimized and set to be $t_{\text{Ag}} = 70\text{ nm}$, $t'_{\text{SiO}_2} = 180\text{ nm}$, and $t_{\text{Ti}} = 5\text{ nm}$, respectively. The thickness of the insulator substrate which supports GSPs is considered as $t_{\text{SiO}_2} = 30\text{ nm}$. The unit cell is periodically arranged along the x direction with $p = 1200\text{ nm}$, and the corresponding unit cell width is $w = 1160\text{ nm}$. Furthermore, the MIM grating structure in design II is separated by graphene layers from the substrate. The 2D graphene layers (single- or three-layer graphene) are added for the manipulation of the surface conductivity at the mid-infrared (MIR) region to have a real-time tunability in the infrared response of the structure within the atmospheric absorption window and quench the LWIR mode response, specifically the fourth resonance occurred in design II (λ'_4) due to intrinsic vibrational modes (optical phonons) of the SiO_2 layer. The surface conductivity (σ_s) of a monolayer graphene in the simulations follows the well-established Kubo formula with intra-band (σ_{intra}) and inter-band (σ_{inter}) contributions as [43],

$$\sigma_s = \sigma_{\text{intra}} + \sigma_{\text{inter}}, \quad (4)$$

$$\sigma_{\text{intra}} = -j \frac{e^2 k_B T}{\pi \hbar^2 (\omega - j2\Gamma)} \left[\frac{\mu_c}{k_B T} + 2 \ln \left(e^{-\mu_c/k_B T} + 1 \right) \right], \quad (5)$$

$$\sigma_{\text{inter}} \simeq \frac{-je^2}{4\pi \hbar} \ln \left(\frac{2|\mu_c| - (\omega - j2\Gamma)\hbar}{2|\mu_c| + (\omega - j2\Gamma)\hbar} \right), \quad (6)$$

where ω , T , e , $\hbar$, and k_B are representing the angular-frequency of the incident plane wave, the temperature, electron charge,

Figure 5. (a) Schematic diagram of the extended nanoantenna emitter (design II) and the overall detection scenario of a hot object. (b) Spectral absorption of design II without/with a single-layer ($N = 1$) graphene when $\mu_c = 0.2$ eV, 0.4 eV, and 0.6 eV at $T = 300$ K. (c) Spectra absorption of design II without/with a three-layer ($N = 3$) graphene when $\mu_c = 0.2$ eV, 0.4 eV, and 0.6 eV at $T = 300$ K. (d) The simulated absorption spectrum of design II with different values of scattering rate for the three-layer ($N = 3$) graphene case when $\mu_c = 0.6$ eV at $T = 300$ K. Simulated normalized contour plots of absorptivity versus wavelength for different thicknesses of (e) the top SiO₂ layer ($100 \text{ nm} \leq t_{\text{SiO}_2} \leq 300 \text{ nm}$ when $t_{\text{Ag}} = 70 \text{ nm}$, $t_{\text{Ti}} = 5 \text{ nm}$, $t_{\text{SiO}_2} = 30 \text{ nm}$, $w = 1160 \text{ nm}$, and $p = 1200 \text{ nm}$), and (f) the thickness of Ti layer ($5 \text{ nm} \leq t_{\text{Ti}} \leq 25 \text{ nm}$ when $t_{\text{Ag}} = 70 \text{ nm}$, $t_{\text{SiO}_2} = 180 \text{ nm}$, $t_{\text{SiO}_2} = 30 \text{ nm}$, $w = 1160 \text{ nm}$, and $p = 1200 \text{ nm}$).

Planck's and Boltzmann's constants, respectively. In addition, μ_c and 2Γ ($2\Gamma = \frac{\hbar}{\tau}$, τ is the electron-phonon relaxation time) are the chemical potential and scattering rate of a monolayer graphene accounting for the Fermi energy (E_F) level and the intrinsic losses, respectively. One of the main advantages of using graphene is that its Fermi level can be easily tuned over a wide range by applying an external gate voltage (electrostatic biasing), leading to different surface conductivities. Therefore, it is possible to tune the MIR resonance of design II and reduce the peak absorption of the fourth resonance by varying the Fermi level via electrostatic biasing. The relation between Fermi energy level and the electrostatic biasing is given by an approximate closed-form expression as [44]

$$E_F = \hbar v_F \sqrt{\frac{\pi C_d V_g}{e}}, \quad (7)$$

where $C_d = \epsilon_d \epsilon_0 / t_s$ is the electrostatic gate capacitance, t_s is the thickness of gate oxide, V_g is the applied gate voltage, and v_F is the Fermi velocity ($1.0 \times 10^6 \text{ m s}^{-1}$ in graphene), respectively. As a result, the electrostatic biasing of the graphene layers in design II can be achieved by placing conductive contacts between the graphene and the bottom Ag reflector (electrostatic ground) and applying a gate voltage. The bias then allows for controlling the chemical potential of graphene layers independently [44, 45].

Table 2. Absorption resonance wavelengths of the proposed wavelength-selective nanoantenna emitter (design II) without a graphene layer, with a single-layer graphene, and a three-layer graphene (at different chemical potentials: $\mu_c = 0.2$ eV, 0.4 eV, and 0.6 eV at $T = 300$ K), together with peak values of the fourth resonance and the corresponding relative reduction rates obtained via comparing the results with design II without a graphene layer.

		Resonance				Intensity of #4 and reduction rates	
		#1	#2	#3	#4		
Design II (without a graphene layer)		$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 5750$ nm	$\lambda'_4 = 10260$ nm	0.47	
Design II (with a single-layer graphene)	$\mu_c = 0.2$ eV	$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 5656$ nm	$\lambda'_4 = 10234$ nm	0.43	−8.51%
	$\mu_c = 0.4$ eV	$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 5551$ nm	$\lambda'_4 = 10184$ nm	0.39	−17.02%
	$\mu_c = 0.6$ eV	$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 5432$ nm	$\lambda'_4 = 10147$ nm	0.35	−25.53%
Design II (with a three-layer graphene)	$\mu_c = 0.2$ eV	$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 5555$ nm	$\lambda'_4 = 10135$ nm	0.35	−25.53%
	$\mu_c = 0.4$ eV	$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 5170$ nm	$\lambda'_4 = 10032$ nm	0.28	−40.42%
	$\mu_c = 0.6$ eV	$\lambda'_1 = 929\text{--}1472$ nm	$\lambda'_2 = 2080$ nm	$\lambda'_3 = 4896$ nm	$\lambda'_4 = 9957$ nm	0.22	−53.19%

The simulated absorption spectra of design II including different cases are presented in figure 5(b) when $\Gamma = 0.0032$ eV and $T = 300$ K. The extension of design I to design II without a graphene layer leads to having a broadband resonance (λ'_1) with a perfect absorption ranging from 929 nm to 1472 nm (suitable for solar applications [46, 47]), where three narrowband absorptions at the longer wavelengths of $\lambda'_2 = 2080$ nm, $\lambda'_3 = 5750$ nm, and $\lambda'_4 = 10260$ nm are excited (see figure 5(b)). According to the monolayer graphene characteristic [48, 49], the obtained broadband response of design II should stay almost unchanged in the NIR region, while the λ'_3 and λ'_4 resonances at the MIR region experience blue-shifts by adding the single-layer graphene and increasing μ_c from 0.2 eV to 0.6 eV. In addition, the amount of absorption at the λ'_4 resonance, caused by the vibrational modes of SiO₂ layer, decreases by 25.53% (see the trend between the blue and yellow dot lines in figure 5(b)) for those cases without the graphene layer and with the single-layer graphene, when μ_c is 0.6 eV. This is due to the fact that a partial amount of power is reflected back from the single-layer graphene and the localization of the electric field decreases within the lower SiO₂ layer. As several works have been reported to effectively design few-layer graphene structures for tuning the resonances at the MIR region [50, 51], we next demonstrate the optical performance of design II for the case of the three-layer ($N = 3$) graphene. Here, it is taken into consideration that the surface conductivity (σ_s) for N -layer graphene is defined as $N\sigma_s$ [52]. Figure 5(c) shows the resonance wavelengths of the three-layer graphene device obtained from FDTD method as a function of μ_c ranging from 0.2 eV to 0.6 eV. The resonance wavelengths exhibit a similar trend as observed in the single-layer structure in terms of blue-shifting of the MIR resonances and reducing the peak absorption of the fourth resonance. It is observed in figure 5(c) that increasing the number of graphene layers from $N = 1$ to $N = 3$ can further shift the MIR resonance wavelengths toward the shorter wavelength regions. In addition, compared to the case without the graphene layer, the structure containing the three-layer graphene with $\mu_c = 0.6$ eV, can suppress the λ'_4 absorption peak by 53.19% (see the trend between the blue and yellow dot lines in figure 5(c)).

The three-layer graphene device also suppresses the λ'_4 absorption peak ~ 2.1 times more than the one obtained by the single-layer graphene structure. It should be noted that the general functionality of design II with graphene layers is negligibly affected for different values of scattering rate as demonstrated for the three-layer graphene device in figure 5(d) when the chemical potential is assumed 0.6 eV. This means that variation of scattering rate due to the impurities, defects, and interfaces for realistic graphene layers [53, 54] does not affect the response of the proposed structure. All in all, the absorption spectra of design II perfectly match the atmospheric absorption windows with tunability characteristic [55] that make it suitable for different thermal camouflage scenarios as well as solar energy harvesting application due to the broadband absorption within a wide spectral range of the NIR region. The absorption resonance wavelengths of design II, together with the peak values of the fourth resonance and the corresponding relative reduction rates are all summarized in table 2.

3.2. Geometric parameters effects

In order to investigate the performance of each layer and their contributions to the resonances, we once again examine how changes in t'_{SiO_2} , and t_{Ti} can affect the overall absorption spectrum of design II without considering the graphene layer. Figure 5(e) shows the dependence of the normalized absorbed power by the structure on the changes of t'_{SiO_2} , while keeping all of the other geometrical parameters unchanged ($100 \text{ nm} \leq t'_{\text{SiO}_2} \leq 300 \text{ nm}$ when $t_{\text{Ag}} = 70 \text{ nm}$, $t_{\text{Ti}} = 5 \text{ nm}$, $t_{\text{SiO}_2} = 30 \text{ nm}$, $w = 1160 \text{ nm}$ and $p = 1200 \text{ nm}$). The result exhibits a broadband perfect absorption at the NIR region (with a peak absorption at (λ'_1)) and a sharp narrowband response (λ'_3) at the atmospheric absorption window for all t'_{SiO_2} values, where only the former resonance experiences a redshift as the spacer thickness increases. This phenomenon demonstrates that the NIR response (λ'_1) is due to the added top layers to the system, while the wavelength resonances including λ'_2 and λ'_3 are due to the formation of gap plasmons (similar to design I) in the interfaces of the SiO₂ substrate and the Ag layers. To have a solar absorber operating in the NIR region

Figure 6. Absolute values of the total electric-field distributions on the $x-z$ plane obtained for a two-unit cell of design II (without graphene layers) at the resonance wavelengths of (a) $\lambda'_1 = 1205$ nm, (b) $\lambda'_2 = 2080$ nm, and (c) $\lambda'_3 = 5750$ nm, respectively. Absolute values of the total electric-field distributions on the $x-z$ plane obtained for a two-unit cell of design II (with the three-layer graphene when $\mu_c = 0.6$ eV) at the resonance wavelengths of (d) $\lambda'_4 = 1205$ nm, (e) $\lambda'_4 = 2080$ nm, and (f) $\lambda'_4 = 4896$ nm, respectively. In all the figures, dashed white lines represent the Ag area.

with an absorption above 90%, the optimal thickness of the SiO_2 interlayer (t'_{SiO_2}) is set at 180 nm. Figure 5(f) shows the impact of changes in t_{Ti} on the normalized spectral absorption of design II without considering graphene layer, when it varies from 5 nm to 25 nm ($5 \text{ nm} \leq t_{\text{Ti}} \leq 25 \text{ nm}$ when $t_{\text{Ag}} = 70 \text{ nm}$, $t'_{\text{SiO}_2} = 180 \text{ nm}$, $t_{\text{SiO}_2} = 30 \text{ nm}$, $w = 1160 \text{ nm}$ and $p = 1200 \text{ nm}$). Accordingly, the resonances around 8 μm and 10 μm are efficiently excited by moving toward thicker values of the Ti layer ($t_{\text{Ti}} > 20 \text{ nm}$) besides the reduction in the amount of absorption of the resonance (λ'_3) in the atmospheric absorption window. As a result, the optimal performance can be achieved with the thickness of $t_{\text{Ti}} = 5 \text{ nm}$.

3.3. Physical mechanism

In order to reveal the physical mechanism of the proposed selective nanoantenna emitter (design II) under the normal incidence, electric-field distributions at the resonance wavelengths are obtained on the $x-z$ plane and illustrated in figure 6, corresponding to the cases without graphene and with the three-layer graphene ($\mu_c = 0.6$ eV). It is seen from figures 6(a) and (d) that at the resonance wavelength of $\lambda'_1 = 1205$ nm, the incident light penetrates through the thin Ti layer and bounces back at the bottom Ag grating layer. The two reflectors dominantly excite the FP cavity resonance leading to a broadened absorption response thanks to the lossy behavior of Ti in the NIR region [42]. However, the distributions of the

electric-field at the other excited resonances are intrinsically different. In particular, at the resonance wavelength of $\lambda'_2 = 2080$ nm presented in figures 6(b) and (e), the electric-field localizations inside the spacer layer correspond to the excitation of the third-order mode GSP resonance [34–39], while the absorptions at the resonance wavelengths of $\lambda'_3 = 5750$ nm and $\lambda'_3 = 4896$ nm are dominantly attributed to the excitation of GSPs with the first-order mode. This can be seen in figures 6(c) and (f) for the design without graphene layer and the design with the three-layer graphene, respectively.

3.4. Power analysis

To evaluate the performances of the second nanoantenna emitter (design II) in thermal camouflage technology, we once again calculate the IR signatures of the conventional surface and the extended nanoantenna emitter (design II without/with the three-layer graphene when $\mu_c = 0.6$ eV) to compare with the spectral radiant emittance of the blackbody radiation at 300 K. The IR signatures in the MWIR and LWIR wavelength ranges can be reduced by 98.67% and 88.74% without considering the graphene layers as shown in figure 7(a). As the temperature increases, these two values become 97.90% and 88.64% at 400 K and 96.92% and 88.65% at 500 K as illustrated in figures 7(b) and (c). Meanwhile, the selective nanoantenna emitter can reduce the radiant energy by 91.50%, 94.40%, and 96.21% for the whole wavelength spectrum at

Figure 7. IR signatures of a blackbody, a conventional surface, and the selective nanoantenna emitter (design II without/with the three-layer graphene ($N = 3$) when $\mu_c = 0.6$ eV) at different temperatures of (a) 300 K, (b) 400 K, and (c) 500 K.

Table 3. The reduction rates of the selective nanoantenna emitter (design II without/with the single- and three-layer graphene when $\mu_c = 0.2$ eV, 0.4 eV, and 0.6 eV) in the wavelength ranges of 3–5 μm , 8–12 μm , and the entire band at different temperatures.

		The reduction rates			
		Temperatures	3–5 μm	8–12 μm	0.9–12 μm
Design II (without a graphene layer)		300 K	98.67%	88.74%	91.50%
		400 K	97.90%	88.64%	94.40%
		500 K	96.92%	88.65%	96.21%
Design II (with a single-layer graphene)	$\mu_c = 0.2$ eV	300 K	98.56%	89.21%	91.85%
		400 K	97.79%	89.07%	94.59%
		500 K	96.82%	89.06%	96.29%
	$\mu_c = 0.4$ eV	300 K	98.53%	89.76%	92.25%
		400 K	97.76%	89.57%	94.82%
		500 K	96.79%	89.53%	96.41%
	$\mu_c = 0.6$ eV	300 K	98.41%	90.22%	92.59%
		400 K	97.67%	90.00%	95.01%
		500 K	96.74%	89.94%	96.51%
Design II (with a three-layer graphene)	$\mu_c = 0.2$ eV	300 K	98.31%	90.09%	92.49%
		400 K	97.53%	89.87%	94.94%
		500 K	96.57%	89.81%	96.44%
	$\mu_c = 0.4$ eV	300 K	97.74%	91.29%	93.37%
		400 K	97.10%	91.00%	95.43%
		500 K	96.28%	90.89%	96.67%
	$\mu_c = 0.6$ eV	300 K	95.31%	92.10%	93.96%
		400 K	95.00%	91.79%	95.67%
		500 K	94.57%	91.65%	96.56%

300 K, 400 K, and 500 K, respectively. Figures 7(a)–(c) also show the IR signatures of the selective nanoantenna emitter with the three-layer graphene when $\mu_c = 0.6$ eV. The results show better performance in terms of the reduction rate in comparison to the case without graphene layers. Table 3 summarizes the reduction rates of the selective nanoantenna emitter (design II) for all cases in the wavelength ranges 3–5 μm , 8–12 μm , and the entire band at different temperatures. In general, the reduction rates exhibit a similar trend for all cases such that the IR signatures decrease in the MWIR and LWIR ranges as the temperature increases, while the reduction rate for the entire wavelength range increases as the temperature increases.

4. Conclusions

In conclusion, we proposed a GSP-based wavelength-selective nanoantenna emitter (design I) suitable for multiple thermal camouflage scenarios. Triple narrowband perfect absorptions are achieved at the resonance wavelengths of 1524 nm, 2279 nm, and 6000 nm, whose absorption peaks perfectly match the atmospheric absorption spectrum. The proposed nanoantenna emitter is designed to have low emissivity within atmospheric windows and its performance is validated using numerical and analytical methods. Later, we proposed a multilayer grating structure as an extension of design I to cover solar thermal application besides multiple thermal camouflage

scenarios. Design II contains a nearly perfect absorption ranging from 929 nm to 1472 nm and a narrowband absorption at the resonance wavelength of 5750 nm, where the later absorption resonance is tuned and modified by adding graphene layers. Furthermore, we have also demonstrated that the multi-layer graphene structure could outperform the single-layer one in terms of shifting the MIR resonance wavelength and reducing the absorption peak of the fourth response. Finally, the performances of the selective nanoantenna emitters in thermal camouflage applications are validated by calculating the spectral radiant emittances. It is shown that the infrared signatures of design I and design II (without/with graphene layers) are significantly reduced compared to the blackbody radiation energy for the entire wavelength spectrum at least by 96% and 91%, respectively, ranging from the room temperature to 500 K.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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