Adaptive Multiple-band Absorber Based on VO₂ Metasurface

Siyi Ma¹ and Desong Fan^{1,*}

Abstract

The applications of present absorbers encounter the bottleneck of its single-band and static resonance peak. To overcome these obstacles, we proposed a multiple-band absorber out of phase transition material vanadium dioxide (VO₂) and demonstrated the switch and modulation of resonances. The proposed VO₂ metasurface can excite complex resonances via the top nanoparticle component and Fabry-Perot (FP) resonance via the bottom multilayer component, respectively. And these resonances can be tailored independently by controlling geometrical parameters and switched on and off by varying their temperatures. The physical mechanisms of these resonances are elucidated through an analysis of electromagnetic field distributions. This synergy of multiple resonances on VO₂-based metasurface provides a novel and facile way to build adaptive multiple-band absorbers, which may inspire developments in adaptive radiative cooling, thermal management as well as other applications.

Keywords: Metasurface; Resonance; Multiple-band; Vanadium dioxide; Emittance.

Received: 30 December 2020; Revised: 09 March 2021; Accepted date: 12 April 2021.

Article type: Research article.

1. Introduction

Humans live in and enjoy a vivid world where various colors are displayed in vision. That is thanks to the selective absorption of visible light by the objects.^[1] Compared with that of visible light in nature, wavelength-selective absorption of the infrared band has attracted more attention in the industry. For instance, in applications, as diversified as photovoltaic systems, sensing, and thermal management, absorbers with tailored radiation are highly desirable and demanded.^[2-4]

To obtain tailored absorption, metasurface was proposed and exploited to excite resonance and generate field enhancement at the target wavelength.^[5-7] It is an artificial structure based on the radiation-matter interaction at the subwavelength scale, including multilayers, photonic crystals, and other engineered surfaces.^[8-11] With their potential applications in detectors, emitters, and spectroscopic imagers, the on-demand metasurface of multiple absorptions has attracted more interest.^[12-14] Previous reports have shown the realization of multiple absorptions by the stack of single resonances together to achieve multiple-band or broadband absorption.^[15,16] However, all these multiple-band metasurfaces reported were almost based on metal-insulator-metal (MIM) structures, corresponding to plasmonic

resonance.^[17,18] The combination of similar resonance leads to similar absorption peaks and a narrow modulation range, which hampers the actual applications of absorbers. There remains much to explore in more combinations of resonance to achieve the multi-functional and highly-tunable absorber with multiple-band resonance.

In recent years, Vanadium dioxide (VO₂) has provoked great interest in the design of metasurface due to its unique optical properties. On the one hand, VO₂ exhibits metal permittivity at high temperatures, thus supporting many types of resonance.^[19-22] Compared to conventional metal, VO₂ is a poor and incomplete reflector and its permittivity can be continuously regulated, which is also represented in graphene.^[23] This property enables the stack of resonances by combining diverse VO₂ metasurfaces, thus for a multiple-band absorber. On the other hand, VO₂ undergoes a phase transition between the semiconductor phase (VO₂(M)) and the metal phase (VO₂(R)) on femtosecond timescales near curie temperature T_c (~68 °C). The rapid phase change behavior of VO₂ endows the VO₂ metasurface with the ability to switch on or off-resonance.^[24,25] Acknowledging its fascinating features, the VO₂ metasurface seems to be a good candidate for designing an adaptive multiple-band absorber.

In this paper, we first proposed VO₂ nanoparticles (NPs) metasurface to obtain thermal-induced plasmonic resonance in the near- and mid-infrared region. To achieve multiple resonances with perfect absorptance, we introduced a typical VO₂ multilayer that can excite Fabry-Perot (FP) resonance in

¹ MIIT Key Laboratory of Thermal Control of Electronic Equipment, School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu, 210094, China.

* Email: dsfan@njust.edu.cn (D. Fan)

Fig. 1 A schematic of (a) the plasmonic resonance, which is made of 2D VO₂ NPs/Ag metasurface, (b) the FP resonance, which is made of VO₂/HfO₂/Ag metasurface, and (c) the multiple-band resonance, which is made of VO₂ NPs/VO₂/HfO₂/Ag metasurface.

the far-infrared (FIR) region at the bottom of the VO₂ NPs metasurface. The composite metasurface exhibits improved radiation properties, which embody the broadened bandwidth and enhanced intensity of resonances. The main novelty of the present work lies in the usage of the VO₂ layer which not only enables the stack of the two metasurfaces but also can modulate the intensity of resonances by varying its temperatures.

2. Modeling and numerical methods

Active modulation of thermal emission can be achieved by either the two-dimensional (2D) array of VO₂ NPs or the VO₂ multilayer under external thermal stimuli. These two absorbers are effective and complementary to each other to enhance the thermal emittance and emittance regulation capacity in a broad range of the infrared spectrum. Fig. 1(a) shows the diagram of the VO₂ NPs array metasurface, where PMMA matrix embedding VO₂ nanospheres was deposited on the silver substrate. PMMA is chosen for rare absorption in the infrared region, compared with other polymers.^[26] The VO₂ NPs metasurface exhibits thermal-induced plasmonic resonance in the near-infrared (NIR) and mid-infrared (MIR) regions but has a negligible effect in the far-infrared region. Fig. 1(b) shows the diagram of a sandwich-like multilayer metasurface, which consists of a highly reflecting silver substrate, a HfO₂ dielectric spacer, and a thin VO₂ layer. As a typical dielectric material, HfO₂ was chosen as the spacing layer for the high refractive index and negligibly small extinction coefficients in the infrared region until 12 μm. The VO₂ multilayer metasurface exhibits thermal-induced FP resonance in the FIR region. Fig. 1(c) shows the diagram of the composite metasurface which composes of a PMMA matrix embedding VO₂ NPs, VO₂ layer, HfO₂ spacer, and silver substrate from up to down. The integration of the plasmonic resonance of VO₂ NPs metasurface with the FP resonance of VO₂ multilayer metasurface makes it possible to control the emittance from NIR to FIR region simultaneously. By accurate control of structural parameters of the two components independently, we can obtain switchable resonances at demanded wavelengths in the infrared region.

The adaptive multiple-band absorber in Fig. 1(c) exhibits two distinct radiative behaviors at various temperatures, which

Fig. 2 Illustrations of radiative behaviors of the tunable VO₂ composite metasurface (a) at high temperature and (b) at low temperature. (c) Real simulation environment with applied periodic boundary conditions.

is illustrated in Fig. 2(a). At low temperatures below T_c, the VO₂ metasurface at the semi-conducting phase exhibits high reflectance or low absorptance in the whole infrared band. When upon heating above T_c, thermochromic VO₂ undergoes a phase change to a metallic phase, and the VO₂ metasurface exhibits multiple resonances in the infrared region. The finite difference time domain (FDTD) simulations were performed to investigate and validate the radiative performance of these VO₂ metasurfaces. As shown in Fig. 2(c), the normal incident plane wave, introduced into the computational region from the top side of the structure, was assumed to be transverse magnetic (TM) polarized light. Assuming its lateral extension to be infinite, the Perfectly Matched Layer is set in the y direction of the simulation region, and Periodic Boundary Conditions are set in the x, z direction, while Bloch Boundary Condition is applied in the x, z direction at oblique incidence cases. Nonuniform mesh techniques were employed for computational demand in full-field 3D simulation, while fine mesh grids must be used for simulating these plasmonic nanostructures to ensure the convergence of the algorithm.

At a high temperature above 68 °C, VO₂ is an isotropic metal, the complex electrical permittivity ϵ_m of VO₂ can be described by a Drude model as:

$$\epsilon_m = -\epsilon_\infty \frac{\omega_p^2}{\omega^2 + i\omega\Gamma} \quad (1)$$

where ω is the angular frequency, $\epsilon_\infty = 9$ represents the high-frequency constant, and the plasma and collision frequency is represented by $\omega_p = 8000 \text{ cm}^{-1}$ and $\Gamma = 10000 \text{ cm}^{-1}$ respectively.^[27] At a low temperature below 68 °C, VO₂ is a dielectric but uniaxial medium which can be described by a dielectric function tensor.^[28] The optical constants of other materials were obtained as in Ref.^[26,29]

3. Results and discussion

In this paper, we calculated the spectral reflectance $R(\lambda)$ of three metasurfaces at two temperatures by numerical simulation. According to Kirchhoff's law, the spectral emittance $\epsilon(\lambda)$ is equal to the spectral absorptance $\alpha(\lambda)$. Consequently, for the opaque structure, the spectral emittance can be obtained as $\epsilon(\lambda) = \alpha(\lambda) = 1 - R(\lambda)$. The three metasurfaces exhibit their resonance characteristics at corresponding wavelengths and modulation of emittance at various temperatures, which are shown in Figs. 3(a)-(c). In the VO₂ NPs metasurface with the sphere diameter $D = 360 \text{ nm}$, the gap between two particles $d = 100 \text{ nm}$, two emission peaks occur with perfect absorption at $\lambda = 1.15 \mu\text{m}$ and $3.4 \mu\text{m}$ at

high temperatures. In the VO₂ multilayer metasurface with the thickness of VO₂, HfO₂ layer $t = 60 \text{ nm}$, $s = 1200 \text{ nm}$, respectively, an emission peak with emittance $\epsilon = 0.85$ at $7.9 \mu\text{m}$ occurs at high temperature. At low temperatures, the resonances of the VO₂ structure are quenched off or sharply attenuated.

Though a single metasurface exhibits high emittance at high temperatures and large emittance modulation, it is defective for the limitation of narrow-band resonance. We combined the two metasurfaces to achieve multiple-band resonance in the infrared region at high temperature, thus for a broadband absorber. On the one hand, the two emission peaks with near-perfect emittance are maintained in the NIR and MIR region in the VO₂ NPs/VO₂ component at the top, by replacing the Ag substrate with the VO₂ layer in Fig. 3(a). On the other hand, different from the high reflectance of the NPs/Ag structure, VO₂ NPs/VO₂ component exhibits high transparency in the FIR region, which provides a golden opportunity for the VO₂ multilayer component at the bottom to play a role in the FIR region. FIR incident light goes through the transparent VO₂ NPs/VO₂ component and interacts with the bottom component to provide a broad emittance peak, acting like the single VO₂ NPs/Ag metasurface in Fig. 3(b). Due to the combination of the two components, the composite metasurface can excite multiple resonances in the infrared region, with enhanced emittance and broadened bandwidth

Fig. 3 Normal emittance spectrum for (a) the 2D VO₂ NPs/Ag metasurface, (b) the VO₂/HfO₂/Ag metasurface, and (c) the VO₂ NPs/VO₂/HfO₂/Ag metasurface. (d) The directional emittance of the VO₂ composite metasurface at the resonance wavelength $\lambda = 1.2, 4.3, 10.3 \mu\text{m}$ at high temperature.

compared to single metasurfaces, which is shown in Fig. 3(c). In addition, depending on the phase change, VO₂ metasurfaces reveal their temperature-dependent resonance on-off character. At low temperatures, the emission spectrum exhibits several narrow peaks but on the whole low absorption. Though it is undesirable but inevitable for the increasing absorptance at low temperatures for the stacking structure, the composite metasurface still exhibits a satisfactory emission spectrum and great modulation of emittance at various temperatures. For the proposed metasurface with the diameter of VO₂ particles $D = 360$ nm, the gap between two particles $d = 100$ nm, and the thickness of VO₂, HfO₂ layer $t = 60$ nm, $s = 1200$ nm, respectively, we obtain two broad and near-perfect emission peak at wave bands of 1-5 μm and 8-14 μm , which is potential for the ideal adaptive emitter in the atmospheric window. Fig. 3(d) plots the directional emittance of the VO₂(R) composite metasurface at the resonance peak wavelength of $\lambda = 1.2, 4.3, 10.3$ μm with the incident angle varying from -60° to 60° at TM polarization. The emittance remains near unity from the normal direction to $\theta = 50^\circ$ and slightly decreases at $\theta = 60^\circ$, which means the metasurface is insensitive to incident angles.

We choose four wavelength points where the greatest modulation of emittance exists for three metasurfaces and plot local absorption power P_{abs} of them in Figs. 4(a)-(h), which is defined as the power absorbed per unit volume at each position, normalized to the source power. For clear description, we adopt a white wavy line to cut off the cross-section at the proper position. For all three structures, a large increase in the absorption power at high temperatures confirms the resonant absorption characteristics of these designs. For the composite

metasurface, absorption power is concentrated in the position of VO₂ NPs at 4.3 μm wavelength, which is corresponding to the plasmonic resonance of VO₂ NPs/VO₂ components at the top, while it is concentrated in the position of the VO₂ layer at 7.5 μm wavelength, which is corresponding to the FP resonance of VO₂/HfO₂/Ag components at the bottom.

3.1 VO₂ NPs metasurface

Due to the different nature of VO₂ in different phase states, the physical mechanisms of the VO₂ metasurfaces are not the same, corresponding to the different radiation characteristics. VO₂ exhibits a negative real part of permittivity at high temperatures, which is crucial to excite plasmonic resonance as found in most noble metals. In consequence, the metasurface of the 2D VO₂ NPs array, exhibits surface plasmon polariton (SPP) resonance at the short-wave band and the hybrid resonance at the long-wave band at high temperature, leading to enhanced absorption of resonance. At low temperatures, the VO₂ metasurface in a transparent semiconducting state shows low absorption in NIR and MIR regions. A similar structure has been studied for excellent modulation of radiated power rather than emissivity and it lacks mechanism analysis.^[20]

To better understand the physical absorption mechanism, the electromagnetic field distributions at the peak wavelength were simulated by FDTD solutions. The electromagnetic field distributions of peak wavelength $\lambda = 1.24$ μm are shown in Figs. 5(a-b), where solid black lines represent the cross-section of the structure within two periods, with the corresponding materials marked out. At low temperatures, the

Fig. 4 Calculated absorption power (P_{abs}) for the wavelength of (a) (e) 3.4 μm in VO₂ NPs/Ag metasurface, (b) (f) 6.8 μm in VO₂/HfO₂/Ag metasurface, (c) (g) 4.3 μm and (d) (h) 7.5 μm in the VO₂ NPs/VO₂/HfO₂/Ag metasurface.

Fig. 5 (a) The electric field distributions and (b) magnetic field distributions at $\lambda = 1.24 \mu\text{m}$ at low temperature. (c) The magnetic field distributions and (d) electric field distributions at $\lambda = 1.15 \mu\text{m}$ at high temperature in the VO_2 NPs metasurface.

magnetic intensity is strongly confined to the center of the particle whose amplitude is more than six times of incident lights and attenuates gradually along the direction of the radius. Meanwhile, the intensity of the electric field is gentler with a low gradient, with a loop current in a clockwise direction. Due to the semi-conducting VO_2 possessing a higher refractive index ($n = 3.2$) than PMMA ($n = 1.5$), most of the incident lights enter into the transparent VO_2 particle and hardly leave the particle after multiple reflections, which is called total internal reflection (TIR). This often occurs under the situation that the light moves from an optically denser medium (a medium with a higher refractive index) to an optically thinner medium (a medium with a lower refractive index), with an incident angle greater than critical angle θ_c (when the light is far from the normal line). The particularity of the sphere shape makes the propagating light much easier to enter from VO_2 to PMMA matrix at a larger incident angle, bringing about the exotic properties of electromagnetic field distribution in our proposed structure. At high temperatures, the VO_2 NPs array exhibits intense absorption in the wavelength region of 1-3.5 μm . From the electromagnetic field distributions of resonance wavelength $\lambda = 1.15 \mu\text{m}$ in Figs. 5(c-d), we can see that the field intensity is strongly

confined to the interface between the dielectric PMMA matrix and metallic VO_2 particle, and the amplitude of the electric field is almost twice the incident waves. Different from total internal reflection at low temperature, the field intensity is concentrated on the interface, and rapidly attenuates along the direction perpendicular to it, which is exactly in line with the characteristics of SPP resonance.

The electromagnetic field distributions at $\lambda = 3.5 \mu\text{m}$ are plotted in Fig. 6, where the circle represents the current loop, with the arrow indicating the direction of the electric field. These antiparallel currents between the metallic VO_2 particles and the substrate interact with the incident electromagnetic wave, causing an inverse magnetic resonance, which is called magnetic polariton (MP) resonance. Due to the excitation of MP resonance, the magnetic field at $\lambda = 3.5 \mu\text{m}$ was confined to the narrow area, while the amplitude of the magnetic field is three times the incident waves, which eventually leads to strong absorption at the corresponding wavelength. At high temperatures, the metasurface shows near-perfect emittance of 0.96 at $\lambda = 3.5 \mu\text{m}$. Except the presence of the concentration of magnetic field, the standing wave exists between two metallic VO_2 particles, corresponding to the plasmonic coupling effect. From the electric field distribution shown in

Fig. 6 (a) The magnetic field distribution and (b) the electric field distribution of the VO₂ NPs metasurface at $\lambda = 3.5 \mu\text{m}$ at high temperature.

Fig. 6(b), the electric field was confined to the gap between the two VO₂ particles, and the amplitude of it is more than five times of incident waves. The electromagnetic wave entering into the gap couples with that reflected by the side-surface of VO₂ particles, and thus the standing wave is built up, which is a type of quasi-FP resonance. Therefore, the resonance peak at $3.5 \mu\text{m}$ is attributed to the hybrid of the plasmonic coupling effect and substrate effect. A conclusion is drawn by us that the broad emission enhancement in the NIR and MIR band is attributed to a complex coupling of multiple resonances.

As known to us, the physical mechanisms of emission enhancement in the metasurface of VO₂ NPs array are

complex and difficult to explain neatly or even. For simplifying the simulation model, we assumed that the VO₂ NPs are dispersed uniformly, whose gap is twice the distance between the particle and the substrate. Taking the controllability of parameters and the feasibility of experimental preparation into consideration, we focused on studying the synthetic effect of particle size and the doping concentration on the emittance spectrum, respectively. Emittance spectra of VO₂ NPs metasurface with sphere diameter from 100 to 500 nm were computed while the gap between the two particles was kept at 100 nm, which is shown in Figs. 7(a)-(c). At low temperatures, the VO₂ turns off the

Fig. 7 Normal emittance spectra of the VO₂ NPs metasurface with 100 nm gap and various sphere diameters (a) at high temperature, (b) at low temperature, and (c) the difference of emittance between the two temperatures. Normal emittance spectra of the VO₂ NPs metasurface with 360 nm diameter various gaps between the two particles (d) at high temperature, (e) at low temperature, and (f) the difference of emittance between the two temperatures.

SPP and hybrid resonance. The VO₂ NPs metasurface exhibits very low absorptance, except for the narrow absorption peak of total internal reflection, which redshifts with the increase of the particle size. At high temperatures, the VO₂ turns on the SPP and hybrid resonance, and thus the VO₂ NPs metasurface exhibits a broad band of high absorptance. As the sphere diameter increases from 100 to 500 nm, the position of the SPP resonance peak barely changes, while the position of hybrid resonance red shifts linearly with wavelength. In the case of other parameters constant, with the increase of the particle size, the interaction surface between two particles and that between the particle and the substrate surface get much larger, leading to a broader wave band with field enhancement.

To investigate the influence of the doping concentration of VO₂ NPs on the radiation characteristics, we calculated the emittance spectra of VO₂ NPs metasurface with the two-particle gap from 0 to 600 nm while the sphere diameter was kept at 360 nm, which is shown in Figs. 7(d)-(f). At low temperatures, the emittance is nearly zero in the whole wave band, except for some narrow absorption peaks. At high temperatures, when the particle layer has a non-close-packed configuration ($d > 0$), two obvious emission peaks exist in the NIR and MIR bands. With the decrease of doping concentration, the resonance peak at the short-wave band redshifts, while that at the long-wave band blue shifts. The resonance at the long-wave band shows up under a narrow range of the doping concentration of VO₂ particles, and the range is influenced by the diameter of VO₂ particles. When the gap is large up to 500 nm, the long-wave peak disappears, which implies that the plasmonic coupling effect and substrate effect eliminates when the VO₂ particle is far from other particles and the substrate. The resonance position in the produced metasurface is partially dependent on the ways to disperse VO₂ NPs during film preparation. And we can easily control the dispersion condition in the experiment because the particles are fixed on a produced sample.

3.2 VO₂ multilayer metasurface

We have discussed both resonance wavelengths and spectral width of a single metasurface of VO₂ NPs array, which can be modulated by controlling the structural parameters to meet various applications. And the resonances can be feasibly switched by cycling through a semiconductor-metal transition (SMT) of VO₂. However, there is still plenty of room for improvement to reach broader resonance enhancement with higher absorption to meet various demanded applications. Inspired by previous reports,^[30,31] we introduce a VO₂ multilayer metasurface that is placed at bottom of the VO₂ NPs metasurface to form multiple absorbers, as shown in Fig. 1(c). In the FIR region, the structure of VO₂/spacer/metal multilayer has gained much attention for its simple preparation in structure, the high emittance at targeted wavelength, and the excellent regulation of emittance, which is attributed to the switchable excitation of FP resonance.^[32] For the low temperature (semiconducting) state of the VO₂ layer, lights could be simply reflected by the Ag back layer through the transparent HfO₂ and VO₂ layers in the FIR region. As a result, the multilayer, acting like a metal reflector, exhibits a strongly suppressed emissivity. The high-temperature (metallic) state of the VO₂ layer, acts like a semi-transparent metallic layer, serving as the top mirror of a Fabry-Perot resonator. Consequently, the metallic VO₂ multilayer metasurface behaves like a Fabry-Perot resonance cavity. Therefore, the radiation enhancement of broad bandwidth results from the ohmic losses of the semi-transparent metal film and the wave destructive interference. Furthermore, the multilayer metasurface switches between the IR reflector and the Fabry-Perot cavity accompanied by the SMT of the top VO₂ layer. We can switch the emission enhancement from ‘off’ to ‘on’ by increasing the temperature.

To investigate the physical mechanism of the emission peak in the VO₂ multilayer, we calculate the spectral reflectance of the multilayer structure using the equivalent interface method. For a monolayer in Fig. 8(a), the reflection coefficient is obtained by the following expression:

Fig. 8 A schematic of reflection of (a) a monolayer and (b) a bilayer structure.

$$R = \frac{R_{01} + R_{12}e^{2i\beta_1}}{1 + R_{01}R_{12}e^{2i\beta_1}} \quad (2)$$

where 0, 1, 2 represent the three mediums from top to down, with corresponding optical properties (complex refractive index) N_0, N_1, N_2 ; R_{01}, R_{12} represents the reflection coefficient at interface 01 and 12, which can be described as:

$$R_{mn} = \frac{N_m - N_n}{N_m + N_n} \quad (3)$$

$$\beta_i = \frac{2\pi}{\lambda} N_i d_i \cos \theta_i \quad (4)$$

For a multilayer in Fig. 8(b), interface 123 is assumed to be equivalent to interface 12 and interface 23, and thus the reflection coefficient at interface R_{123} can take place of R_{12} in equation (5), which is described as:

$$R_{123} = \frac{R_{12} + R_{23}e^{2i\beta_2}}{1 + R_{12}R_{23}e^{2i\beta_2}} \quad (5)$$

To obtain total absorption in a multilayer, the reflectivity should be 0, that is $|R_{123}|^2 = 0$.

Given that:

$$1 + R_{01}R_{123}e^{2i\beta_1} \neq 0 \quad (6)$$

We obtain:

$$R_{01} + R_{123}e^{2i\beta_1} = 0 \quad (7)$$

That means that the two vectors should be equal and opposite in direction :

$$|R_{01}|^2 = |R_{123}|^2 e^{\frac{-4\pi k_1 d_1}{\lambda}} \quad (8)$$

$$\psi_{123} + \frac{4\pi n_1 d_1}{\lambda} - \psi_{01} = (2m + 1)\pi \quad (9)$$

where ψ_{123} and ψ_{01} represent the phase angle of the reflection coefficient R_{123} and R_{01} , respectively; $\cos \theta = 1$ in the normal incidence. From these expressions, we find that the normalized total phase shift inside the cavity consists of the traveling phase shift $4\pi nd/\lambda$ and the interface phase shift $\psi_{123} - \psi_{01}$. For a multilayer structure, when the total phase shift inside the cavity is in odd integer multiples of π , it mainly derives from the traveling phase shift. At that condition, a standing wave occurs and Fabry-Perot resonance is excited. As for our proposed metasurface with 1 μm thickness of HfO_2 in normal incidence, the simulated resonance wavelength

occurs at the $\lambda = 6.5, 2.5, 1.5 \mu\text{m}$, which exactly corresponds to $m = 0, 1, 2$. Thus the spacer thickness to achieve emission enhancement at the target wavelength can be predicted by $s = (2m+1)\lambda_0/4n$, where m is an integer.

The resonance wavelength and resulting absorption enhancement can be easily tuned by varying the parameters of the multilayer. As the top mirror of the Fabry-Perot resonator, VO_2 in a hot state is a poor reflector compared to noble metals such as silver or gold, contributing to an insufficiently perfect but far-broader emission peak. Due to the optical properties, the strength of the Fabry-Perot absorption can be determined by the thickness of the VO_2 metallic mirror. To investigate the role of VO_2 film thickness on the radiation characteristics of multilayer metasurface, the emission spectra of VO_2 multilayer with 1000 nm-thick HfO_2 and 200 nm-thick Ag layer were calculated under a varied thickness of VO_2 layer from 60 to 100 nm. As is shown in Fig. 9(a), with the increasing thickness of the VO_2 layer, the emission spectra change mainly in the intensity and bandwidth of the emission peak, while the location of peaks hardly changes, in both high and low temperatures. As the thickness of VO_2 increases, the effect of destructive interference gets weakened, and the emission peak flattens out. This means that a thinner VO_2 layer provides an almost perfect but narrow emission peak, while a thicker VO_2 layer provides a broad but eliminated emission peak. We adopt a suitable thickness of VO_2 by practical applications. In an FP resonance cavity, the location of resonance peaks is determined by the spacer thickness. To study the role of HfO_2 thickness on the radiation characteristics, the emission spectra of the VO_2 multilayer (with 1000 nm-thick HfO_2 and 200 nm-thick Ag) were calculated under a varied thickness of the VO_2 layer from 800 to 1200 nm. As is indicated in Fig. 9(b), with the increasing thickness of HfO_2 spacer, the emission peak moves to the location of longer wavelength, while the intensity and bandwidth of the peak remain almost the same, which is typical properties of Fabry-Perot resonance. Thus, we can

Fig. 9 Normal emittance spectrum of VO_2 multilayer with (a) different thicknesses of VO_2 layer and (b) different thicknesses of HfO_2 layer.

choose the spacer thickness to achieve resonance at the target wavelength.

As for a composite metasurface, the emission spectrum is approximately superimposed from the emission spectrum of the two single metasurfaces, including the intensity and position of peaks. For the practical aim, we can modulate the resonance peaks by changing the geometric parameters of the single metasurfaces independently and then obtain the demanded multiple resonances by fine-tuning the composite metasurface. In addition to the selective absorption at desired wavelengths during the structure design process, the switch of resonances can be also realized by varying the temperature, which meets different application needs.

4. Conclusion

In this paper, a VO₂ composite metasurface was designed and explored to achieve an adaptive, multiple-band, and highly efficient absorber. To depict the radiation characteristics of the multiple-band absorber, we investigate the single VO₂ NPs metasurface and multilayer metasurface, respectively. In the VO₂ NPs metasurface, emission enhancement in the NIR and MIR region at high temperatures is obtained by the excitation of SPP resonance and the hybrid of MP and quasi-FP resonance. In the VO₂ multilayer metasurface, the emission enhancement in the FIR region at high temperatures is obtained by the excitation of FP resonance. Our studies demonstrate that the composite metasurface based on the stack of the two above can obtain multiple resonances with broader and higher emittance enhancement at high temperatures. And these resonances can be tailored independently by controlling the geometrical parameters of a single metasurface independently. In addition, when the temperature decreases below the transition temperature, VO₂(M) turns off all the resonances and the three VO₂ metasurfaces exhibit low emittance. Our proposed VO₂ metasurface offers a way to build multiple-band perfect absorbers with dynamic modulation and this work will advance the development of radiative cooling and other applications.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 51876091), and the Natural Science Foundation of Jiangsu Province (Grant No. BK20180070).

Supporting information

Not Applicable.

Conflict of interest

There are no conflicts to declare.

References

- [1] B. M. Loeffler, R. G. Burns, Shedding Light on the Color of Gems and Minerals: The selective absorption of light according to wavelength-the result of various electronic processes whose

energies correspond to certain wavelengths of visible light—gives minerals their distinctive hues, *American Scientist*, 1976, **64**, 636-647, doi: 10.2307/27847555.

[2] A. P. Raman, M. Abou Anoma, L. Zhu, E. Rephaeli, S. Fan, Passive radiative cooling below ambient air temperature under direct sunlight, *Nature*, 2014, **515**, 540-544, doi: 10.1038/nature13883.

[3] C.-C. Chang, W. J. M. Kort-Kamp, J. Nogan, T. S. Luk, A. K. Azad, A. J. Taylor, D. A. R. Dalvit, M. Sykora, H.-T. Chen, High-temperature refractory metasurfaces for solar thermophotovoltaic energy harvesting, *Nano Letters*, 2018, **18**, 7665-7673, doi: 10.1021/acs.nanolett.8b03322.

[4] G. Hou, Z. Wang, Z. Lu, H. Song, J. Xu, K. Chen, Enhanced broadband plasmonic absorbers with tunable light management on flexible tapered metasurface, *ACS Applied Materials & Interfaces*, 2020, **12**, 56178-56185, doi: 10.1021/acsami.0c16189.

[5] B. Zeng, Z. Huang, A. Singh, Y. Yao, A. K. Azad, A. D. Mohite, A. J. Taylor, D. R. Smith, H.-T. Chen, Hybrid graphene metasurfaces for high-speed mid-infrared light modulation and single-pixel imaging, *Light: Science & Applications*, 2018, **7**, 51, doi: 10.1038/s41377-018-0055-4.

[6] C. M. Watts, X. Liu, W. J. Padilla, Metamaterial Electromagnetic Wave Absorbers, *Advanced Materials*, 2012, **24**, OP98-120, doi: 10.1002/adma.201200674.

[7] S. Shrestha, Y. Wang, A. C. Overvig, M. Lu, A. Stein, L. Dal Negro, N. Yu, Indium tin oxide broadband metasurface absorber, *ACS Photonics*, 2018, **5**, 3526-3533, doi: 10.1021/acsphotonics.8b00781.

[8] A. Sakurai, K. Yada, T. Simomura, S. Ju, M. Kashiwagi, H. Okada, T. Nagao, K. Tsuda, J. Shiomi, Ultranarrow-band wavelength-selective thermal emission with aperiodic multilayered metamaterials designed by Bayesian optimization, *ACS Central Science*, 2019, **5**, 319-326, doi: 10.1021/acscentsci.8b00802.

[9] W. Li, Y. Shi, K. Chen, L. Zhu, S. Fan, A comprehensive photonic approach for solar cell cooling, *ACS Photonics*, 2017, **4**, 774-782, doi: 10.1021/acsp Photonics.7b00089.

[10] L. Long, Y. Yang, L. Wang, Simultaneously enhanced solar absorption and radiative cooling with thin silica micro-grating coatings for silicon solar cells, *Solar Energy Materials and Solar Cells*, 2019, **197**, 19-24, doi: 10.1016/j.solmat.2019.04.006.

[11] D. Costantini, A. Lefebvre, A.-L. Coutrot, I. Moldovan-Doyen, J.-P. Hugonin, S. Boutami, F. Marquier, H. Benisty, J.-J. Greffet, Plasmonic metasurface for directional and frequency-selective thermal emission, *Physical Review Applied*, 2015, **4**, 014023, doi: 10.1103/physrevapplied.4.014023.

[12] H. T. Miyazaki, T. Kasaya, M. Iwanaga, B. Choi, Y. Sugimoto, K. Sakoda, Dual-band infrared metasurface thermal emitter for CO₂ sensing, *Applied Physics Letters*, 2014, **105**, 121107, doi: 10.1063/1.4896545.

[13] K. Chen, R. Adato, H. Altug, Dual-band perfect absorber for multispectral plasmon-enhanced infrared spectroscopy, *ACS Nano*, 2012, **6**, 7998-8006, doi: 10.1021/nn3026468.

[14] J. W. Petefish, A. C. Hillier, Multipitched diffraction gratings for surface plasmon resonance-enhanced infrared reflection

- absorption spectroscopy, *Analytical Chemistry*, 2015, **87**, 10862-10870, doi: 10.1021/acs.analchem.5b02864.
- [15] B. Zhang, J. Hendrickson, J. Guo, Multispectral near-perfect metamaterial absorbers using spatially multiplexed plasmon resonance metal square structures, *Journal of the Optical Society of America B*, 2013, **30**, 656, doi: 10.1364/josab.30.000656.
- [16] C. Wang, M. Huang, Z. Zhang, W. Xu, Dual band metamaterial absorber: combination of plasmon and Mie resonances, *Journal of Materials Science & Technology*, 2020, **53**, 37-40, doi: 10.1016/j.jmst.2020.02.058.
- [17] R. A. Deshpande, F. Ding, S. Bozhevolnyi, Dual-band metasurfaces using multiple gap-surface plasmon resonances, *ACS Applied Materials & Interfaces*, 2020, **12**, 1250-1256, doi: 10.1021/acsami.9b15410.
- [18] F. Chen, H. Zhang, L. Sun, J. Li, C. Yu, Temperature tunable Fano resonance based on ring resonator side coupled with a MIM waveguide, *Optics & Laser Technology*, 2019, **116**, 293-299, doi: 10.1016/j.optlastec.2019.03.044.
- [19] Y. Ke, Y. Yin, Q. Zhang, Y. Tan, P. Hu, S. Wang, Y. Tang, Y. Zhou, X. Wen, S. Wu, T. J. White, J. Yin, J. Peng, Q. Xiong, D. Zhao, Y. Long, Adaptive thermochromic windows from active plasmonic elastomers, *Joule*, 2019, **3**, 858-871, doi: 10.1016/j.joule.2018.12.024.
- [20] M. Chen, A. M. Morsy, M. L. Povinelli, Design of VO₂-coated silicon microspheres for thermally-regulating paint, *Optics Express*, 2019, **27**, 21787, doi: 10.1364/oe.27.021787.
- [21] K. Sun, C. A. Riedel, A. Urbani, M. Simeoni, S. Mengali, M. Zalkovskij, B. Bilenberg, C. H. de Groot, O. L. Muskens, VO₂ Thermochromic metamaterial-based smart optical solar reflector, *ACS Photonics*, 2018, **5**, 2280-2286, doi: 10.1021/acsphotonics.8b00119.
- [22] Y. Guo, B. Xiong, Y. Shuai, J. Zhao, Thermal driven wavelength-selective optical switch based on magnetic polaritons coupling, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 2020, **255**, 107230, doi: 10.1016/j.jqsrt.2020.107230.
- [23] Y. Zhao, Q. Huang, H. Cai, X. Lin, H. He, T. Ma, Y. Lu, Dual band and tunable perfect absorber based on dual gratings-coupled graphene-dielectric multilayer structures, *Optics Express*, 2019, **27**, 5217, doi: 10.1364/oe.27.005217.
- [24] S.-H. Wu, M. Chen, M. T. Barako, V. Jankovic, P. W. C. Hon, L. A. Sweatlock, M. L. Povinelli, Thermal homeostasis using microstructured phase-change materials, *Optica*, 2017, **4**, 1390, doi: 10.1364/optica.4.001390.
- [25] L. Long, S. Taylor, L. Wang, Enhanced infrared emission by thermally switching the excitation of magnetic polariton with scalable microstructured VO₂ metasurfaces, *ACS Photonics*, 2020, **7**, 2219-2227, doi: 10.1021/acsphotonics.0c00760.
- [26] X. Zhang, J. Qiu, J. Zhao, X. Li, L. Liu, Complex refractive indices measurements of polymers in infrared bands, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 2020, **252**, 107063, doi: 10.1016/j.jqsrt.2020.107063.
- [27] H. Wang, Y. Yang, L. Wang, Wavelength-tunable infrared metamaterial by tailoring magnetic resonance condition with VO₂ phase transition, *Journal of Applied Physics*, 2014, **116**, 123503, doi: 10.1063/1.4896525.
- [28] A. S. Barker, H. W. Verleur, H. J. Guggenheim, Infrared optical properties of vanadium dioxide above and below the transition temperature, *Physical Review Letters*, 1966, **17**, 1286-1289, doi: 10.1103/physrevlett.17.1286.
- [29] E. D. Palik, Selenium (Se), *Handbook of Optical Constants of Solids*, 1998, **2**, 691-703, doi: 10.1016/b978-0-08-055630-7.50042-0.
- [30] M. Ono, K. Chen, W. Li, S. Fan, Self-adaptive radiative cooling based on phase change materials, *Optics Express*, 2018, **26**, A777, doi: 10.1364/oe.26.00a777.
- [31] W. W. Zhang, H. Qi, A. T. Sun, Y. T. Ren, J. W. Shi, Periodic trapezoidal VO₂-Ge multilayer absorber for dynamic radiative cooling, *Optics Express*, 2020, **28**, 20609, doi: 10.1364/oe.396171.
- [32] X. Wang, Y. Cao, Y. Zhang, L. Yan, Y. Li, Fabrication of VO₂-based multilayer structure with variable emittance, *Applied Surface Science*, 2015, **344**, 230-235, doi: 10.1016/j.apsusc.2015.03.116.

Author information

Siyi Ma is currently pursuing the master's degree in Power Engineering with the Nanjing University of Science and Technology, Nanjing, China. Her research focuses on light-matter interaction of micro-nano structures and adaptive thermal radiation.

Desong Fan is an associate Professor at Nanjing University of Science and Technology. His current research interests include thermal radiation, electronic cooling, thermal management, and solar energy conversion and utilization.

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.