Surface plasmon-enhanced dual-band infrared absorber for VO_x-based microbolometer application*

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We propose a periodic structure as an extra absorption layer (i.e., absorber) based on surface plasmon resonance effects, enhancing dual-band absorption in both middle wavelength infrared (MWIR) and long wavelength infrared (LWIR) regions. Periodic gold disks are selectively patterned onto the top layer of suspended SiN/VO_2/SiN sandwich-structure. We employ the finite element method to model this structure in COMSOL Multiphysics including a proposed method of modulating the absorption peak. Simulation results show that the absorber has two absorption peaks at wavelengths $\lambda =$ 4.8 μm and $\lambda = 9$ μm with the absorption magnitudes more than 0.98 and 0.94 in MWIR and LWIR regions, respectively. In addition, the absorber achieves broad spectrum absorption in LWIR region, in the meanwhile, tunable dual-band absorption peaks can be achieved by variable heights of cavity as well as diameters and periodicity of disk. Thus, this designed absorber can be a good candidate for enhancing the performance of dual band uncooled infrared detector, furthermore, the manufacturing process of cavity can be easily simplified so that the reliability of such devices can be improved.

Keywords: surface plasmon resonance effects, dual-band absorption, vanadium oxide, uncooled infrared detector

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1. Introduction

Thermistor bolometers are constructed from sintered mixture of various semiconducting oxide that have a higher temperature coefficient of resistance (TCR) than metals (2%–4%/°C).[1] The most popular thermistor material used in fabrication of the micromachined silicon bolometer is vanadium oxide (VO_x).[2] A thin film of the mixed oxides sputtered on an Si_3N_4 microbridge substrate is originally developed at Honeywell.[1,3] VO_x based micrometers with better responsivity[4] and lower noise factor[5] are widely used in missile warning system and military equipment. Dual band infrared detector has always been a keen interest for many applications with more superior performance[6,7] and wider working band.[8] In general, there are three methods to achieve dual band absorption. The first method is the integration of patterned gold black with a microbolometer enhancing dual band absorption,[9] but the adhesive of gold black is not good and this method is difficult to modulate the tunable absorption peak. The second method is the integration of photon detector and thermal detector, photon detector is used as middle wavelength infrared (MWIR) detector, thermal detector is used as long xuebaowavelength infrared (LWIR) detector.[10] However, the device structure and read out circuit is very complicated, which leads to increasing cost and reliability problems. The third method is controlling the height of the cavity by electrostatic actuating, modulating the height of cavity between 1 μm and 2.5 μm to achieve dual band response at wavelengths of 3 μm∼5 μm and 8 μm∼12 μm.[11] Due to additional driving device, the device structure is very complicated, which leads to increasing cost and this method is difficult to modulate the tunable absorption peak. Up to now, no method of enhancing dual band absorption and modulating the absorption peak flexibly but being manufactured in an easy way is proposed.

Recently, plasmonic resonant coating enhanced absorption has been proposed.[9] With regard to plasmonic materials, such as gold (Au) and silver (Ag) are the two most

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widely used materials in the visible and IRregions.[12] Optimization for MWIR or LWIR is usually achieved by Fabry Perot (FP)[13,14] or other resonant structures.[15–17] It is sometimes assumed that perfect absorbers based on dielectric cavities cannot be made much thinner than the operating wavelength, and that plasmonic nanostructures are required to overcome this limitation.[18,19] Although ultrathin dielectric film enhances absorption, however, it cannot be applied in actual VO_x-based microbolometer devices and it is difficult to modulate the absorption peak flexibly. Plasmonics has developed high-performance room-temperature air-bridge microbolometer arrays using VO_x thin films.[9,20] Various periodic structures using different materials have been demonstrated as narrow-band thermal emitters, including Al–Al_2O_3–Al trilayers[12] and hole arrays of Ag–SiO_2–Ag.[21]

In this paper, compared with traditional microbolometer based on VO_x thin film, additional patterned periodic gold disk array on the top based on surface plasmon resonance effects is proposed, enhancing dual-band absorption in both MWIR and LWIR regions. An air-bridge SiN/VO_2/SiN sandwich-structure with patterned periodic gold disks on the top enhances dual band absorption. In addition, a gold mirror used for reflector on silicon substrate and optical resonant cavity enhance absorption. The absorption of the designed structure is investigated by modeling and simulation method in COMSOL Multiphysics. Simulation results show that the absorber has two absorption peaks at wavelengths $\lambda = 4.8$ μm and $\lambda = 9$ μm with the absorption magnitudes more than 0.98 and 0.94 in MWIR and LWIR regions, respectively. In addition, the absorber achieves broad spectrum absorption in the LWIR region

2. Dual-band absorber structure

The structure consisting of seven layers is shown in Fig. 1(a). From the bottom silicon layer used as substrate to the top periodic gold disk array, this step-by-step integration of components takes place in a bottom-up fashion. A gold mirror is used for reflector on silicon substrate. Air-bridge SiN/VO_2/SiN sandwich-structure is on the top of reflector, forming optical resonant cavity. The thermal conductivity of SiN is relatively small and the vacuum cavity below, which leads to concentrating heat on VO_2 thin film. The thickness of SiN thin film is defined as s. The thickness of VO_2 thin film is defined as T. The height of cavity is defined as H. Periodic array of gold disks are patterned onto the top layer. The diameter of gold disk is defined as D. The periodicity of disk is defined as P. The thickness of the disk is defined as t. Absorption is calculated as minus the reflectance, as the transmittance is zero due to the optically thick gold reflector.[9] The top view of the structure is shown in Fig. 1(b).

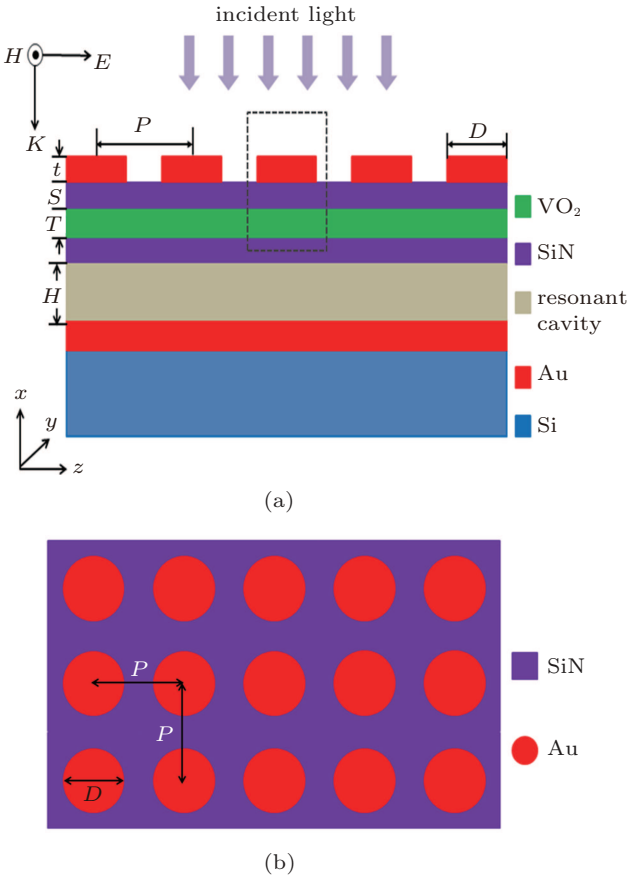


Fig. 1. (color online) (a) Schematic diagram of the dual-band absorber structure and (b) top view of the dual-band absorber structure.

3. Simulation and discussion

We have employed the finite element method to model this seven-layered structure in COMSOL Multiphysics.[22] In the simulations, periodic boundary conditions are employed along the y and z axes to account for the periodic arrangement of the unit cells. Perfectly matched layers (PMLs) surrounded by scattering boundary condition faces are utilized along the x axis to avoid multiple reflections due to geometry truncation. The permittivity of bulk gold in the mid-infrared is described by the Drude model $\varepsilon_{\mathrm{Au}} = \varepsilon_\infty - \omega_p^2/(\omega^2 - \mathrm{i}\omega\gamma_\mathrm{p})$,[23] where the background dielectric constant is $\varepsilon_\infty = 1$, the plasma frequency $\omega_\mathrm{p} = 1.37 \times 10^{16}$ rad/s and the damping constant $\gamma_\mathrm{p} = 4.08 \times 10^{13}$ rad/s. The permittivity of Si is set to 11.5.[24] In the simulation, the permittivity tensor was employed to consider the uniaxial anisotropy of dielectric VO_x:[25]

$$\varepsilon = \begin{pmatrix} \varepsilon_0 & 0 & 0 \\ 0 & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{pmatrix}$$

it exhibits ordinary dielectric response denoted as ε_0, when incident electric field is perpendicular to optical axis, and extraordinary response ε_F when electric field is parallel to optical axis. The permittivity of SiN uses a function of the form[26]

$$\varepsilon = \varepsilon_\infty + \sum_{j=1}^{\infty} \frac{\gamma_{pj}^2}{\gamma_{0j}^2 - \gamma^2 - \mathrm{i}\gamma_{\tau j}\gamma}.$$

The physical model is electromagnetic waves, frequency domain (emw) in radio frequency. The absorption is obtained by

$$A(\lambda) = 1 - R(\lambda) - T(\lambda), \tag{1}$$

where $A(\lambda)$, $R(\lambda)$, and $T(\lambda)$ are the absorption, the reflection, and the transmission.[20] The transmission $T(\lambda)$ can be regarded as zero because of the gold mirror,[20] which is a good reflector in the infrared region. Therefore, the absorption in simulation can be simplifiedto[5,20]

$$A(\lambda) = 1 - R(\lambda). \tag{2}$$

Figure 2 shows the influence of optical resonant cavity and plasmon on absorption. Curve 1 in Fig. 2 shows that the absorption of absorber without cavity and disk. The absorption originates from the inherent character of material photoabsorption, thus absorptivity is relatively small and dual band absorption is not obvious. Curve 2 in Fig. 2 shows that the absorber having a cavity with parameter $H = 500$ nm enhances absorption due to resonant absorption but absorptivity is relatively small in the MWIR region. Curve 3 in Fig. 2 shows that the absorber having both cavity and disk with parameters $H = 500$ nm, $D = 1.5$ μm, $P = 2.6$ μm enhances the dual band absorption and has two absorption peaks in the MWIR and LWIR regions. Curve 3 shows that the absorber has two absorption peaks at wavelengths $\lambda = 4.8$ μm and $\lambda = 9$ μm with the absorption magnitudes more than 0.98 and 0.94, while the absorber achieves broad spectrum absorption in the LWIR region. From Fig. 2, we can conclude that the optical resonant cavity certainly enhances absorption and surface plasmon enhances the dual band infrared absorption.

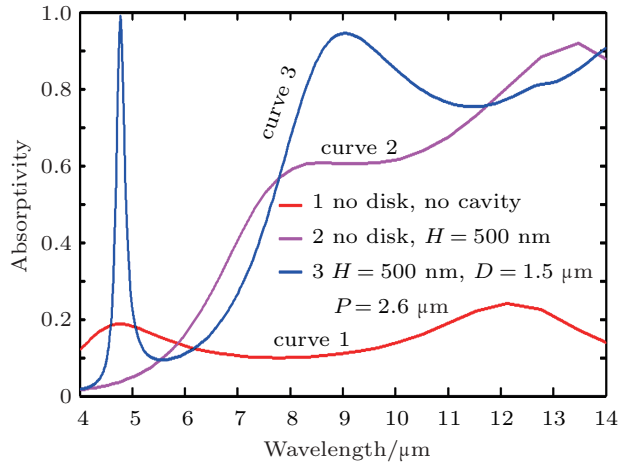


Fig. 2. (color online) Influence of optical resonant cavity and plasmon on absorption, curve 1 shows the influence of absorber without cavity and gold disk on absorption, curve 2 shows the influence of absorber with a cavity with parameter $H = 500$ nm on absorption, curve 3 shows the influence of absorber with both cavity and disk with parameters $H = 500$ nm, $D = 1.5$ μm, $P = 2.6$ μm on absorption.

From curve 3 in Fig. 2, we can conclude that theheight of cavity in dual band absorber is greatly reduced, compared with the traditional resonant cavity height (about a quarter of radiation infrared wavelength), thus improving device reliability but simplifying process and reducing cost of device. A VO_x thin film is formed as an air bridge, utilizing gold reflector and revised numerical electrodynamics calculations indicate an average absorptance of 71% for the LWIR.[9]

We further investigate the effects of the height of cavity, the diameter, and the periodicity of the disk on dual band absorption. Figure 3(a) shows the influence of height of cavity on wave absorption, with the parameters $P = 2.6$ μm and $D = 1.5$ μm. The height of cavity is respectively 300 μm, 500 μm, and 700 μm. The simulation result indicates that the absorption peak in the LWIR region locates in 8.4 μm, 9 μm, and 9.4 μm respectively. It concludes that the absorption in the LWIR region can be tuned through varying the height of cavity. Then, the height of cavity is set to 500 nm. Figure 3(b) shows the influence of periodicity of disk on wave absorption, with the parameters $H = 500$ nm and $D = 1.5$ μm. The periodicity of the disk is respectively 2.4 μm, 2.6 μm, 2.8 μm. The simulation result indicates that absorption peaks in the MWIR region respectively locates in 4.6 μm, 4.8 μm, 5 μm, while the absorption peak in the LWIR region is invariable. It concludes that absorption peaks in the MWIR region can be tuned through varying periodicity sizes. Finally, the height of cavity is set to 500 nm and the periodicity of the disk is set to 2.6 μm. Figure 3(c) shows the influence of diameter of the disk on wave absorption, with the parameters $H = 500$ nm and $D = 2.6$ μm. The diameter of the disk is respectively 1.3 μm, 1.5 μm, 1.7 μm. The simulation result indicates that absorption magnitudes in the infrared region can be tuned through varying diameters.

From Figs. 3(a), 3(b), and 3(c), a method of modulating the absorption peak is proposed as follows: Firstly, the absorption peak in the LWIR region can be tuned by varying the height of cavity. Secondly, under the same cavity height, the absorption peak in the MWIR region can be tuned by varying the periodicity of the disk. Finally, under the same cavity height and periodicity of the disk, absorption peaks magnitudes in the infrared region can be tuned by changing slightly the diameter of the disk. The resonance wavelength of the resonant cavity is dependent on the height of cavity, the resonance wavelength of single disk is dependent on the diameter of the Au-disk resonator, while the periodicity of gold particle array affects the frequency of Bloch wave and couplings between the adjacent particles.[12] As can be seen in Figs. 3(a), 3(b), and 3(c), the frequency of Bloch wave is dependent on the height of cavity and the periodicity of the disk. With the increasing of the periodicity constant of the disk, the frequency of Bloch wave decreases, the periodicity of the disk mainly affects the frequency of Bloch wave. The diameter of the disk almost has no effect on the frequency of the long wavelength wave. The

resonance absorption frequencies can be understood with the equivalent circuit approach, and the resonance frequency can be expressed by

$$\omega = \frac{1}{\sqrt{LC}}, \tag{3}$$

where L is the effective inductance and C is the effective capacitance.[27] When the frequency of incident electromagnetic wave is consistent with the oscillation frequency of metal-free electron, the energy of incident electromagnetic wave gets enhanced absorption. Such characteristics may be significant in the absorption according to the potential application demand.

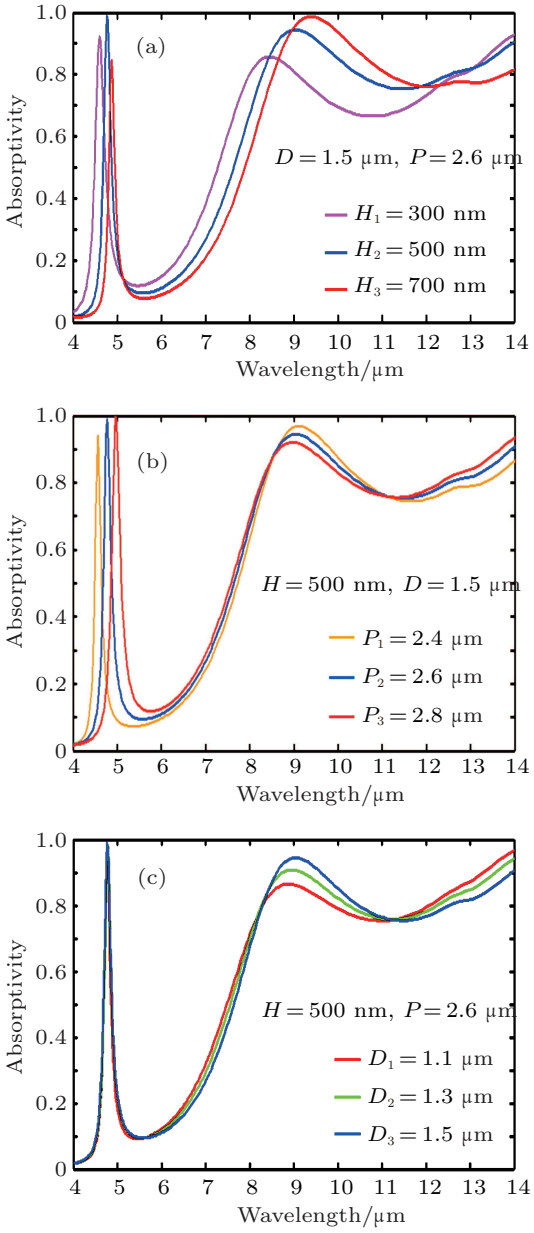


Fig. 3. (color online) (a) Influence of height of cavity on absorption, the diameter of disk is 1.5 μm, the periodicity of the disk is 2.6 μm, the height of cavity is respectively 300 nm, 500 nm, 700 nm. (b) Same as panel (a) but the height of cavity is 500 nm, the periodicity of the disk is respectively 2.6 μm, 2.8 μm, 3 μm. (c) Same as panel (a) but the periodicity of the disk is 2.6 μm, the diameter of the disk is respectively 1.3 μm, 1.5 μm, 1.7 μm.

In order to check the robustness of this method, we discussed the influence of the fabrication tolerance on the absorption characteristics with simulation. Figure 4 shows the absorption spectra of the dual-band absorber for different thicknesses of the gold disk, VO_2 thin film and SiN thin film. As can be seen in Fig. 4, the dual-band absorption peaks are still nearly invariable and the absorption magnitudes are more than 0.9 for both absorption peaks with the different thicknesses of t (from 45 nm to 55 nm), T (from 45 nm to 55 nm) and s (from 180 nm to 220 nm). From Fig. 4, we can conclude that the absorption peak will maintain with the fabrication tolerance more than 10% for the geometric parameters t, T, and s. And the fabrication tolerance defined as ratio of the deviation from the optimized geometric parameter to the optimized geometric parameter.

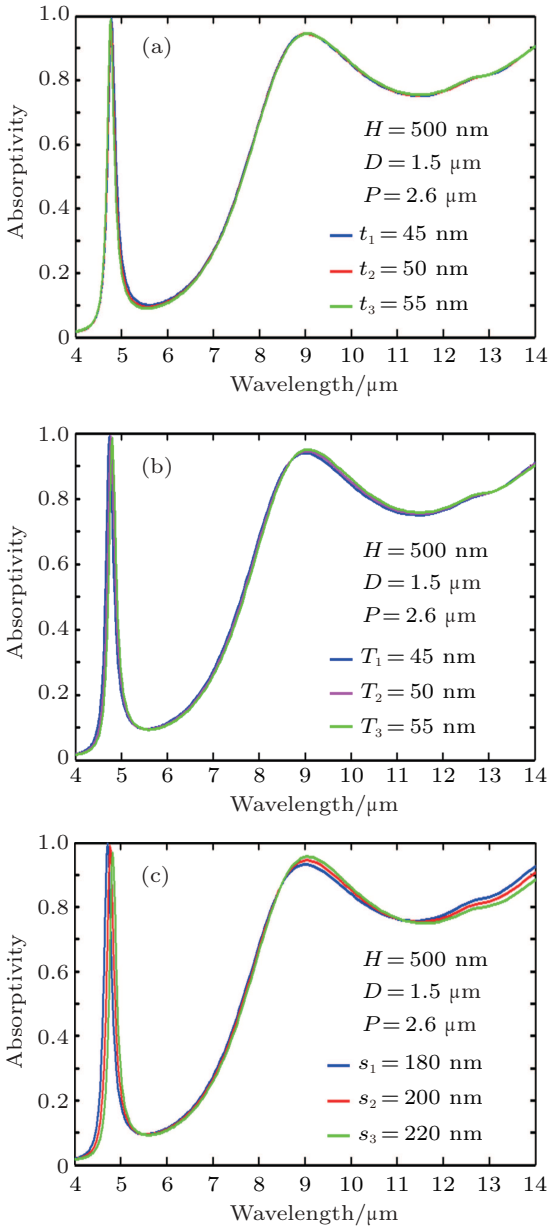


Fig. 4. (color online) Absorption spectra of dual-band absorber for (a) different thicknesses of the gold disk (from 45 nm to 50 nm), (b) different thicknesses of VO_2 thin film (from 45 nm to 50 nm), (c) different thicknesses of SiN thin film (from 180 nm to 220 nm).

In order to understand the dual-band absorption characteristics, we plot the intensity of electric field at resonant absorption wavelengths $\lambda = 4.8$ μm and $\lambda = 9$ μm on the upper surface of VO_2 thin film. The absorber without cavity and disk, and the absorber with a cavity serve as references for comparison. As seen in Fig. 5, the electric field intensity of the incident electromagnetic field is defined as $|E_0|^2$ the enhancement of the electric field intensity is defined as $|E|^2/|E_0|^2$. The detailed enhancement of absorber without cavity and disk, absorber with a cavity, absorber with cavity and plasmon structure at resonant wavelengths $\lambda = 4.8$ μm and $\lambda = 9$ μm is correspondingly 0.036, 0.067, 8.6, and 1.56. We can conclude that the absorber with cavity and plasmon structure enhances the dual band absorption, resulting in enhanced absorption on VO_2 thin film by tens-fold to hundreds-fold compared with absorber without cavity and disk, absorber with a cavity.

Since the thermal conductivity of SiN is relatively small and the vacuum cavity is low, a suspended SiN/VO_2/SiN sandwich-structure is proposed to concentrate heat on VO_2 thin film. Periodic gold disks are selectively patterned onto the top layer to enhance the electric field intensity. The modeling simulation results prove that the enhancement of the electric field intensity on gold disk has no effect on the transmission of electromagnetic wave resulting in the second enhancement of the electric field intensity on VO_2 thin film. The electromagnetic energy will be effectively transformed into heat due to the enhanced electric field

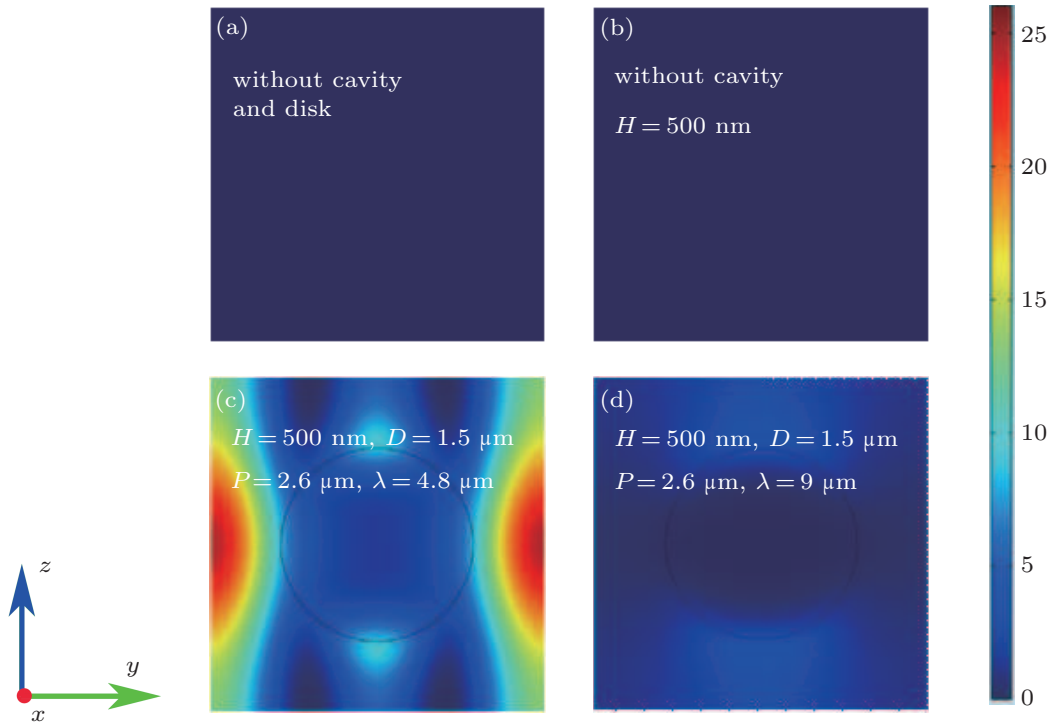


Fig. 5. (color online) (a) The enhancement of the electric field intensity for absorber without cavity and disk, (b) the enhancement of the electric field intensity for absorber with cavity with the parameter $H = 500$ nm, (c) the enhancement of the electric field intensity at resonant absorption wavelength $\lambda = 4.8$ μm, (d) the enhancement of the electric field intensity at resonant absorption wavelength $\lambda = 9$ μm.

4. Conclusion

We have studied a periodic structure based on surface plasmon resonance effects, enhancing the dual-band absorption in the MWIR and LWIR regions. Simulation results show that the absorber has two absorption peaks at wavelengths $\lambda = 4.8$ μm and $\lambda = 9$ μm with the absorption magnitudes more than 0.98 and 0.94 in the MWIR and LWIR regions, respectively. In addition, the absorber achieves broad spectrum absorption in the LWIR region, making the full use of atmospheric window of infrared. In the meanwhile, tunable dual-band absorption peaks can be achieved by variable heights of cavity as well as the diameter and periodicity of the disk. Compared with the traditional resonant cavity height (about a quarter of radiation infrared wavelength), the height of cavity is greatly reduced. The absorber is a good candidate for manufacturing of dual band uncooled infrared detector, greatly simplifying the process and improving reliability. Thus, this designed absorber can be a good candidate for enhancing the performance of dual band uncooled infrared detector, furthermore, the manufacturing process of cavity can be easily simplified so that the reliability of such devices can be improved. Furthermore, the gold mirror can be fabricated with electron-beam evaporation[28] and the SiN/VO_2/SiN sandwich-structure with gold disks can be fabricated with lift-off electron-beam lithography.[29] Thus, such a dual-band absorber structure is realizable based on the tech-

niques presently.

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