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Polarization-selective dual-band infrared plasmonic absorber based on sub-wavelength gaps

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ABSTRACT

A dual-band (mid- and long-wave infrared) polarization-selective plasmonic absorber was designed and numerically investigated. This absorber traps definite polarization light and reflects light that is perpendicular to the polarization direction. It is extremely sensitive to polarization angle and can keep robustness to oblique incidence. The extinction rate does not reduce when the incident angle is even near 80° and rate value keeps above 130 for both resonance peaks. The absorber can respond to mid- and long-wave infrared atmospheric windows simultaneously and achieve near-unity absorption at 3.3 μm and 9.8 μm for specific polarization under normal radiation. The resonance condition is tuned by altering the geometric design. Owing to its high absorptivity and fine polarization properties, the absorber combines the advantages of a light absorber and a polarizer, and can be utilized in an uncooled infrared polarization detector, which simplify the optical system design and avoid the polarization information reconstruction error caused by the misplacement between the polarizer and the pixel.

1. Introduction

Metamaterials are artificial composite structures with extraordinary electromagnetic properties which are often not available to materials in nature. The interaction between incident light and metamaterials can excite plasmonics that is the electromagnetic oscillation of free electrons and photons in the metal surface area. Metamaterial absorbers based on plasmonics can realize the local field enhancement effect and convert light energy into heat energy because of phonon absorption and ohmic loss [1]. The optical applications of metamaterial absorbers are extensive, such as thermal IR sensors [2–4], thermophotovoltaics [5], biomedical optics [6] and imaging devices [7,8]. In particular, due to the absorption enhancement property and energy conversion mechanism, metamaterial absorbers become very attractive in uncooled detection technology. The absorptivity of uncooled infrared detectors determines the utilization level of infrared radiation, which greatly affects the performance of detectors. With the development of plasmonics, various absorbers with high absorptivity have been researched in polarization-sensitive [9–15] or polarization-insensitive [16–22] fields.

Compared with polarization-insensitive, a polarization-sensitive absorber can be realized by adjusting asymmetry of its structure, such as an elliptical, rectangle, or L-shape pattern, etc. [23–25]. It can collect not only intensity, phase, but also polarization information. An absorber with high polarization sensitivity can be applied to detection technology to enhanced target contrast, which can make up for the shortcomings of intensity-based detection under complex camouflage conditions. In polarization detection technology, because of its advantages of compact structure, excellent real-time detection, and outstanding response efficiency, the application of division-of-focal-plane polarimetry has become common in many areas [26,27]. A traditional division-of-focal-plane detector measures the polarization information by integrating polarizers on imaging pixels [28,29]. However, in the integration process, polarizers are extremely sensitive to setting angles, which inevitably reduces the accuracy of polarization. Actually, a polarization detection can be obtained without polarizers or other optical resonance structures when a polarization-sensitive light absorber is introduced in uncooled detection technology. It can not only simplify the optical system design but also avoid the polarization information reconstruction error caused by the misplacement between the polarizer and the pixel [23,30].

In addition, a multiband infrared detector can acquire the infrared image of the object in different spectral bands (specifically in mid-

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and long-wave infrared regions), making full use of the complementarity of the multiband imaging information, and improving recognition ability [31]. Multiband spectrum response of infrared detectors can be adjusted by the design of metamaterial structures, which breaks through the limitations in the traditional multiband detection which requires a series of optical systems [32]. Traditional metamaterial structures to achieve multiband response are utilizing super-unit or multiple stacked layers structure which adds the difficulty of fabrication technology. It is alternative option that a simple structure with hybridization of different plasmonic resonance modes is designed to exhibit multiband response. Therefore, designing a polarization-sensitive absorber that can response simultaneously in mid- and long-wave spectral ranges is of great significance for optimizing the performance of uncooled infrared detection.

In this paper, a dual-band polarization-sensitive plasmonic absorber is proposed. It is a metal–insulator–metal stack metamaterial structure based on sub-wavelength gaps. The absorber is sensitive to polarization angle and can keep robustness to oblique incidence of near 80°. Due to the resonances of high order modes, it can respond in mid- and long-wave infrared two atmospheric windows simultaneously and achieve near-unity absorption at 3.3 μm and 9.8 μm. The response wavelengths could be tuned over a broad spectral range by changing the geometry parameters. Its structure was simple and could be easily processed. Owing to the well extinction effect, the absorber can be applied to a polarization-selective uncooled IR detector to realize polarization detection without a polarizer or other optical resonance structures. The application can avoid the effective polarization information reconstruction error, which is caused by the alignment deviation between the polarizer and the pixel. Moreover, it can simplify the optical system design and achieve the measurement of complete polarization information in real-time.

2. Modeling and structure

The concept schematic of the plasmonic absorber is shown in Fig. 1(a). It consists of continuous gold film at the bottom, dielectric Ge in the middle, and air gaps formed between the neighboring gold walls at the top. The cross schematic of the structure is shown in Fig. 1(b), where g and h represent the width and height of the air gaps, respectively; p is the period, and t is the thickness of the dielectric layer. To prevent transmission, the thickness of the bottom gold layer is larger than the skin depth. In our simulations, the absorption structure could be regarded as an infinite two dimensional array. The unit cell was set using periodic boundary conditions along X directions and perfect matching layer was set along Y directions. Z directions were not considered. Mesh type was set to auto-optimization gradient meshes. The absorber was illuminated by a plane wave from y positive direction under TM (electric field perpendicular to the gaps) and TE (electric field parallel to the gaps) polarization waves. The permittivity of Ge is about 16.2 in mid-infrared region and 16 in long-infrared region [33]. The permittivity of gold $\varepsilon_{Au} = 9 - {\omega_p}^2/\left(\omega^2 + i\omega\gamma\right)$, the plasmonic frequency $\omega_p = 2\pi \times 2.175 \times 10^{15}\ s^{-1}$, and the collision frequency $\gamma = 2\pi \times 1.5958 \times 10^{13}\ s^{-1}$ [34].

To investigate the extinction effect of the absorber, the absorptivity under two different polarization light is shown in Fig. 2(a). The value of absorption can be close to 1 for TM wave, while the absorptivity is extremely low when the incident light is TE wave. Extinction efficiency of a structure can be expressed by extinction rate which is defined as $Ext = A^{TM}/A^{TE}$, where A^{TM} is the absorptivity of the metamaterials under TM polarization light radiation, and A^{TE} corresponds to the TE polarization light. To increase extinction rate, an approach is to improve A^{TM} and reduce A^{TE}. But A^{TM} cannot exceed 1, an effective method is to enhance the reflection intensity of TE polarization wave. Fig. 2(b) shows the reflectivity of Au plate and the metamaterial structure. By comparison, the order of magnitude is merely 10^{-3} for the difference of reflectivity. Thus, the absorber can reflect almost all TE polarization light and the fine extinction effective of the sample is reasonable.

3. Results and discussion

The electric field distribution of the resonance peaks was calculated to reveal the physical mechanism of the absorption properties. The field intensity enhancement under the normal incidence of different polarization light radiation is shown in Fig. 3. In the field distribution, charges are accumulated at the edges of the gaps between the neighboring gold walls. In the dielectric layer, the distribution of charges forms one current loop, as shown in Fig. 3(a). Thus, the resonance peak at 9.8 μm is caused by the fundamental response. In like manner, in Fig. 3(b), the resonance peak at 3.3 μm is caused by the third order response. As for the excitation of second order mode, it is necessary to induce a net dipole moment in the nanostructure and couple strongly to the incident field. The proposed absorber structure could not possess a net dipole moment for odd order modes. Thus, the second-order resonance is not excited [35]. Meanwhile, the current loops give rise to the excitation of magnetic resonance between the top metal strips and the continuous bottom metal layer. Surface plasmonic polaritons which is excited by magnetic polarities led to high absorption at the response wavelength. However, the electric intensity lacked any obvious enhancement in Fig. 3(c)–(d), while the light radiation of the TE polarization wave was mainly reflected by the metamaterials and hardly occurred in the absorber. The metamaterials provided almost no response to the TE polarization light. The electric field intensity distribution in the gap is shown in Fig. 4(a). It is clear that the electric intensity was strongly enhanced under the TM radiation at the edges of the gaps. It can be seen that the maximum absorption and electric intensity enhancement values could be obtained approximately at the same response wavelength location, as shown in Fig. 4(b). In other words, the resonance wavelength can be achieved when the electric intensity enhancement was maximum.

In practical applications, fabrication error is a significant parameter which influences absorption performance of polarization-selective absorption devices. Therefore, the relationship between absorption spectrum and geometric parameters is investigated in Fig. 5. When the absorber was illuminated by the TM polarization light under normal incidence, a dual-band spectral response was obtained. The optimized set of geometric parameters are $g = 140$ nm, $h = 70$ nm, $t = 120$ nm, and $p = 1000$ nm. The resonance condition can be tuned by changing the structural parameters of the absorber. In the following simulations, the single variable is insured. In Fig. 5(a), it can be clearly seen that the absorption wavelengths of the dual bands gradually red-shifted as the period increased from 0.9 μm to 1.2 μm. Moreover, the absorptivity of both the fundamental and third order modes is near-unity. It is of great reference value to estimate the resonance peak shifts caused by the change in the geometric parameters of the absorber. An absorption spectrum with a different gap width is shown in Fig. 5(b). The width of the top gaps ranged from 0.1 μm to 0.2 μm. It is obvious that the absorption peak of the fundamental mode is blue-shifted as the width increased, while the absorptivity remained near 100%. The peak location of the third order resonance dose not change much because the wavelength moving range of the fundamental mode trebles that of the third order mode. This will be explained in more details. The absorption spectrum with different gap heights and dielectric layer thicknesses is shown in Fig. 5(c)–(d), where it can be seen that the variety of the h and t values cannot obviously influence the absorption properties of dual bands. It indicates that the good absorption performance would be retained with processing errors.

The y component of electric field in fundamental mode is shown in Fig. 6(a). There forms one current loop in the dielectric layer between the metal strips on the top and the continuous metal film at the bottom, which indicates the feature of magnetic resonance. To illustrate the physical mechanism of the absorption effects, equivalent LC circuits are utilized to predict the magnetic resonance condition according to the charge distribution in the field distribution [36–39]. The equivalent circuit model of the plasmonic absorber is shown in

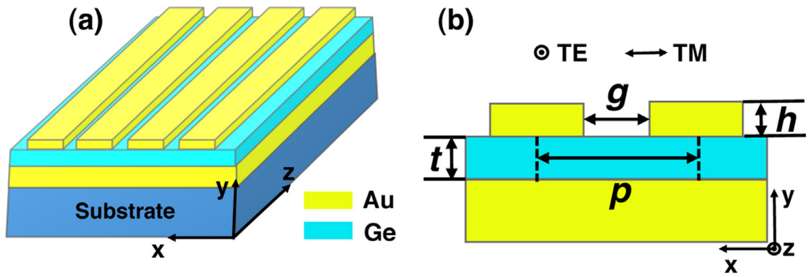

Fig. 1. (a) 3D diagram of absorber with gold strips at the top, dielectric layer in the middle, and continuous gold layer at the bottom. (b) The cross schematic of the sample, where the width and height of the gaps are represented by g and h, respectively. The period is represented by p, and t is the thickness of the dielectric layer in the middle.

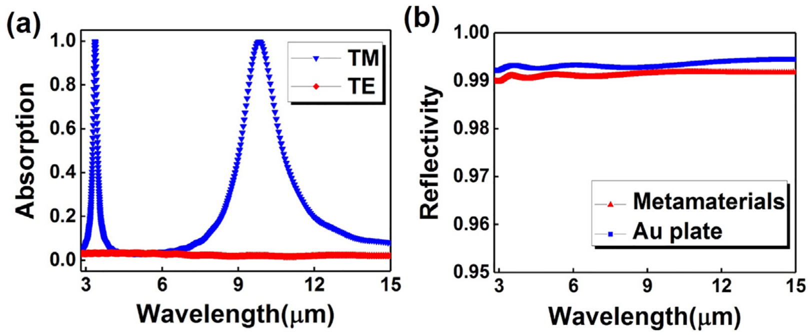

Fig. 2. (a) Absorption spectral line under TM and TE polarization radiation. If not specified, $g = 140$ nm, $h = 70$ nm, $t = 120$ nm, and $p = 1000$ nm. (b) The reflectivity of Au plate and metamaterials, respectively.

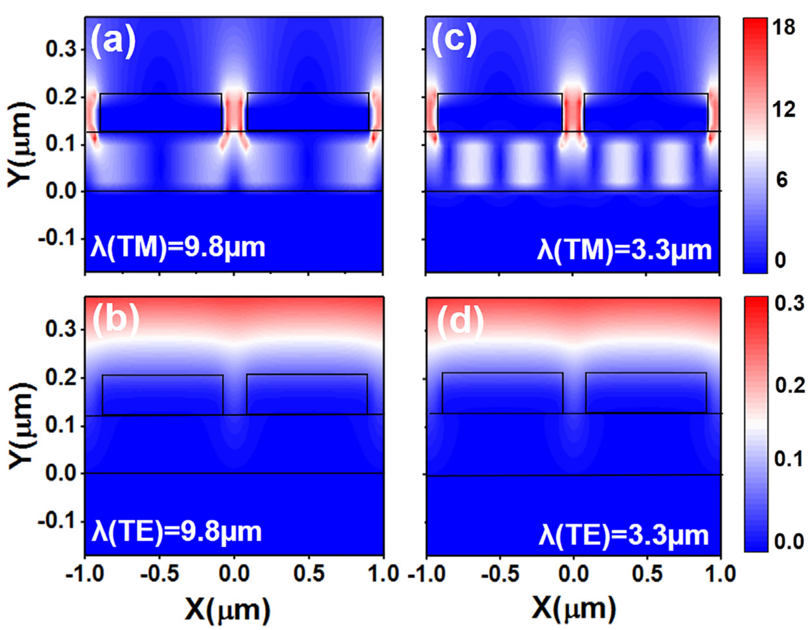

Fig. 3. Electric intensity enhancements of dual-band response. (a)–(b) The fundamental and third order resonance modes are radiated by TM polarization light. (c)–(b) The fundamental and third order resonance modes are radiated by TE polarization light.

Fig. 6(b). Note that both sides of the LC circuit are periodic and infinite. The arrows represent the direction of the electric current loop in a unit. Here, $C_1 \sim \varepsilon_0 l h/g$ is the gap capacitance between the adjacent metal strips; $C_2 \sim \varepsilon_0 \varepsilon_d l\,(p-g)\,/\mathrm{t}$ is the parallel plate capacitance, where c' is adjusting parameter of LC circuit mode, ε_d is the dielectric constant of the middle layer and l is the length of the metal strips in the z direction; $L_1 \sim \mu_0\,(p-g)\,\mathrm{t}/2l$ accounts for the effective inductance between two parallel plates by a distance of t; $L_2 \sim -(p-g)\,/\varepsilon_0 \varepsilon'_m \omega^2 l h_{eff}$ is the inductance introduced by drifting electrons; h_{eff} is the effective thickness of the electric current; ε'_m is the real part of the metal's dielectric function. The total impedance of the absorber can be expressed as follows:

$$Z_{total}\,(\omega) = j\omega[\frac{L_1 + L_2}{1 - \omega^2 C_1\left(L_1 + L_2\right)} - 2\frac{1}{\omega^2 C_2} + \left(L_1 + L_2\right)] \tag{1}$$

Under the magnetic resonance condition for the fundamental mode, $Z_{total}\,(\omega) = 0$ where ω is the angle frequency. Therefore, the resonance wavelength of the fundamental mode can be represented by $\lambda = \frac{2\pi c}{\omega}$, while the high order resonance wavelength can be obtained as $\lambda_n = \frac{\lambda}{n}$, where n is the resonance order. In this study, the fundamental resonance wavelength for the polarization-selective plasmonic absorber is approximately three times more than the third order resonance

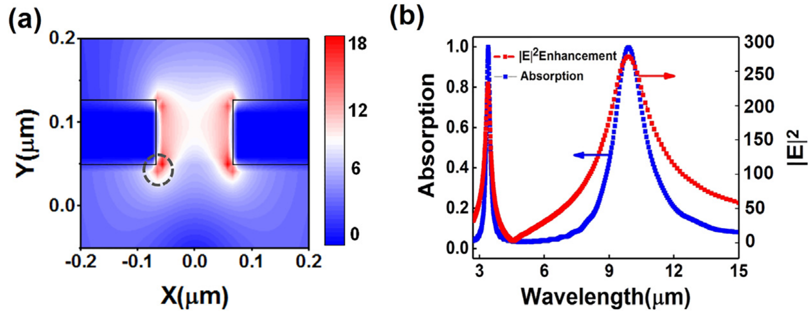

Fig. 4. (a) Electric field distribution in the gap, the location of dashed circle is the setting position of point detector. (b) Absorption spectral line and electric field intensity enhancements as functions of incident wavelength under TM polarization light radiation.

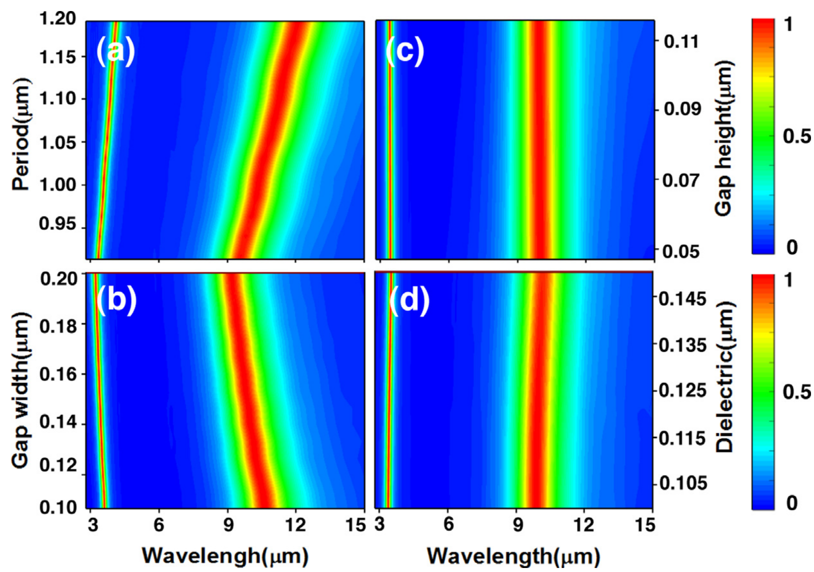

Fig. 5. Absorption spectrum under normally incident TM polarization light corresponding to different geometric parameters. (a) Absorption spectrum in different period values. (b)–(c) Dependence of absorption spectrum on gap width and height, respectively. (d) Relationship between absorption spectrum and thickness of dielectric layer.

wavelength. Therefore, the spectrum change range of the fundamental mode is also three times that of the third order mode with the variation of geometric parameters. Equivalent LC circuits can be used to evaluate the emittance band edges by evaluating the resonance wavelength of the magnetic response to provide design guidelines.

Fig. 6(c)–(d) shows the absorption spectrum with different periods and gap widths. The red line represents simulation values of resonance wavelengths and the blue line represents calculated values of equivalent LC circuit mode. Six different points of periods and gap widths are respectively selected to verify the coherence between simulation and calculated results. It is clear that the equivalent LC circuit modes match well with simulation modes.

The polarization sensibility of a plasmonic absorber can be investigated by varying the polarization angle of the incident light. The metamaterials are normally incident by polarization light. The polarization results are shown in Fig. 7(a). It is clear that the absorber is extremely sensitive to the polarization angle of incident light. The absorptivity changes accordingly when the polarization angle is slightly changed. The two peaks can both reach to near-unity absorption when the polarization angle is 0°. However, the absorptivity is extremely low for both peaks when the polarization angle is 90°. It can be seen that the absorptivity of the two peaks reduces as the polarization angle increased. The stability of absorptivity under oblique incidence is important factor in practical applications. Therefore, the incident angular dependence of extinction rate was calculated in Fig. 7(b). The angle of incidence is in y–z plane. The extinction rate does not reduce when the incident angle is even as large as 80° and rate value keeps above 130 for both peaks in infrared region.

These results supplied powerful evidence to support the assertion that the plasmonic absorber based on gaps structure was extremely sensitive to polarization angle and could keep robustness to oblique incidence. It possessed near-unity absorptivity in mid- and long-wave infrared atmospheric windows, simultaneously. The absorber sample could be fabricated using thermal evaporation method and focused ion beam technology. Thermal evaporation is used for depositing the conducting layer of gold as well as germanium, which is the dielectric layer. 1-D periodic gaps structures could be formed on the germanium layer by focused ion beam technology. Thus, its structure is simple and easily fabricated. Moreover, the plasmonic absorber could be developed for polarization detection by using CMOS techniques.

4. Conclusion

A polarization-sensitive absorber based on gaps structure was proposed to achieve good extinction performance in mid- and long-wave infrared regions. Surface plasmonic polarities excited by magnetic resonance were utilized to achieve near-unity absorption at 3.3 μm and 9.8 μm under normal radiation for TM polarization. With regard to TE polarization, the light was reflected almost entirely. In comparison with the traditional multiband structure which is based on the super-unit or multiple stacked layers, the single-pattern absorber could obtain dual-band absorption peaks by combining the fundamental and high order resonances. Its structure was simple and easy to process. By changing

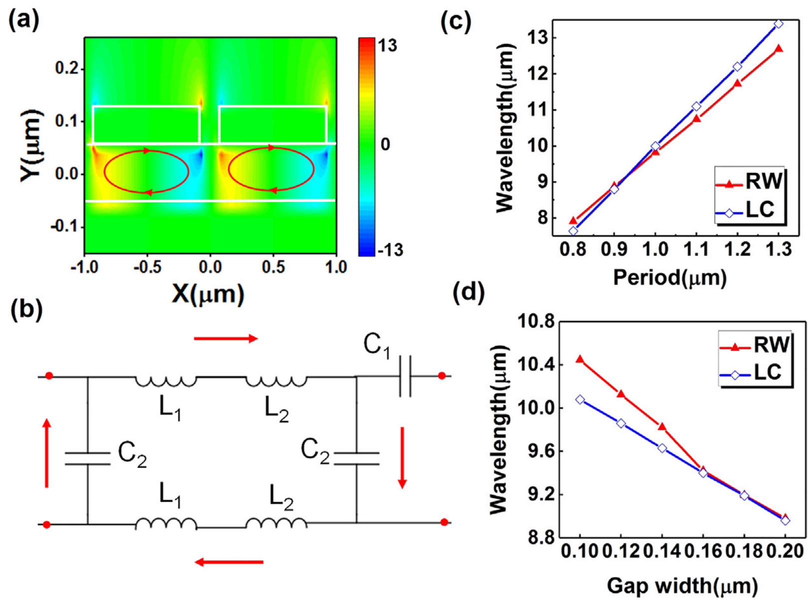

Fig. 6. (a) The y component of electric field for fundamental mode under TM polarization light radiation. (b) Equivalent LC circuit mode of plasmonic absorber unit cell for fundamental resonance mode. (c) Calculated resonance wavelengths of equivalent LC circuit mode and simulation resonance wavelengths with different periods and (d) gap widths . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

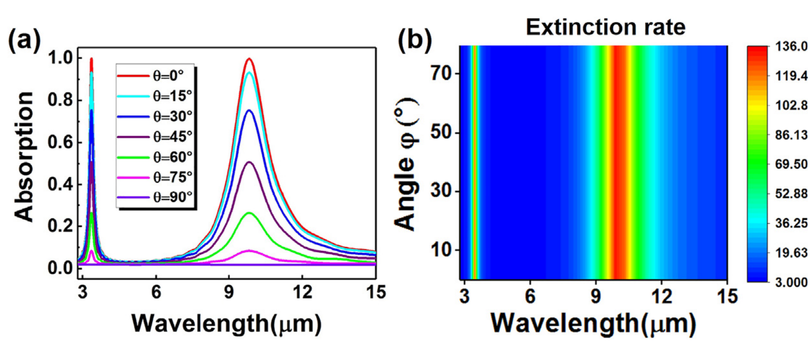

Fig. 7. (a) Absorptivity of the metamaterial structure according to different polarization angles. (b) Extinction rate as a function of incident angle in y–z plane and wavelength.

structure parameters, the response wavelength could be tuned over a broad spectral range. Moreover, the absorber was sensitive to the polarization angle of the incidence light and could keep robustness to oblique incidence. The extinction rate did not reduce when the incident angle was even as large as 80° and rate value kept above 130 for both peaks in infrared region. The proposed absorber could be utilized in a dual-band uncooled infrared polarization detector, which simplified the optical system design and avoided the polarization information reconstruction error caused by the misplacement between the polarizer and the pixel.

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