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Polarization controllable multispectral symmetry-breaking absorber in mid-infrared

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The versatility of mid-infrared metamaterial absorbers along with the ease of fabrication has been widely used in thermal imaging, molecule sensing, and many other applications. Controllable multi-spectral absorption is highly required for small footprint, multi-purpose, and real-time sensing applications. In this paper, we present the polarization control of interchangeable multispectral absorption based on the dual-band metamaterial absorber in split mode. Large modulation depth of absorption is obtained during multi-band transition through polarization control. We perform theoretical and numerical analysis to explain the results by formulating an equivalent circuit for the asymmetric cross resonator. Thermal controllability is also demonstrated to show the reversible and repeatable manipulation of absorption intensity at a given wavelength. Moreover, we characterized the limitation of this device under extreme high temperature. This work offers a design methodology for interchangeable multispectral metamaterial absorber from a new perspective by adopting polarization of incident light as a control mechanism, and this will open up possibilities for many valuable applications in the future. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4960347]

I. INTRODUCTION

Metamaterials are artificially engineered materials, which can enable exotic electromagnetic properties that do not exist in nature.¹ These artificial materials are usually constructed by arranging the subwavelength sized unit cells in a periodic array. The unit cell can be shaped into various patterns to achieve numerous electromagnetic properties, such as invisible cloaking,^{2,3} super lensing,^{4,5} slow light,^{6,7} perfect absorption,^{8–11} and many more at desired spectral range. Perfect absorber is one of the promising metamaterial devices and has attracted many attentions due to the potential applications especially in the mid-infrared regime, such as biomedical and gas sensing,^{10,12–17} thermal imaging,^{18,19} thermophotovoltaic energy harvesting,²⁰ and emitters.²¹ Metamaterial perfect absorber is primarily a metal-insulator-metal (MIM) structure, with continuous bottom metallic reflector, a middle dielectric layer, and top metamaterial metal layer. The thick bottom metal layer blocks light from transmission. The top metamaterial and spacer layers can be engineered to achieve specific values of permeability and permittivity to achieve impedance matching with the free space and this allows for reduced reflection of incident light.²² When the transmission and reflection are minimized at a specific wavelength, narrow band and near perfect absorption can be achieved.¹³ Such straightforward design approach enables advantageous performance, for instance, ultra-narrow band,²³ multispectral,^{24,25} and broadband absorption.^{26,27} The exotic structured metamaterial absorbers with innovative fabrication approach have also been studied to achieve enhanced performance.^{28,29}

Multispectral absorbers possess immense research interest, as they are widely exploited in thermal imaging, multi-gas monitoring, and biochemical sensing.^{14,18} The simplest form of multispectral absorber is the dual band absorber. Usually, dual band absorber designs are realized by one of the following approaches: (i) incorporating two independent resonators corresponding to each absorption wavelength into a single supercell,^{21,30–34} (ii) using two dielectric spacer materials with same metamaterial resonators,³³ (iii) breaking symmetry of resonator geometry,^{14,35–37} such as split ring resonators (SRRs)³⁶ and cross resonator.^{14,35} From the design principles of dual band absorbers, multispectral absorbers can be realized by scaling up the resonator numbers or increasing the dielectric materials in multi-MIM device configuration. However, these approaches demand for more footprint and complex fabrication processes. Alternatively, in the case of symmetry breaking approach, the dual band resonance comes into being due to the asymmetric distribution of resonance energy. This method takes better use of planar area resource and possesses noncomplex patterns with less stacked layers. Chen et al. reported the symmetry breaking in metamaterial absorbers for dual band response for a particular polarization of incident light.¹⁴ The spectral response of the dual band absorption peak was studied with respect to the offset of the symmetry breaking structure. This asymmetry offset defined as the distance of cut wire from the symmetric plays a vital role in creating dualband resonance. By changing this offset, the dual-band spectrum was adjusted accordingly; however, the length of the symmetry breaking structure has minimal influence on the dual band absorption characteristics.

In the study of influence of incident polarization, the dimension of the symmetry breaking structure becomes important. Polarization response on asymmetry metamaterial absorber enables not only resonance wavelength and intensity change38,39 but also interchangeable transition between the existing Eigen-resonances; in other words, control on the number of resonance bands. More specifically, by arbitrarily rotating the polarization angle of incident light, several Eigenresonances can switch from one to another freely and continuously. Therefore, we develop a design methodology for polarization-sensitive tunable metamaterial absorbers in the infrared region. By properly designing the cut wire length and asymmetry offset, the asymmetry metamaterial absorber is able to achieve mode transition among single-band, doubleband, and even multiple-band resonance as polarization angle of incident light switches for multispectral application purposes.

Active control of metamaterial absorbers has also been reported using electrical,^{34,40} thermal,^{41–43} strain,⁴⁴ and micro-electromechanical systems (MEMS)^{45,46} approaches to alter material property of the active medium incorporated in the metamaterial absorbers or to provide structural reconfiguration of the metamaterial absorber. Thermal control has been widely used to tune the material properties of active materials such as vanadium oxide^{41,43} and Ge₃Sb₂Te₆ (GST).⁴² To date, there are not many reports of thermal control or characterization of metamaterial absorber at room temperature behaves differently from elevated temperatures whereby the conductivity of the metallic structure is reduced to modulate the resonant absorption of metamaterial absorber across the entire spectral range.

In this paper, we explore the possibility of controlling the spectral response of a symmetry breaking resonator based metamaterial absorbers with respect to varying polarization of the incident mid infrared light. In the first part, we report the dual-band response with various asymmetry offsets and cut wire lengths. Fine polarization tuning is then performed on this peak-split absorber to achieve the interchangeable multispectral resonance transition. In addition, an equivalent circuit is modelled for the asymmetric cross absorber. Finally, we demonstrate an active control of this absorber using thermal stimulus and characterize its performance at high temperature up to 400 °C. We choose CMOS-compatible material for this absorber with the standard fabrication process which is ideal for mass production at low cost and high yield.

II. DESIGN AND FABRICATION

The cross metamaterial absorber consists of 200 nm thick ground molybdenum plane as a perfect reflector, which is much thicker than the skin depth in the mid-infrared spectral range. The sandwiched spacer layer is 150 nm thick aluminium oxide deposited by atomic layer deposition (ALD) process. The top layer is an array of molybdenum (Mo) metamaterial cross pattern fabricated by sputtering, photolithography, and etching. The total area for each device is $300 \,\mu\text{m}^2$, and area for metamaterial pattern is $205.2 \,\mu\text{m}^2$ with 57 by 57 unit cells. Wave propagation k at normal incidence has polarization angle of 90° when the electric field oscillates along y-axis as illustrated in Fig. 1(a). There are three device groups, A, B, and C, to be discussed in this paper. The detailed geometry differences among these devices are summarized in the table in Fig. 1(c). Except for these geometrical variations from cut wire length L1 and asymmetric offset Δ , the rest of geometric parameters remain the same: the pitch of the unit cell is $3.6 \,\mu\text{m}$, and the width W for both cross wires and length of L2 are 400 nm and $2.4 \,\mu\text{m}$, respectively.

In the experiments, the mid-infrared reflection spectra of each device are measured by Agilent Cary-620 Fourier transform infrared spectroscopy (FTIR). Since there is zero transmission (T%) due to the bottom ground metal which permits no light through the absorber, the absorption (A%) intensity is acquired by characterizing the reflection (R%) intensity, as A(%) = 100%-R(%). Polarization response is characterized in the far field spectroscopy by adding CaF₂ polarizer which is transparent over the mid-infrared region of interest.



FIG. 1. (a) The schematic of metamaterial absorber. The highlighted unit cell is extracted with the annotation of asymmetry offset Δ . The incident light with propagation k, E-field, and H-field is shown above the device. The E-field along the x-axis is defined as 0° polarization. (b) SEM photo of Device A3. The horizontal and vertical cross wire lengths are denoted as L1 and L2. They are in the same width W. The pitch of periodic cross array pattern is equal in both x and y axes. (c) The two tables show the specific geometrical parameters of each device. Device groups A, B, and C differ in L1 length. Each device belonging to the same group has different asymmetry offsets.

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Temperature control is carried out by placing the sample on the heating stage in a closed chamber. The heater is equipped with water circulator for stabilizing the target temperature.

III. RESULTS AND DISCUSSION

A. Peak-split dual-band resonance of geometric asymmetry

Devices A1–A4 have the same cut wire length of 2400 nm but different asymmetry offsets. A1, with symmetric cross, is the initial state. From the absorption spectra in Fig. 2(a) for A1 to A4, we can clearly observe the continuous evolution from a single absorption peak to two separated peaks moving towards the opposite direction as the asymmetry increases. Furthermore, the absorption intensity reduces as the asymmetry offset is increased. An exception occurs at the shorter resonance wavelength of A2 where its absorption intensity is lower than A3, not obeying the trend. Interestingly, this exceptional case has been reproduced by simulation. The incident light polarized at 90° with E-field oscillating along wire L2 enables current circulation looping through this metallic wire and bottom metal reflector, with most of the power concentrated within the dielectric spacer. When the cut wire is no longer located at the center, the single cut wire L2 will behave as two asymmetric wires of lengths L2' and L2'', where L2 = L2' + L2''. The current circulation occurs at the asymmetric parts of cut wire L2 and thus generates two oscillation frequencies corresponding to two asymmetric wire lengths. The simulated magnetic field distributions provide solid proofs for this explanation. In Figs. 2(d) and 2(e), the left and right columns depict H-field profiles in x-y and x-z cross sections at A1's single absorption peak and A3's two absorption peaks frequencies. It can be clearly seen that there are two equally distributed magnetic fields in A1, producing the same surface current circulations along the equal effective length, i.e., half of the metallic wire L2. In other words, the absorption due to the two symmetric half wires of L2 occurs at the same frequency and hence a single absorption peak is attained. Unlike this case, the magnetic field of asymmetric cross resonator has been divided into two unequal parts by the cut wire, so there are two absorption bands as shown in Fig. 2(a). It is well known that this type of resonance in metamaterial absorber is the magnetic polariton (MP) resonance. Since the MP resonance power is not concentrated in one location any more, instead is migrated to the two parts of wire L2, and the absorption intensity of asymmetry split MP modes decreases.



FIG. 2. (a) Asymmetry offset effect: FTIR measured absorption spectra of device A1–A4 at 90° polarization angle. (b) Cut wire length effect: FTIR measured absorption spectra of device A1, A3, B1, B2, C1, and C2 at 90° polarization angle. The red, blue, and green colored boxes indicate MP resonances from asymmetry and symmetry cross resonators. (c) FDTD simulation absorption spectra of device A1–A3, B2, and C2 at 90° polarization angle. (d) and (e) Left column: x–y cross section of simulated H-field distribution for devices A1 at 7.56 μ m, A3 at 5.68 μ m, and 8.23 μ m. Right column: x–z cross section of simulated H-field distributions, respectively.

Chen et al. have reported that the absorption peak wavelength is proportional to the effective metallic wire length and this relationship is consistent with our observations.¹⁴ However, in the x-y cross section of H-field, it is observed that the cut wire is also involved in MP resonance besides the metal wire with effective length L2. In order to know how the cut wire length influences MP resonance in this absorber, the absorption spectra of devices B and C with cut wire length of 2800 nm and 3200 nm are studied. In Fig. 2(b), the symmetric A1, B1, and C1 have slight resonance wavelength shift and intensity change. However, the spectra of different cut wire lengths display distinguishable resonance wavelength shifts under the asymmetry offset of 400 nm. The longer cut wire length results in the larger resonance wavelength. The 400 nm cut wire length variation contributes to the average wavelength shift of 417.76 nm for MP resonances in the shorter wavelength region and 197.27 nm for MP resonances in the longer wavelength region.

In Fig. 2(c), the Finite-difference time-domain (FDTD) simulation results show the same trend as experimental results in terms of the asymmetry offsets and cut wire lengths, however with slight mismatches of the resonance wavelength values and peak absorption intensities. The possible reasons for this discrepancy between simulated and measured data could be caused due to the following reasons: first, simulations run based on the assumption of normal incidence; however, the approximated oblique angle of 45° is used in the FTIR reflection measurement. Second, micromachining process cannot guarantee the exact same shape as the desired design. As we can see from scanning electron

microscope (SEM) image, the sharp corners in cross pattern become rounded due to limitations in the photolithography and etching processes. This geometrical imperfection leads to a lower Q-factor due to the weak capability of rounded corner in electric field and power confinement at resonance frequency. The Palik models for Mo and Al₂O₃ employed in simulation is reliable,^{47,48} but the fabrication condition may bring in the slight difference to the permittivity, causing the deviation of resonance wavelength.

To gain more insight into the cut wire effect, we refer to the surface current profiles plotted in Figs. 3(a)-3(c) for A1 and A3 at a polarization angle of 90°. The bold arrow indicates the current flow in the interface of the metallic wire as the main excitation and normal arrow indicates that of cut wire as the subordinate portion. It can be noticed that the shortcut taken by surface current flow in the bottom metal sheet interface intends to be a straight path that forms the triangle-shaped closed loop. This bottom current path is highlighted in the dotted-outlined arrows. Equivalent resistor-inductor-capacitor (RLC) circuit is a simplified model and is adopted here to numerically predict the electromagnetic behavior of light-electron interaction in these metamaterial resonators. The conventional equivalent RLC circuit has been explored, $^{49-53}$ to model simple resonator patterns, such as square, rod, and L-shape. Based on the previous works, the equivalent RLC circuit for cross absorber is upgraded into three-dimensional configuration by considering the cut wire effect as shown in Fig. 3(d). The inset is the simplified equivalent circuit model. The surface current routes are traced and electrical components with the



FIG. 3. (a) Surface current of symmetry absorber at resonance wavelength of 7.56 μ m at 90° polarization angle. (b) and (c) Surface current of asymmetry absorber at two resonance wavelengths of 8.23 μ m and 5.68 μ m at 90° polarization angle. (d) Equivalent RLC circuit model of asymmetry cross absorber A3 at 90° polarization angle. The inset shows the simplified circuit for resonance wavelength calculation.

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calculated values are introduced to mimic the real situation. In particular, $R_{1,t}$, $L_{1,t}$, and $L_{m1,t}$ are the resistance, kinetic inductance, and the mutual inductance (from two parallel metallic rod and plate separated by spacer) of the effective part from metal wire L2; $R_{c,t}$, $L_{c,t}$, and $L_{mc,t}$ are those of effective part of cut wire; and R_b , L_b , and $L_{m,b}$ are those of bottom metal reflector. The resistance and kinetic inductance from two metal wires of the same width w on the top layer are written as $R_t = R_{1,t} + R_{c,t} = \frac{l'_1 + l'_2}{\delta \cdot \omega \cdot w \cdot \varepsilon_0} \left(\frac{\varepsilon''}{\varepsilon'^2 + \varepsilon''^2}\right)$ and $L_t = L_{1,t}$ $+L_{c,t} = -\frac{l'_1+l'_2}{\delta\cdot\omega^2\cdot w\cdot\varepsilon_0} \left(\frac{\varepsilon'}{\varepsilon'^2+\varepsilon''^2}\right)$ where ε_0 denotes the vacuum permittivity, δ is the effective penetration depth, ε' and ε'' are the real and imaginary parts of Mo permittivity, and ω is the angular frequency of incident light. In this model, the influences of top cross right-angled bend capacitance and inductance are neglected, as well as the ones between the neighboring unit cells. The mutual capacitance and inductance are the integrals of the effective displacements d_1 and d_2 along the two effective metal wires on top layer, in the way that top metal wires project on the triangle edge. This is because the cut wire induced triangle closed loop forces the effective displacement between top and bottom metal layer no longer equal to the thickness of Al_2O_3 spacer d. Hence, we have the mutual capacitance $C_m = \frac{2\beta\epsilon_0\epsilon_dwl}{d} = \int_0^{l'_1} \frac{2\beta\epsilon_0\epsilon_dw}{d_1} dx_1$ $+ \int_0^{l_2} \frac{2\beta\epsilon_0\epsilon_d w}{dz} dx_2$ ($0 \ll x_1 \ll l_1', 0 \ll x_2 \ll l_2'$) where ϵ_d is the dielectric constant of Al₂O₃ and β is the factor to characterize the capacitor's surface non-uniform charge distribution. The first term is the cut wire part with the effective length of l'_1 , value of $\frac{L_1}{2}$ and the second term is the wire L2 part with the effective length of l'_2 . We have the relationship of $d_1 = \sqrt{d^2 + (l'_1 - x_1)^2 \cdot \sin^2\theta}$ and $d_2 = \sqrt{d^2 + (l'_2 - x_2)^2 \cdot \cos^2\theta}$ where $\sin \theta = \frac{l'_1}{\sqrt{l'_1^2 + l'_2^2}}$. Similarly, $L_m = \frac{\mu_0 dl}{2w} = \int_0^{l'_1} \frac{\mu_0 d_1}{2w} dx_1 + \int_0^{l'_2} \frac{\mu_0 d_2}{2w} dx_2 (0 \ll x_1 \ll l'_1, 0 \ll x_2 \ll l'_2)$, where μ_0 denotes the vacuum permeability

$$Z_{total} = R_t + R_b + \frac{1}{i\omega C_m} + i\omega(L_t + L_b) + 2i\omega L_m, \quad (1)$$

$$\lambda_r = 2\pi c \cdot C_m \cdot \sqrt{2L_m + L_t + L_b}.$$
 (2)

The total impedance is expressed as in Equation (1). The resonance wavelength λ_r can be obtained when nullifying the imaginary part of the total impedance, expressed as Equation (2) in which *c* is the speed of light in vacuum. Based on this equation, the resonance wavelengths are calculated to be 5.7310 μ m and 8.1763 μ m for A3 at 90° polarization incidence.

B. Polarization control of interchangeable multispectral resonance

Polarization control of the asymmetric cross-shaped metamaterial absorber unleashes a tremendous potential of asymmetric resonators as the building blocks for mid-infrared multispectral sensing. Fig. 4(a) is the FTIR



FIG. 4. (a) FTIR measured absorption spectra of device A3 at polarization angles from 0° to 90° . The red, blue, and green boxes indicate the three MP resonance modes of different polarization angles. (b) FDTD simulated absorption spectra of device A3 at polarization angles from 0° to 90° . (c) The absorption peak intensity variation of three MP resonances as a function of polarization angle for both simulated and experimental results. The peak absorption at 7.01 μ m, 5.11 μ m, and 7.87 μ m for measured data is in solid line and symbol. 7.45 μ m, 5.68 μ m, and 8.23 μ m are simulation results in dashed line and half-filled symbol. (d) The resonance wavelength distributions of devices A2, B2, and C2. The inset describes FTIR measured absorption spectra of device B2 under polarization control.

measured absorption spectra of device A3 with 400 nm asymmetry offset under varying polarization angle from 0° to 90°. As the polarization of the incident light is varied, the absorption resonances experiences interchangeable transition with respect to the numbers of absorption bands. At 0° polarization incidence, a single absorption peak appears at 7.01 μ m, while two absorption peaks are observed at 5.11 μ m and 7.87 μ m at 90° polarization incidence. More interestingly, within this polarization range, the occurrence of three peaks manifests the multispectral capability of this absorber from 60° to 80° . In addition, under the continuous polarization manipulation over a full 360° angle, the MP resonance can exhibit repeatable interchangeable transition. The simulated result shown in Fig. 4(b) clearly illustrates the polarization controlled interchangeable resonance band transition of the asymmetric cross metamaterial absorber. This set of spectra delineates the creation and suppression of each resonance band with the obvious multispectral emerging from 20° to 70° . For convenience, the three resonance bands are marked by colored boxes in red, blue, and green and named as MP1, MP2, and MP3 in Figs. 4(a) and 4(b). The polarization response of interchangeable multispectral transition is validated by both experimental and simulated results. Next, we analyze this transitional response quantitatively.

Fig. 4(c) shows the peak absorption variation for all three MP resonances in the process of polarization modulation. The solid and dashed lines represent the experimental and simulated results, respectively. The simulated results with steeper slopes present a stronger modulation. Since the ideal case ruled out the imperfection by micro-fabrication techniques and surrounding interference in testing environment. These variations lead to more curved trends in the measured results and are not very linear. But the linear portion still can be extracted from 30° to 90°. Thereby, the modulation rate of absorption peak intensity as the function of polarization angle is $|11.72\%-54.08\%|/|90^{\circ}-30^{\circ}|$ $=7.06\%/10^{\circ}$ for MP2 at 7.01 μ m. Similarly, MP1 at 5.11 μ m and MP3 at 7.87 μ m have polarization modulation depth of 3.10%/10° and 4.59%/10°. MP2 has larger modulation rate than MP1 and MP3. Absorption peak intensity modulation depth for MP2 is |51.09%-11.72%|/51.09% = 77.06%. MP1 and MP3 have modulation depth of 75.14%and 70.68%, respectively.

The cut wire lengths and asymmetry offsets should be specifically tailored to fulfill the prerequisite geometrical condition where the distinctive resonance band transition can be achieved by polarization control. In Fig. 4(d), three devices with different cut wire lengths and same asymmetry offset reveal their resonance wavelength location. Device A3 has balanced MP resonance wavelengths distribution; while for B2 and C2, the peak absorption wavelengths of MP2 and MP3 are too close. As a result, device B2 has no polarization-dependent multispectral performance as shown in the inset of Fig. 4(d) where the blue and green boxes are overlapped. Consequently, A3 is the best design showing good characteristic of distinguishable polarization controlled multispectral transition. Fig. 5(a) shows the simulated surface profile of the absorption intensity over the mid-infrared wavelength range of 4.5–9 μ m as a function of polarization angle change, which sweeps from 0° to 90° in step of 5°. We can clearly follow the multispectral transition, and easily identify the multispectral range regarding polarization angle from this surface profile. The horizontal dotted line represents the absorption intensity at polarization angle of 60°, within the multispectral range. For 60° polarization angle of interest, the magnetic field distributions in x–y and y–z cross sections are shown in Figs. 5(b)–5(d). The three concurrently occurring MP resonances correspond to three coupling modes between resonator and incoming electromagnetic field. MP1 and MP3 are the two Eigen-resonance modes of asymmetry geometry, while MP2 is the Eigen-resonance mode of the cut wire.

The electric field E of polarization angle at 60° has equal x-component E' and y-component E'. From the surface current profile of Figs. 5(e)-5(g), MP2 resonance is generated by the x-component E' which stands for the 0° polarization situation. MP1 and MP3 are ascribed to y-component E' which is consistent with the 90° polarization situation. Therefore, the aforementioned Eigen-resonance modes determine the multispectral resonance band location in the spectrum, upon which the absorption peak intensities vary with the x- and y-components of electric field. Furthermore, the location of the multispectral resonance at any polarization angle can be predicted by calculating the Eigen-modes from the equivalent circuit model in Sec. III A.

C. Characterization of thermal manipulation on multi-band resonances

As a mean of active control, thermal stimulus was explored within the safe operation range of metamaterial absorber to guaranteed an effective tuning means without adversely affecting the fabricated devices. It is found that heater temperature cannot be above 200 °C, otherwise the sign of failure gradually appears after several rounds of heating. In order to characterize thermal effect on multi-band resonance, Device A3 at polarization of 70° is selected as the study sample. Fig. 6(a) shows the absorption spectra of A3 in the heating and cooling experiments. It can be found that the absorption intensity keeps increasing as the temperature is increased. The increase in absorption peak intensities for all three resonance bands are implied by arrows pointing upwards. From 50 °C to 200 °C, MP1, MP2, and MP3 resonances have experienced absorption peak intensity increase by 3.24%, 3.57%, and 2.47%, with the modulation depth of 25.89%, 12.90%, and 10.98%. In the cooling process from 200 °C to 50 °C, the absorption peak intensities of these three bands decline by 1.49%, 0.32%, and 0.75%, with the modulation depth of 9.46%, 1.13%, and 2.99%, respectively. This cooling process has weaker modulation capability compared to heating process. Although the cooling-down the devices cannot provide a completed recovery, this thermal process can still be considered as a repeatable and reversible modulation method. Hence, we continue carrying out three more cycles of temperature testing to characterize the thermal control of multispectral resonance. In Fig. 6(b), the absorption



FIG. 5. (a) FDTD simulated absorption surface profile at polarization angle from 0° to 90°. (b)–(d) FDTD simulated H-field distribution of MP1, MP2, and MP3 resonances at polarization angle of 60°. The top row is x–y cross section and bottom row is x–y cross section. The white outlines describe the top wire, spacer layer, and bottom layer of metamaterial absorber. (e)–(g) Surface current profiles of polarization angle at 60° at resonance wavelength of 5.68 μ m, 7.45 μ m, and 8.23 μ m.

peaks of three MP resonances exhibit the expected change for four testing cycles. In each cycle, the device was heated up to 200 °C and then cooled down, in 50 °C steps. To ensure accuracy, the heater was stabilized for at least five minutes before each measurement. MP1 and MP3 experienced better modulation pattern of reversible variation than MP2. The overall trend remains similar for all three modes in the experiments within acceptable error tolerance. The reason for the thermal induced absorption change can be explained by the thermally modulated material properties of the constituent layers. Lossy metal in infrared region can be described by the Drude model with metal permittivity written as $\varepsilon = 1 - \frac{\omega_p^2}{i\omega\gamma + \omega^2}$, where ω_p is the plasma frequency and γ is the damping factor. At high temperatures, the electron random scattering in metal layer becomes stronger; hence, the value of damping factor γ is larger. In this case, the real part of Mo permittivity is decreased which results in the reduced conductivity of Mo. Simultaneously, the imaginary part of Mo permittivity is increased which contributes to metal absorption. Also, the line width broadening and absorption profile flattening can be attributed to the increase in the imaginary part $\text{Im}(\epsilon)$ of Mo.⁵⁴

Because the observation of accumulated effect from heating in this device is always evident, we may infer that the device could be led to a final failure after going through the heating cycles for several times. To facilitate this process, the temperature is raised up to 400 °C in step of 100 °C for three cycles. Each cycle took approximately three hours and the recess period between two rounds was more than 12 h to ensure that the device has been fully cool down. In the end, nearly all of the resonances are found to be disappeared. Figs. 6(c) and 6(e) and Figs. 6(d) and 6(f) are the atomic force microscope (AFM) and SEM images before and after the high temperature testing trials. The AFM image of the top metallic layer in (c) shows the formation of small isolated islands on the Mo surface due to the sputtering deposition. After high temperature treatments, the island-topology has been transformed into the rough surface. In SEM images, the comparison between the original smooth metallic cross structure and the severe damaged surface provides the



FIG. 6. (a) FTIR measured absorption spectra of device A3 at 70° polarization while heating up from 50°C to $200\,^\circ\text{C}.$ The resonance bands from left to right are labelled as MP1, MP2, and MP3. The arrow reveals temperature modulation direction. The inset shows the measured spectra during cooling process from 200 °C to 50 °C. (b) The peak absorption variation of the three MP resonance bands of device A3 in a four-cycles temperature testing. (c) and (d) AFM and SEM images of the metal layer and unit cell of device A3 before heating up to $400 \,^{\circ}$ C. (e) and (f) AFM and SEM images of the metal layer and unit cell of device A3 after heating up to 400 °C for three times.

evidences related to structural deformation based failure at extreme high temperature.

IV. CONCLUSION

In summary, we have experimentally demonstrated the viability to control the multispectral absorption transition by polarization manipulation of the asymmetric cross metamaterial absorber in mid-infrared spectral region. Appropriate geometry has been designed where dual-band resonance is distinguished from the single peak, thus the significant modulation depth of 77% is obtained. We simulated magnetic field and surface current distribution to elucidate the underlying mechanism, and the equivalent circuit is established to predict the resonance wavelength. In addition, the thermal active control exhibits reversible and repeatable maximum absorption tunable behaviour. Finally, the performance of this absorber is characterized and pushed to its limit until failure under extreme temperature. This thorough study of polarizationcontrollable mid-infrared absorber and this design method will be beneficial in many research and application fields, such as multispectral sensing, mid-infrared imaging, and photovoltaic solar cells.

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