



Reconfigurable broadband metasurface with switchable functionalities in the visible range

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Abstract: In this article, we propose a broadband reconfigurable multifunctional meta-structure for the first time in the visible range. This device can be reconfigured between an achromatic metalens and a broadband absorber by switching the state of the phase change material (VO₂). Our designed VO₂ based novel multistage meta-atoms helped us overcome the inherent limitation of small optical contrast between PCM states in the visible regime, which hinders the realization of reconfigurable multifunctional devices in this band. We have used the finite-difference time-domain (FDTD) technique to characterize the designed multifunctional device. The structure showed a maximum switching ratio of 21.1dB between the on and off states in the operating band of 678nm to 795nm, the highest among previously reported broadband metalens-absorber systems in any design band. A small focal length shift within $\pm 5\%$ in the on state within this spectral band verifies the achromatic focusing characteristics of our reconfigurable meta-device. Our device proves the feasibility of reconfigurable metasurfaces with switchable functionalities in the visible band and has the prospects to bring about a revolution in next-generation integrated photonic platforms.

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1. Introduction

Metasurfaces, the two-dimensional analog of metamaterials [1], have attracted immense interest from the scientific community over the last two decades for their unique capability of controlling and manipulating light. Based on this distinctive feature of metasurfaces, several meta-devices like metalens [2,3], absorber [4,5], invisible cloak [6], beam steering [7], holography [8,9], nano-lasers [10], color displays [11] have been developed. But with the ever-increasing demand for miniaturization and integration in complex systems, there has been a growing interest in combining several of these functionalities into a single metasurface.

Several works involving multifunctional metasurfaces have been reported in recent years for the IR and microwave regime [12–17]. These devices utilize phase change materials (PCM), graphene, varactor diode, PIN diode, and micro-electromechanical system (MEMS) for switching between different functionalities. Among these approaches PCMs like vanadium dioxide (VO₂), Ge₂Sb₂Te₅ (GST), Ge₂Sb₂Se₄Te₁ (GSST) provide the most viable path to commercialization of reconfigurable, multifunctional meta-devices due to their repeatable, fast, and reversible switching, notable contrast in optical properties of the two states, and chemical stability [18–20]. VO₂ has emerged as a lower power-consuming alternative to other PCMs [21]. Thermal, optical, or electrical stimuli can cause VO₂ to switch from an insulating to a metallic state [22]. This ultrafast phase transition with a picosecond timescale [23] at a relatively low temperature of 68°C [24] and significant dissimilarity in optical properties of the two states [25] makes VO₂ a suitable candidate for broadband switchable meta-device design in the IR and microwave range [12,26,27]. But the relatively small variation in refractive index for the two states of VO₂ and PCMs in general in the visible regime, however, makes broadband switchable characteristics difficult to realize. There have been reports of metasurfaces with switchable functionality in

the visible range [28–32]. But the switching is based on the incident light polarization, and these devices offer very similar functionalities. To the best of our knowledge, a reconfigurable metasurface with diversified functionalities in the visible spectrum has not yet been reported.

In this paper, we propose a broadband reconfigurable metasurface that can be switched between an achromatic metalens and a near-perfect broadband absorber in the visible portion of the EM spectrum by exciting phase transition of VO₂. There have been reports of metasurfaces with VO₂ sandwiched between two dielectric layers [33–35]. These devices utilize the metal-insulator phase transition of VO₂ to alter the optical cavity length, producing tunable optical characteristics in the IR regime. However, they have been unable to extend the operating band to the visible regime due to the small optical contrast between the two states of the phase change material. In this work, we have designed a broadband switchable absorber in the visible range as the unit cell of our dual-functional device taking advantage of this cavity length modulation scheme. The multistage structure of our meta-atom has allowed us to enhance the additional Fabry-Perot cavity mode induced in the metallic state of VO₂ due to the small contrast between the two states. The cell has near-perfect absorption in the metallic phase and good reflection characteristics in the insulating phase of VO₂ in the 689.3–774.6nm band. This is an unprecedented absorption characteristic in the visible range compared to absorption peak tuning demonstrated in previous PCM-based absorber structures [36–39]. We utilize this broadband switchable absorber as a constituent meta-atom for our multifunctional meta-device, which acts as an achromatic metalens and a broadband absorber in the visible range for the insulating (on) and metallic (off) state of VO₂, respectively. The device shows a normalized focal length shift within $\pm 4\%$ in the on state, along with a switching ratio between 9dB and 12.1dB within the switchable absorption band of 689.3–774.6nm. This broadband reconfigurable multifunctionality of our designed metasurface extends over the 678nm to 795nm band quantified by a small focal length shift of 9.48% in the on state and a maximum contrast of 21.1dB between the on and off states within this operating band. This broadband metalens-absorber system has the highest switching ratio among those previously reported for any design band [32,40–42]. This kind of dual-functional meta-device may find wide range of applications in smart bioimaging due to its dose-sensitive, ultrafast switching capability. This work will open new horizons for miniaturized integrated photonic devices in visible range by paving the way for reconfigurable multifunctional devices.

2. Unit cell structural layout

Our reconfigurable multifunctional metasurface is designed based on switchable absorber meta-atoms. Figure 1 illustrates the structural layout of the designed meta-unit. The unit cell is constructed from three stages, each of which consists of a thin VO₂ sheet placed between two Silicon Carbide (SiC) layers. A thick layer of Silver is used as the substrate of this structure to minimize the transmission through the substrate. The substrate thickness (h) has been chosen accordingly. The previous works in Ref. [43–46] show the feasibility of the practical realization of such a structure. However, the hands-on fabrication of the proposed absorber cell is beyond the extent of this work.

We have numerically investigated switchable absorption characteristics of the meta-atom by FDTD method using the commercial software Lumerical FDTD Solutions. In the simulation environment, an x-polarized plane wave source propagating along the negative y direction illuminates the unit cell as depicted in Fig. 1(b) by the directions of electric field vector (E) and propagation vector (k) respectively. The structural parameters of the unit cell shown in Fig. 1(b) have been varied in the FDTD simulation to achieve the optimum bandwidth and modulation depth of the absorption characteristics. The reflection (R) from a single cell was calculated by a 2d frequency domain power monitor. Since the transmission through the thick Ag layer is negligible, the absorption of the structure is given by $A = 1 - R$. The simulation setup contains periodic and perfectly matched layer (PML) boundary conditions in the longitudinal (x) and transverse

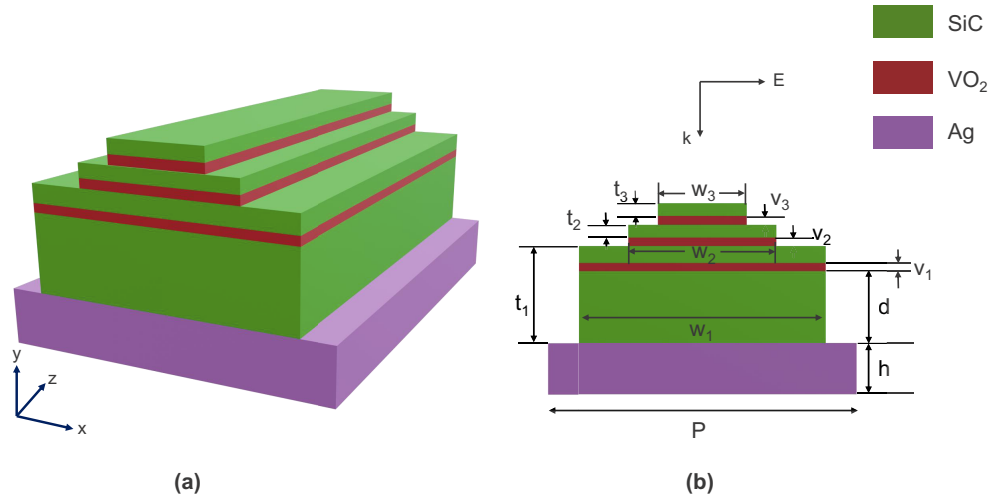


Fig. 1. The (a) 3D schematic and (b) x-y plane cross-sectional view of our proposed broadband switchable absorber unit with different structural parameters marked. P is the periodicity of the unit cell, while the thickness of the substrate is marked as h . The cavity length, width, and VO_2 layer thickness of the i th stage are represented by t_i , w_i , and v_i respectively with $i=1,2$, and 3. d marks the position of the VO_2 layer above the substrate in the lowest stage.

(y) directions, respectively. We have used the experimentally obtained optical properties of the insulating and metallic phases of VO_2 reported by Dicken et al. [25] in our numerical model. For refractive indices of Ag and 6H-SiC, the Palik model [47] and Ref. [48] has been used, respectively. Further details regarding the optical constants of different materials, along with their extracted values from these references, can be found in Fig. S1 of the Supplemental Document.

3. Absorption characteristics of the unit cell

The contrast in absorption characteristic of our designed unit cell at the on (VO_2 in the insulating phase) and off (VO_2 in the metallic phase) states, is depicted in Fig. 2. The absorption spectrum for the insulating phase shows two narrow peaks at 669nm (Mode 1) and 815nm (Mode 3). In the metallic phase, another peak becomes prominent at 786nm (Mode 2) as marked in Fig. 2. The emergence of an additional peak in the metallic state results in a broadband absorption spectrum under external stimulus. Here, Modes 1, 2, and 3 refer to the three different resonant wavelengths in the absorption spectrum, a terminology used in a similar sense in earlier works [49].

The blue-shaded region in Fig. 2 from 689.3nm to 774.6nm represents the region throughout which there is an absorption above 90% in the off state and below 50% in the on state and is termed as the switchable absorption band of our standard unit cell. This 85.3nm band shows broadband "on-off" switching characteristics between the two phases of the PCM in the real sense, compared to simple absorption peak shifting in previously reported works for the visible regime [36–39]. We chose the absorption threshold for the off-state to ensure a near-perfect broadband absorption. The threshold for the maximum allowed absorption for the on state was determined, keeping in mind the final design goal which is reflection mode achromatic focusing in the insulating phase of VO_2 . The specific value of minimum reflection (50%) for the on state of the standard cell of Fig. 2 within the band is based on previous relevant works on tunable metalens and multifunctional meta-devices, where a much lower reflection (or transmission) efficiency of constituent unit cells produced satisfactory focusing performance [50–52]. We have used a much higher threshold (50%) for minimum reflection from the standard unit cell in the on

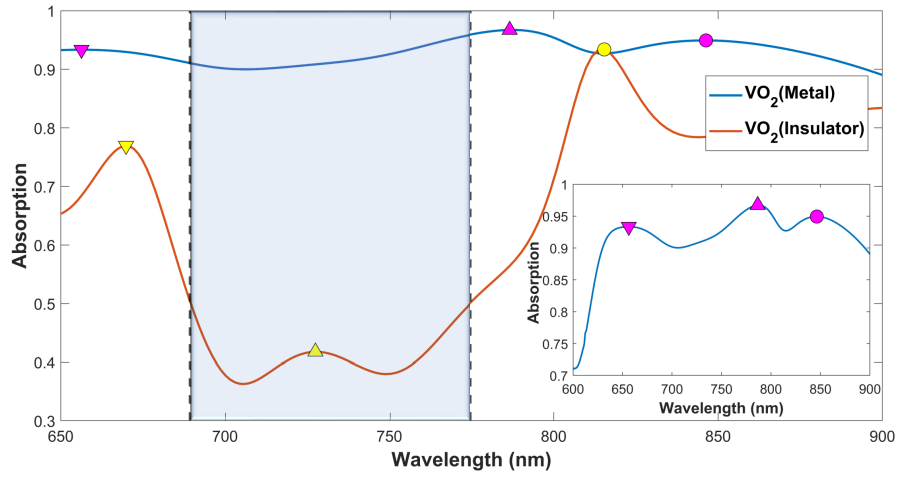


Fig. 2. The absorption spectra of the unit cell for the metallic and insulating phases of the VO₂ layer with $P=600\text{nm}$, $h=100\text{nm}$, $w_1=480\text{nm}$, $w_2=288\text{nm}$, $w_3=172.8\text{nm}$, $d=140\text{nm}$, $v_1=v_2=v_3=17\text{nm}$, and $t_1=190\text{nm}$, $t_2=t_3=24.75\text{nm}$. The shaded region represents the switchable region with absorption greater than 90% for the metallic state and less than 50% for the insulating state. The inset gives an enlarged view of the absorption curve at the off state (metallic phase of VO₂). The symbols ∇ , Δ , and $\circ$ represent the positions of Modes 1, 2, and 3, respectively. Mode 2 in the insulating state is extremely weak and will not be further investigated.

state compared to these previous reports, providing us with enough flexibility to choose the rest of the constituent meta-atoms of our reconfigurable metasurface.

To further investigate the origin of this broadband switchable absorption characteristics, we have simulated the spatial electric field profiles of the unit cells in both the on (insulating) and off (metallic) states, as shown in Fig. 3. For the field profiles, we have used the standard structure as in Fig. 2. The Mode numbers for metallic and insulating states have been assigned based on the similarity of the electric field distribution profiles. The field profiles for the insulating and metallic states in Mode 3 appear to be different, unlike Mode 1, though the salient features are very similar, as shown in Fig. 3(b) and (e), respectively. This visual mismatch is caused by the unusually high field concentration around the VO₂ edges in the upper stages of the unit cell that shifts the color bar scale upwards in the metallic state. This is caused by the dominance of the upper stages of the structure to the neighboring cell coupling and will be discussed in detail later in this section. To validate our observations from the field distribution, we have also studied the impact of different structural parameters on the absorption spectrum depicted in Fig. 4, 5, and 6. When varying one of the parameters, the others have been kept constant at their standard values.

For Mode 1, the electric field is concentrated around the Ag substrate and the SiC spacer for the insulating state (Fig. 3(a)), indicating the contribution of a Fabry-Perot (FP) cavity mode. The similarity of SiC and VO₂ refractive indices at room temperature (insulating state) means that a continuous cavity is formed between the substrate and the upper stage SiC-air interface with a cavity length of $t_1 + t_2 + t_3$. This FP cavity length is directly proportional to the resonant wavelength [53], which causes the redshift of Mode 1 position with increasing t_1 , t_2 , and t_3 in Fig. 4(a-c) respectively. Also, the insensitivity of Mode 1 on lower VO₂ layer position (d) (Fig. 5(a)) further indicates the formation of a continuous cavity in the insulating state. The red shift of this resonant wavelength with cavity widths (w_1 , w_2 , w_3) in Fig. 5(c), 6(a), and (b) is also consistent with previously reported observations [54,55] for FP resonance. The metallic state shows strong field concentration around the VO₂ layers and the corresponding spacer (SiC)

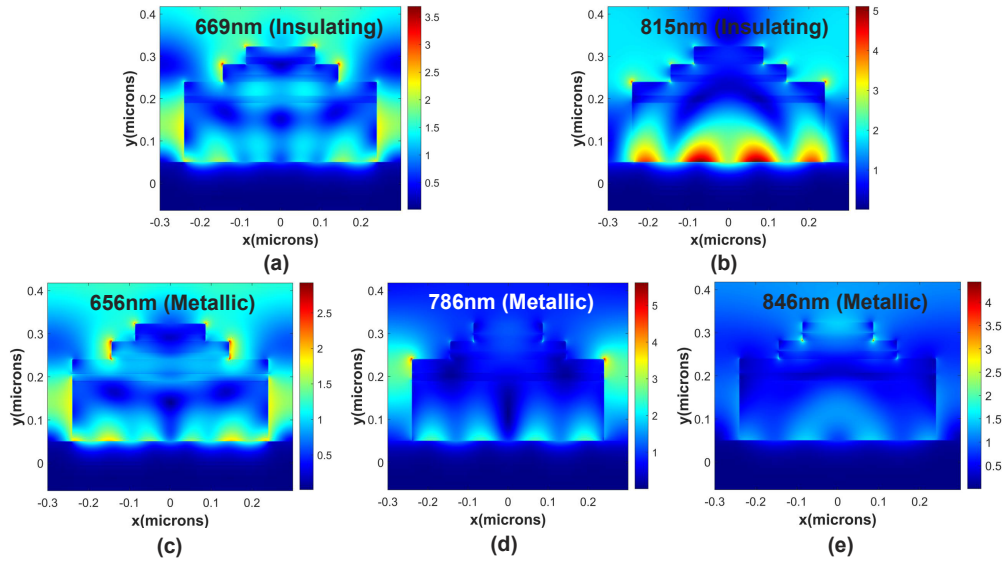


Fig. 3. The spatial electrical field distribution of the unit cell in the x-y plane for (a-b) Mode 1 and 2 in the insulating state and (c-e) Mode 1,2, and 3 in the metallic phase of VO_2 . The magnitude values of the total electric field have been normalized by the incident field magnitude.

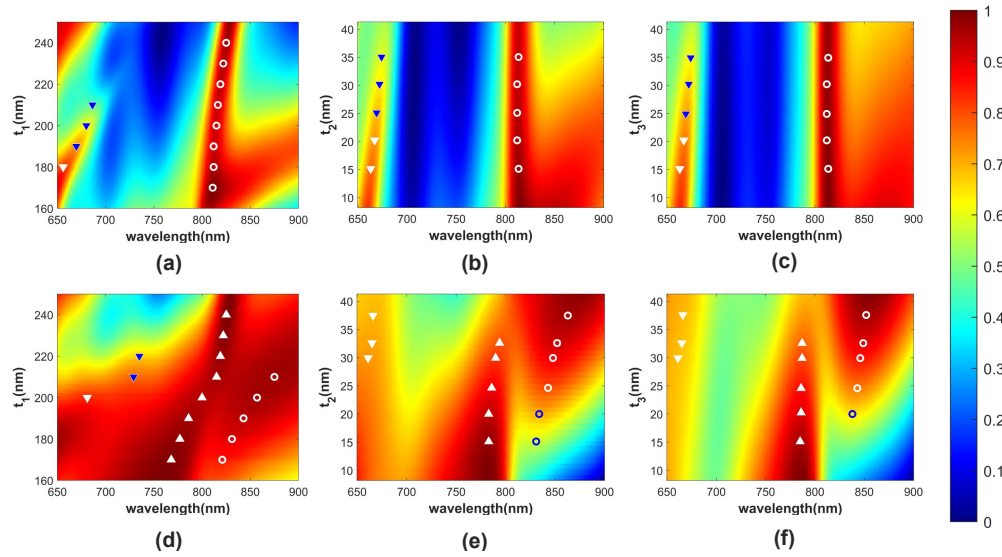


Fig. 4. Absorption color maps as a function of wavelength and t_1 , t_2 , t_3 for (a-c) insulating and (d-f) metallic VO_2 , respectively. The symbols ∇ , Δ , and $\circ$ represent the shifting of Modes 1, 2, and 3 resonant peaks, respectively.

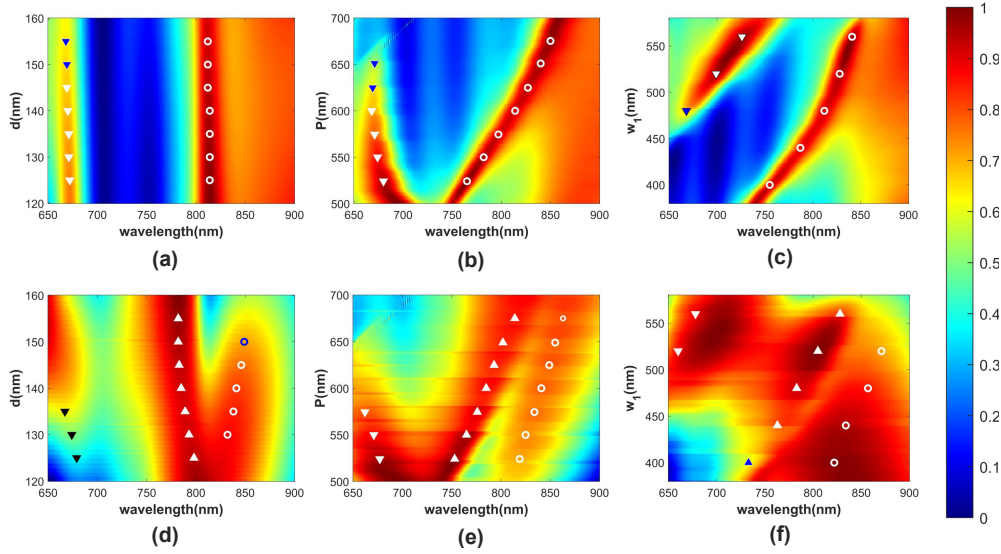


Fig. 5. Absorption color maps as a function of wavelength and d , P , and w_1 for (a-c) insulating and (d-f) metallic VO₂, respectively. The symbols ∇ , Δ , and $\circ$ represent the absorption peak variation paths for Modes 1, 2, and 3, respectively.

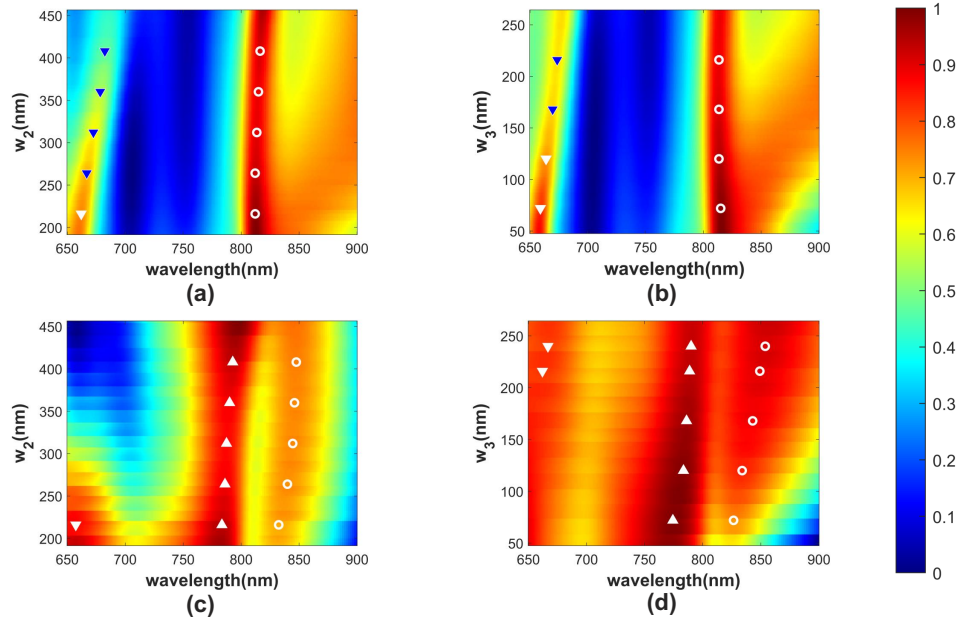


Fig. 6. Absorption color maps as a function of wavelength and w_2 , w_3 for (a-b) insulating and (c-d) metallic VO₂, respectively. The symbols ∇ , Δ , and $\circ$ represent the absorption peak variation paths for Modes 1, 2, and 3, respectively.

(Fig. 3(c)), indicating FP cavity modes formed between the metallic VO₂ and SiC-air interfaces. Apart from a strong dependence on t_1 , t_2 , and t_3 as depicted in Fig. 4(d-f), the absorption peak shows a strong blueshift with increasing d as well (Fig. 5(d)). This is due to the dependence of the cavity length ($t_1 - d$) on d , unlike the insulating phase with a continuous cavity between Ag and SiC. This resonant peak also shows a strong dependency on w_1 , as shown in Fig. 5(f), similar to that for the insulating state.

For Mode 2 in the metallic state, the absorption peak shows a strong dependency on t_1 and d in Fig. 4(d) and Fig. 5(d) respectively, indicating the contribution from the lower FP cavity with a length of ($t_1 - d$). The resonant wavelength also shows a weak redshift with increasing t_2 and t_3 (Fig. 4(e-f)). The increase of this peak wavelength with increasing w_1 , w_2 , and w_3 in Fig. 5(f), 6(c), and (d), respectively, is also consistent with our previous observations. The field distribution at this wavelength (Fig. 3(d)), as well as strong dependency on the period (P) in Fig. 5(e), shows the impact of adjacent cell coupling on this absorption peak. As P increases, the greater separation between the neighboring cells causes a decrease in the resonant energy and hence causes the redshift.

The field distribution of Mode 3 for insulating VO₂ in Fig. 3(b) shows field concentration between Ag and the top SiC-air interface. This indicates the presence of an FP mode, further validated by the redshift of the peak wavelength with increasing t_1 (Fig. 4(a)). However, the weak dependency on t_1 , t_2 , and t_3 compared to Mode 1 suggests a weak contribution from the FP resonance. The resonance position moves towards higher wavelengths as the lower cavity width (w_1) increases (Fig. 5(c)), but is almost insensitive to the other cavity widths (w_2 , w_3), shown in Fig. 6(a-b). The strong redshift with increasing P in Fig. 5(b) indicates the contribution of unit cell coupling to this absorption peak. For the metallic state of VO₂ at higher temperatures, the field distribution (Fig. 3(e)) is very similar to that for the insulating state (Fig. 3(b)). The visual dissimilarity is due to a shift in the color scale bar, caused by a high field concentration at the edges of the upper VO₂ layers in the structure, indicating the dominance of upper stages to the adjacent cell coupling compared to the insulating state [56]. As a result, the position of this peak shows very similar dependency on t_1 , and w_1 as for the insulating state. However, the mode wavelength shows strong dependency on w_2 and w_3 in Fig. 6(c)-(d). Specifically the redshift with increasing upper cavity width (w_3) is quite strong, and the field is also concentrated around that stage (Fig. 3(e)). There is also a weak dependency on d (Fig. 5(d)), which is due to the relatively weak FP cavity mode contribution from the lower cavity, as evident in the field profile as well. The strong dependency of the resonant wavelength on the period (P) in Fig. 5(e) validates the major contribution from unit cell coupling indicated in the spatial field distribution.

The difference in the resonant wavelengths for the on and off states for the same mode is dictated by the change of the real part of the permittivity in the metallic state [57] and the origin of the resonance. In the case of Mode 1, the resonance is mainly dominated by FP cavities, as discussed earlier. As VO₂ transitions to a metallic state, the reduced real permittivity means a decrease in optical path length for the FP cavity, causing the blue shift [58]. For Mode 3, the absorption peak is primarily caused by the strong coupling between the adjacent unit cells, as can be seen in the field distributions of Fig. 3(b) and (e), and further validated by the effects of different structural parameters on the mode wavelength, discussed previously. The strong redshift of the resonant wavelength in the metallic phase with increasing upper cavity widths (w_2 , w_3) in Fig. 6(c-d) indicates that the resonance in the metallic state is dominated by coupling between the upper stages of neighboring cells. This is further validated by the high field concentrations around the edges of the upper VO₂ layers in the metallic state (Fig. 3(e)). The insensitivity of the resonant mode in the insulating phase to w_2 and w_3 (Fig. 6(a-b)) means that the neighboring cell coupling has very little contribution from the upper stages as opposed to the metallic state. Since these upper stages have greater separation from each other, compared to the lowest stage, Mode 3 in the metallic state is redshifted with respect to the insulating phase in Fig. 2. Mode 2 for the

insulating state is extremely weak and hence has not been investigated in our work, as mentioned earlier.

4. Design of the switchable broadband metasurface

We have utilized the switchable broadband absorber proposed in Section 2 as a unit cell to design our broadband meta-device reconfigurable between an achromatic metalens and a broadband near-perfect absorber. The design methodology for broadband achromatic metalens has been previously reported [59,60]. Apart from that, we have selected the unit cells to maintain their switching bandwidth as defined in Section 3. Addressing these requirements in all the points on the metalens ensures that the metasurface can be switched between its on(achromatic metalens) and off(broadband absorber) states.

The required relative phase $\phi(r, \omega)$ at any point r on the metalens with respect to its center for a focal length of f is given by [61]

$$\phi(r, \omega) = -\frac{\omega}{c}(\sqrt{r^2 + f^2} - f) \quad (1)$$

where c and ω represent the speed and angular frequency of the incident light respectively. This equation should be satisfied at the complete frequency range of the design to achieve achromatic focusing. Equation (1) can be expanded about a reference frequency of ω_r using the Taylor series theorem

$$\phi(r, \omega) = \phi(r, \omega_r) + \left. \frac{\partial \phi(r, \omega)}{\partial \omega} \right|_{\omega=\omega_r} (\omega - \omega_r) + \left. \frac{\partial^2 \phi(r, \omega)}{2 \partial^2 \omega} \right|_{\omega=\omega_r} (\omega - \omega_r)^2 + \dots \quad (2)$$

The first term in Eq. (2) is the one that is satisfied in single wavelength metalens. The first $\left(\left. \frac{\partial \phi(r, \omega)}{\partial \omega} \right|_{\omega=\omega_r} \right)$ and second order derivative terms $\left(\left. \frac{\partial^2 \phi(r, \omega)}{\partial^2 \omega} \right|_{\omega=\omega_r} \right)$ around ω_r in the equation, are called relative group delay and group delay dispersion respectively [60]. For achromatic focusing with a bandwidth of $\Delta\omega$ around ω_r , these terms, along with the other higher order derivatives, must be satisfied at each point on the metalens. For our switchable metasurface, another requirement is maintaining the switchable absorption characteristic at each point of the lens. We define this switchable band as the region with less than 60% absorption in the on state and greater than 90% absorption in the off state.

To satisfy these constraints, we have constructed a meta-atom library by simulating our unit cell absorber structure reported in Section 2 with different structural parameters. For this, the cavity lengths (t_1, t_2, t_3), widths (w_1, w_2, w_3), and position of VO₂ above the substrate (d) in Fig. 1(b) have been varied. The thicknesses of the VO₂ layers (v_1, v_2, v_3) have also been tuned and have been kept equal to each other for all the meta-atoms considered. Three representative meta-atom structures and their corresponding phase spectra are illustrated in Fig. 7(a). The linear shaded region of the spectrum, from 685.6nm to 774nm, is considered the achromatic band for this broadband metalens design. Figure 7(b-d) shows the required values of relative phase, group delay, and delay dispersion on each point of the metasurface. These requirements have been satisfied for the on state(insulating VO₂) only since in the off state(metallic VO₂), the device will work as a nearly perfect absorber. This is ensured by maintaining a less than 60% absorption for the on-state and greater than 90% absorption in the off-state throughout the design bandwidth. The choice of these threshold values are based on previous relevant work as discussed previously [50–52]. Figure 7(e) shows the realized upper and lower absorption band limits. The two lines in the figure labeled "required" represent the upper and lower boundaries of the linear region marked in Fig. 7(a). The relative phase, and delay requirements have been closely satisfied in all the points by choosing appropriate meta-atom cells from our constructed library, as shown in Fig. 7(b,c). However, due to the uniformity of the basic structure throughout the device and the

constraint of aligning the absorption band with the linear phase band, the relative group delay dispersion requirement could not be satisfied perfectly in all the points (Fig. 7(d)). The higher order derivative terms in Eq. (2) have not been considered in our design as the relative values of these terms are negligible for all our selected meta-atoms.

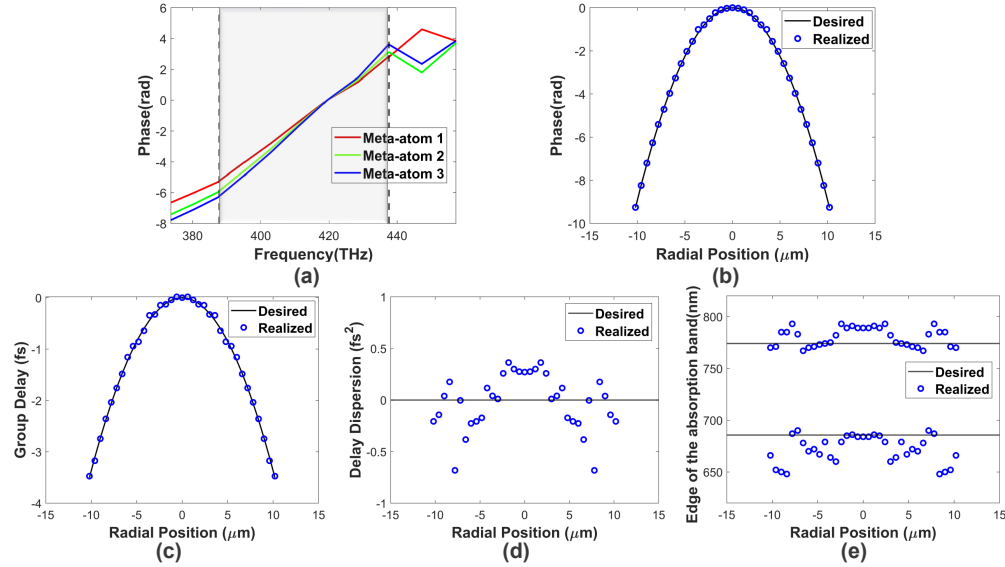


Fig. 7. (a) Phase spectra of three representative unit cells from our meta-atom library. The shaded area (685.6nm to 774nm) marks the linear phase region of the meta-atoms. The structural parameters (d , w_1 , w_2 , w_3 , t_1 , t_2 , t_3 , $v_1 = v_2 = v_3$) for the Meta-atom 1 to 3 are (140, 485, 242.5, 145.5, 190, 22.75, 24.4, 17.5), (145, 461, 189, 152, 186, 20, 20, 16), and (140, 490, 416.5, 73.5, 190, 24.75, 24.5, 17) respectively in nanometer units. Required and realized (b) relative phase, (c) relative group delay, (d) relative group delay dispersion, and (e) switchable absorption band spread as a function of radial position on the metasurface. The desired values in (b-d) are for an achromatic metalens designed for a focal length (f) of $49\mu\text{m}$ with a radius of $10.2\mu\text{m}$. The requirement for the switchable band in (e) means that the upper and lower limits of the realized unit cell band should be above and below the reference lines respectively. The realized values in (b-e) represent the response of the appropriate unit cell chosen from our meta-atom library for that position.

It is worth noting that, though we have looked to satisfy the switchable reflection characteristic of the unit cell in the achromatic band of 685.6–774nm, it is better satisfied in the switchable absorption band (689.3–774.6nm), as can be seen in Fig. 7(e). The on-state functionality of our reconfigurable device, the achromatic focusing, has been designed for a band of 685.6nm to 774nm as marked in Fig. 7(a). This is the band where all the selected constituent meta-atoms show a nearly linear phase profile necessary for the achromatic metalens design methodology we have used. So, we expect to achieve both on-off switching and achromatic focusing in the overlap of the two bands, which is the same as the switchable absorption band for all practical purposes. The switchable absorption band is regarded as the design band for our multifunctional device, and both terms will be used interchangeably in this work. This terminology is used only for clarity and has no impact on the design and performance of the proposed metasurface.

5. Characterization of the reconfigurable broadband meta-device

Our dual-functional metasurface has been constructed by placing the unit cells reported in Section 4 at their respective positions, as schematically shown in Fig. 8(a). It is worth noting

that Fig. 8(a) is an artistic depiction of the focusing action of our meta-device in the on state and not a representative of the actual structure. To evaluate the broadband switching and focusing characteristics, we simulated the structure by the FDTD technique in the commercial software, Lumerical FDTD Solutions. For this, the structure was illuminated with an x-polarized source propagating in the -y direction. PML boundary conditions were used in both the x and y directions, a typical setting used in previous works [62].

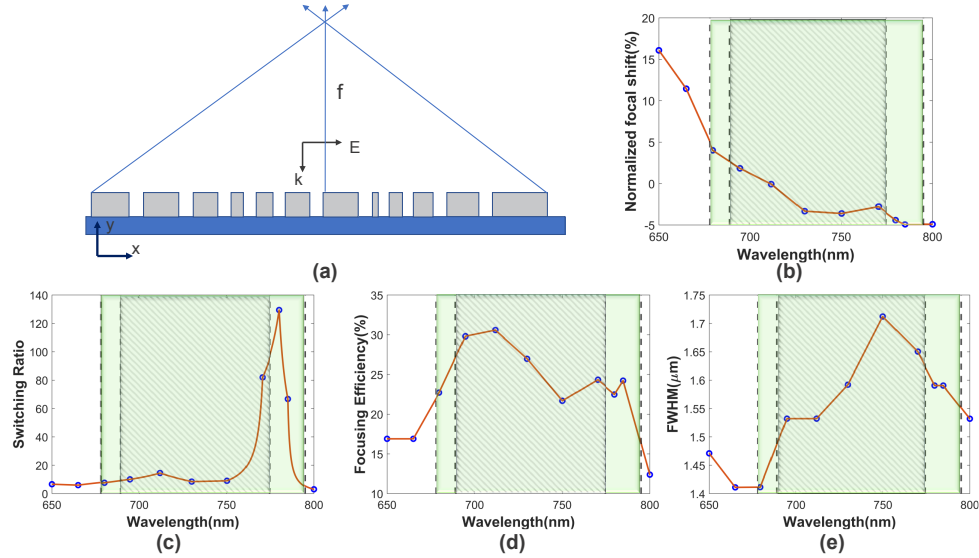


Fig. 8. (a) Schematic representation of the designed metasurface for a focal length of f , (b) Focal length shift normalized to the reference wavelength at 712nm in the on state, (c) Intensity switching ratio at the on and off states, (d) Focusing efficiency, (e) Full-width at half-maximum(FWHM) of the broadband system as a function of wavelength in the on state. The lines joining the simulation data points have been added for ease of visualization. The green shaded regions in (b)-(e) represent the operating spectral band of our device from 678nm to 795nm. The overlapping hatched regions depict the switchable absorption band (design band) from 689.3nm to 774.6nm.

The achromatic focusing of the multifunctional meta-device in the on state is quantified by normalized focal shift and is defined as $(f(\lambda) - f_0)/f_0$. $f(\lambda)$ and f_0 represent the focal lengths at a wavelength λ and at the reference wavelength of 712nm respectively. This value remains between $\pm 5\%$ over the range of 678-795nm and within $\pm 4\%$ in our design band as depicted in Fig. 8(b).

The switching ability is evaluated by switching ratio, which is defined as the ratio of squared maximum electric field values in the on (insulating VO_2) and off (metallic VO_2) states. This quantity remains above 8 throughout the switchable absorption band of Fig. 2. The peak value of 129.5 occurs just outside this band (Fig. 8(c)), proving an excellent switching characteristic of our meta-device in the visible regime. Figure 9 illustrates the spatial field distributions in the on and off state for four different wavelengths in our operating band. The distributions clearly show the contrast in the on-off states. The small shifts from the reference focal plane (white dashed lines) in Fig. 9(e-h) represent the achromatic focusing in the on state.

Figure 8(d) depicts the focusing efficiency of the metasurface in the on state as a function of wavelength. This value is defined as the ratio of power in a circle with a radius of $1.5 \times \text{FWHM}$ around the on-axis focal point and the incident power in the on state [64]. The efficiency remains between 22-30.57% over the designed frequency range but drops sharply beyond that. This low efficiency may be attributed to the relatively high absorption at some points, even in the on state.

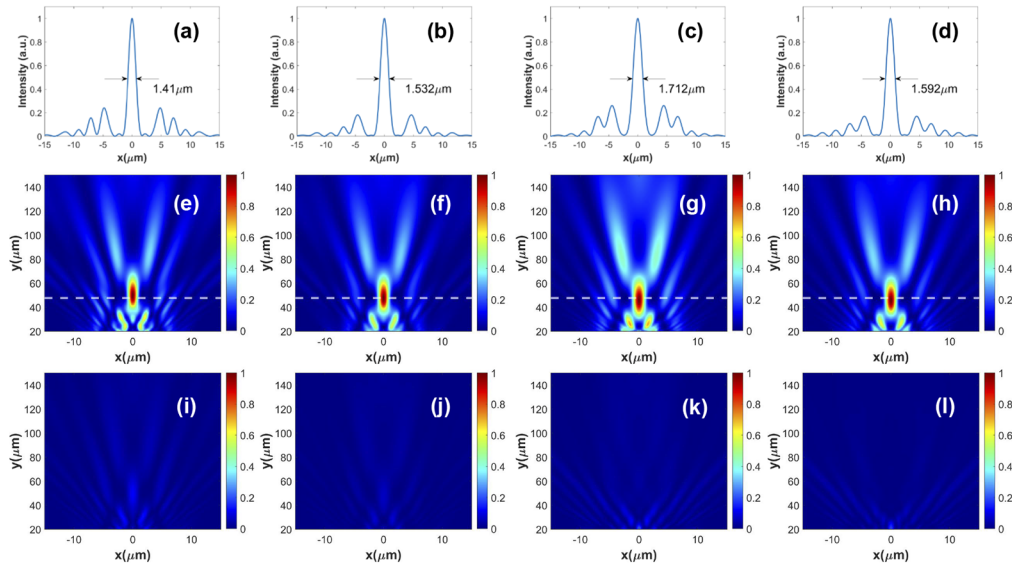


Fig. 9. Focusing and switching characteristics of the designed metalens. (a-d) Normalized cross-sectional intensity profile. The x-y plane spatial field profiles for the (e-h) insulating (on state) and (i-l) metallic (off state) phase of VO₂ at four different frequencies. The four operating wavelengths are 680nm, 712nm, 750nm, and 780nm moving from left to right. The color bars in each wavelength have been normalized by the corresponding on-state field maxima. The white dashed lines represent the focal plane at the reference wavelength (712nm) and illustrate the small shift in focal length over the operating bandwidth.

Figure 8(e) shows the Full Width at Half Maximum (FWHM) of our metalens over the range of 650nm to 800nm. FWHM is defined as the width of the spatial region around the on-axis focal point beyond which the power distribution falls below half its maximum value at the focal spot [65]. The values are in very good agreement with the theoretical limit ($\frac{0.514\lambda}{NA}$), showing the diffraction-limited focusing performance of the device in on state [66].

Our dual-functional meta-device was designed to produce high on-off contrast within the switchable absorption band of 689.3-774.6nm (the hatched region in Fig. 8(b-e)), which shows a switching ratio between 9dB and 12.1dB. However, a maximum switching ratio of 21.1dB occurs just outside the band at 780nm, as shown in Fig. 8(c). The on-state functionality of our reconfigurable device, the achromatic focusing, in this design band is quantified by a small normalized focal length shift of less than $\pm 4\%$, along with a reasonable focusing efficiency of 22-30.57% within this band. Though technically we designed the device for this switchable absorption band as discussed in Section 4, we observe the excellent performance of our designed structure over a spectral band of 678-795nm. FDTD simulations show a focal length shift of 9.48% in the on state and a switching ratio of not less than 7dB throughout the band. Also, a maximum switching ratio of 21.1dB occurs within this 678-795nm band which is defined as the operating bandwidth of our device (the green shaded region of Fig. 8(b-e)). Such an extension of the operational bandwidth beyond the actual design band is commonly and rightfully used in relevant previous works [40,41,59]. The exact choice of this extended band is based on threshold values of 7dB and 10% for the minimum switching ratio and maximum focal length shift, respectively, which ensures satisfactory performance of the device throughout this band [32,40-42]. The sharp decrease in the focusing efficiency (Fig. 8(d)) and increase in normalized focal length shift (Fig. 8(b)) beyond the operating bandwidth limits the spectral band for switchable characteristics of the device to 678-795nm.

Table 1 compares our designed structure and other relevant metasurfaces. Our maximum switching ratio (21.1dB) within the operating band is the highest among all the broadband metalens-absorber devices. Among the previous works, the metalens-absorber system of Ref. [63] has a higher maximum switching ratio (29.5dB) than our observed value (21.1dB) in this work, however, their reported system only works at a particular wavelength of 5.2 μm , whereas our device is broadband in nature. The other performance parameters are also in excellent agreement with the previously reported ones. The only related device in the visible range [32] is not achromatic and is polarization-switched, further asserting the novelty of our proposed platform.

Table 1. Comparison of our switchable metasurface with previously reported metalens-absorber platforms.

Switching mechanism	Operating wavelength range	Maximum switching ratio	Focusing efficiency	Focal shift	Reference
Polarization switching	632,670,710, 750nm	12dB	–	Focal plane switching with wavelength	[32]
PCM(GST)	1.49-1.65 μm	16 (12.04dB)	23-33%	13.6%	[40]
PCM(GSST)	5.2 μm	29.5dB	23.7%	–	[63]
PCM(VO ₂)	10-11.2 μm	25 (13.98dB)	26.3-48.4%	14.38%	[41]
PCM(GST)	10-11 μm	–	–	10.92%	[42]
PCM(VO ₂)	678-795nm	129.5 (21.1dB)	19.1-30.57%	9.48%	This work

The results show that our meta-device acts as a broadband near-perfect absorber in the visible range under sufficient electrical, optical, or thermal excitation, which causes the VO₂ layers to make a transition to the metallic state [22]. The metasurface switches back to a broadband achromatic metalens once the excitation is removed, which we refer to as the on state of the device (insulating VO₂). The excellent broadband switching and focusing characteristic of our designed metasurface quantified by the switching ratio and focal shift and visually shown in Fig. 9 makes it suitable for applications like optical switches for integrated photonics, communication networks, and imaging [67]. As a specific application, the switchable metalens can be used in bio-imaging as a focusing element with protective features against an overdose of illumination. VO₂ in our device can be switched optically, even by a laser with a high dose. The red region of the visible spectrum is generally preferred for imaging due to its ability to penetrate deeper into the bio-tissues [68]. Nearly constant focal length over a broadband regime in the red portion shows the suitability of our device for imaging in the on state. The high switching ratio under red light illumination (Fig. 8(c)) means that it can automatically turn off under overdose protecting the tissue samples. This novel structure can pave the way for future smart miniaturized imaging systems in the visible regime.

6. Conclusion

In this article, we report a reconfigurable multifunctional broadband metasurface in the visible range. The device can be switched between an achromatic metalens and a nearly perfect absorber by changing the VO₂ from insulating to the metallic state through optical, thermal, or electrical stimulus. The low contrast in optical properties between PCM states at visible wavelengths has been a major obstacle to reconfigurable multifunctional broadband device development in the

past. The cascaded meta-atom of our metasurface allowed us to overcome this obstacle. Multiple FP cavities formed at the metallic state of VO₂ ensured nearly perfect absorption for the off state and reasonable reflection in the on state for the 689.3nm to 774.6nm spectral band, showing excellent switching behavior. We used this absorber cell to construct our final meta-device. We have performed numerical simulations to verify the achromatic focusing and broadband switching characteristics of the metasurface. Analysis of the spatial field profiles for the on and off states reveals a maximum intensity contrast of 21.1dB and a focal length shift of 9.48% in the on state over the chosen operating wavelength range of 678–795nm. This is the highest reported switching ratio for a broadband metalens-absorber platform in any frequency band. These features make our device suitable as an optical switch in many applications. We expect the findings of our work to pave the way for novel reconfigurable multifunctional devices in the visible range for complex miniaturized photonic platforms.

Disclosures. The authors declare no conflict of interest.

Data availability. Data underlying the findings of this work are not public at this time but will be made available upon reasonable request to the authors.

Supplemental document. See [Supplement 1](#) for supporting content.

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