Supplementary Materials

Switchable Metasurface with VO_2 Thin Film at Visible Light by Changing Temperature

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Optimization of VO_2-based Reflectarray Metasurface

In order to achieve the geometric phase control, it is necessary to achieve a π-phase change between two normal incident lights with the orthogonal polarization states along l-axis and s-axis directions. The Au nanorod structure is optimized to get high reflectivity with π-phase difference. Figure S1 shows reflection and phase difference with respect to the length and width of the Au nanorod at low temperature (the insulator phase of VO_2) and at high temperature (the metal phase of VO_2). At L = 200 nm and w = 80 nm as marked with the white dashed circles in Fig. S1, both reflections of l-axis and s-axis polarized lights are over 70% around 700 nm with π-phase difference at low temperature. However, the phase difference is zero at high temperature. It means that the normal incident light with the circular polarization is reflected as the opposite circular polarization state at low temperature, however, at high temperature, the polarization state of the reflected light does not changed.

We confirmed the performance of the reflectarray metasurface consisting of the 45°-rotated Au nanorod. Here, when the input light has the linear polarization along the x-axis, the co-polarized reflection, R_{co} indicates the reflection of the same polarization state (x-axis), and the cross-polarized reflection, R_{cr} indicates the reflection of the orthogonal polarization state (y-direction) to the input polarization. According to the PB-phase principle, when the x-polarized incident light is reflected by metasurface consisting of 45°-rotated Au nanorod, the polarization direction of the reflected light is y-axis. This means the phase change of the reflected light is 90° which is known as geometrical phase change. According to Fig. S2 (b), R_{cr} is high near 700 nm at w = 80 nm when the VO_2 is the insulator phase at low temperature, however, R_{co} is almost zero at high temperature. In contrast, R_{co} at low temperature is high instead of low R_{cr} at low temperature. This means that the polarization conversion occurs only at the low temperature, therefore, the designed structure can act as a reflectarray metasurface at the low temperature.

We also investigated the dependence of the thickness of VO_2 film on the polarization conversion. To achieve the maximum polarization conversion ratio (PCR) at low temperature and the minimum PCR at high temperature simultaneously, there is an optimum thickness to make a constructive interference at the cross-polarized reflected light. Figure S3 shows reflection spectra of different thickness (t) of VO_2 film. At t = 76 nm, R_{cr} is over 70% at λ =700 nm at low temperature. In contrast, R_{cr} is almost zero at high temperature. In case of high temperature, as the thickness of VO_2 becomes small, R_{cr} increases at λ =700 nm, so *PCR* at high temperature becomes large. However, in case of low temperature, as the thickness increases, R_{cr} decreases which reduces the *PCR*. This implies that *PCR* is maximized around t = 76 nm which is an optimum value for switchable metasurface with VO_2 thin film at 700 nm.

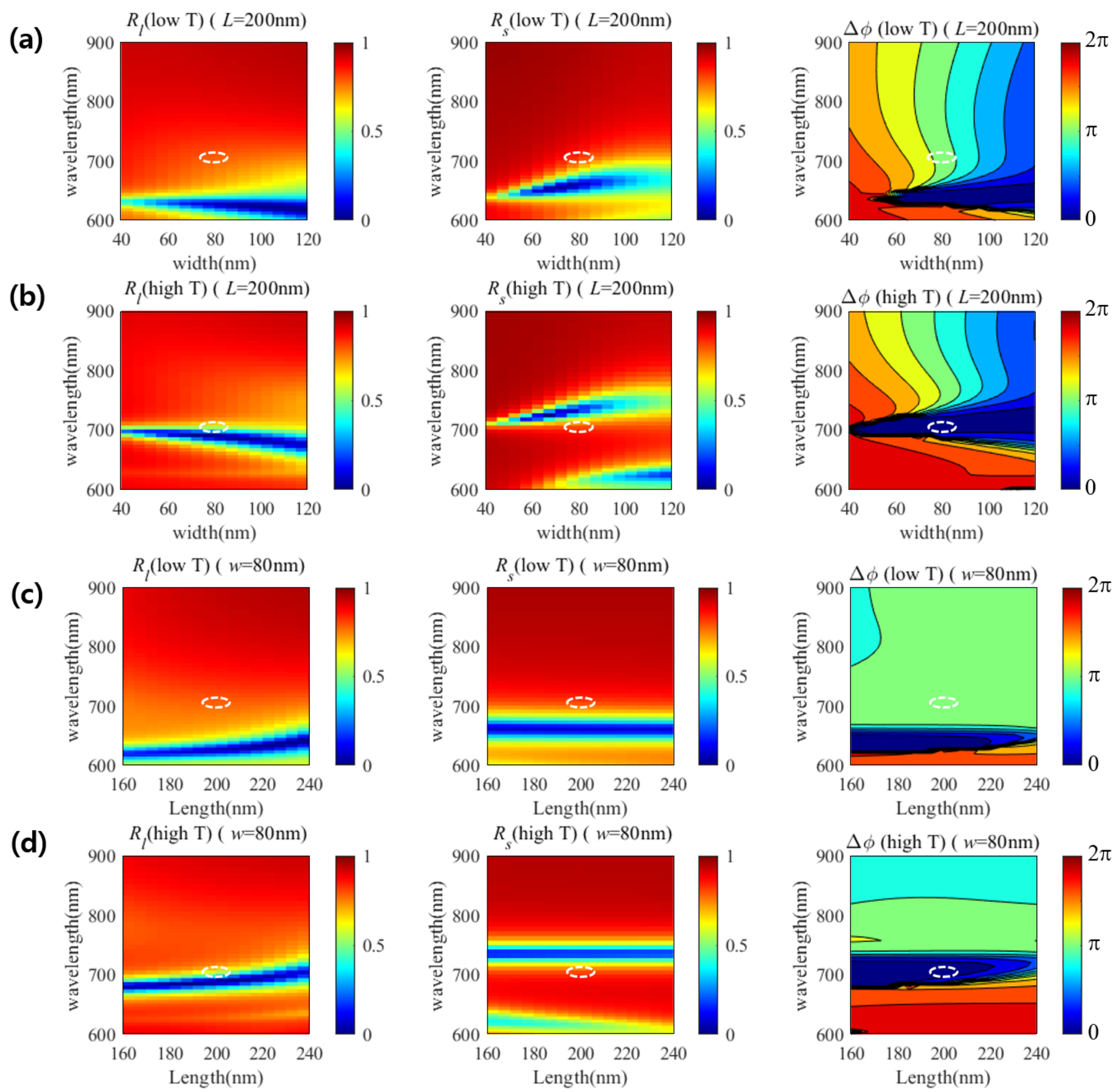

Figure S1. Optimization of the Au nanorod in a VO_2 based reflectarray metasurface. (a) Width dependence of the Au nanorod with L = 200 nm at low temperature and (b) at high temperature. (c) Length dependence of Au nanorod with w = 80 nm at low temperature and (d) at high temperature. The left column is the reflectivity at the linear polarization parallel to the Au nanorod (l-axis), the middle is the reflectivity at the polarization perpendicular to the Au nanorod (s-axis), and the right is the phase difference between the reflected lights

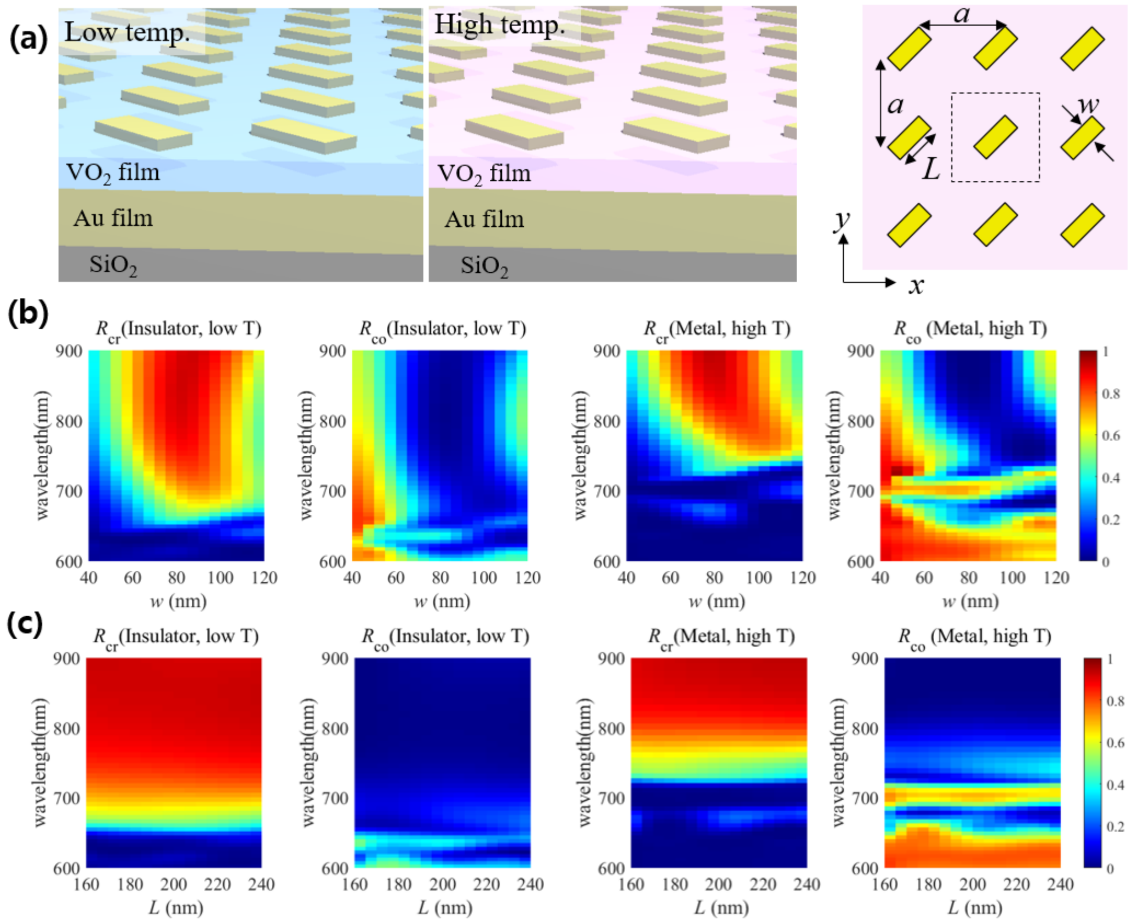

Figure S2. Characterization of a VO_2 based reflectarray metasurface consisting of the 45°-rotated Au nanorods (a) Schematic views of VO_2 based switchable metasurfaces. The left (or the middle) picture shows the reflectarray metasurface at low temperature (or high temperature). The right is the top-view of the metasurface. (b) Reflection spectra with respect to the width of the Au nanorod at L = 200 nm (c) Reflection spectra with respect to the length Au nanorod at w = 80 nm. The left two columns in (b) and (c) correspond to the reflection of the orthogonal polarization state (R_{cr}) and the same polarization state (R_{co}) to the input polarization at low temperature, respectively. The right two columns in (b) and (c) correspond to R_{cr} and R_{co} at high temperature, respectively.

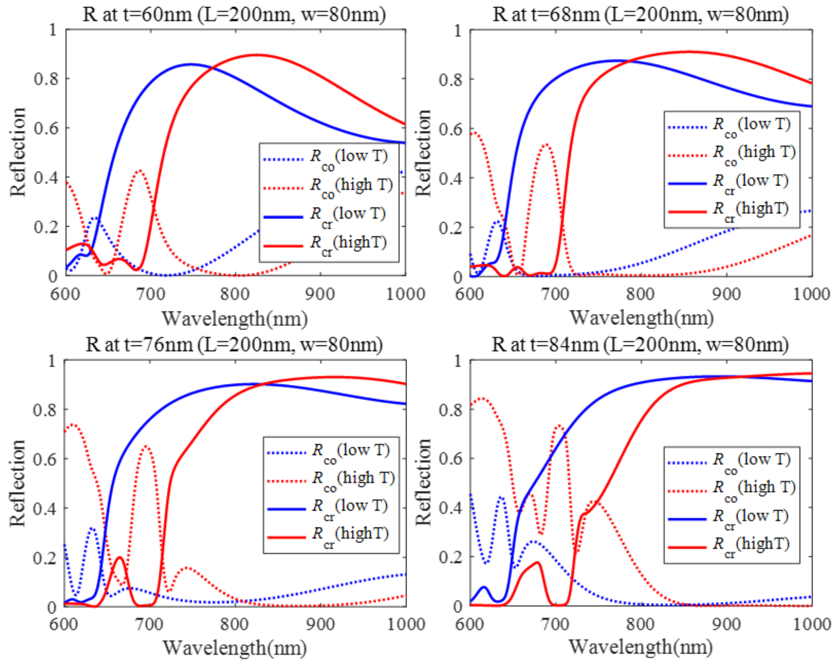

Figure S3. Reflection spectra with different thickness of VO_2 film. The structural parameters of Au nanorod are fixed as the optimum parameters to get high *PCR* (L = 200 nm, w = 80 nm)

Optical properties of VO_2 film with partial metallic phase

We investigated the optical properties of reflectarray metasurface with VO_2 thin film when VO_2 phase changes continuously from the insulator to the metal. Here, Bruggeman effective medium theory was adapted to describe the effective optical constant, $\varepsilon_{\mathrm{eff}}$ of VO_2 which is given by solving the following equation [35],

$$f\frac{\varepsilon_{\mathrm{M}}-\varepsilon_{\mathrm{eff}}}{\varepsilon_{\mathrm{M}}+\left(\frac{1-q}{q}\right)\varepsilon_{\mathrm{eff}}}+(1-f)\frac{\varepsilon_{I}-\varepsilon_{\mathrm{eff}}}{\varepsilon_{\mathrm{I}}+\left(\frac{1-q}{q}\right)\varepsilon_{\mathrm{eff}}}=0$$

where ε_{M} and ε_{I} are complex optical constants of metallic and insulating phase, and f and (1-f) are the volume fractions of metallic and insulating phase, respectively. q is the depolarization factor that depends on the shape of a inclusion. In the simulation, we used the values of f and q from Supporting Online Material of Ref. [35]. We first check the dispersion of the complex permittivity ($\varepsilon_{\mathrm{eff}}$) with different f of metallic phase of VO_2 as shown in Fig. S4. According to the graph, $\varepsilon_{\mathrm{eff}}$ is continuously changed by f, but not linearly proportional to f. Based on Fig. S4, the parameters of two poles of Drude-Lorentz model for the dielectric constants at each f were extracted. The results are shown in the Table S1.

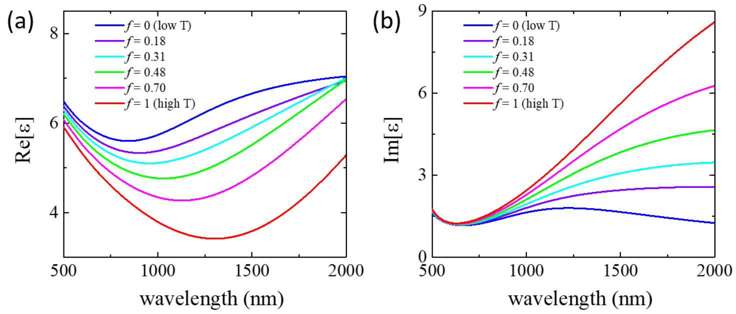

Fig. S4. Dispersions of complex optical constant (ε) with various volume fractions (*f*) of metallic phases of VO_2. (a) Real part of ε (b) Imaginary part of ε.

Table S1. The values of volume fraction *f* and depolarization factor *q* at different temperature [35], and the parameters of two poles of Drude-Lorentz model for dielectric constant of VO_2 with different volume fraction of a metallic phase from the visible to the IR region, where the unit of ω_p and γ_p are $\hbar^{-1}$eV [43].

T(K)	f	q	ε_∞	ω_{p1}	γ_{p1}	f_{p1}	ω_{p2}	γ_{p2}	f_{p2}
< 341	0		3.4	3.735	0.7	1.183	0.956	0.64	1.150
342	0.18	0.2	3.72499	3.57202	0.64257	0.99105	0.55672	0.78217	4.99529
342.6	0.31	0.33	3.93	3.4763	0.62996	0.90132	0.48329	0.70786	7.34863
343	0.48	0.45	4.12972	3.36984	0.60742	0.80917	0.45473	0.62997	9.34546
343.6	0.7	0.5	4.32149	3.26063	0.57332	0.71648	0.38941	0.5713	14.81498
> 344	1		4.5	3.154	0.54	0.6383	0.3132	0.5	27.013