

Mid-infrared optical valve based on VO<sub>2</sub>Antonio García-Martín<sup>\*</sup> and Raquel Álvaro*Instituto de Micro y Nanotecnología IMN-CNM, CSIC, CEI UAM+CSIC, Isaac Newton 8, Tres Cantos, E-28760 Madrid, Spain*Zhuoqun Fang, Alexandre Zimmers<sup>†</sup>, Zhuoying Chen<sup>‡</sup>, and Lionel Aigouy<sup>§</sup>*Laboratoire de Physique et d'Etude des Matériaux (LPEM), CNRS, ESPCI Paris, PSL Research University, Sorbonne Université, 10 rue Vauquelin, F-75231 Paris, France*

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We demonstrate an efficient optical binary-switch effect in nanoslit arrays achieved via the temperature-induced phase transition of VO<sub>2</sub>. Experimental measurements reveal a polarization-dependent 60% reduction in reflectivity during the insulator-to-metal transition. Tuning a single parameter of the slit enables control over the “optical-valve” effect. Full numerical simulations support these findings, predicting a reflectivity reduction up to 90%. The nearly one-to-null transition in reflectivity mimics the operation of a digital switch, with the high-reflectivity and the low-reflectivity states providing a binary response much like digital electronics.

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## I. INTRODUCTION

Plasmonic metasurfaces are artificially engineered two-dimensional nanostructures that manipulate light at sub-wavelength scales by exploiting the collective oscillations of free electrons in metallic nanostructures, known as surface plasmons. These metasurfaces enable control over light propagation, polarization, phase, and intensity, making them essential components in advanced optical technologies [1,2]. A key advancement in this field is the development of dynamically controllable plasmonic metasurfaces, which allow real-time tuning of optical properties through external stimuli such as electrical, thermal, optical, mechanical modulations, and magneto-optical effects [3–8].

Of particular interest is the thermal modulation, which is often realized using phase-change materials, such as vanadium dioxide (VO<sub>2</sub>) and germanium-antimony-tellurium (GST) alloys, which undergo reversible phase transitions that alter their optical and electrical properties [9]. VO<sub>2</sub>, for instance, exhibits an insulator-metal transition (IMT) around 68 °C, allowing for dynamic control of reflection, absorption, and transmission in the infrared regime. This property is particularly useful in applications such as smart thermal management, tunable infrared camouflage, adaptive optical filters, active beam-steering devices, dynamically reconfigurable holographic elements, tunable optical absorbers, and thermal emitters [10–15]. The vast majority of these works are based on shifts in the resonances due to the change in the optical properties of the phase-change material. In contrast to

the visible and the terahertz (THz) regimes, for which those materials are mostly dielectric or perfect metals, respectively, there are few works devoted to the intermediate regime, the mid-IR. In the case of typical phase-change materials such as GST or InSb, the material stays optically dielectric in both phases in the IR [16]. For VO<sub>2</sub> metasurfaces, they rely on hybrid metal-dielectric meta-atoms, where the modification of the optical response is in the meta-atom [17]. In this work, we explore another metal-dielectric metasurface, whose fundamental elements are slits in a metallic layer, where the electromagnetic resonances are modulated by the IMT in VO<sub>2</sub> underneath, Au-VO<sub>2</sub>. We demonstrate that it is possible to get an efficient digital-switch behavior in the optical response of nanoslit arrays by virtue of the phase transition in the VO<sub>2</sub>. We present experimental results showing a 60% reduction of the reflectivity in the metallic to the insulating transition. We also present experimental evidence that the optical-valve effect depends on the polarization of the impinging radiation, can be tuned by modifying just one parameter of the slit, and is independent of the slit arrangement. The experimental findings are confronted with full numerical simulations that validate the findings and give theoretical values as high of 90% reduction of the reflectivity. The nearly one-to-null transition in reflectivity can be regarded as an optical-switch effect. Although the thermal modulation of the developed metasurface using VO<sub>2</sub> is slow compared to electric-field or all-optical modulation techniques, it presents the advantage of being very simple to implement. Heat can be provided by a simple resistive heater. It does not necessitate the design and integration of complex electrodes for electric-field modulation or the use of an external pump laser for optical modulation [18,19]. Therefore, thermal tuning with VO<sub>2</sub> is ideal for applications prioritizing both strong tunability and system simplicity over speed, such as infrared imaging, smart windows, or static beam shaping.

The dramatic switching effect presented here is achieved through the temperature-induced phase transition of VO<sub>2</sub>, which alters the dielectric environment creating a robust,

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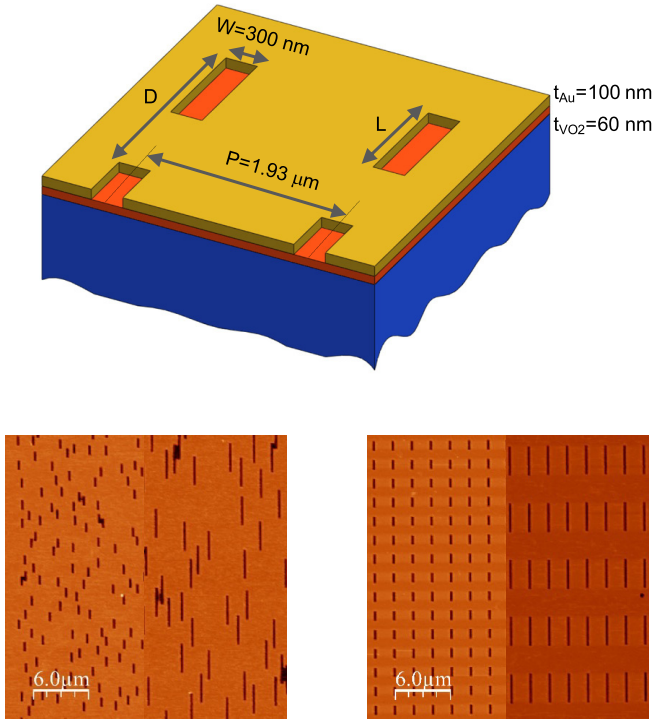


FIG. 1. Sketch of the system under study and experimental Atomic Force Microscope (AFM) images of representative samples, with  $L = 1 \mu\text{m}$  and  $L = 3 \mu\text{m}$  both ordered and disordered.

temperature-controlled optical gating mechanism. The system comprises a trilayer structure arranged as follows: a transparent sapphire substrate, a 60-nm-thick  $\text{VO}_2$  phase-change layer, and a 100-nm-thick gold layer, which is essentially opaque.

## II. METHODS

The 60-nm-thick  $\text{VO}_2$  film was deposited using a modified sol-gel method [20–22]. Gold is deposited by e-beam evaporation with a 2-nm-thick Ti adhesion layer between Au and the  $\text{VO}_2$  layer. The thickness of the layers was determined by x-ray reflectometry. The top gold layer is subsequently patterned by scanning electron microscopy with slits that are 300 nm wide, with lengths varying between  $L=1, 2$ , or  $3 \mu\text{m}$ , and the area covered is  $100 \mu\text{m} \times 100 \mu\text{m}$ . We study two types of patterns, one that is ordered and the other disordered; the disordered arrays are generated following the procedure described in Ref. [23] and follow an algorithm to minimize order-induced diffraction effects and excitation of propagating plasmons. All considered patterns maintain the same fill fraction of slits with a surface coverage of 8% irrespective of the ordering or slit length. In Fig. 1 we present a schematic view of the system under consideration, in this case for an ordered array of slits. In the case of ordered structures, the pitch in the short-axis direction is  $P = 1.93 \mu\text{m}$ , while the pitch in the long axis is  $D (\mu\text{m}) = 1.93 \times L (\mu\text{m})$ , accounting for the constant slits-fill-fraction.

The optical characterization of the system has been carried out using a Fourier transform infrared (FTIR) system in the wavelength range from 2 to  $10 \mu\text{m}$ . The reflectivity spectra were obtained using an IR microscope (Bruker Hyperion) equipped with a liquid nitrogen-cooled Mercury Cadmium

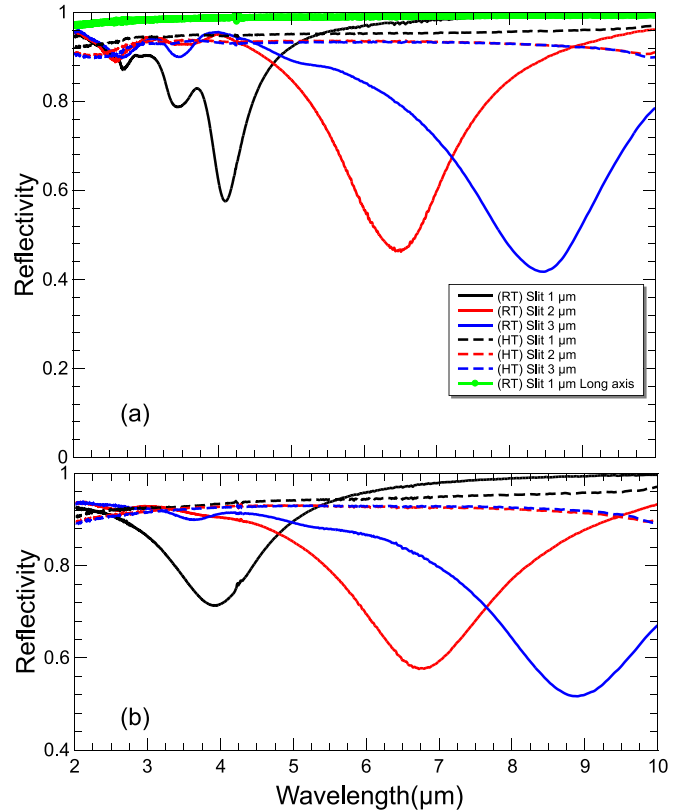


FIG. 2. (a) Experimental reflectivity spectra for ordered slit arrays of 1- $\mu\text{m}$  (black), 2- $\mu\text{m}$  (red), and 3- $\mu\text{m}$  (blue)-long slits with the same fill-fraction coverage. (b) The same but for a disordered system with the same fill fraction, to show that the resonant behavior is not linked to the ordering.

Telluride (MCT) detector, polarizers, and a reflecting  $15\times$  Schwarzschild objective. The microscope was coupled to a FTIR spectrometer (Bruker Vertex 70). The polarization of the incoming electric field of the light is along the short axis unless otherwise stated. To account for the insulator-to-metal transition in the  $\text{VO}_2$ , we use a Peltier stage to perform the reflectivity measurements at low temperature ( $\sim 25^\circ\text{C}$ ) for the isolating/dielectric phase, and high temperature ( $\sim 80^\circ\text{C}$ ) for the conducting/metallic phase.

## III. RESULTS AND DISCUSSION

The results are presented in Fig. 2. In Fig. 2(a) we present the results for the ordered structures and in Fig. 2(b) those for the disordered ones. Continuous lines are for the room-temperature (RT) case, whereas dashed lines are for high temperature (HT). Distinct resonant features in the spectra for RT are clearly observed for the three slit lengths, being the spectral location of the resonance highly dependent on the length of long axis of the slit. Since the spectral dependence of the resonance is with the dimension perpendicular to the polarization direction, the resonance is of magnetic nature [23–26]. This is corroborated by the featureless reflectivity spectrum for the 1- $\mu\text{m}$ -long slit when the polarization of the electric field is along the long axis [see green curve in Fig. 2(a)]. It must be noted that the spectra for the other

long-axis lengths are also featureless. The physical picture for the disordered arrays [Fig. 2(b)] is the same, with resonances occurring at the same spectral positions as for the ordered arrangements, reinforcing the fact that resonances originate from the geometrical aspects of the slit. The only indication of order or disorder is in the small oscillations at 3.5  $\mu\text{m}$ , corresponding to the onset of diffraction, not occurring for the disordered samples. Since optical resonances are affected by the dielectric environment of the resonator, in this case the slit, the spectral shape of the reflectivity should change whenever the surrounding medium does. In our case the VO<sub>2</sub> layer undergoes a phase transition upon increasing temperature. As mentioned, this phase transition is accompanied by a modification of the dielectric constant of the material. The effect is  $\sim 25^\circ\text{C}$ , presented in Fig. 2 as dashed lines. As it can be seen, none of the systems presents a resonant behavior, and the reflectivity is featureless for both periodic and nonperiodic systems. Therefore, the transition of the VO<sub>2</sub> into the metallic phase essentially washes the resonances out. This contrasts with the case of THz regimes, where the transmission/reflectance varies in the whole spectrum [14,27], or with the modulations caused by spectral shifts of the resonances in VO<sub>2</sub> or other phase-change materials [28–31].

To shed some light on the physical problem, we are presenting in Fig. 3(a) theoretical results based on a rigorous, full-vector solution of Maxwell's equations using the commercial software LUMERICAL® by Ansys Inc. This software uses a finite-difference time-domain scheme to solve the electromagnetic fields and thus get transmission and reflection characteristics. For simplicity in the calculations, we restrict ourselves to the periodic case. Thus, we use the same geometrical parameters as in the experimental counterpart. Dielectric properties of sapphire and gold used are those contained in the software (Al<sub>2</sub>O<sub>3</sub> is constant,  $n \approx 1.69$ , and Au is from Johnson and Christy), and VO<sub>2</sub> is obtained from ellipsometry [see Figs. 3(b) and 3(c)]. The mesh in the slit region has a minimum size of 50 nm in each direction and it is allowed to grow with a  $\sqrt{2}$  law outside. As it can be observed, the theoretical results are in very good agreement with all the experimental findings regarding polarization, size, spectral location of the resonances, and temperature range, confirming them. We can clearly see the absence of resonances in the metallic (HT) case and the resonant behavior of the isolating one (RT). In view of the refractive index of the VO<sub>2</sub> in the HT, the material transits from  $\text{Re}(\epsilon_r) > 0$  to  $\text{Re}(\epsilon_r) < 0$ . This is a key issue in the structure under consideration. In the RT case, the surroundings of the Au-engraved slits are all in contact with a dielectric medium, having then a fully perforated metallic thin film. In the HT case, the VO<sub>2</sub> has a dielectric permittivity with  $\text{Re}(\epsilon) < 0$ , similar to that of Au; therefore, the metallic layer, composed now of Au and VO<sub>2</sub>, is connected, having a metallic grating instead of a perforated film. This fact eliminates the resonance, as there is no longer a slit since the whole metal is connected by the *metallic* VO<sub>2</sub> underneath. The theoretical findings predict that the modulation can reach values of a ninefold variation of the reflectivity ( $R \simeq 0.1$  at RT to  $R \simeq 0.9$  at HT). We attribute the difference with the experimental quantitative values to small imperfections in the fabrication process that lead to a broadening and thus a decrease in the intensity of the resonances.

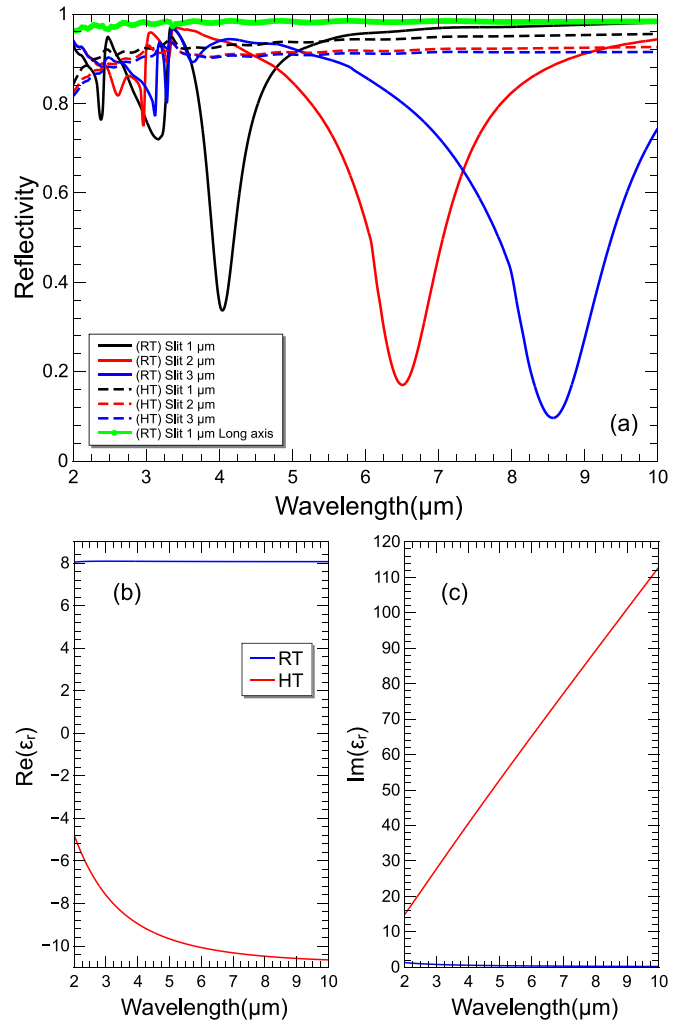


FIG. 3. (a) Theoretical reflectivity spectra for slit arrays of 1- $\mu\text{m}$  (black), 2- $\mu\text{m}$  (red), and 3- $\mu\text{m}$  (blue)-long slits. (b) Real and (c) imaginary parts of the complex permittivity for room- and high temperature obtained by ellipsometry that are used in the calculations.

To further validate our claim that the metallic state of VO<sub>2</sub> at high temperatures is responsible for suppressing the resonances, we present calculations where the etching process extends to both Au and VO<sub>2</sub> layers. This approach isolates the contribution of the VO<sub>2</sub> phase transition, demonstrating that its transition into an optically metallic medium plays a crucial role in eliminating the resonant behavior observed at low temperatures. In Fig. 4, we present the reflectivity curves for the 2- $\mu\text{m}$ -long slit for progressive VO<sub>2</sub> removal. In black we present the same results as in Fig. 3, when the VO<sub>2</sub> layer is intact, i.e., no VO<sub>2</sub> etch. In red, we present the situation in which half of the VO<sub>2</sub> layer is removed in the region of the slit. As shown, the low- (RT) and high- (HT) reflectivity states remain. The effect of removing part of the VO<sub>2</sub> is that the dielectric environment of the slit is different due to the  $n=1$  of the etching, causing a shift in the resonance for RT and a small decrease of the broadband high-reflectivity value. Finally, when the whole of the VO<sub>2</sub> is removed in the region of the slit the “low  $R$ ” vs “high  $R$ ” phenomenon disappears,

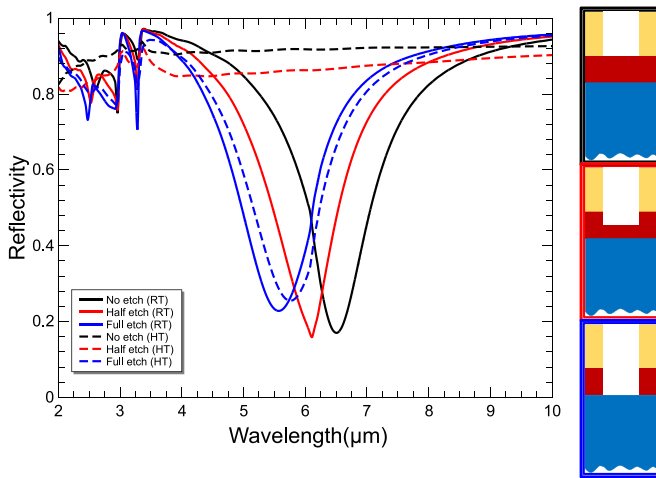


FIG. 4. Theoretical reflectivity spectra for slit arrays of 2- $\mu\text{m}$ -long slits where the  $\text{VO}_2$  in the slits has been also etched. Black depicts no etching, red is when the  $\text{VO}_2$  has been halfway etched, and blue is when the  $\text{VO}_2$  in the slit has been completely removed.

having only the low reflectivity values. Again, due to slight different dielectric environment of the metal in the slit, there is a shift in the resonance position.

#### IV. SUMMARY

In summary, we have presented an experimental and theoretical demonstration of a low-to-high transition, with a 60% (90% as theoretical limit) reflectivity variation, based on the temperature insulator-to-metal transition of  $\text{VO}_2$ . The resonant, polarization-dependent, low-reflectivity state originates in the localized magnetic resonances of slits perforated in gold thin films deposited onto a  $\text{VO}_2$  thin film. The transition

to the metallic state of the  $\text{VO}_2$  erases the slit and thus the resonances disappear, transiting into a high-reflectivity state. The ratio full width at half maximum  $\text{FWHM}/\lambda_{\text{res}}$  gives a value of the order of 25%, allowing a practical implementation of these structures as an effective valve in the mid-IR. We have also proven our claims by progressively eliminating the  $\text{VO}_2$  in the area of the slit, causing the high-reflectivity state not available in the case of a slit that fully perforates Au and  $\text{VO}_2$ .

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#### DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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