Switching Light through Nanostructured Arrays of Sub-wavelength Holes in Vanadium Dioxide

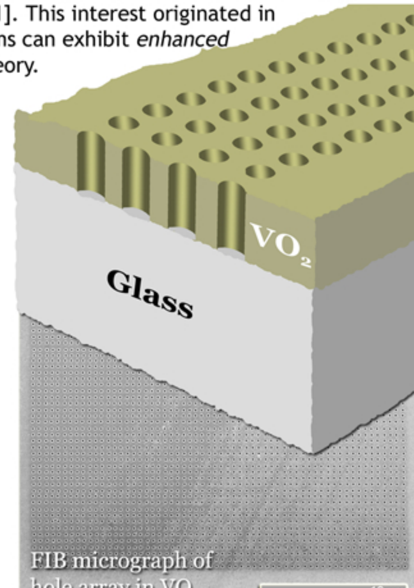
E. U. Donev, J. Y. Suh, R. Lopez, L. C. Feldman, R. F. Haglund

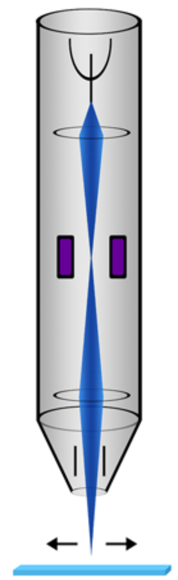
Department of Physics and Astronomy, and *Vanderbilt Institute of Nanoscale Science and Engineering*

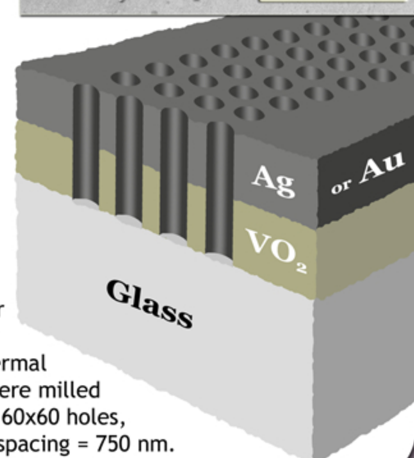
Motivation and Fabrication

Nanoscale apertures have received considerable attention in recent years, partly because of their practical role in near-field scanning microscopy, nanolithography, molecular sensing, and other novel applications [1]. This interest originated in 1998 from observations that ordered arrays of sub-wavelength holes in opaque metal films can exhibit *enhanced optical transmission* (EOT) [2], at great odds with estimates from classical diffraction theory.

We have measured optical transmission of near- and far-field light through periodic arrays of subwavelength apertures in vanadium dioxide (VO_2) thin films. We show that light traversing the air-filled holes can be modulated by the semiconductor-to-metal phase transition of VO_2, by virtue of the markedly different dielectric contrast between holes and surrounding material in the two phases of VO_2.







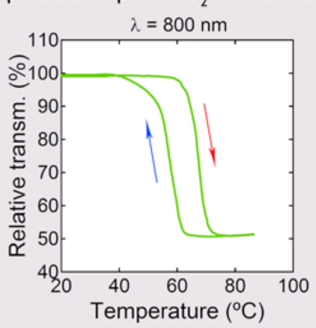
Counterintuitive observations:

1. For VO_2-on-glass, the hole array transmits more than the plain (i.e., no holes) film in the near-infrared (IR), *but* only in the metallic phase.

2. For hole arrays in Au/Ag-on-VO_2-on-glass, near-IR transmission is larger in the metallic phase rather than in the semiconducting phase -- opposite of plain-VO_2 behavior.

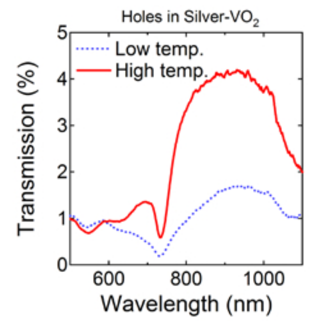
Vanadium Dioxide

VO_2 undergoes an abrupt phase transition ($T_c \approx 67\ ^\circ C$) from a high-temperature metallic phase to a low-temperature semiconducting phase, accompanied by dramatic changes in the electrical and optical properties of the material. The transition can occur in less than 100 fs when induced by a laser pulse [3]. The semiconducting phase of a plain VO_2 film is much more transparent to near-IR light than the metallic phase, as shown by the normalized transmission curves (right) for heating and cooling.

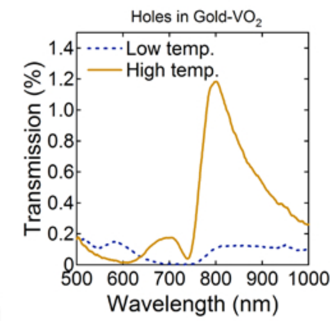


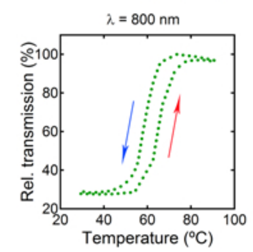
The VO_2 layers (200 nm thick) were fabricated by pulsed-laser deposition; the Ag (160 nm) or Au (230 nm) overlayer -- by thermal evaporation. The hole arrays were milled with a focused-ion beam (FIB): 60x60 holes, diameter = 250 nm, inter-hole spacing = 750 nm.

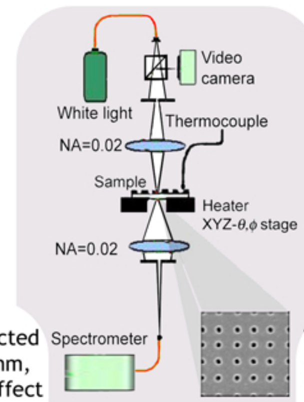
Transmission of Perforated Double-Layers

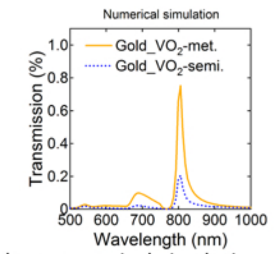


The zero-order transmission (i.e., detected beam collinear with incident beam) of hole arrays in Ag-VO_2 (left) and Au-VO_2 (right) exhibits typical EOT profiles. Through the VO_2 phase transition, the EOT intensity can be switched "on/off" in the near-IR.









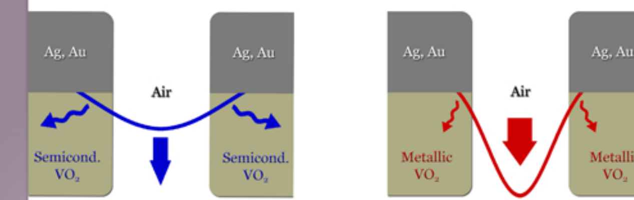
The "reverse hysteresis" above, extracted from the Ag-VO_2 transmission at 800 nm, illustrates the surprising hole-array effect that the high-temperature phase is also the high-transmission state.

The above numerical simulation, based on the *transfer-matrix method* (see below), reproduces most of the salient features of the Au-VO_2 experimental spectra.

Explanation

Generally, the VO_2 hole array transmits less than the plain film because some of the light is diverted away from the normal path due to scattering at the entrance and exit apertures and "leaky evanescent waves" [4] inside the holes (i.e., waves that lose energy as they propagate).

The relative loss of transmitted intensity depends on the dielectric permittivity (ε) contrast between the hole content (air) and its surroundings (VO_2): Lower ε-contrast reduces both the non-zero-order scattering [5] and the evanescent-wave leakage [4] into the VO_2 layer, and vice versa.

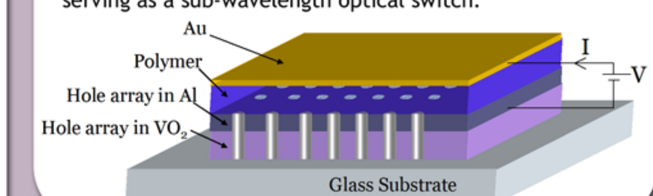


Therefore, in the metallic-VO_2 case, the comparatively low ε-contrast in the near-IR reduces those losses enough to allow the hole-array transmission to exceed that through the plain film.

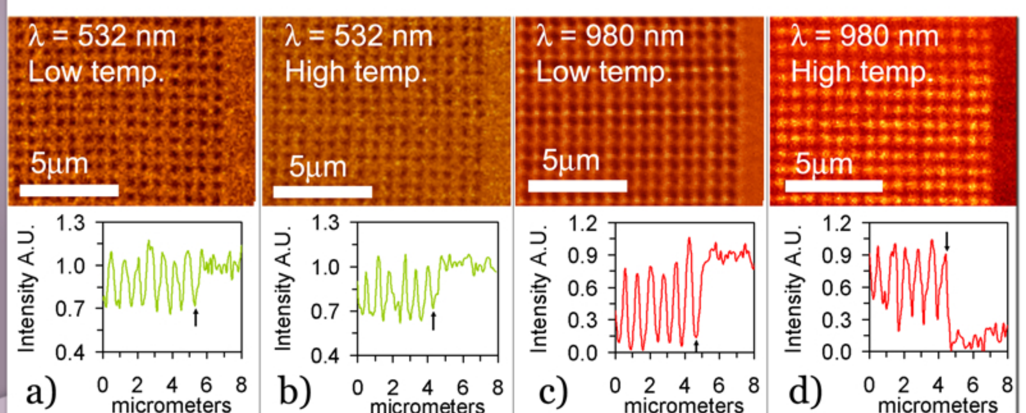
By the same token, the "reverse switching" of the double-layer hole arrays comes about because of the lower ε-contrast, hence smaller transmission losses, at near-IR wavelengths in the metallic phase with respect to the semiconducting phase of the VO_2 layer.

Application

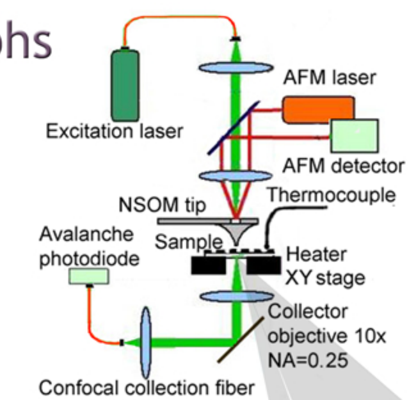
Recently, it was shown [6] that the electroluminescence efficiency of an organic light-emitting diode (OLED) can improve significantly by use of a perforated anode, which allows for light emission from both the back and the front of the device. An additional perforated VO_2 layer, as shown below, could enable the selective modulation of light emanating from an OLED or other light sources, in effect serving as a sub-wavelength optical switch.



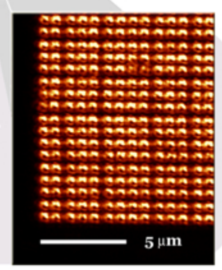
Near-field Scanning Optical Micrographs



NSOM images of far-field transmission through a VO_2 hole array, under near-field illumination, and corresponding plots of intensity *vs.* position along a section of a row of holes and extending into the plain-film area; the rightmost hole is indicated by an arrow in each plot. Only in the metallic phase and under near-IR light do the apertures appear brighter (i.e., transmit more) than the plain film.



The NSOM image on the right shows a Ag-VO_2 hole array: No light can traverse the optically thick Ag layer, so that transmission occurs only through the holes.



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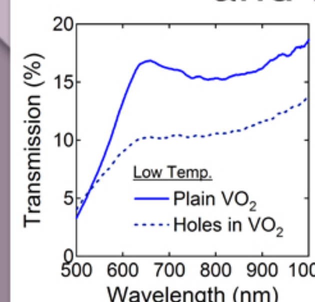
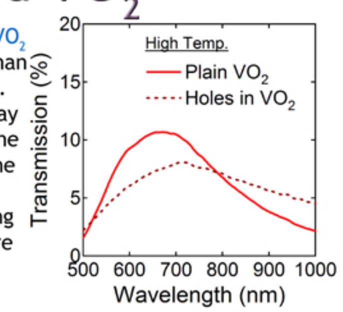
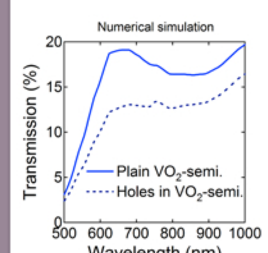
Transmission of Plain and Perforated VO_2

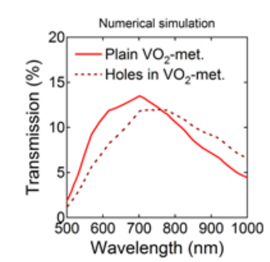


The semiconducting-VO_2 array transmits less than the plain film (left). The metallic-VO_2 array (right) transmits in the near-IR more than the plain film because losses from scattering and "leaky waves" are reduced.





The corresponding numerical simulations (left and right) show good qualitative agreement with the experimental results. Most importantly, they reproduce the near-IR transmission crossover in the metallic phase.



Our code solves the Maxwell equations as an eigenvalue problem via plane-wave decomposition, and propagates the solution across the different layers by means of *transfer matrices*, which contain the continuity conditions for electromagnetic field components at an interface. Hole arrays are represented by the Fourier transform of the piecewise dielectric permittivity.

References

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[6] C. Liu, V. Kamaev, and Z. V. Vardeny, Appl. Phys. Lett. **86** (2005).