PARAMETRIC STUDY OF MODULATED LIGHT TRANSMISSION THROUGH NANOSCALE HOLE ARRAYS

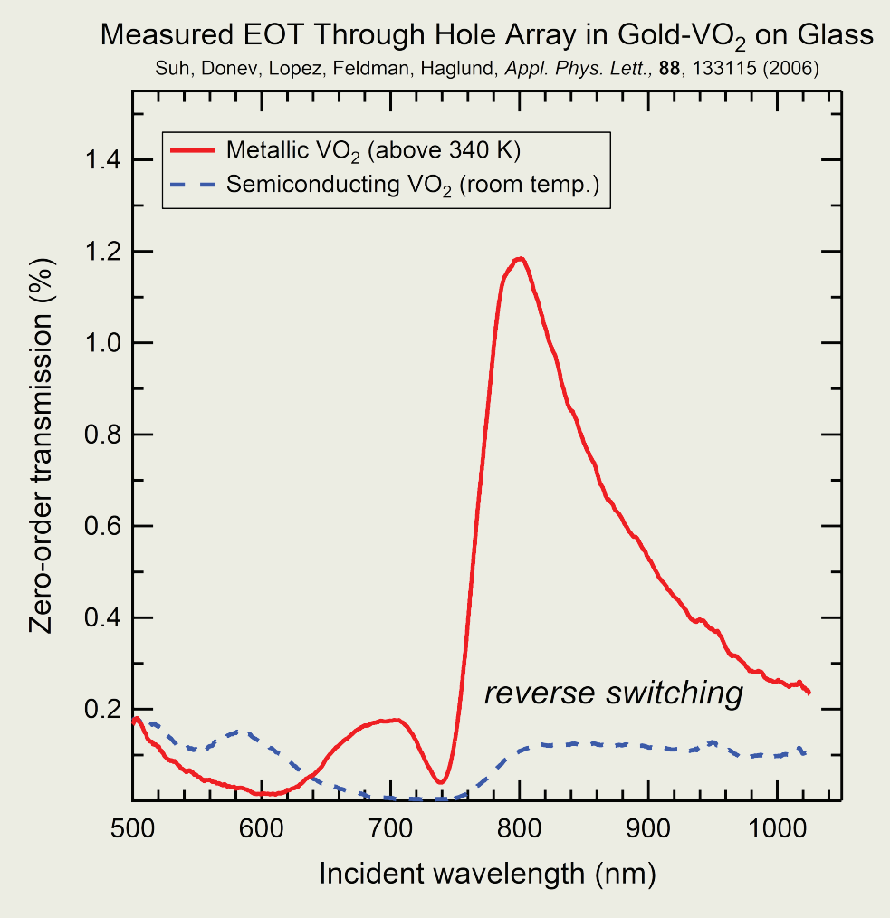
Alaa Adel Abdelhamid, Francis X. Hart, and **Eugenii U. Donev**
Department of Physics and Astronomy, Sewanee: The University of the South, Sewanee, Tennessee, USA

THE EOT EFFECT

Before the discovery of *extraordinary optical transmission* (EOT) in 1998, which spurred the field of plasmonics, subwavelength holes in optically thick (~200 nm) metal films were expected to let through very little light. However, periodic nanohole arrays in plasmonic films, esp. silver (Ag) and gold (Au), can far exceed the expected weak transmission at visible and infrared (IR) wavelengths. The EOT effect is caused primarily by the excitation, interference, tunneling and scattering of *surface-plasmon polaritons and quasi-cylindrical waves*. Typical EOT spectra show asymmetric peaks preceded by sharp minima—a hallmark of *Fano-type interference* between resonant and continuum transmission channels.

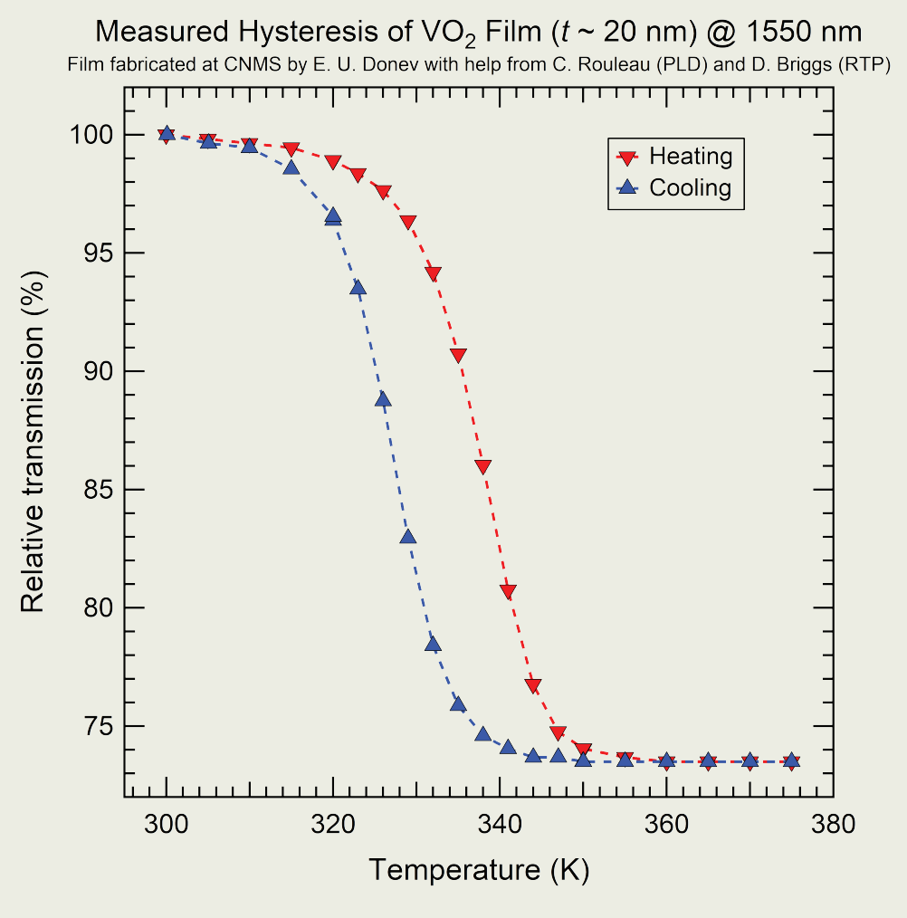
VO_2 AS EOT MODULATOR

The VO_2 phase transition is one of the few means to control the EOT effect dynamically. Previous experiments revealed a surprising effect, dubbed *reverse switching*, whereby Au+VO_2 and Ag+VO_2 nanohole arrays transmit more near-IR light when the VO_2 layer is in the metallic phase—opposite to what a plain VO_2 film does. The current study seeks to explore how the geometrical parameters of the array affect the reverse switching, and to understand its electromagnetic origins.


Measured EOT Through Hole Array in Gold-VO_2 on Glass
Suh, Donev, Lopez, Feldman, Haglund, *Appl. Phys. Lett.*, **88**, 133115 (2006)

VO_2 PHASE TRANSITION

Vanadium dioxide (VO_2) is a correlated-electron material that undergoes phase changes induced by temperature or light. Above 340 K (67 °C), VO_2 switches from a semiconductor to a ("bad") metal before switching back upon cooling with a hysteresis. Even a very thin plain (i.e., no holes) film is much opaquer to IR light in the metallic phase than in the semiconducting phase.

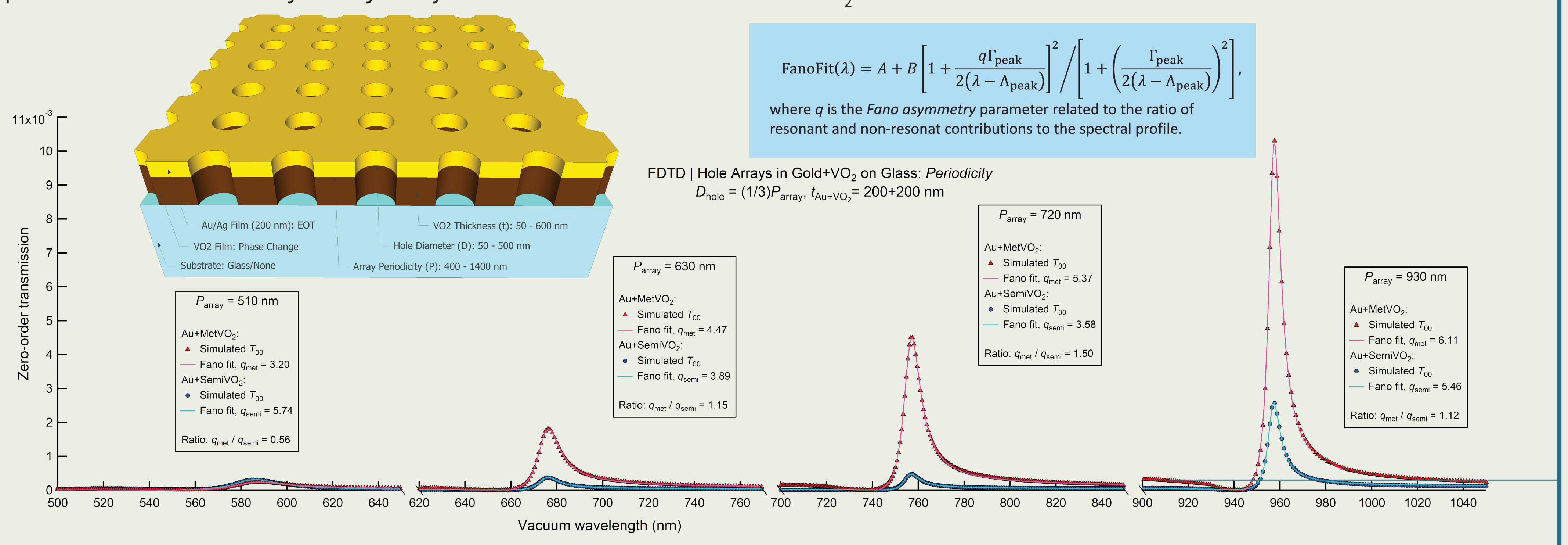

Measured Hysteresis of VO_2 Film (t ~ 20 nm) @ 1550 nm
Film fabricated at CNMS by E. U. Donev with help from C. Rouleau (PLD) and D. Briggs (RTP)

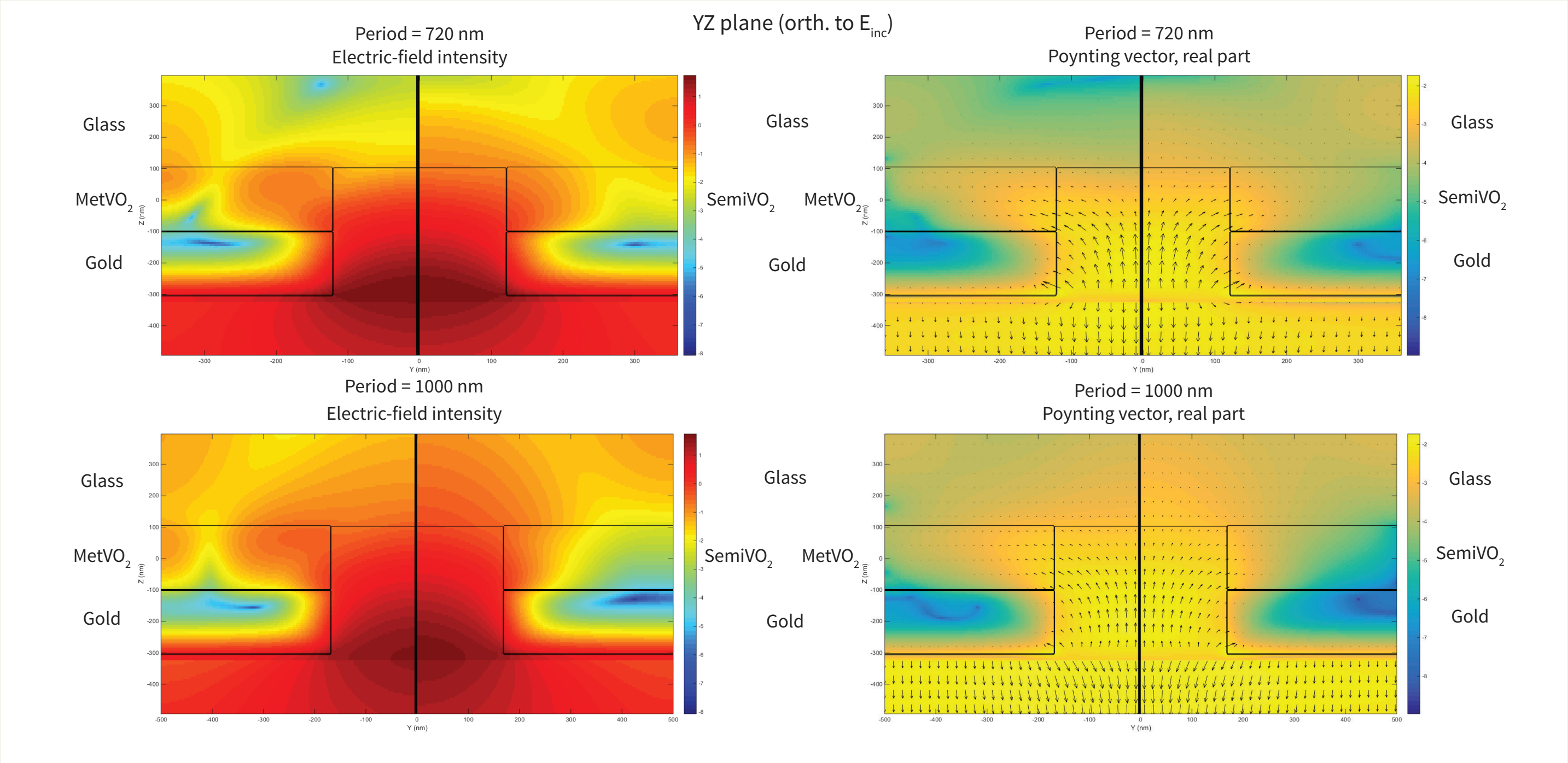
FULL-WAVE 3D NUMERICAL SIMULATIONS

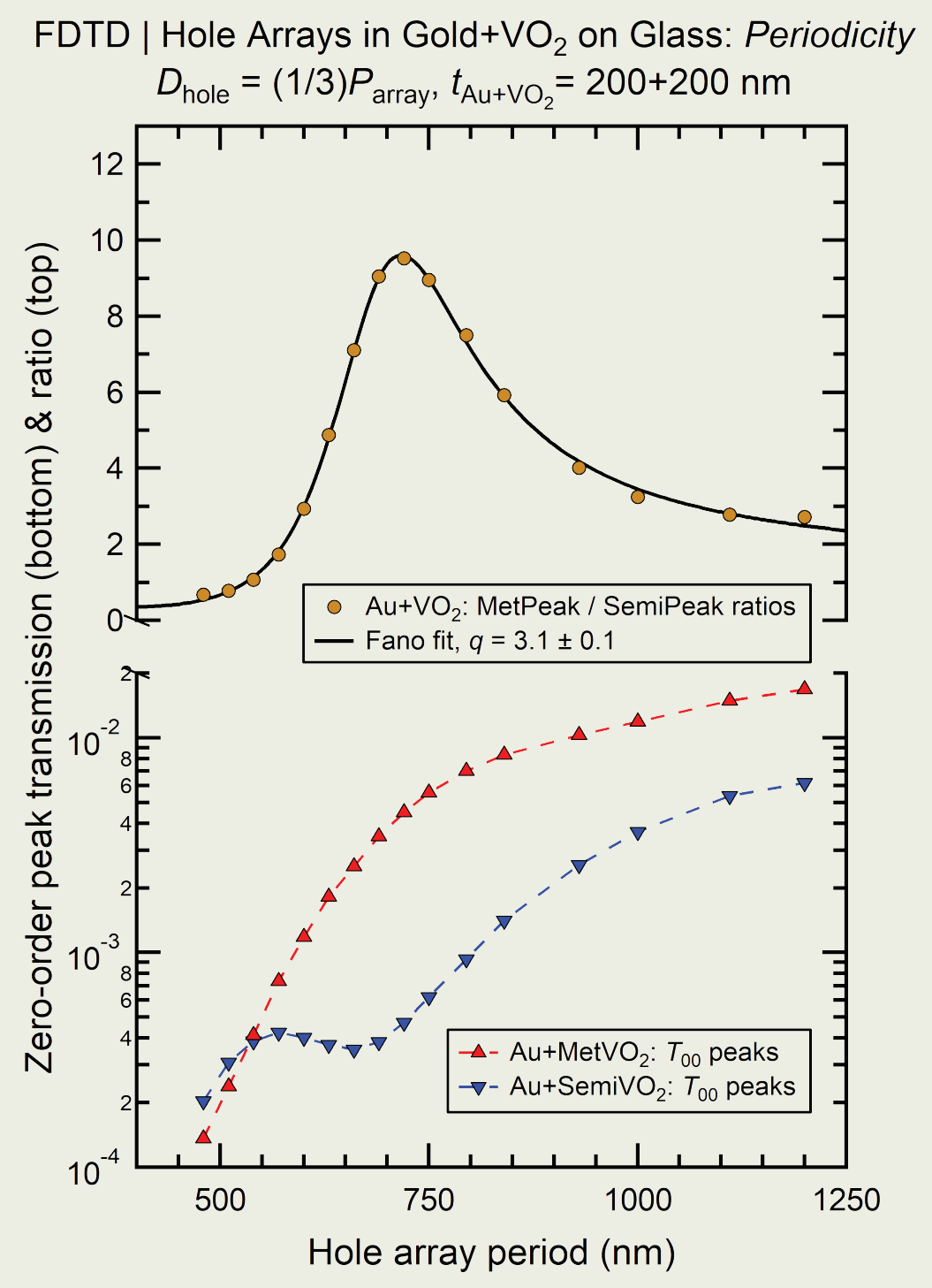
Using the *finite-difference time-domain* (FDTD; Lumerical) method and *finite-element method* (FEM; COMSOL Multiphysics), we have simulated the optical response of nanohole arrays in bilayer films of Au+VO_2 and Ag+VO_2 while varying the periodicity (P), hole diameter (D), VO_2 thickness (t). In the process, we uncovered intriguing "meta-Fano" trends in the ratios of the transmission peaks for the two VO_2 phases, implying interactions between resonant and non-resonant contributions to the modulation mechanism. We suspect that a competition between field penetration and absorption causes a pronounced dip in the transmission of the semiconducting VO_2 within a narrow range of each geometrical parameter. We also identify a lossy Fabry-Perot resonance with variation in VO_2 thickness.

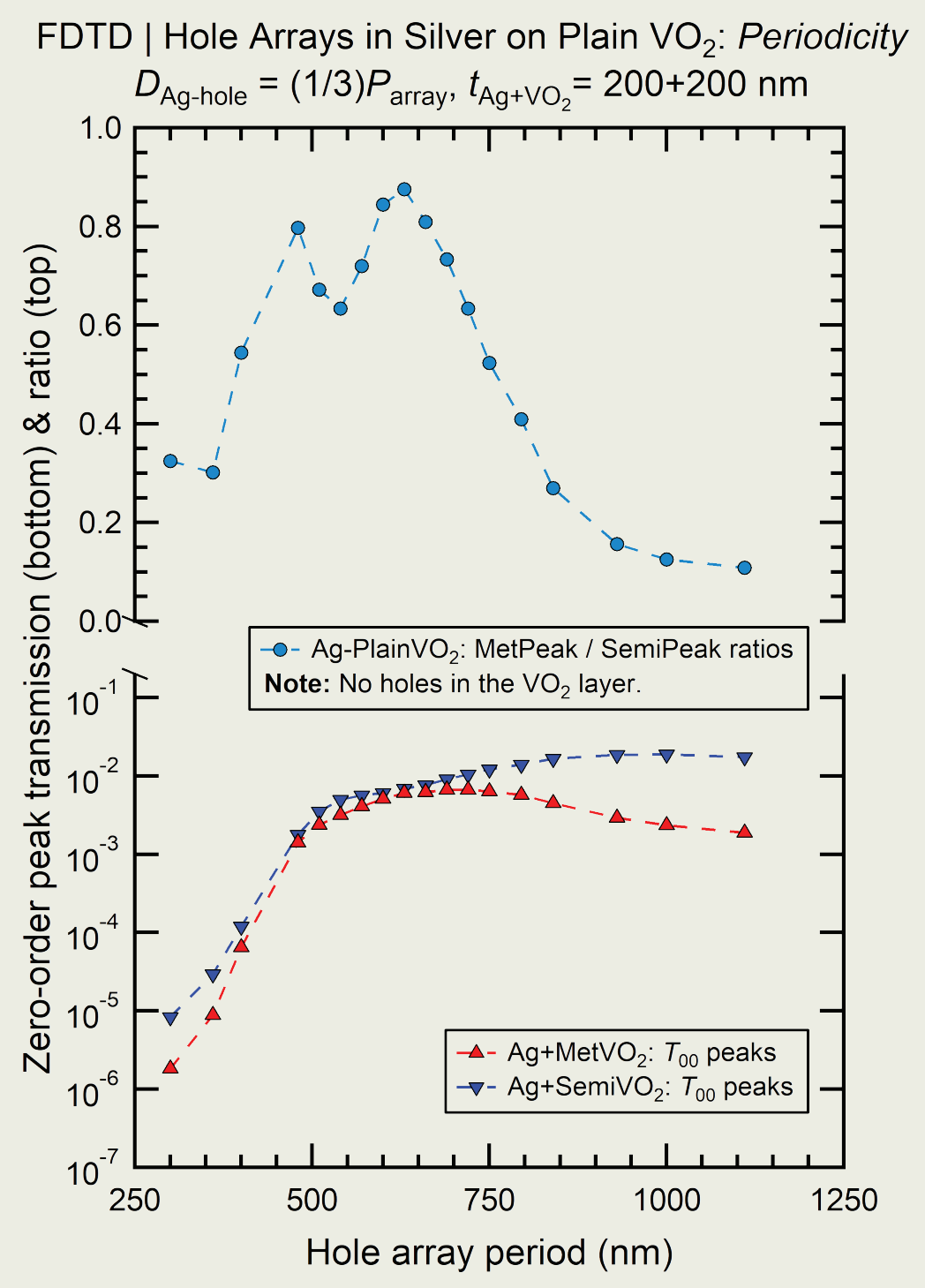
$$\mathrm{FanoFit}(\lambda) = A + B\left[1+\frac{q\Gamma_{\text{peak}}}{2(\lambda-\Lambda_{\text{peak}})}\right]^2 \Bigg/ \left[1+\left(\frac{\Gamma_{\text{peak}}}{2(\lambda-\Lambda_{\text{peak}})}\right)^2\right],$$

where q is the *Fano asymmetry* parameter related to the ratio of resonant and non-resonat contributions to the spectral profile.


FDTD | Hole Arrays in Gold+VO_2 on Glass: *Periodicity*
$D_{\text{hole}} = (1/3)P_{\text{array}}$, $t_{\text{Au+VO}_2} = 200+200$ nm



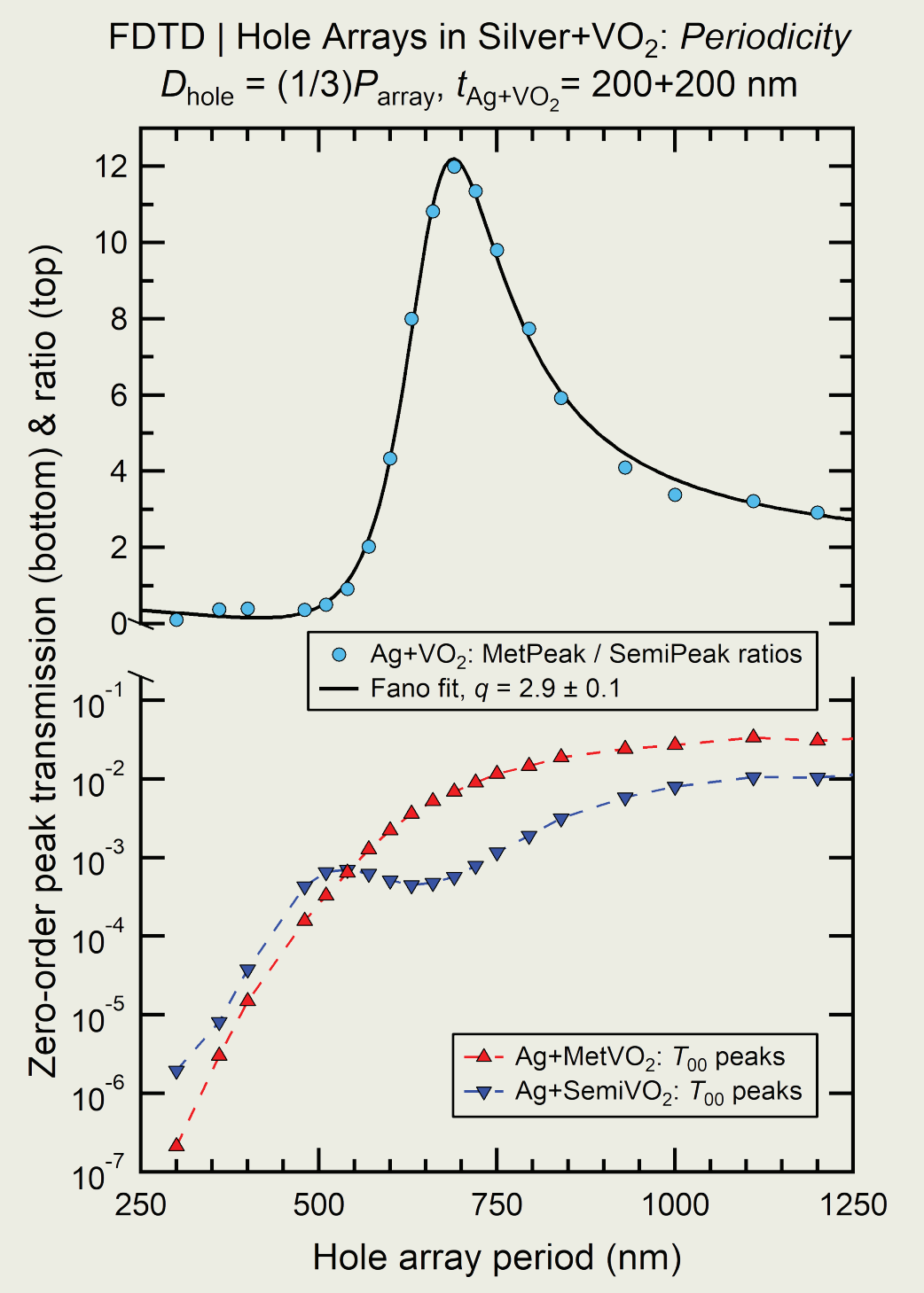

FDTD | Hole Arrays in Gold+VO_2 on Glass: *Periodicity*
$D_{\text{hole}} = (1/3)P_{\text{array}}$, $t_{\text{Au+VO}_2} = 200+200$ nm

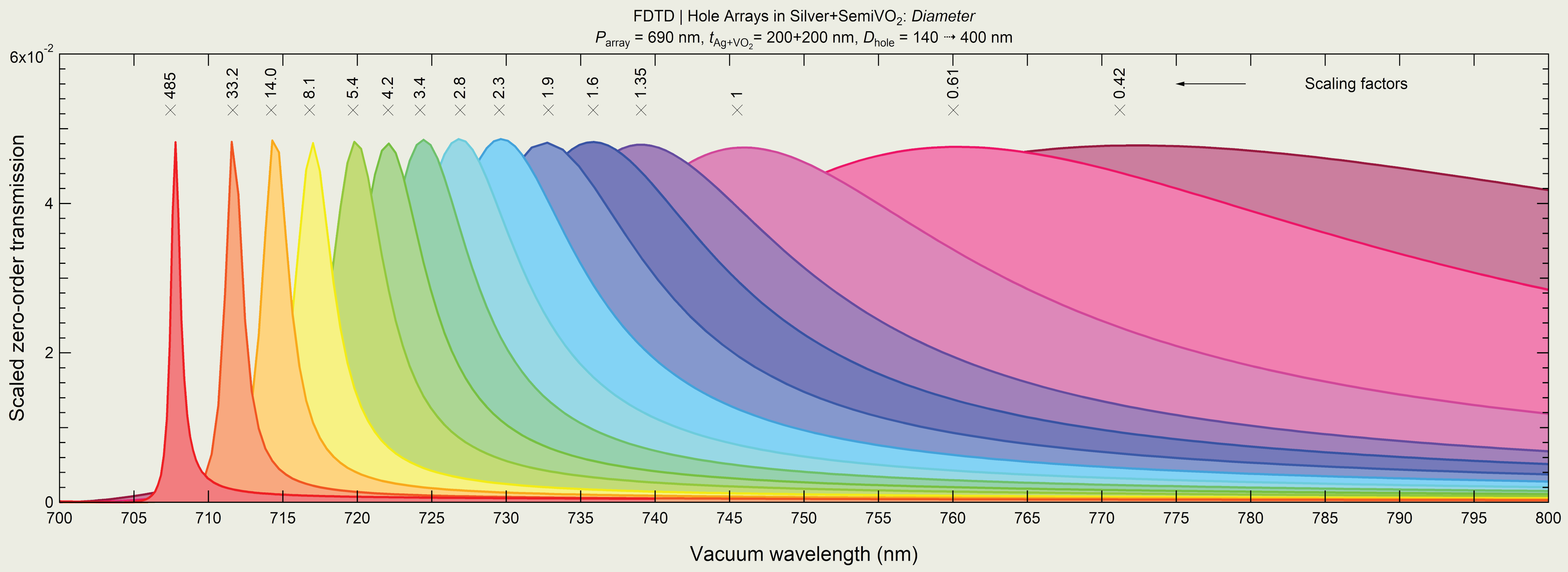

FDTD | Hole Arrays in Silver on Plain VO_2: *Periodicity*
$D_{\text{Ag-hole}} = (1/3)P_{\text{array}}$, $t_{\text{Ag+VO}_2} = 200+200$ nm

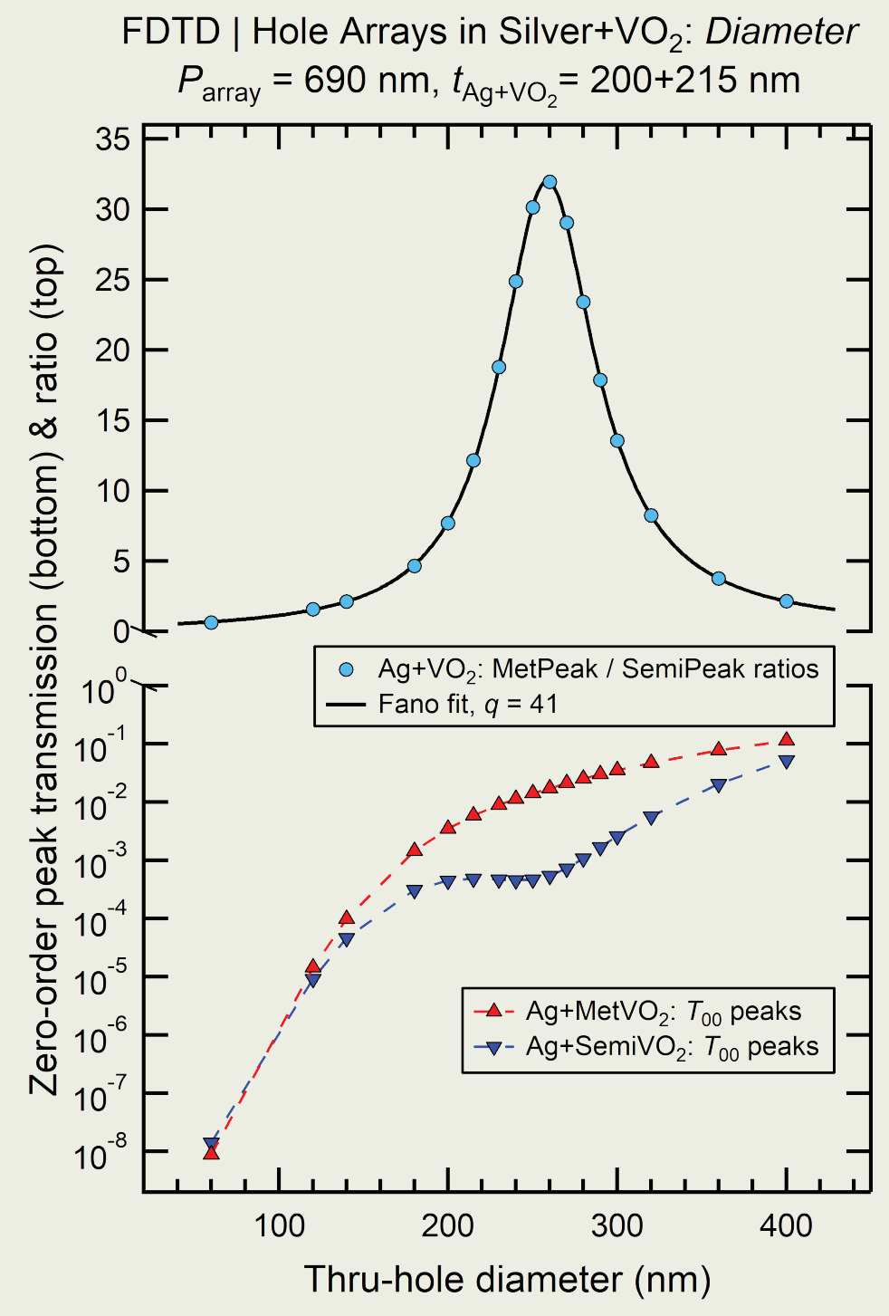
VARYING ARRAY PERIODICITY

As the period of the hole array in Au+VO_2 or Ag+VO_2 increases, the ratio of the EOT peak transmission T_{00} in the metallic phase (MetVO_2) rises sharply and then decreases relative to the semiconducting phase (SemiVO_2). The images of the electric-field intensity and Poynting vector in YZ plane (orthogonal to the incident polarization) show the extent of penetration of the evanescent waves into the VO_2 layer. The peak ratios as a function of hole period follows very closely a Fano-type profile with either plasmonic metal, with or without a substrate.

Intriguingly (see left figure for Ag+PlainVO_2), when the holes perforate only the plasmonic metal but not the VO_2 layer, the peak transmission in the semiconducting phase exceed that in the metallic phase for all array periods.

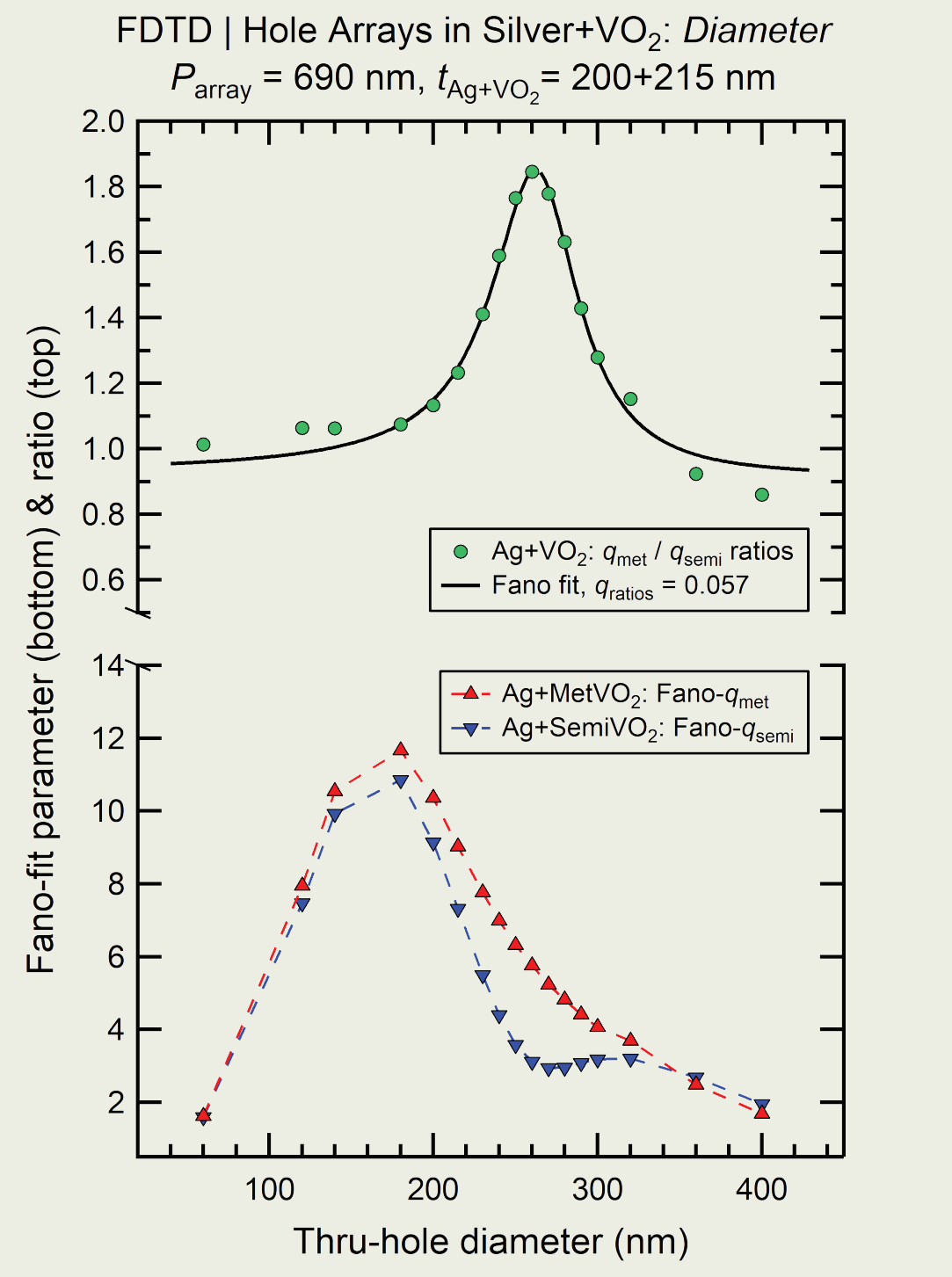

FDTD | Hole Arrays in Silver+VO_2: *Periodicity*
$D_{\text{hole}} = (1/3)P_{\text{array}}$, $t_{\text{Ag+VO}_2} = 200+200$ nm

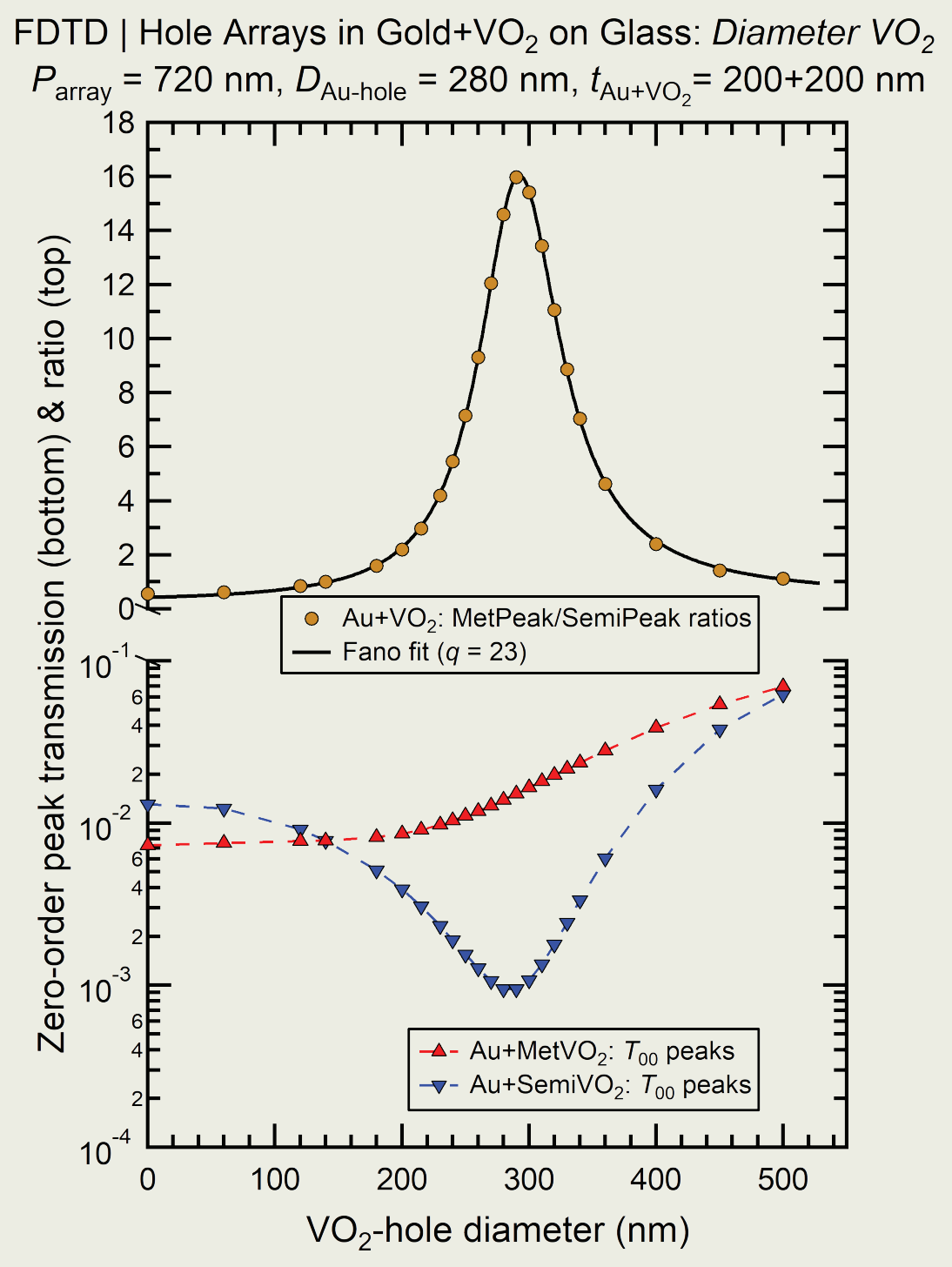

FDTD | Hole Arrays in Silver+SemiVO_2: *Diameter*
$P_{\text{array}} = 690$ nm, $t_{\text{Ag+VO}_2} = 200+200$ nm, $D_{\text{hole}} = 140 \rightarrow 400$ nm


FDTD | Hole Arrays in Silver+VO_2: *Diameter*
$P_{\text{array}} = 690$ nm, $t_{\text{Ag+VO}_2} = 200+215$ nm

VARYING THRU-HOLE DIAMETER

Increasing the diameter of the holes that perforate both the plasmonic metal (Au or Ag) and VO_2 layers results in higher, broader and redshifted T_{00} peaks, as expected. What is unexpected is that the ratio of the peak transmission in the metallic phase (MetVO_2) relative to that in the semiconducting phase (SemiVO_2) itself peaks for a hole diameter around 250 nm, before falling off toward unity. This diameter corresponds to a dip in the SemiVO_2 transmission. A Fano profile fits well to the T_{00} ratio, though with a weak asymmetry. However, the ratio of Fano parameters q from the fits to the individual T_{00} spectra has a more asymmetric shape; the corresponding "meta-Fano" fit (i.e., a Fano fit to Fano-q ratios) is also shown.

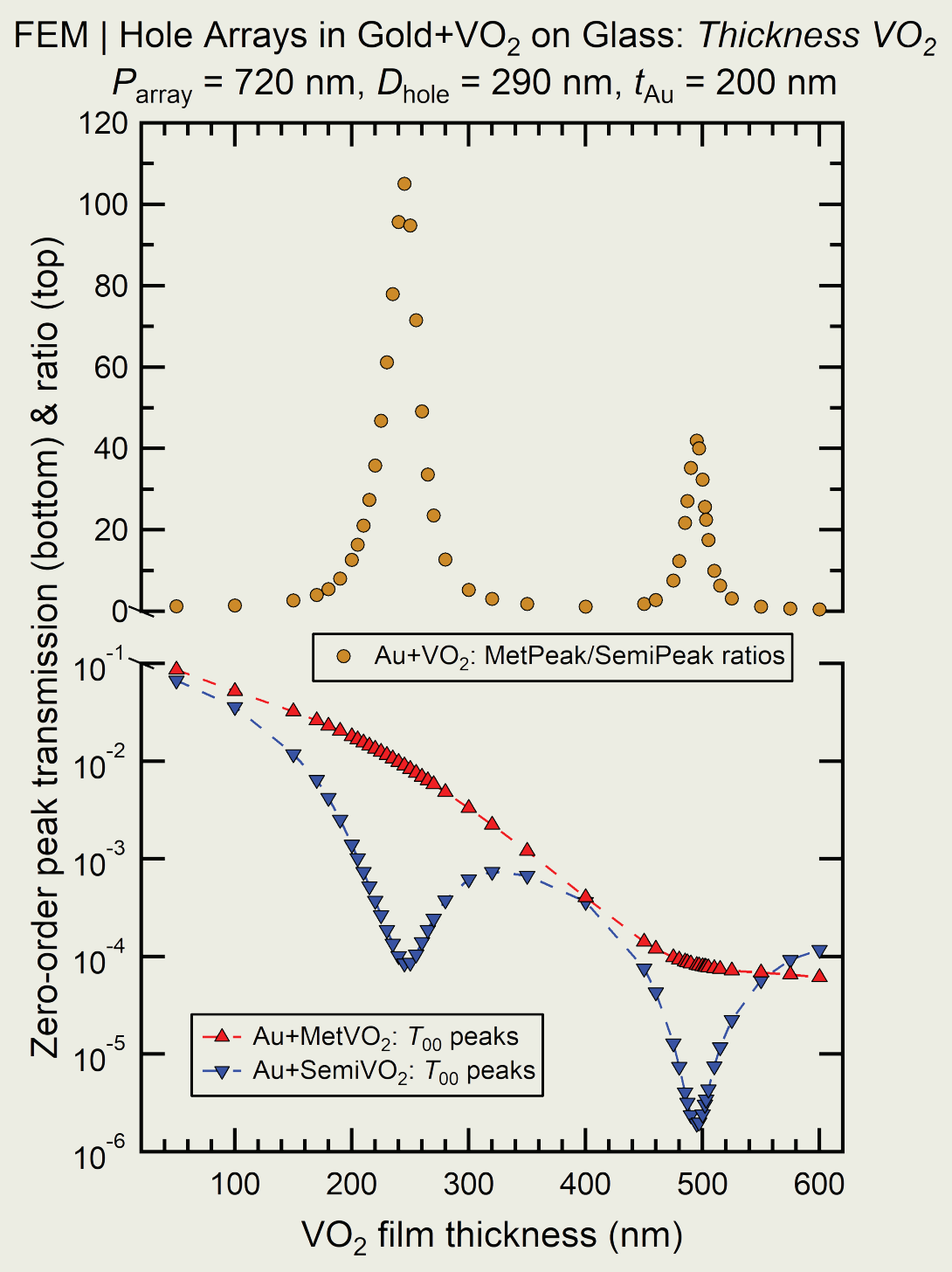

FDTD | Hole Arrays in Silver+VO_2: *Diameter*
$P_{\text{array}} = 690$ nm, $t_{\text{Ag+VO}_2} = 200+215$ nm

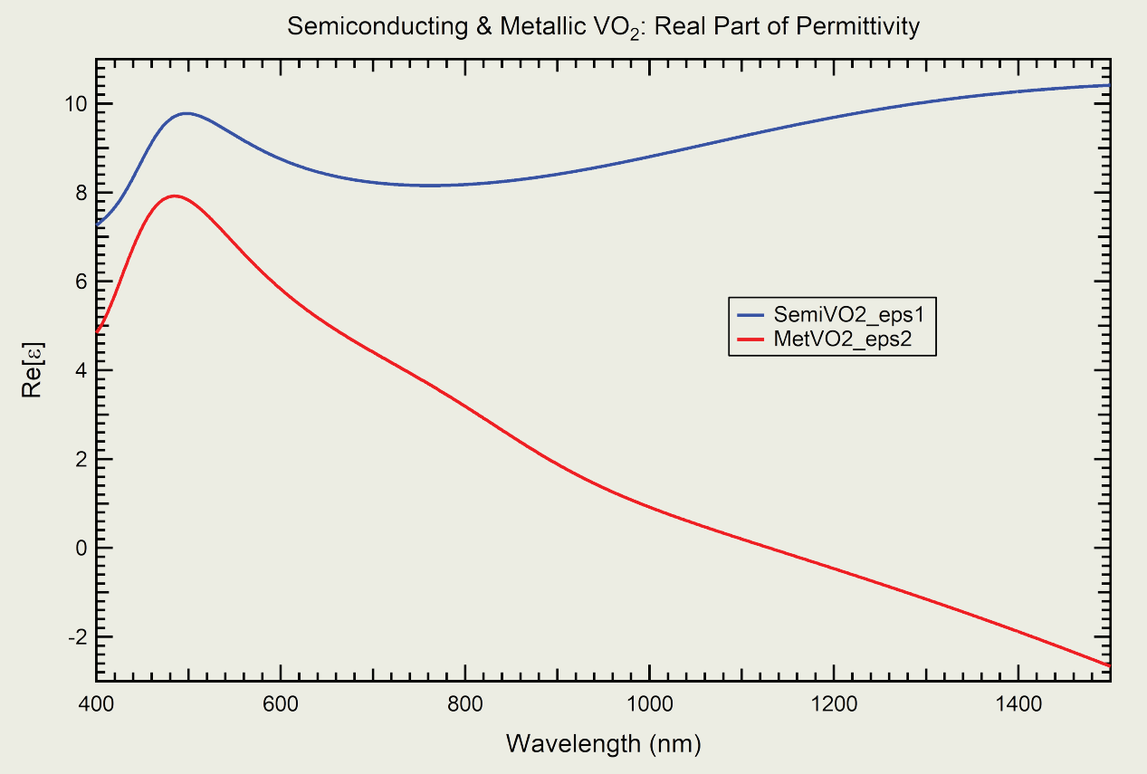

FDTD | Hole Arrays in Gold+VO_2 on Glass: *Diameter VO_2*
$P_{\text{array}} = 720$ nm, $D_{\text{Au-hole}} = 280$ nm, $t_{\text{Au+VO}_2} = 200+200$ nm

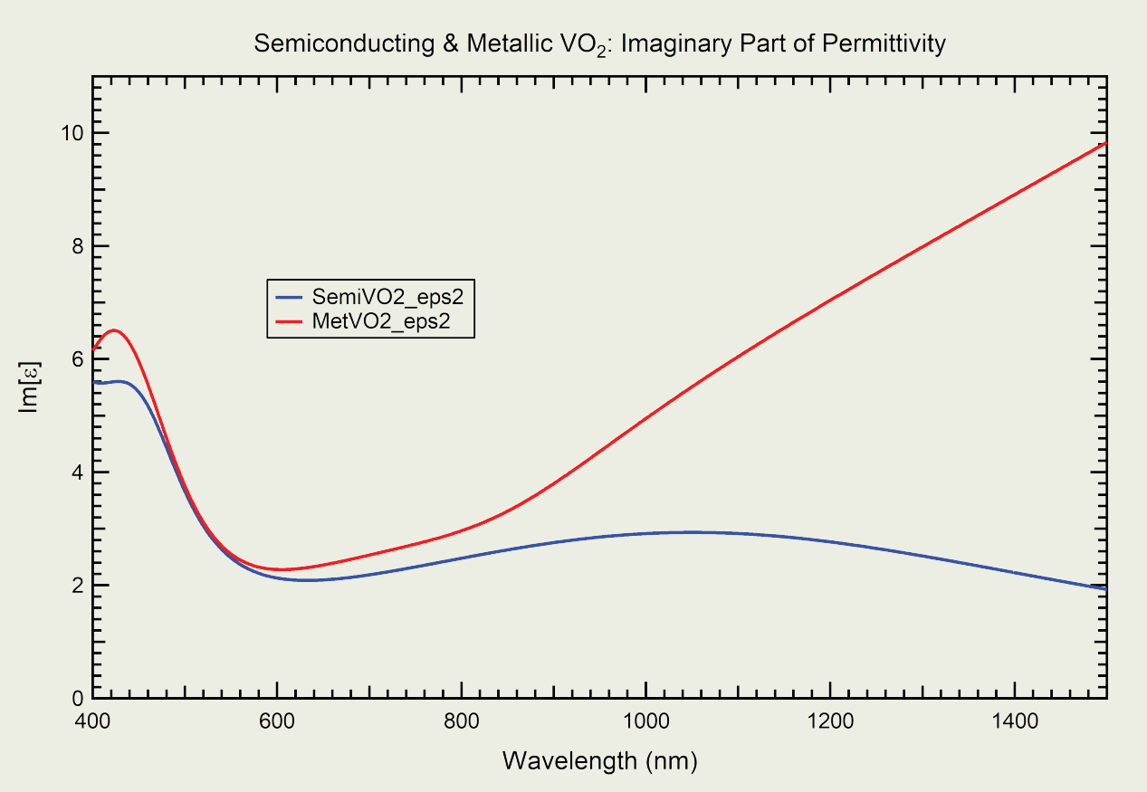
VARYING VO_2 HOLE DIAMETER OR FILM THICKNESS

A similar barely-asymmetric Fano profile fits the MetVO_2-to-SemiVO_2 ratio of T_{00} peaks for a fixed hole diameter in the plasmonic layer and a variable hole diameter in the VO_2 layer. In this case the peaks broaden and redshift much less than in the thru-hole case because the spectral profiles are largely determined by the Au or Ag (fixed period and diameter) due to the EOT effect, whereas the VO_2 modulates mostly the transmission intensity. For the larger VO_2 holes, light emerging from the Au/Ag holes does not reach deep into the VO_2 material, so the effect of the different optical constants of the two VO_2 phases is relatively small, hence the ratio approaches unity.

When the thickness of the VO_2 layer is increased from zero, the T_{00} ratio exhibits sharp symmetric peaks of diminishing amplitude, indicative of lossy Fabry-Perot resonances. Once again, as with variations in the array period and hole diameter, it is the semiconducting phase that behaves differently: The transmission dips in a narrow range around a specific thickness/period/diameter.


FEM | Hole Arrays in Gold+VO_2 on Glass: *Thickness VO_2*
$P_{\text{array}} = 720$ nm, $D_{\text{hole}} = 290$ nm, $t_{\text{Au}} = 200$ nm


Semiconducting & Metallic VO_2: Real Part of Permittivity


Semiconducting & Metallic VO_2: Imaginary Part of Permittivity

WHAT'S GOING ON?

Of course, the VO_2-induced modulation in the EOT through Au/Ag+VO_2 hole arrays can be traced back to the markedly different optical constants of the two VO_2 phases. The FDTD and FEM electromagnetic simulations reveal intriguing transmission trends—'reverse switching' of T_{00} peaks and Fano-type profiles of peak ratios—but an explanation based on physical intuition remains elusive. We "wave hands" that the optimal parameters for maximizing the modulation are those for which the penetration of evanescent waves into the VO_2 film is least/most impeded by dissipation in the metallic/semiconducting phase. The goal of the CNMS portion of this project is to fabricate and test some of the simulated hole arrays to determine whether the Fano-type trends that seem so sensitive to the geometric parameters can survive under real-world experimental conditions (e.g., conical hole shape, surface roughness, and different optical constants). This work is currently underway at CNMS.

ACKNOWLEDGEMENTS

E. U. Donev gratefully acknowledges the support of CNMS staff members, especially Dayrl Briggs, Dale Hensley, Leslie Wilson, Jason Fowkes and Chris Rouleau, whose generously shared time and expertise with nanofabrication and characterization tools and techniques has been instrumental to the progress of this project (CNMS2019-171). E. U. Donev also thanks CNMS and ORNL overall for making this work possible.