Resonant Dust: IR Targets for Tagging and Identification

**Marc L. Simpson, D.P. Hutchinson,
R.K. Richards, J.T. Simpson,
J.O. Caughman**

Oak Ridge National Laboratory

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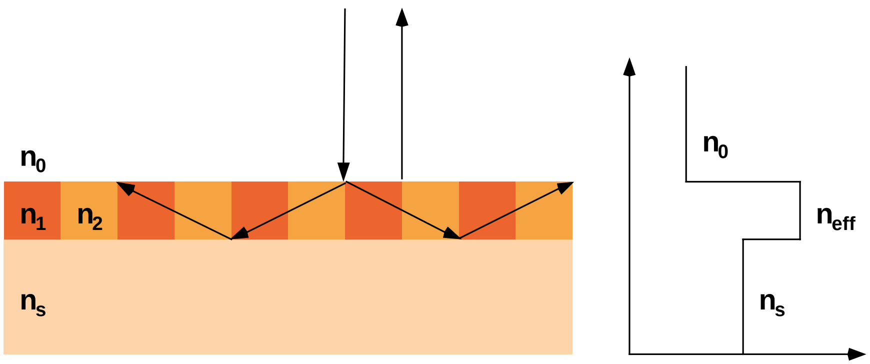
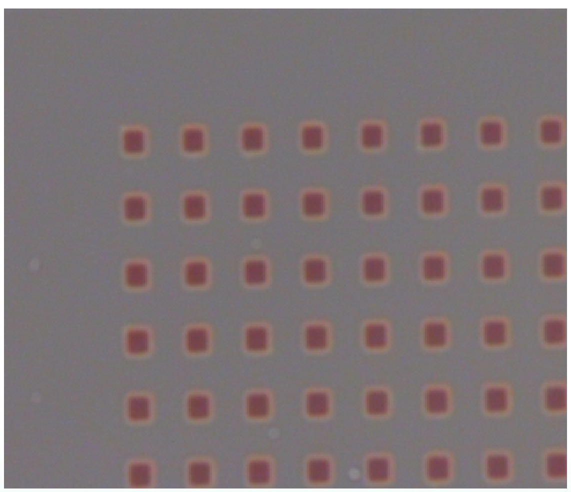
Outline of Talk

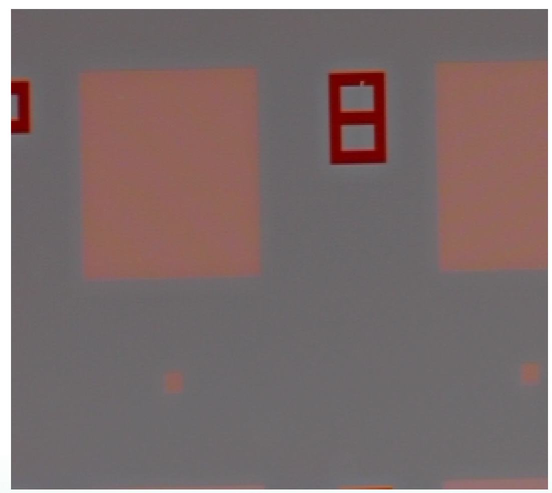
- Overview of tags using subwavelength structures (SWS)
- Embedded structures
  - Photonic bandgap crystals (small holes)
  - Subwavelength structures (small posts)
- Guided mode resonant filters (surface 1D subwavelength gratings)
- Resonant Dust (2D structures…how small??)
- Detection/interrogation
- Future areas of interest (smarter dust)

All-weather IR Tag: Resonant Dust

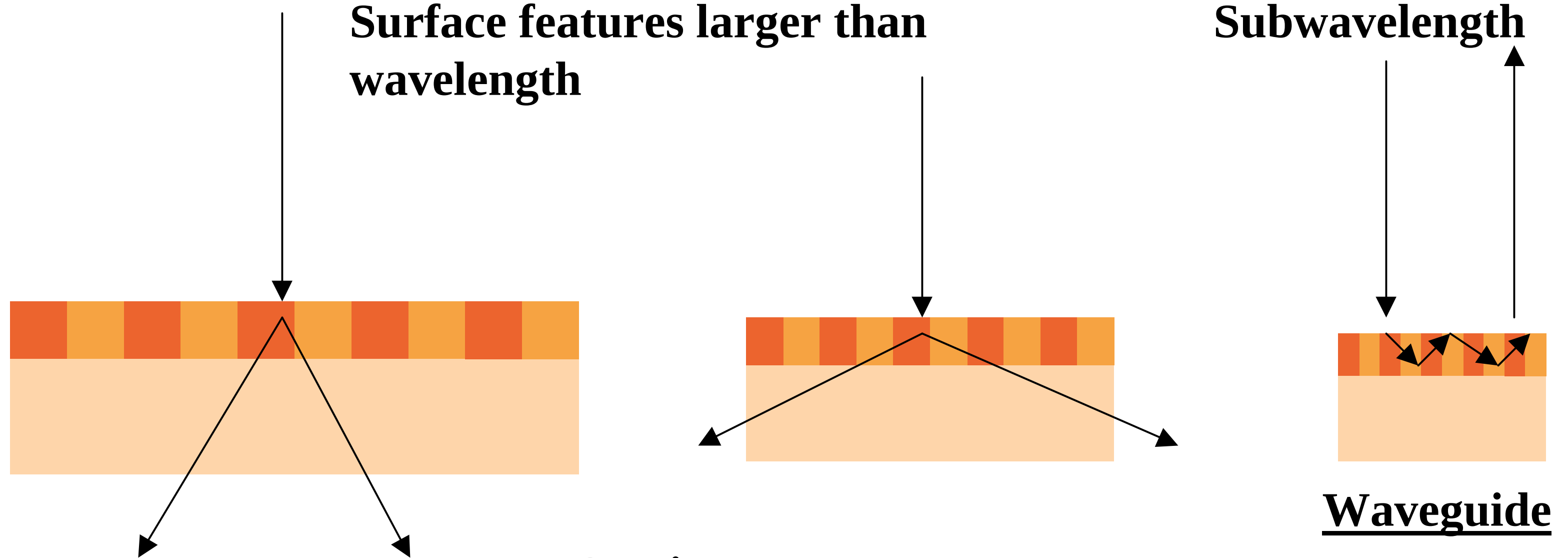


- Small “dust-like particles
- Customized to be sensitive at single wavelengths (LWIR)
- Possible sensitivity to presence/absence of various substances





As Surface Features Get Smaller than the Wavelength of Incident Light, Layer Becomes a Waveguide



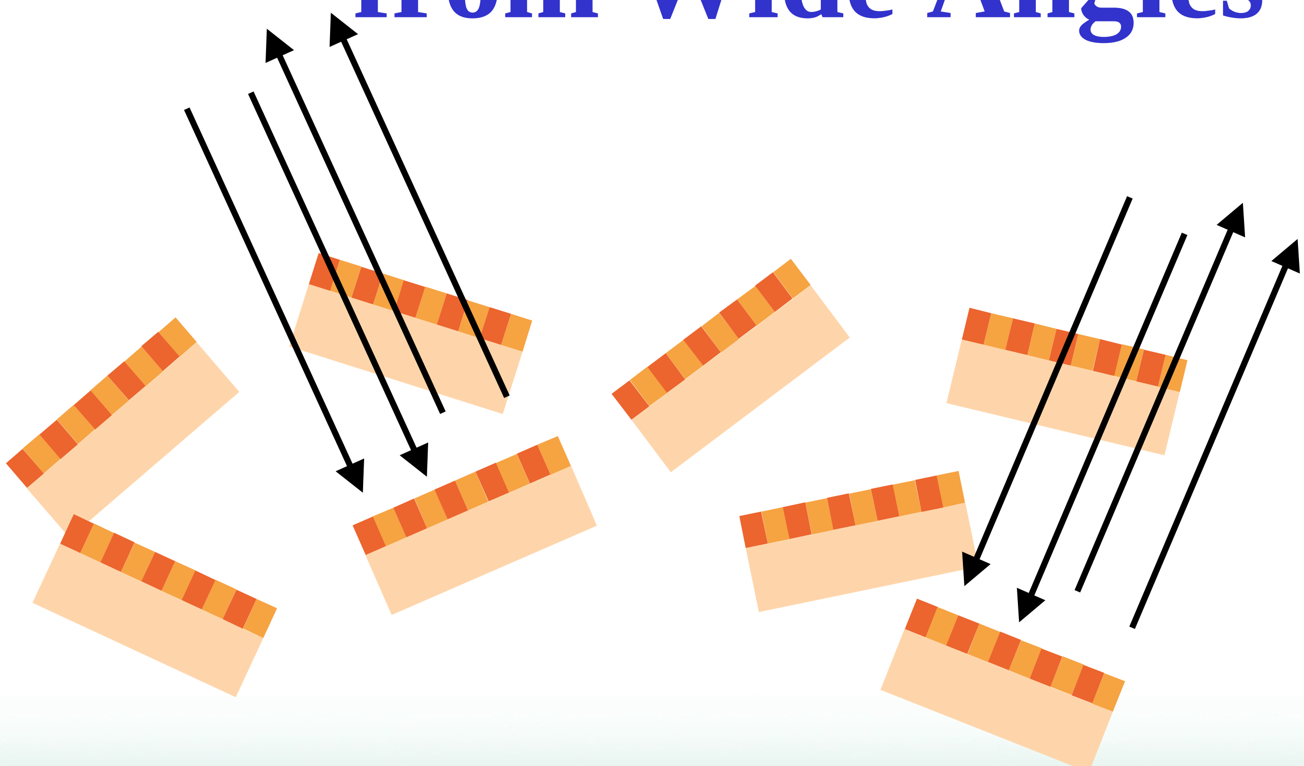
Grating

Low reflectivity:
Multiple diffractive orders transmitted

Waveguide

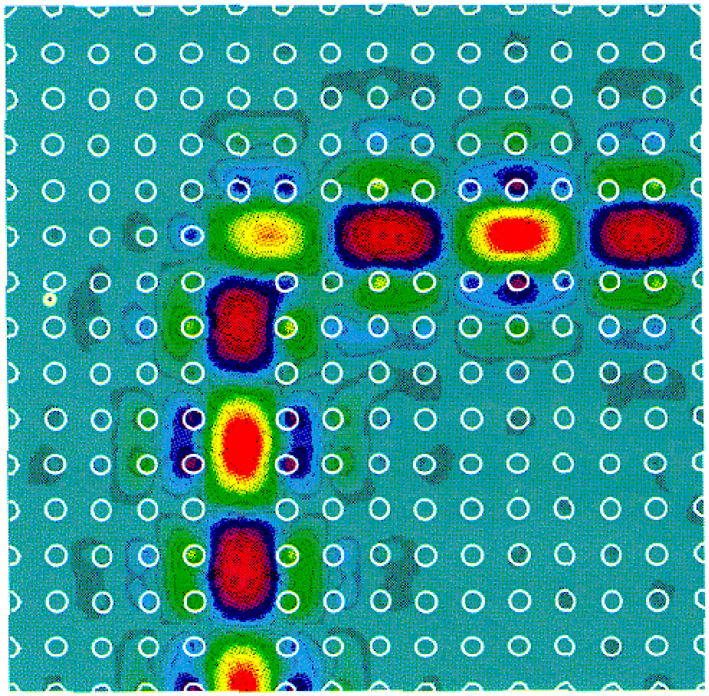
High reflectivity:
Entrance and exit conditions match

Key to Resonant Dust: Random Orientation Provides Signal Return from Wide Angles

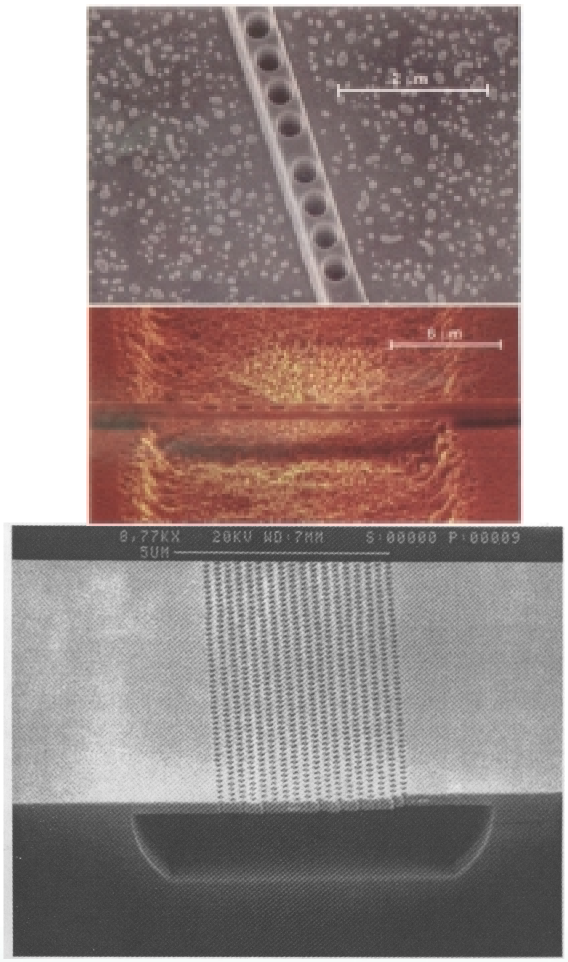


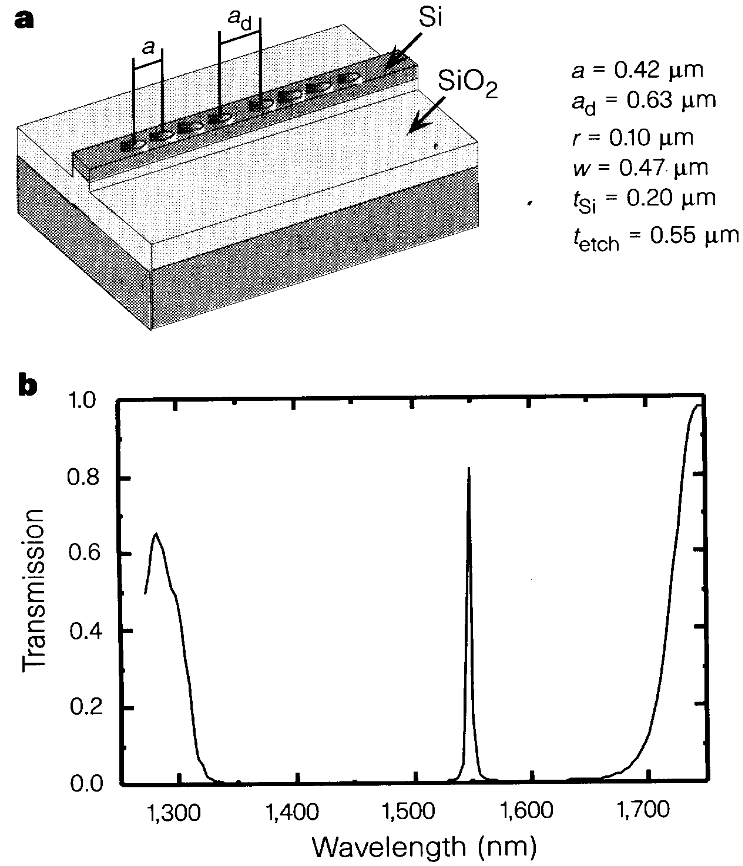
Research in Photonic Bandgap Crystals Involve Features Smaller than a Wavelength

- **Periodic structures of holes with "defect"**
- **Results in "Bandgap" or wavelengths not allowed outside defect region**
- **Low loss transmission or high efficiency filters in waveguides**

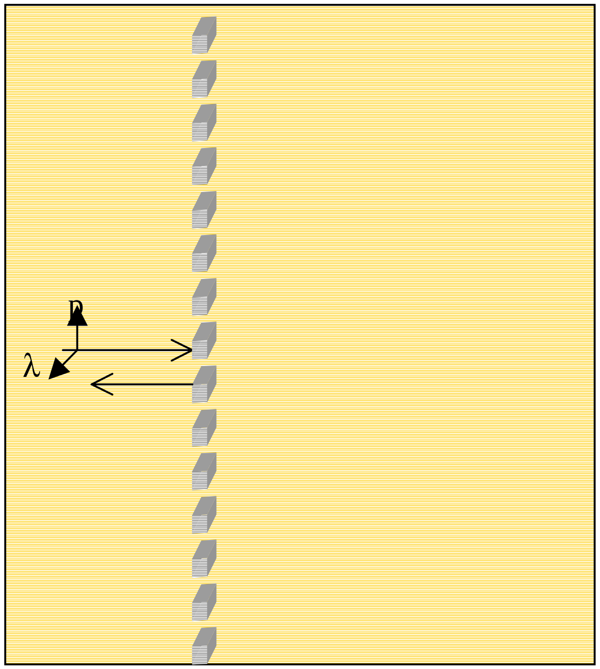


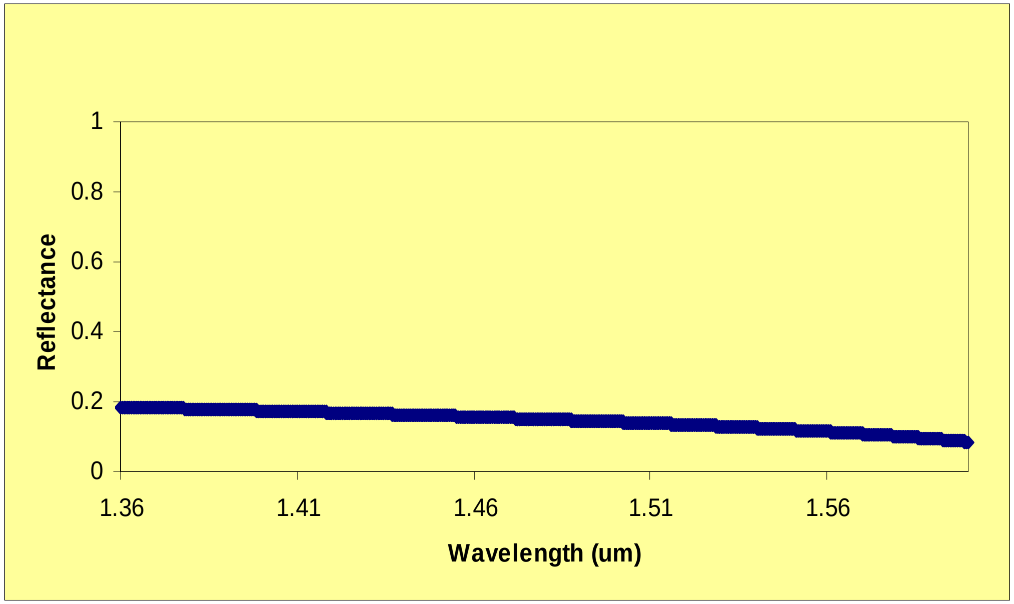
Photonic-Band-Gap (PBG) Devices Based on Arrays of Holes can Guide and Filter Light.



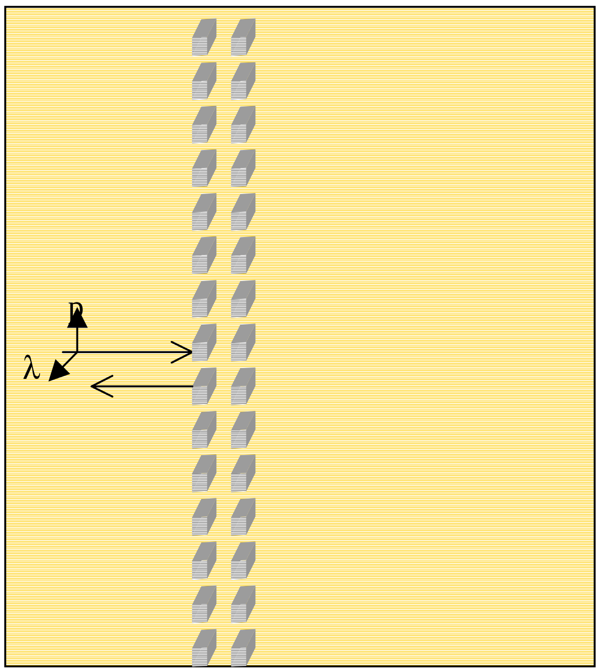


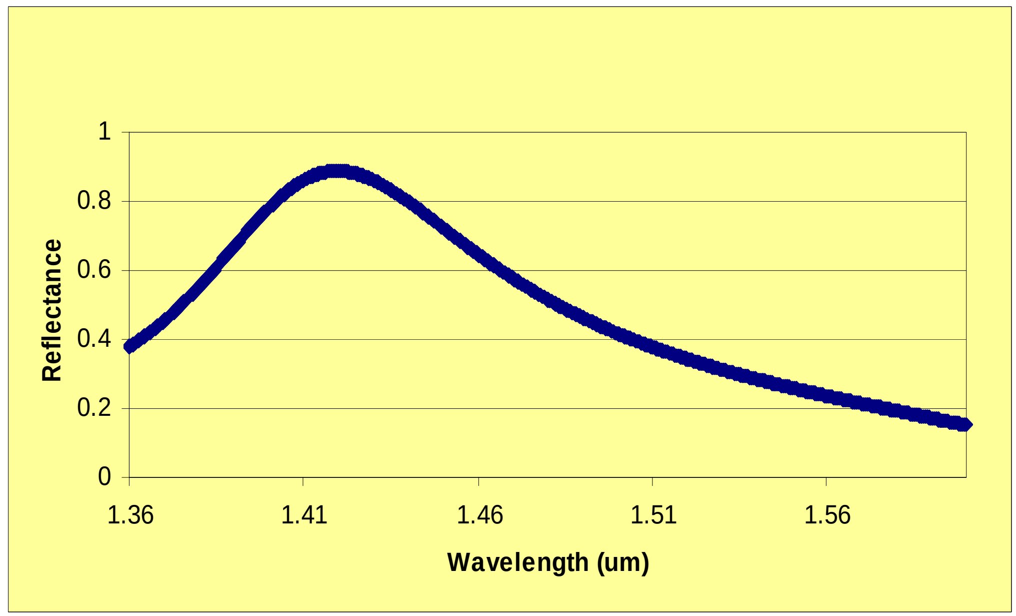
Reflectance from an Infinite Row of Holes (silicon waveguide) Modeled with Rigorous Coupled Wave Analysis



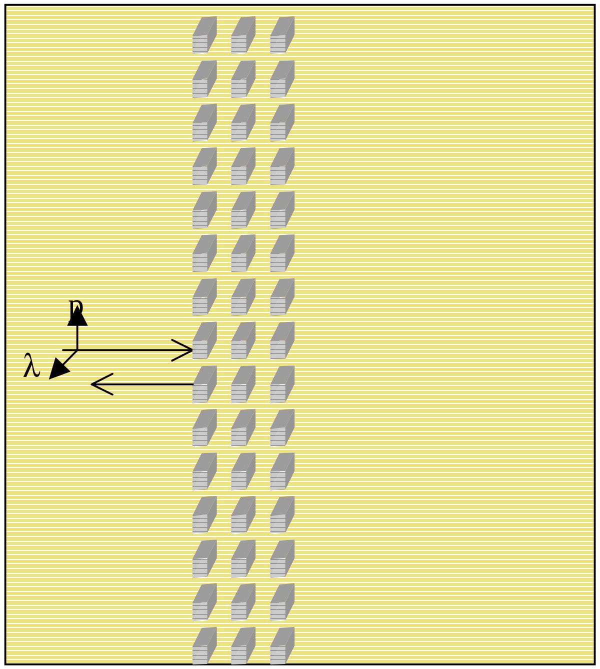


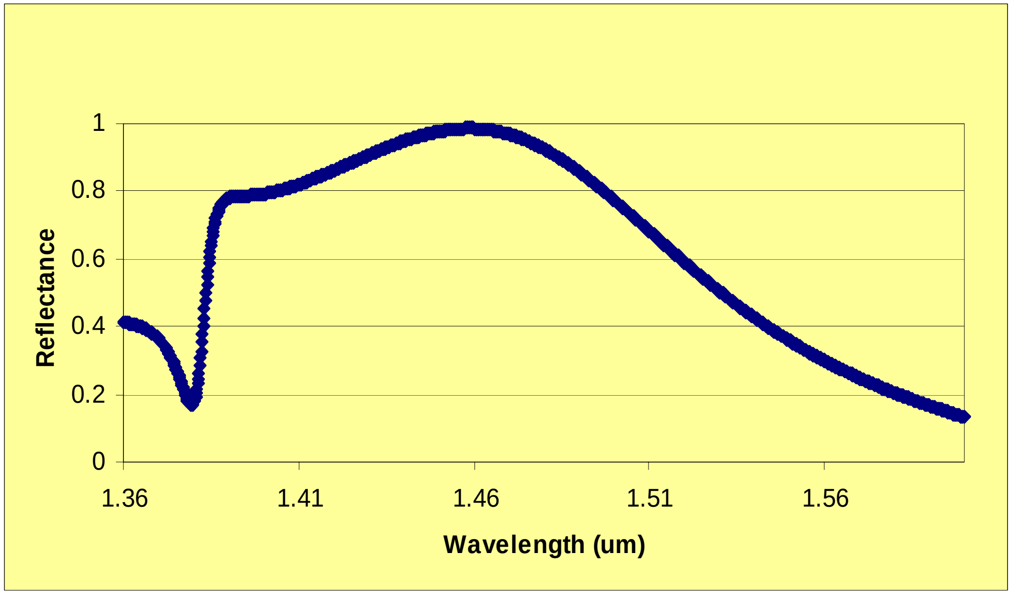
Reflectance from Two Infinite Rows of Holes



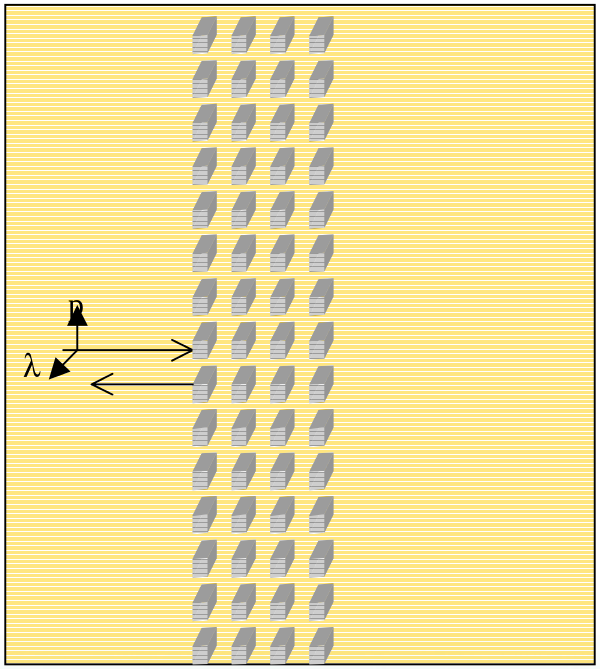


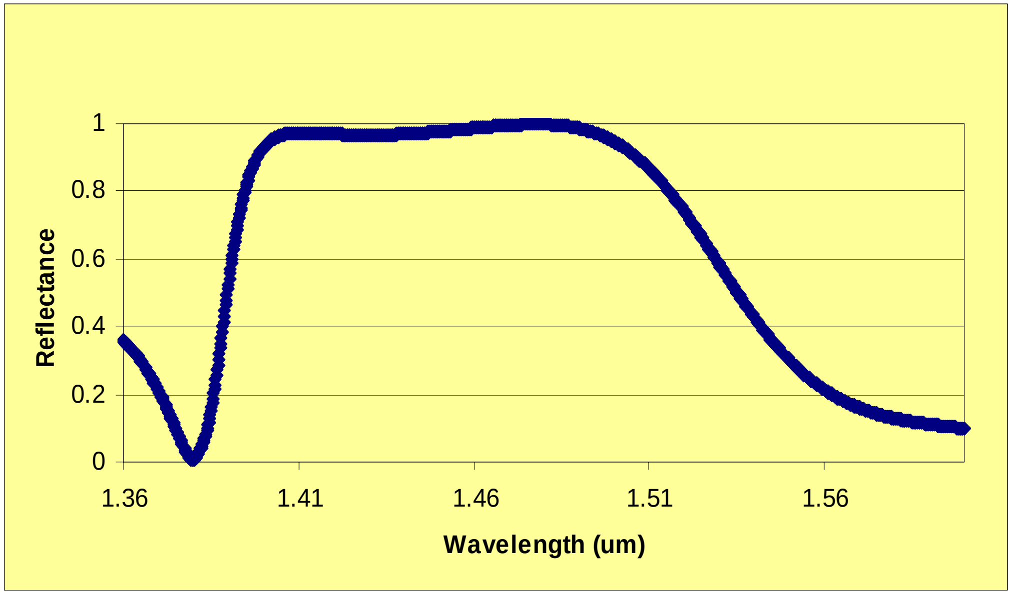
Reflectance from Three Infinite Rows of Holes



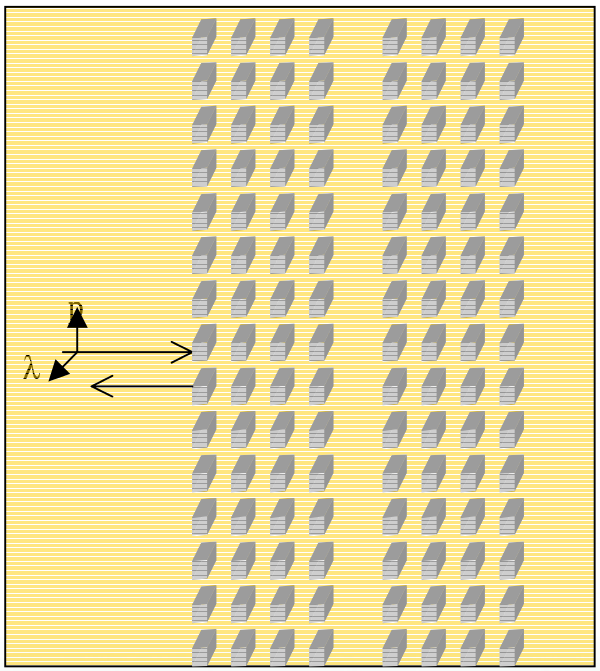


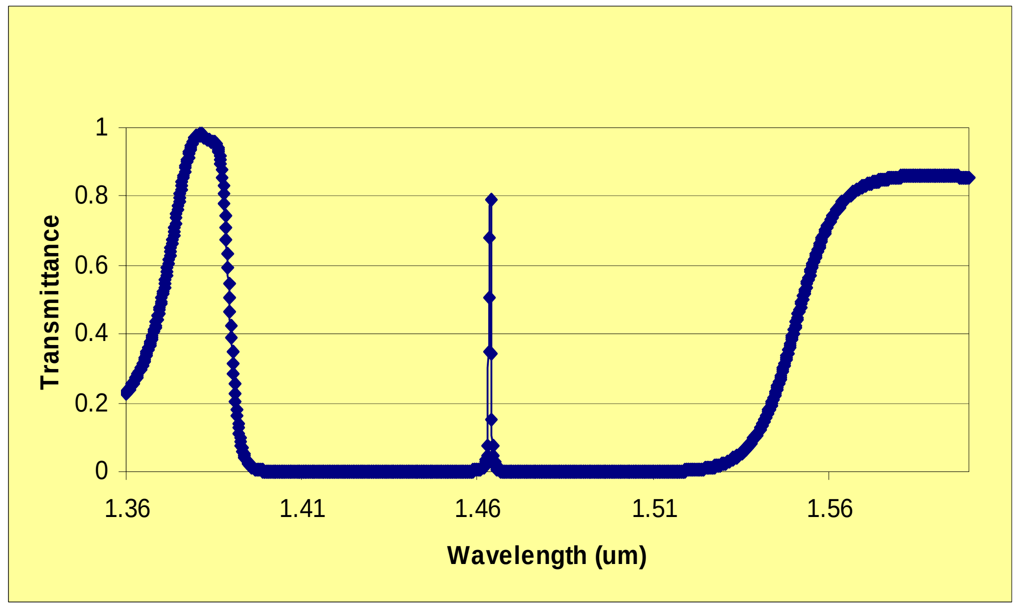
Reflectance from Four Infinite Rows of Holes



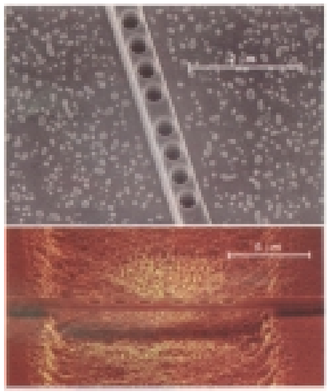


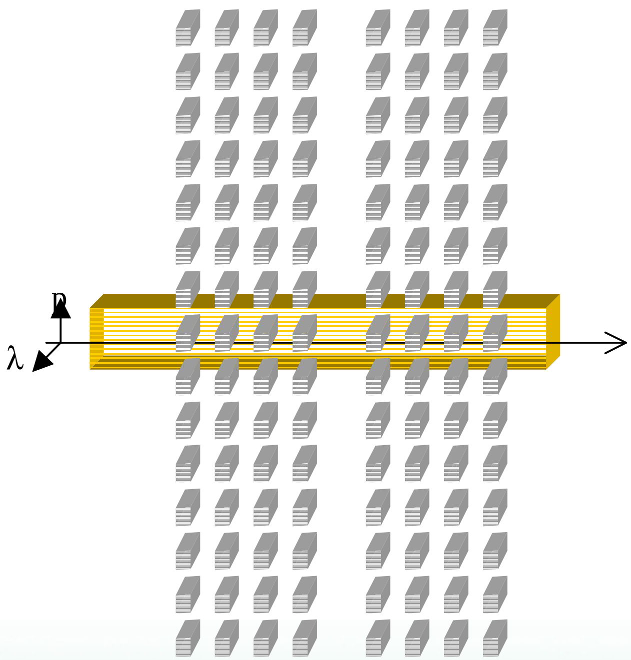
Transmittance from Two Sets of Four Infinite Rows of Holes (i.e. 2 mirrors - Fabry-Perot “Defect”)

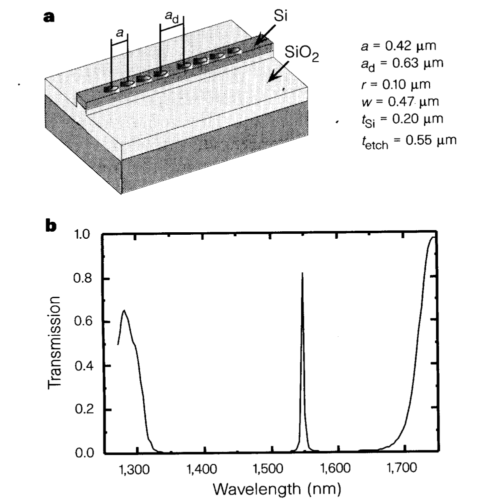


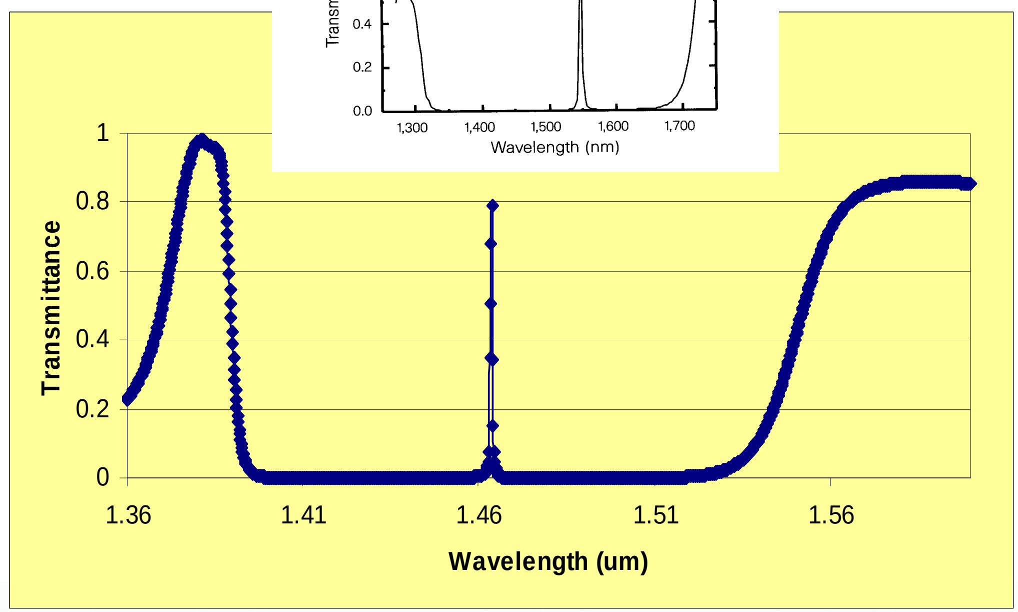


Transmittance from Two Sets of Four Holes in a Narrow Channel Silicon Waveguide (i.e. Joannopoulos et. al., Nature 386)





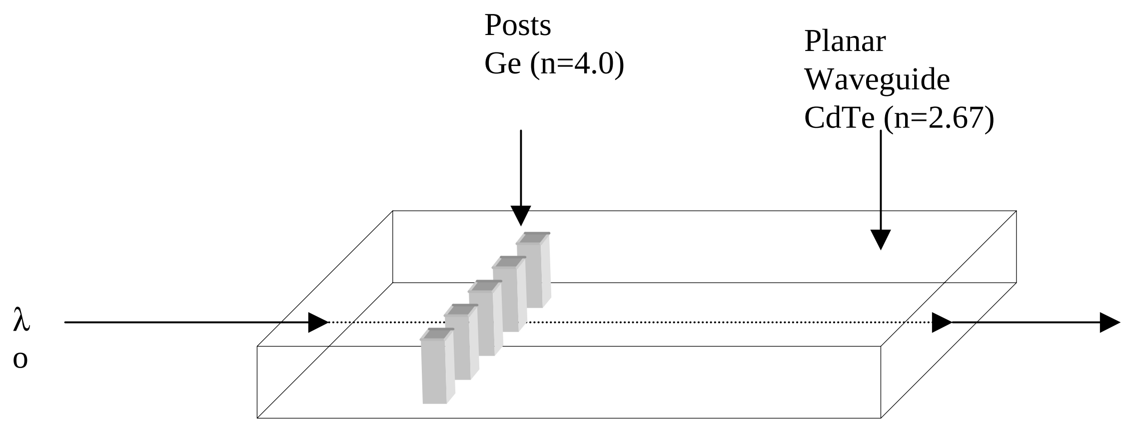




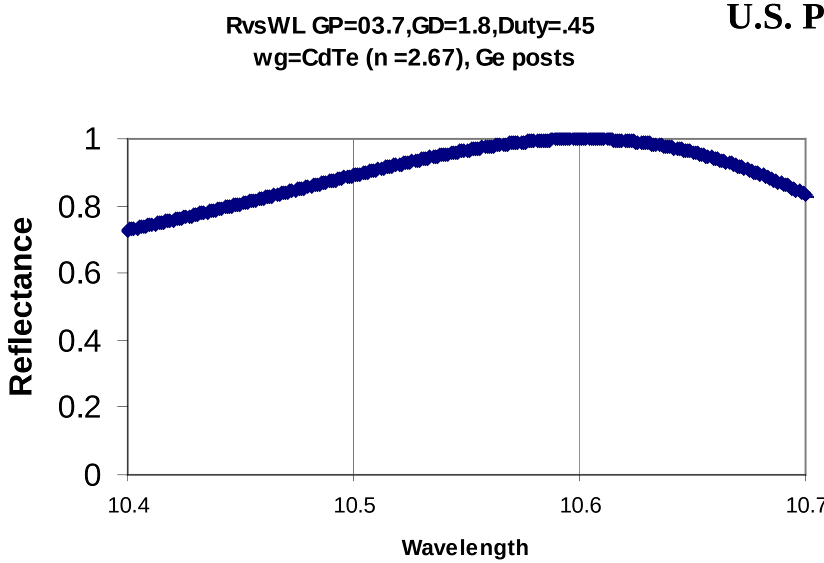
ORNL is Investigating High Index Features "Subwavelength Structures" (SWS)

- **Single linear array of posts replaces multiple arrays of holes**
- **Customize wavelength and polarization by materials, shape, and periodicity of posts**
- **Applications to datacom, telecom, and sensing**

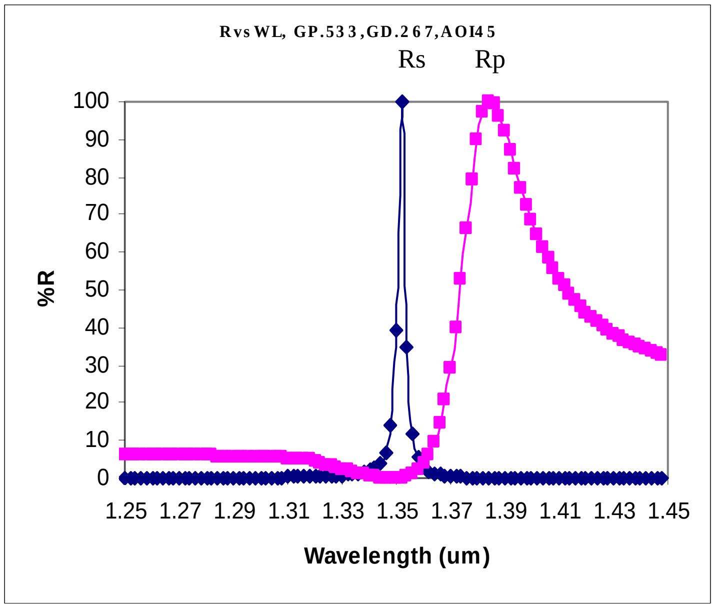
10.6um Broadband Reflector with High Refractive Index Posts

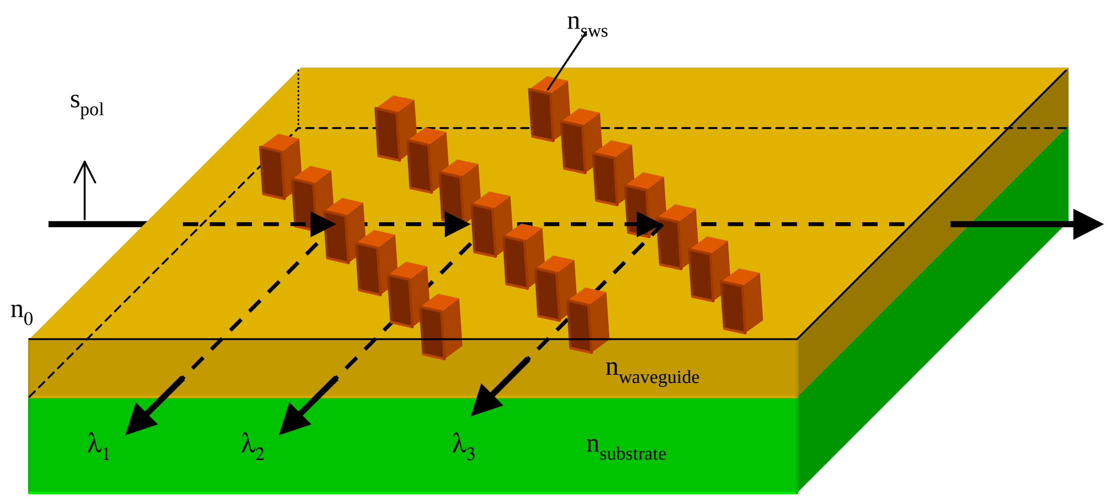


U.S. Patent 6,035,089



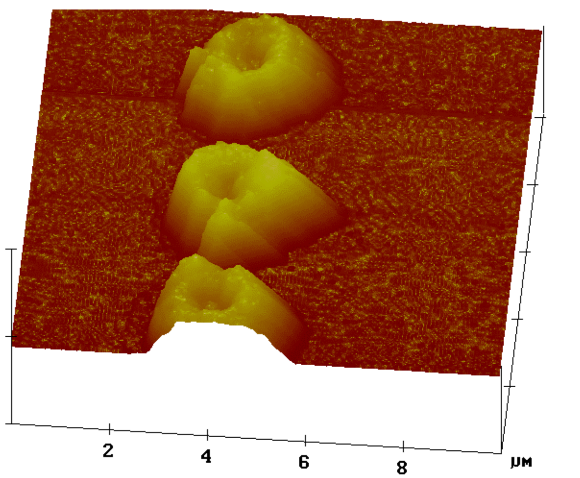
Compact Optical Switching/Multiplexing using SWS

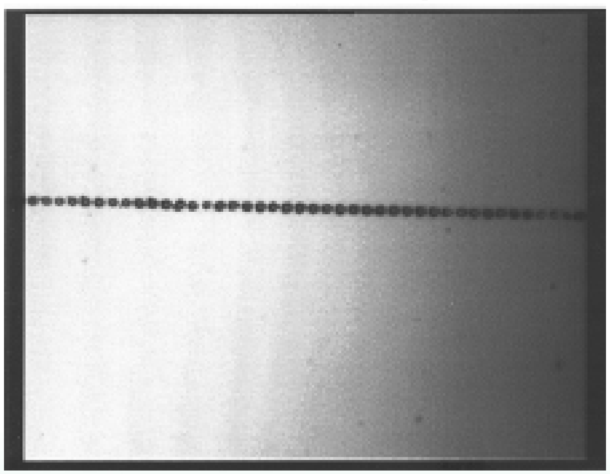


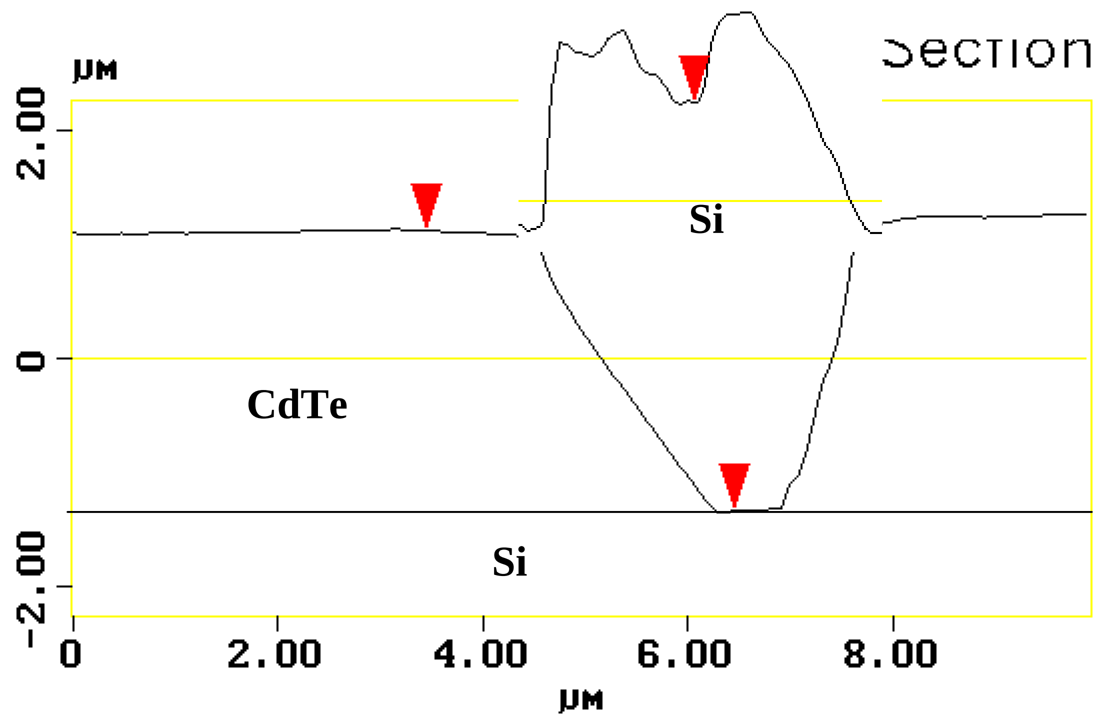


- **Possibilities for WDM and polarization selectivity**
- **Efficient switching using EO waveguide materials**

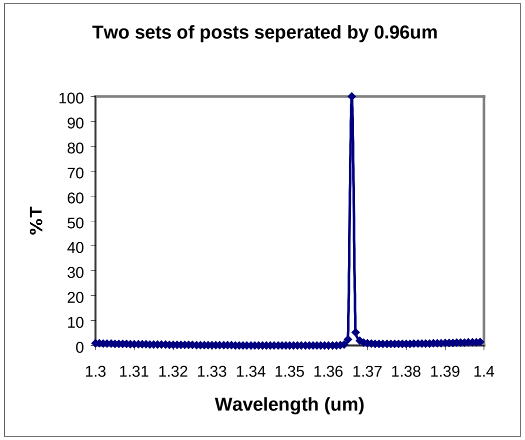
Demonstrated Fab of Si SWS in Single Crystal CdTe on Si

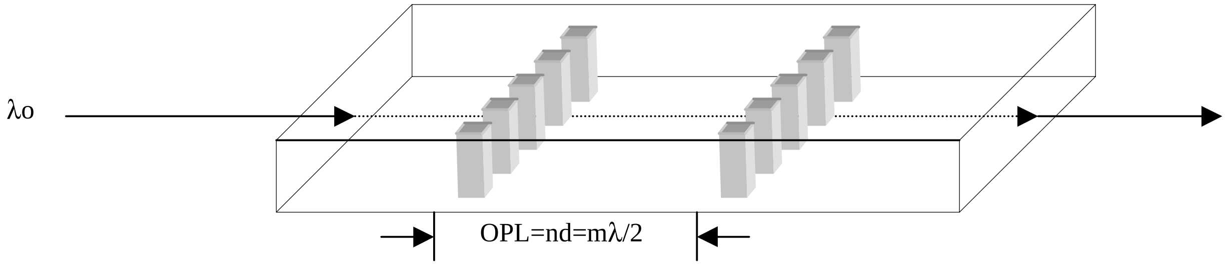


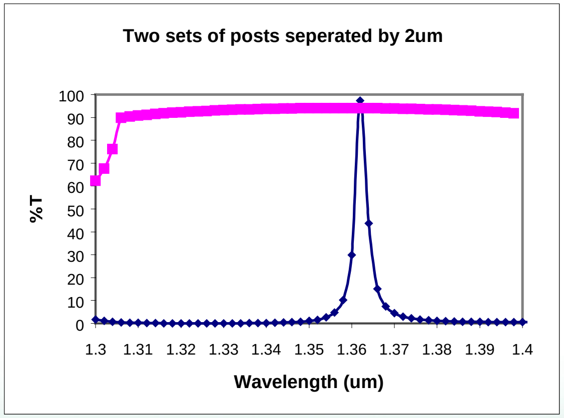




Resonant Cavities using Embedded Subwavelength Structures (SWS)

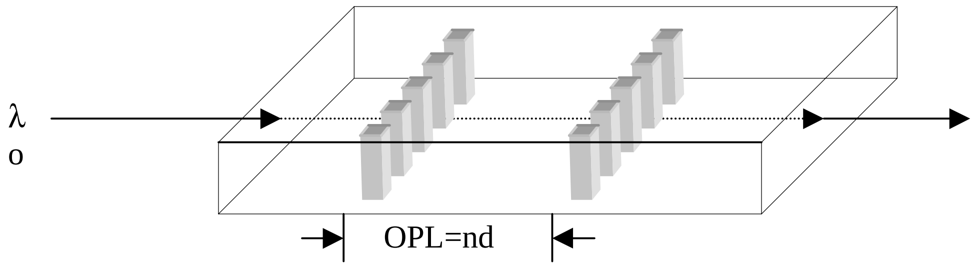


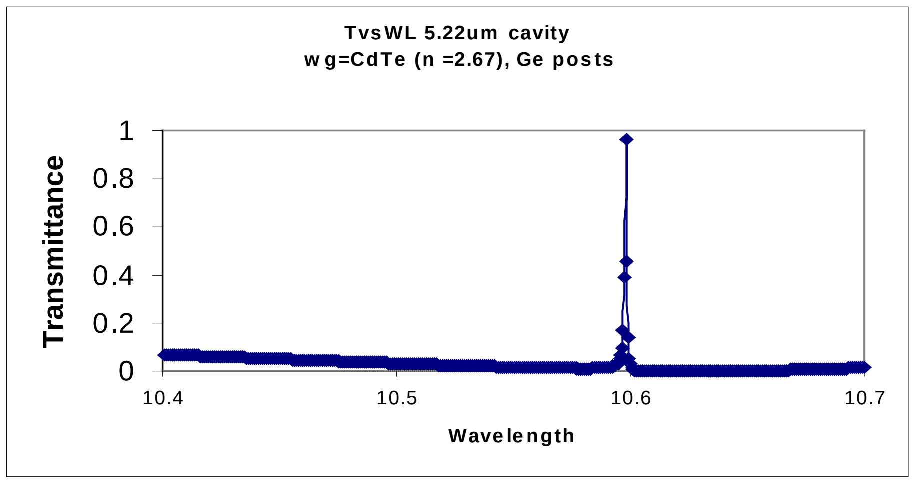




- High index “posts”
- 100 micron Fabry Perot cavity with Q = 1000 provides an effective 10-cm OPL
- Modulation with EO efficient materials

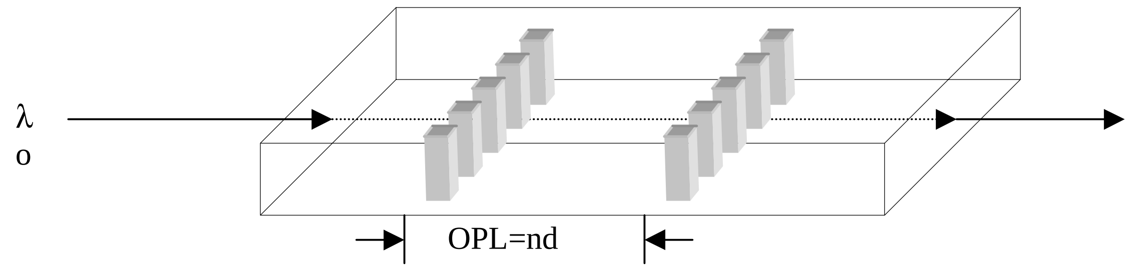
10.6um High Q Resonate Cavity



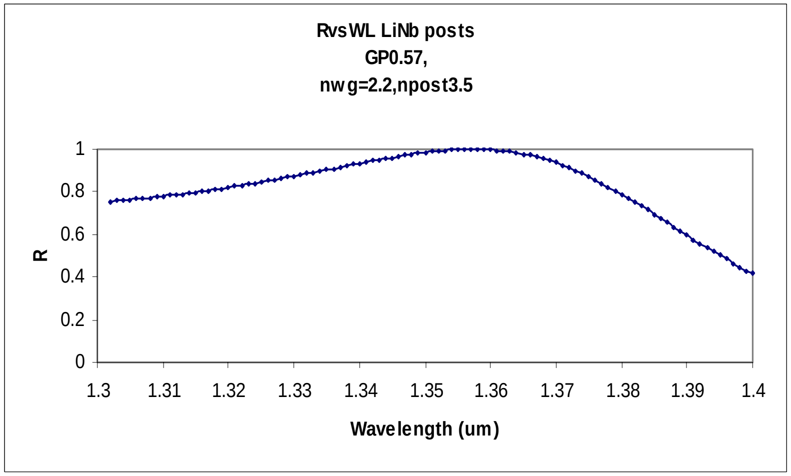


Transmittance of a set of Ge posts spaced 5.22um apart, (Q ~ 4000)

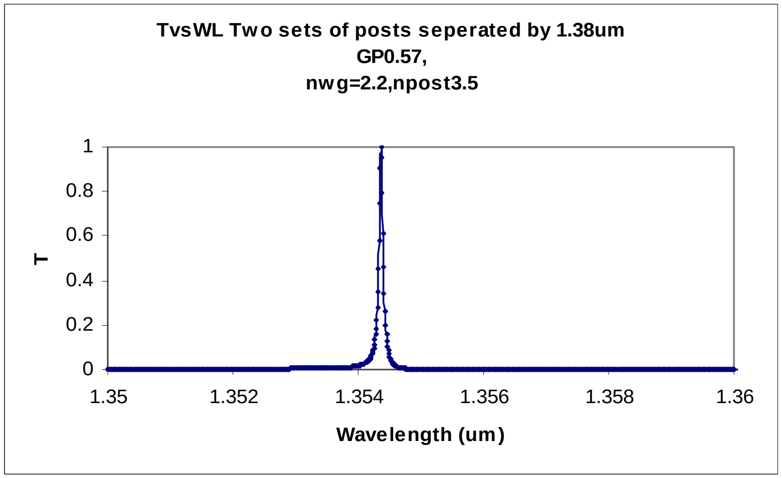
1.36um High Q Resonant Cavity



Silicon Posts, Post Periodicity = 0.57um; Waveguide/Cavity material = LiNb (n=2.2);



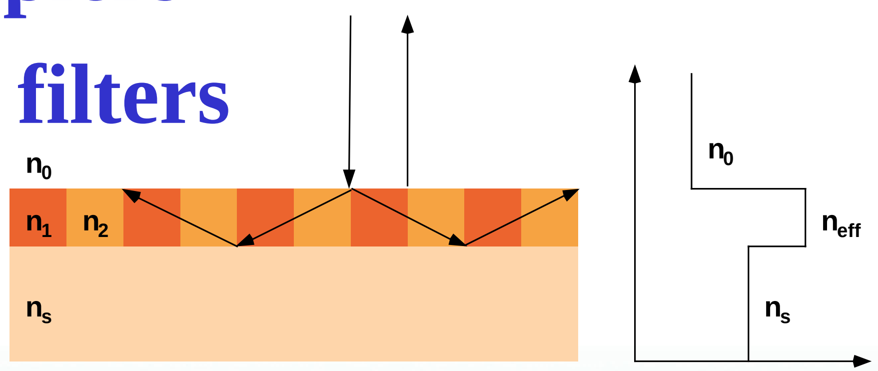
Reflectance of a single Embedded set of Silicon posts in LiNb waveguide



Transmittance of two sets of Silicon posts (n=3.5), separated by 1.38um, embedded in LiNb (n=2.2) waveguide Q ≅ 10,000

Research in Guided Mode Resonant Filters (GMRFs)

- Coupling orthogonal to surface
- Linear gratings formed by surface relief
- Waveguide/grating couplers
- Resonant narrow band filters



ORNL Initially Worked with Sinusoidal GRMFs due to Ease of Fabrication

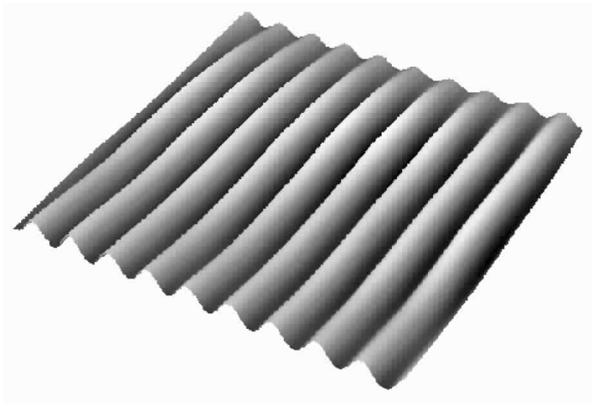
- **Bandwidth (FWHM)**

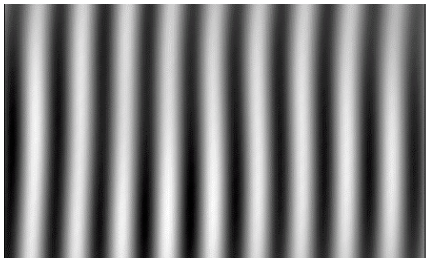
  $\Delta\phi = 0.3^{o}$

  --> $\Delta\lambda = 0.85\text{nm}$

- **Performance limitations**
  - grating nonuniformity
    - ghost interference
    - beam nonuniformity
    - mechanical jitter during exposure

AFM Scan

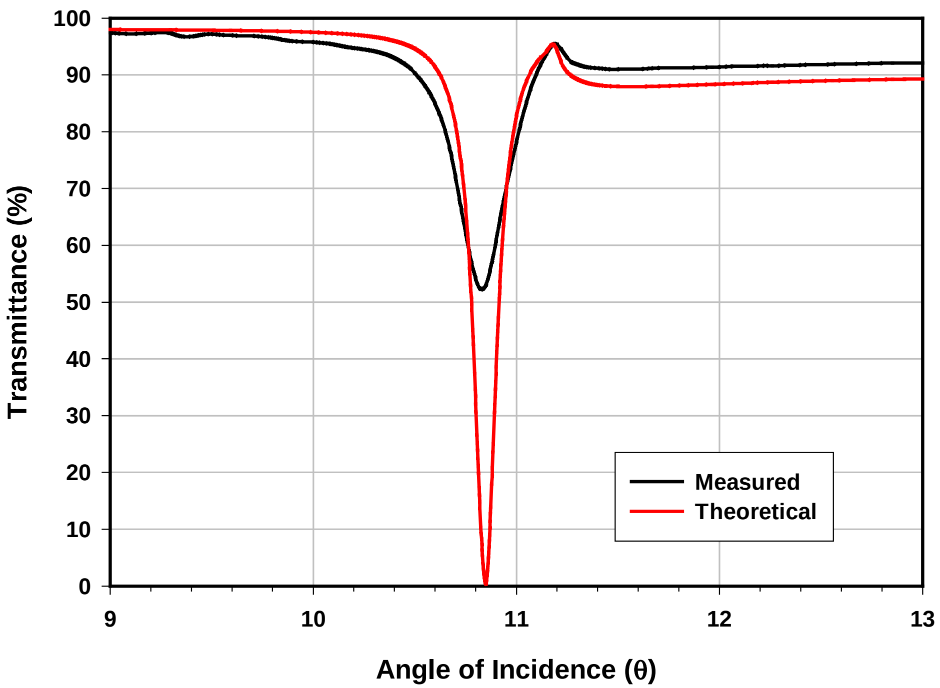




Sinusoidal GMRF Performance

<u>Grating Specs</u>

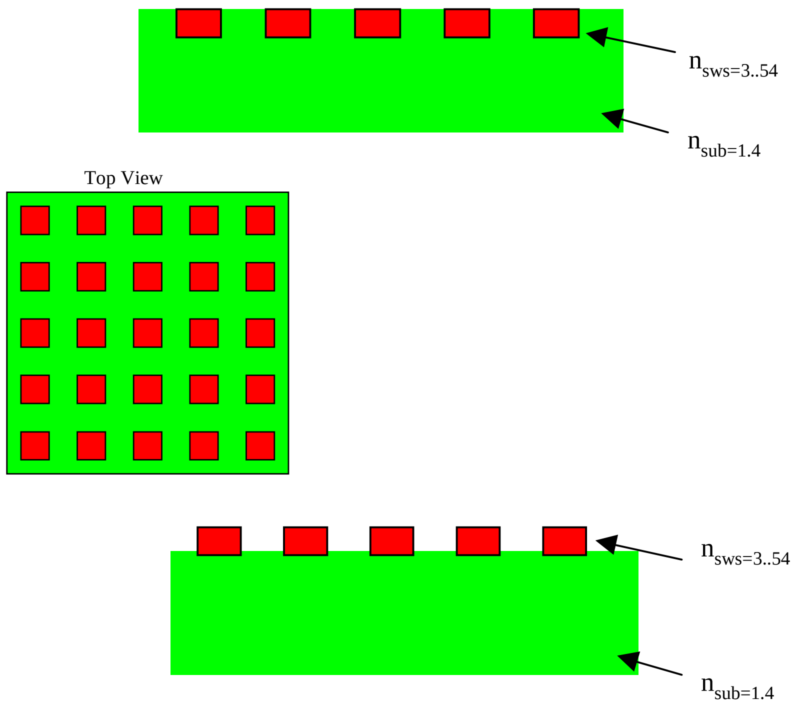
TE polarization
$\phi = 0^o$
$\lambda = 632.8nm$
$n_o = 1.0$
$n_s = 1.516$
$n_c = 1.64$
$d_c = 145nm$
$d_m = 270nm$
$\Lambda = 370nm$

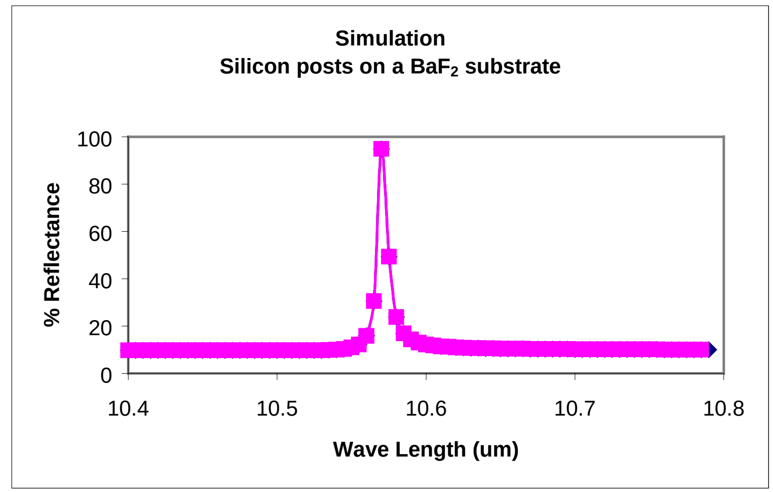


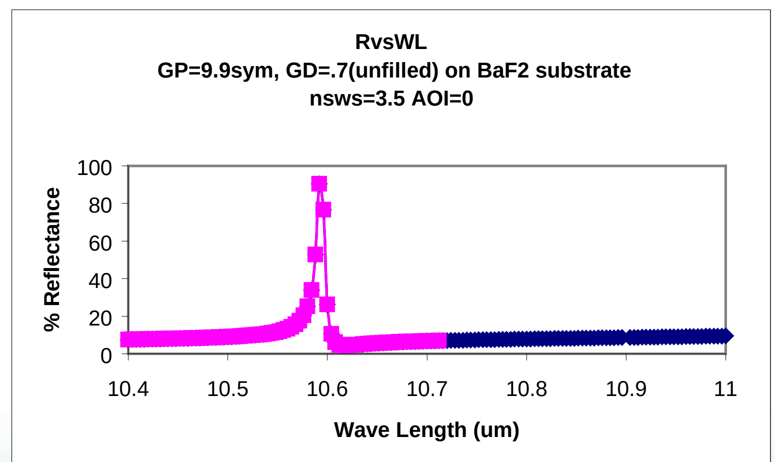
Present Resonant Dust Program R&D

- Proof-of-principle resonant dust concept using 2D surface reliefs
- Rigorous modeling of structures with finite extent (University of Arizona)
- Material science issues related to thin films and monolithic structures

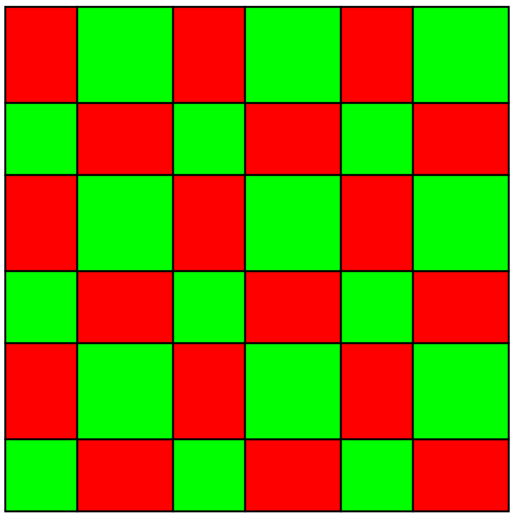
Simulations Expected Reflectance for 2D SWS Layouts



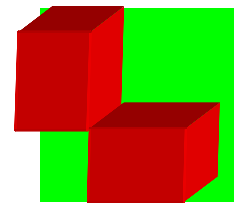




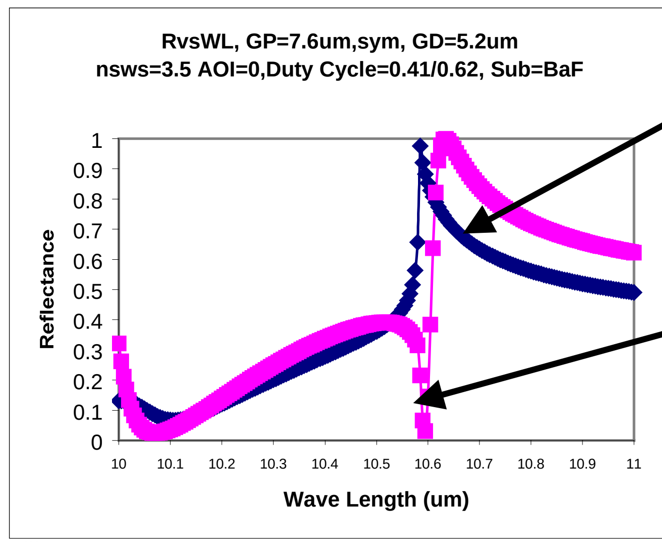
2D- Smart Dust Checkerboard design - polarization selectivity



Si posts (Red) on BaF substrate (Green)



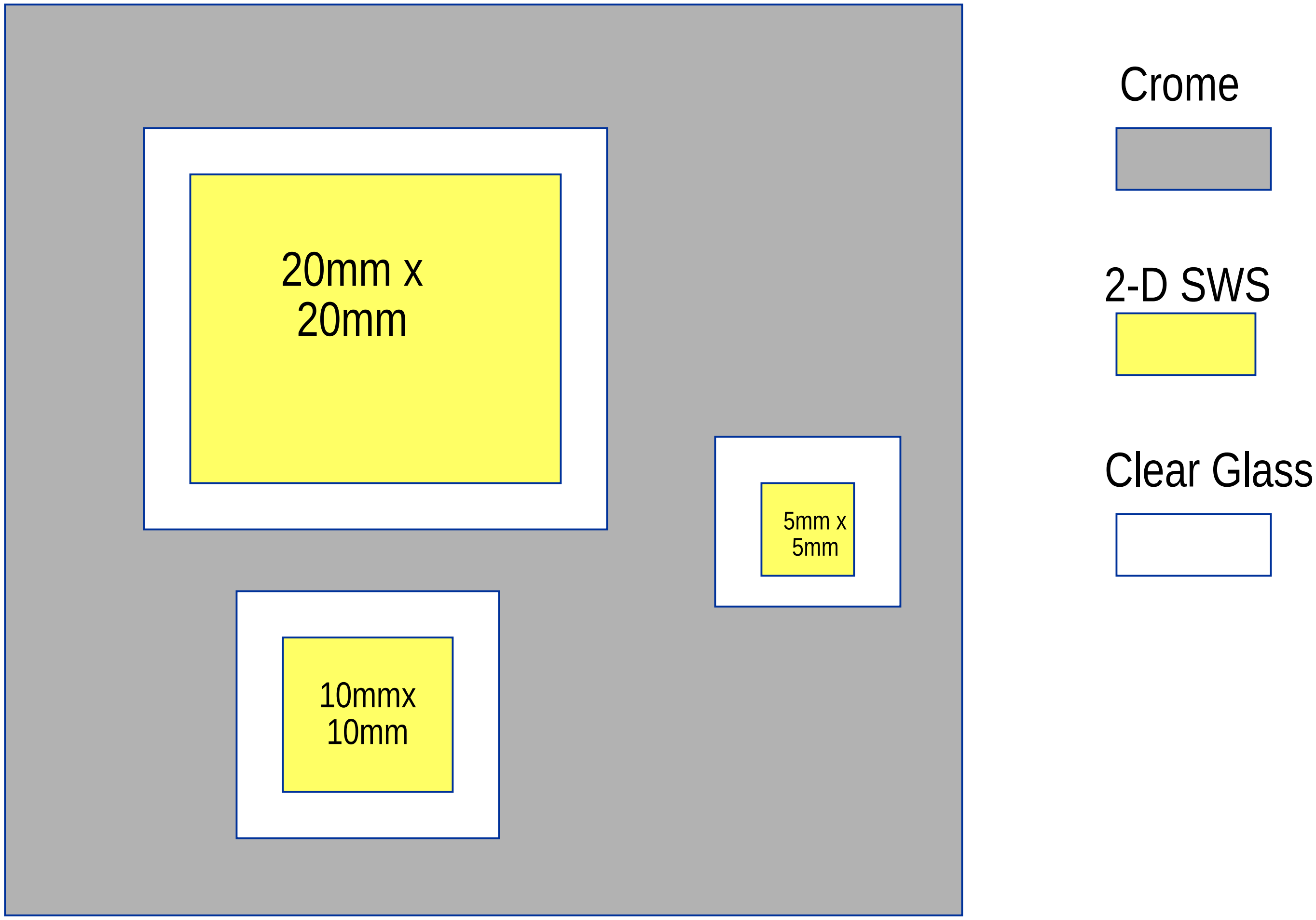
Unit cell



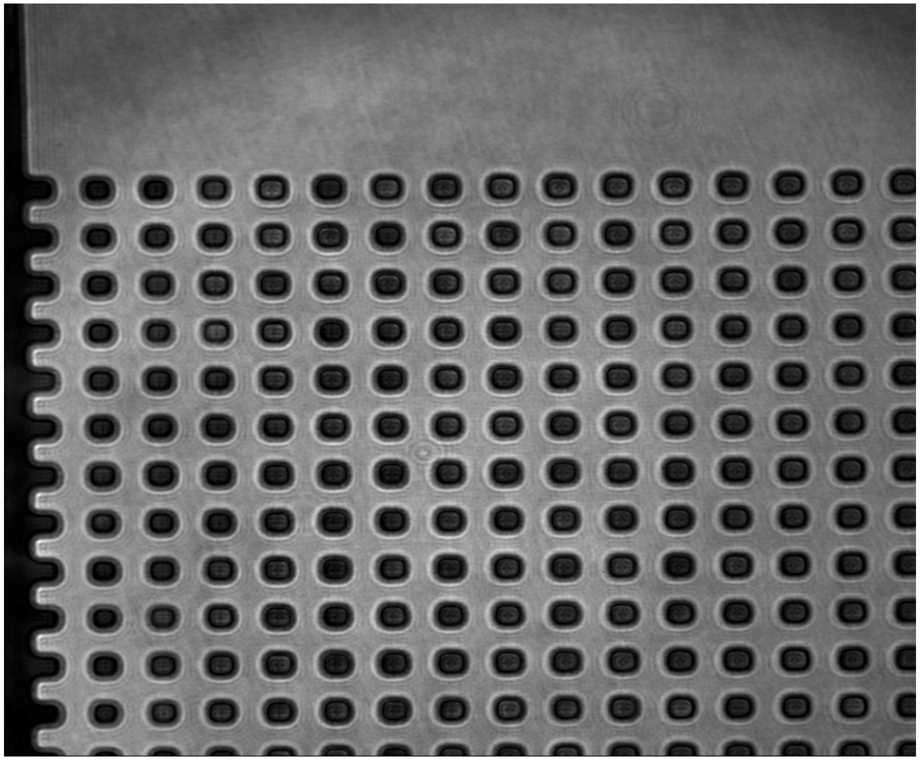
P polarization

S polarization

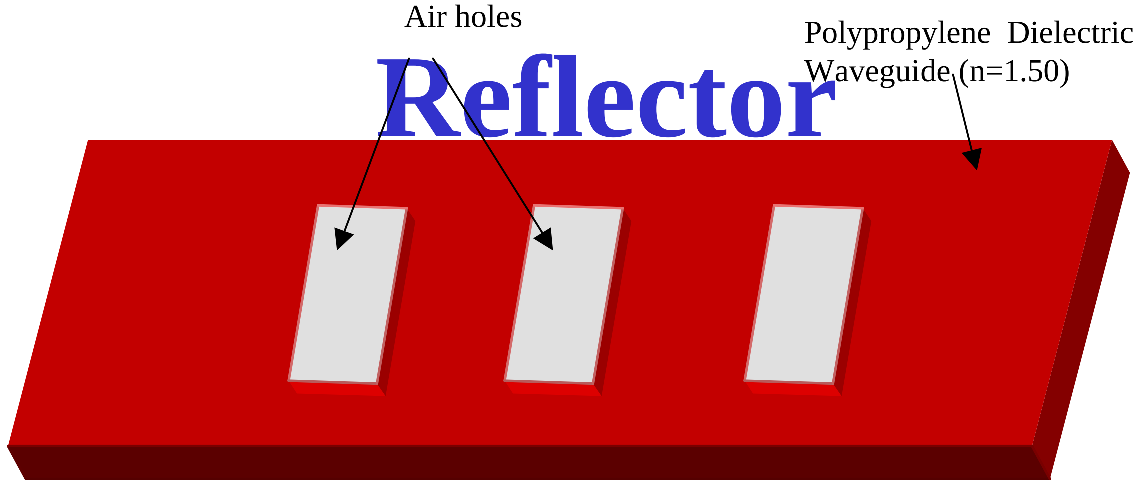
Smart Dust Mask (Different Extents)

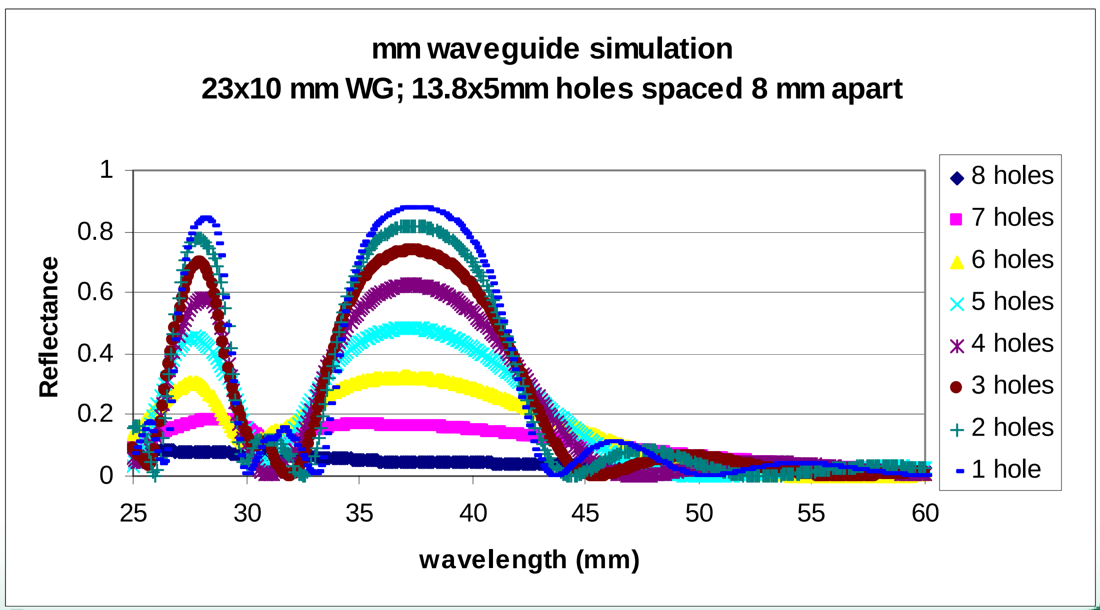


Smart Dust Mask 2-D Subwavelength Structure



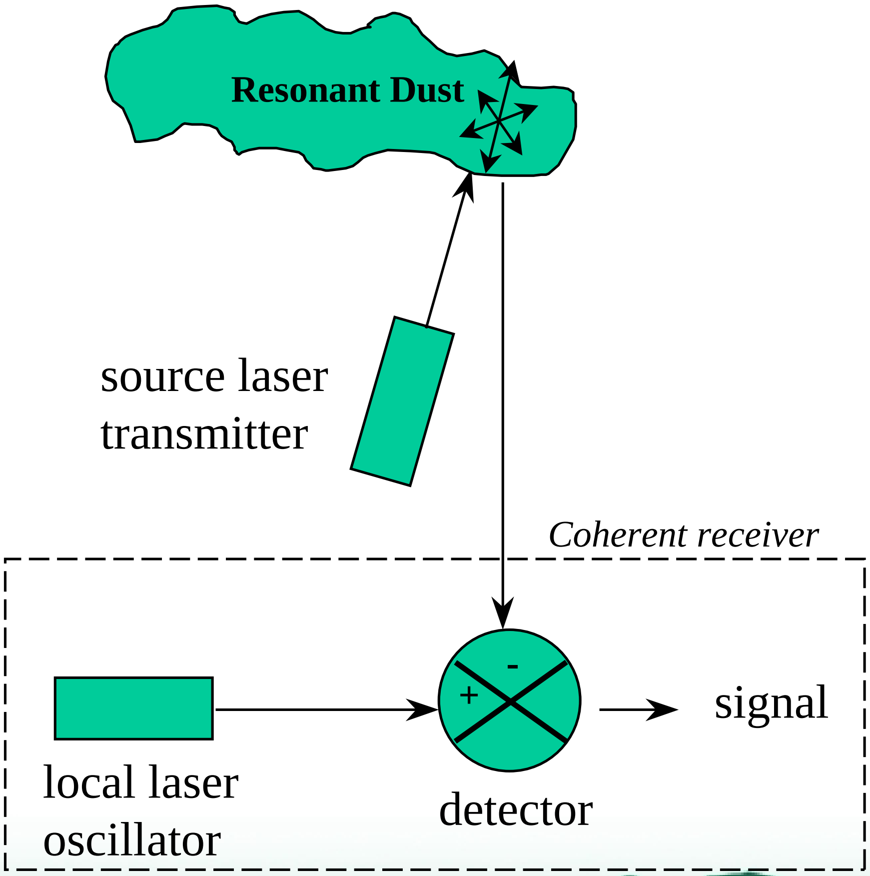
37mm Microwave Broadband Reflector



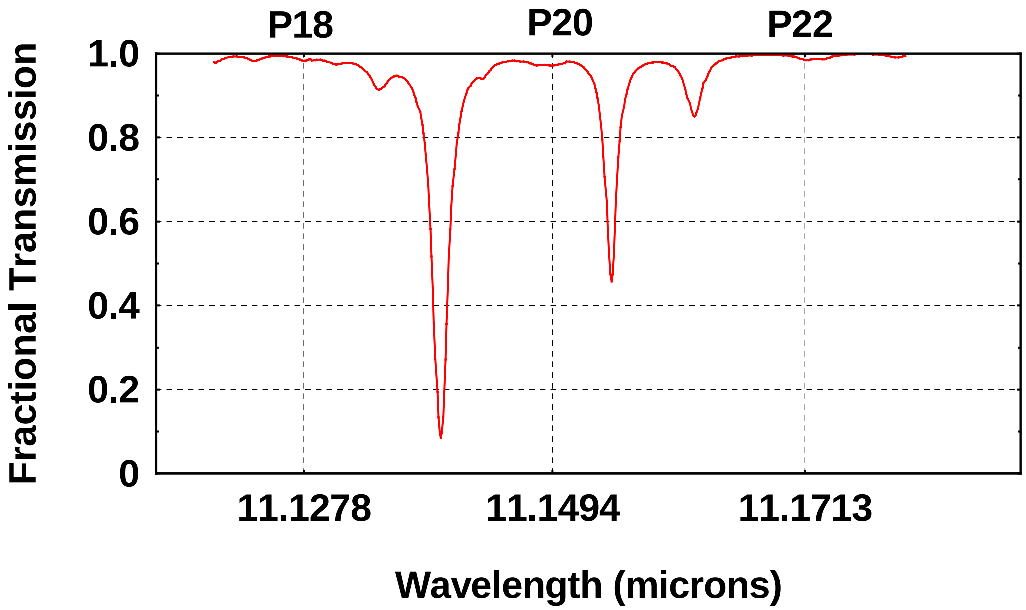


Active Systems Measure Return Signals using a Laser Transmitter

- Differential lidar (DIAL) for spectroscopy
- Doppler lidar for velocity or vibration
- Time-of-flight lidar for range

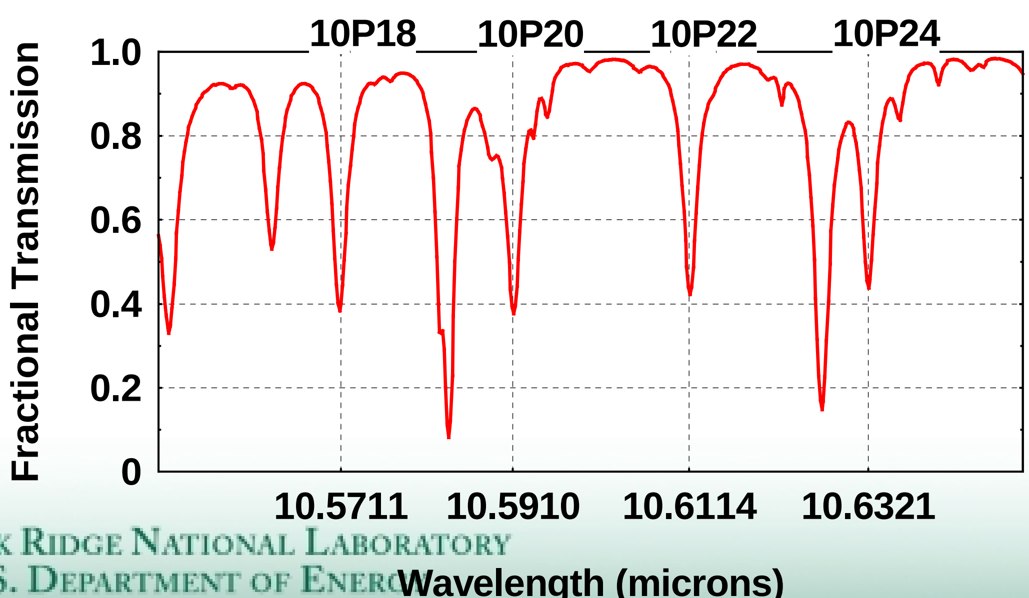


Atmospheric Absorption for 6-Km Path Length



$^{13}C^{16}O_2$

Alternate isotopes of CO_2 can be used to improve atmospheric transmission if an appropriate modulator gas can be found.



$^{12}C^{16}O_2$

Historically, CO_2 Laser Systems Have Been *BIG*

10 Micron Technology is Moving toward Smaller Lasers and Room Temperature Detectors and Arrays

- **Folded cavity and waveguide CO_2 lasers with 0.1 m^2 footprints and >5W output power**
- **Quantum well infrared photodetectors (QWIP) arrays to 640 X 480**
- **HgCdZnTe room temperature detectors**

Heterodyne Detection

- Requires Local Oscillator
- Noise is Different from Video Detection
  - Shot Noise Limit
  - Large Dark Current=Higher Detection Efficiency
- Permits High Resolution Measurements
- Permits Small Signal Measurements

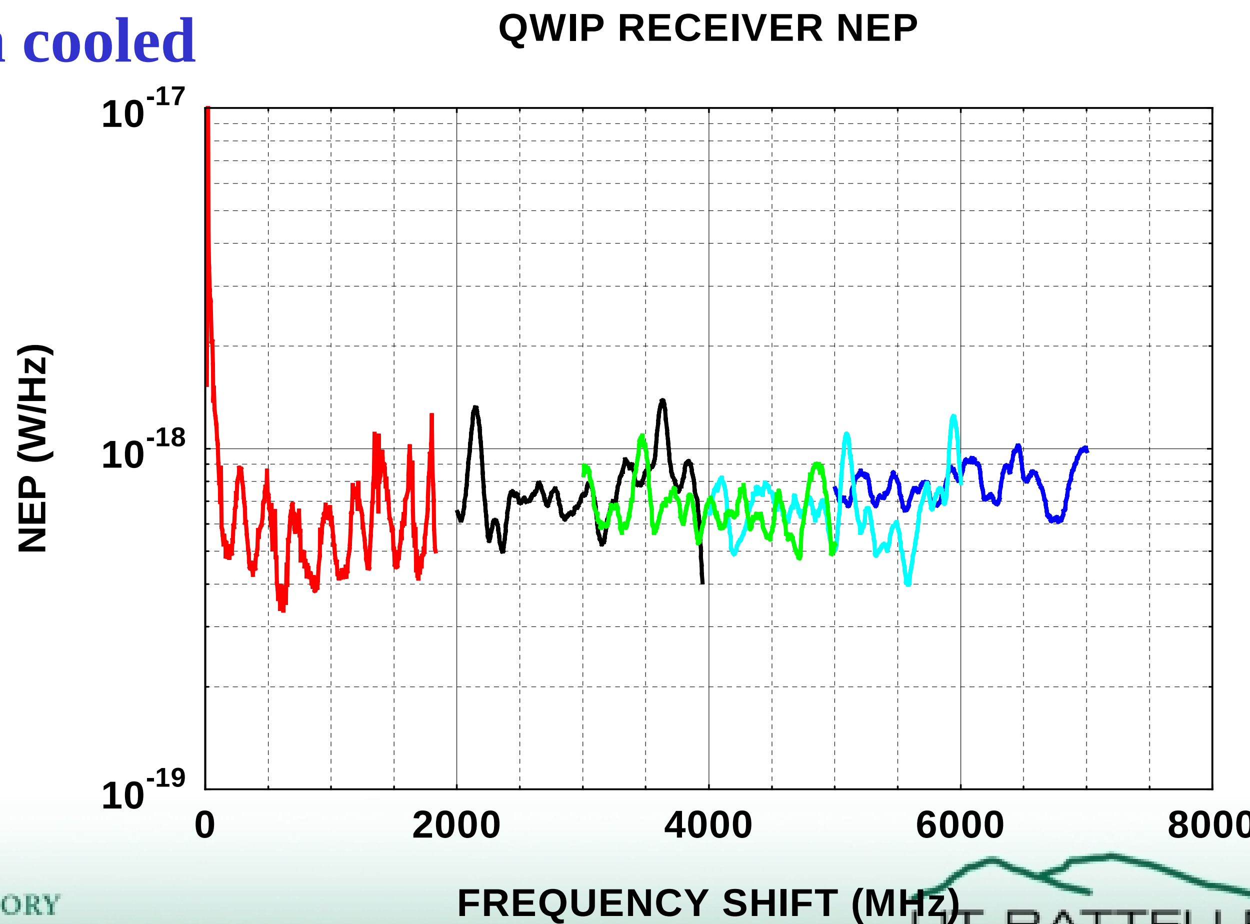
Heterodyne Signal-to-Noise

$$\frac{S}{N} = \frac{Ps}{Ps + NEP}\sqrt{B\tau + 1}$$

- **Ps= Scattered Signal (W/Hz)**
- **NEP= Receiver Noise (W/Hz)**
- **B= Selected Bandwidth (Hz)**
- **tau= Integration Time (sec)**
- **e.g. Ps=10^{-19}, NEP=10^{-19}, B=10^{9}, tau=10^{-6} then S/N=15.8**

Recently We Made Heterodyne Measurements with QWIP Detectors

- Liquid Nitrogen cooled
- 10.6 microns
- 32 wells
- 40x40 microns



Research in Micro/Nano-structures is Important to the Future of Semiconductors, Communications, and Sensors

- R&D in micro optics enabled by MEMS and nanotechnology at National Labs and Universities
- Device breakthroughs in the areas of subwavelength structures and photonic bandgap crystals
- Material science is very important for realizable devices

Future Areas for Research in Micro and Nano-structures for Tagging/Tracking: Smarter Dust

- Anisotropic 2D structures (e.g. polarization sensitivity)
- Customized, multiple wavelength/polarization for ID
- Substance-specific polymer films for detection