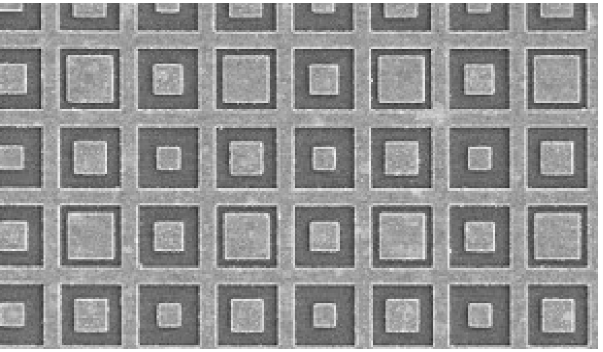
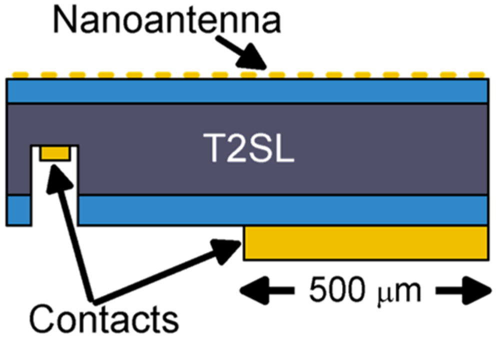
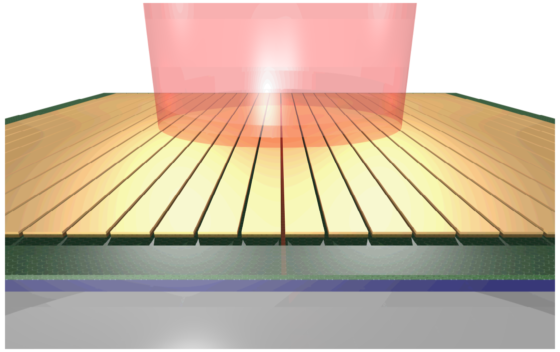
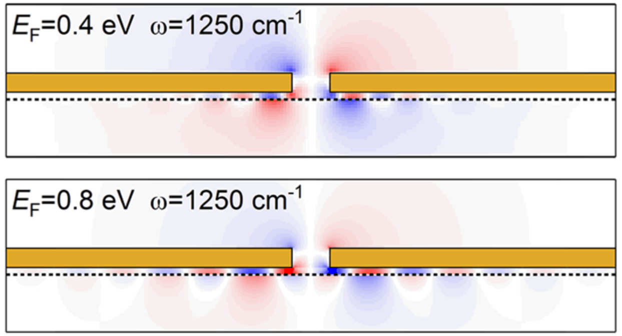
SAND2017-11648PE









Integrating Resonant Structures with IR Detectors

Org. 05265 Applied Photonics Microsystems Research and Technology Seminar

Michael Goldflam

LDRD Laboratory Directed Research & Development

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Collaborators

Sandia National Laboratories

Smart Sensors Technology Grand Challenge

PI: David Peters
PM: Reno Sanchez

Nanoantenna Enhanced Detectors

Evan Anderson	Jin Kim
Salvatore Campione	John Klem
Wesley Coon	S. Parameswaran
Paul Davids	Eric Shaner
Torben Fortune	Michael Sinclair
Sam Hawkins	Anna Tauke-Pedretti
Clark Kadlec	Larry Warne
Emil Kadlec	Joel Wendt
Gordon Keeler	Michael Wood

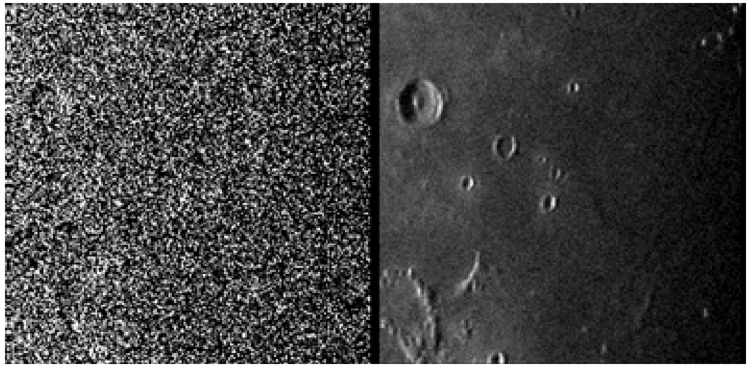
Tunable Filters

Thomas Beechem
Stephen Howell
Anthony McDonald
Isaac Ruiz
Joel Wendt

The Goal

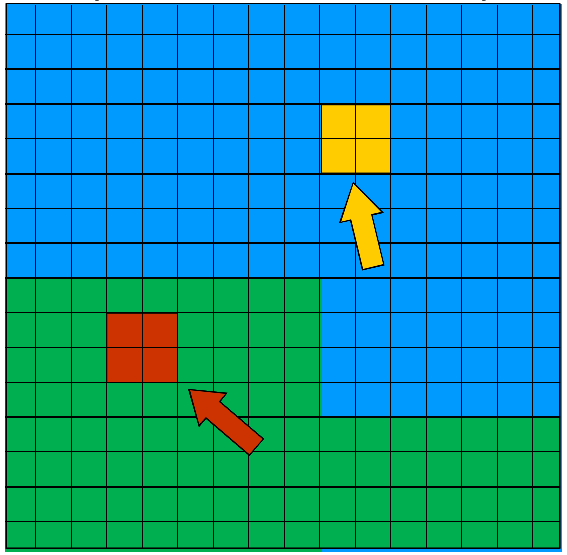
Develop the foundation for a new infrared detector that will lead to an order of magnitude improvement in noise and real-time spectrally tunable pixels.

Noise Reduction



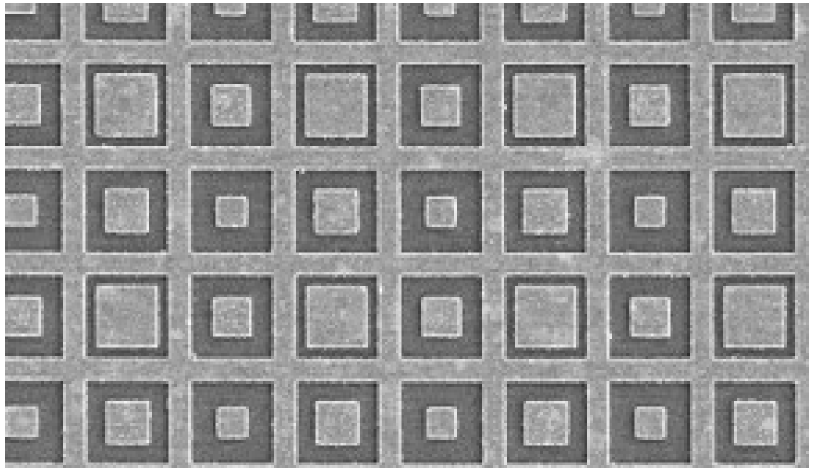
To achieve a radically improved sensor both new architectures and materials must be investigated.

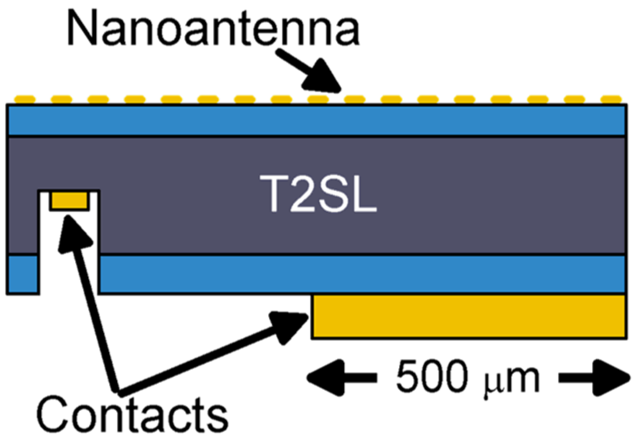
Pixel-Level Active Spectral Tunability



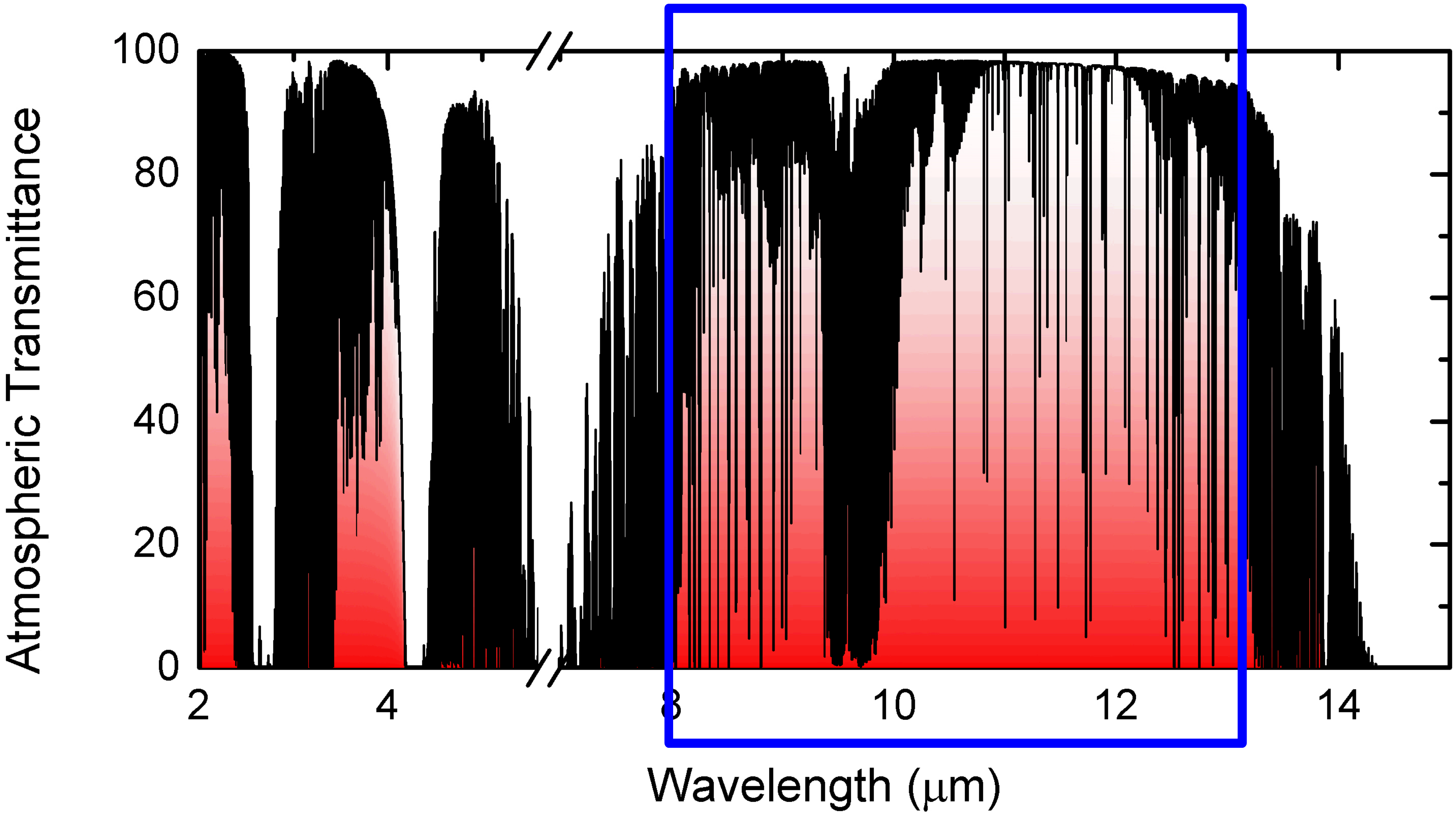
Outline

- Resonantly Enhance IR Detectors
  - Type-II Superlattices
  - Metallic nanostructures
- Tunable IR Filters
  - Graphene
  - Reflectance-mode Filter
- Summary





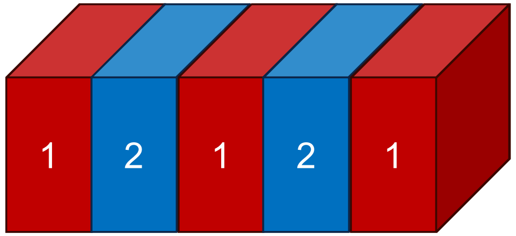
Infrared Detection

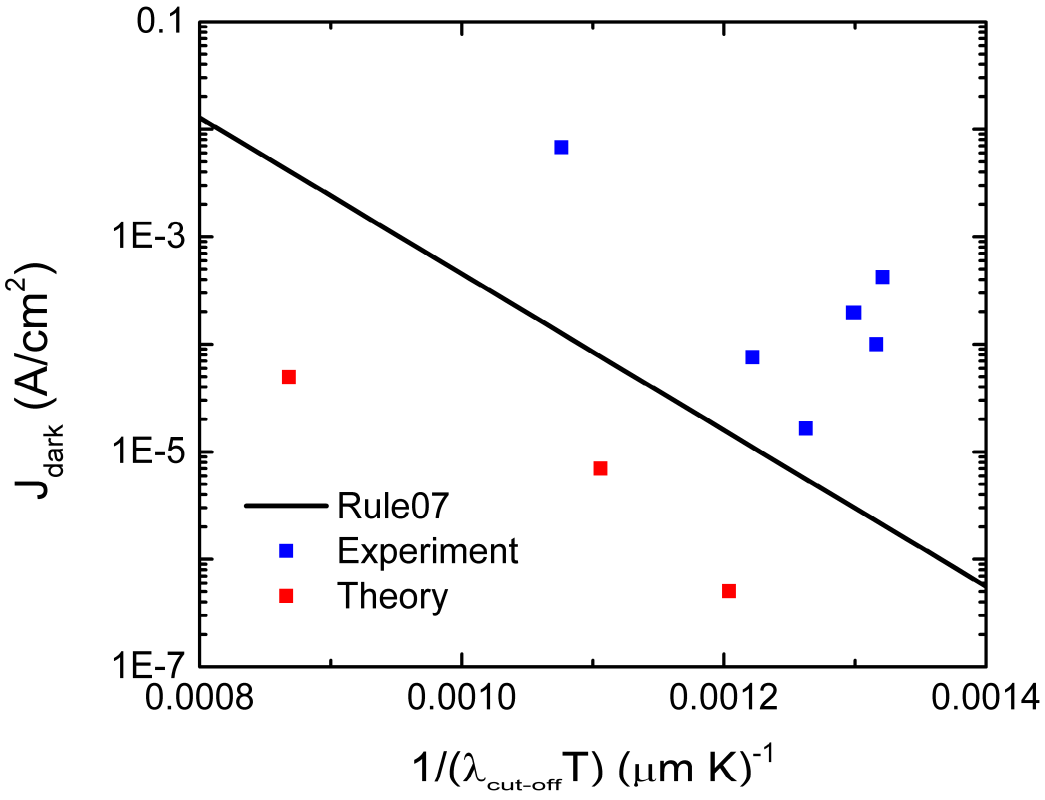


Lord, S. D., 1992, NASA Technical Memorandum 103957, Gemini Observatory

Type-II Superlattices

- InAs/(In)GaSb
- **InAs/InAsSb**
- InGaAs/InAsSb

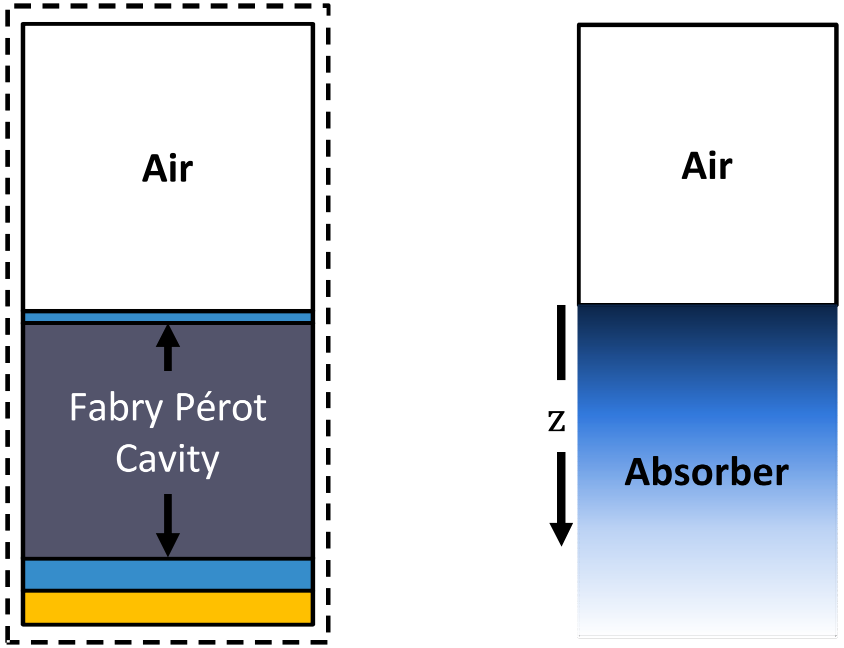




- Bandgap controlled by layer thickness
- Uniform material across wafer
- Predicted lower predicted dark current than MCT.
- Lower absorption coefficient than MCT

W. E. Tennant, J. Electron. Mater. 39 (7), 1030 (2010).

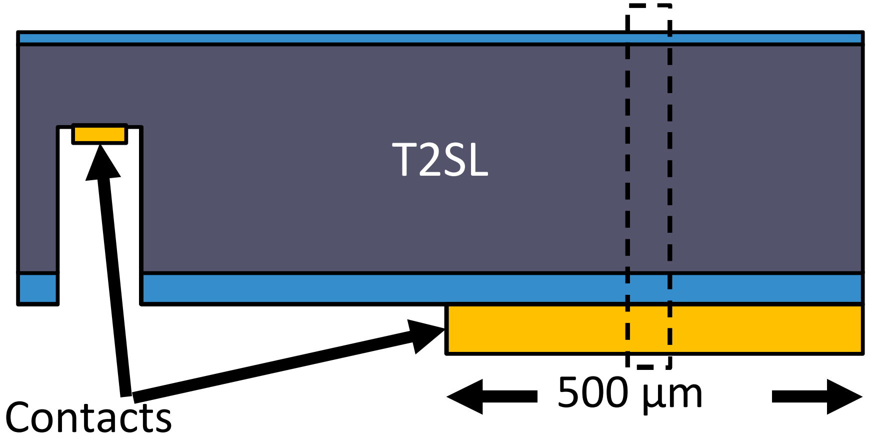
Detector structure



$$\text{Absorption} \propto 1 - e^{-\alpha z}$$

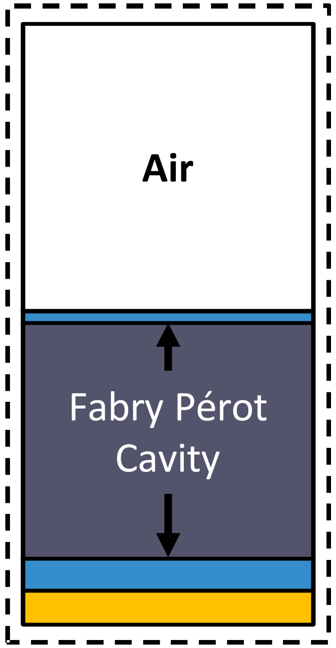
$$J_{\text{diff}} \propto W$$

- Thick structures absorb more but have higher dark current.
- Enhance field in detector using resonant structures → increase QE.
- Important in low background applications.
- Enable higher operating temperature.



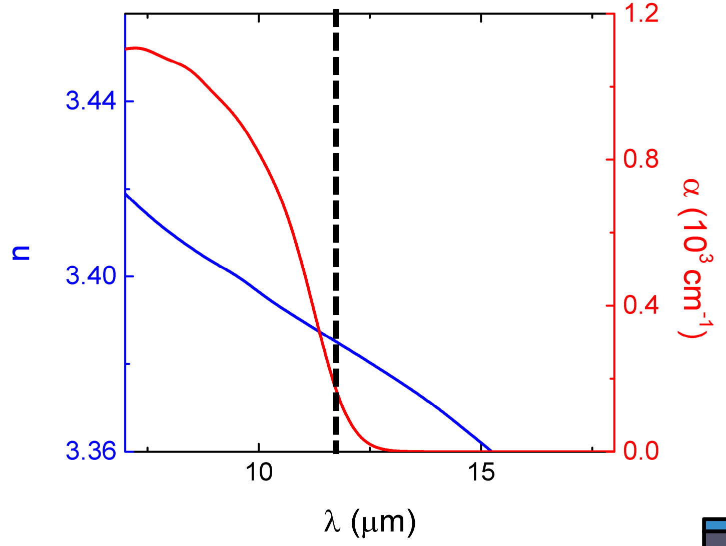
M. D. Goldflam, D. W. Peters et al., Appl. Phys. Lett. 109 (25), 251103 (2016).

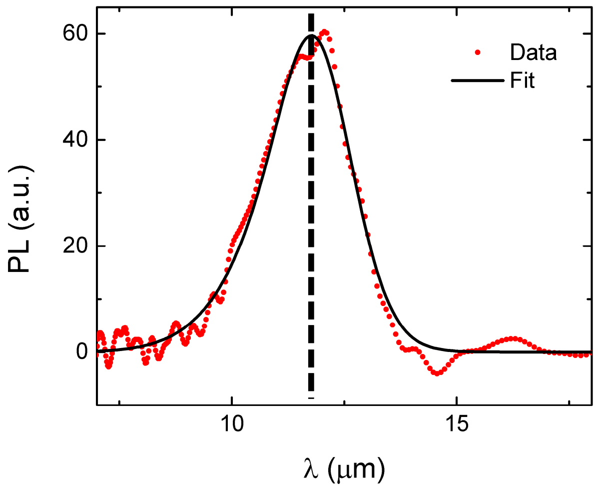
Detector structure



$$\lambda_{res}^{FP} = \frac{4nt}{2m-1}$$

$$t \sim 2\ \mu\text{m}$$





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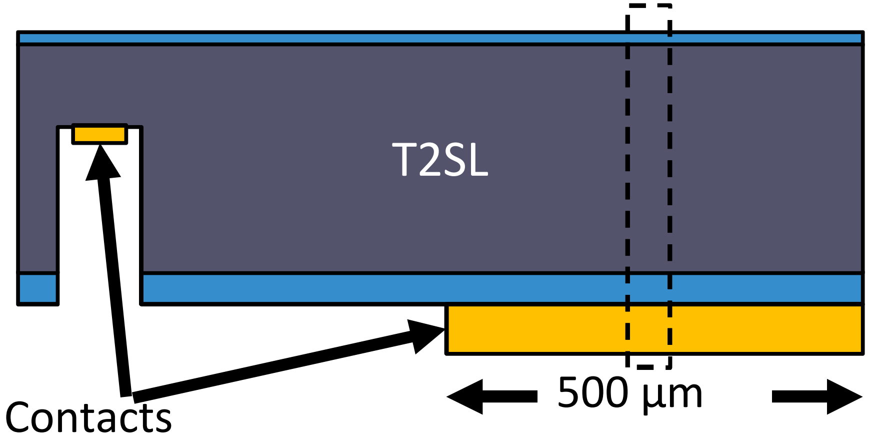
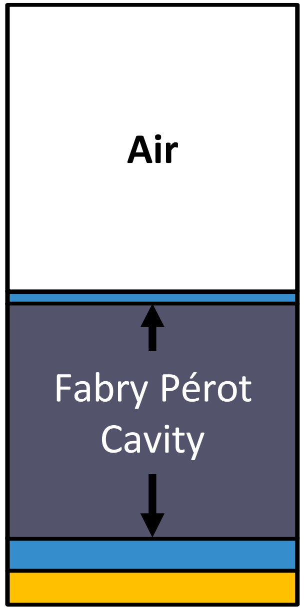


M. D. Goldflam, D. W. Peters et al., Appl. Phys. Lett. 109 (25), 251103 (2016).

Resonant detector: Fabry-Pérot



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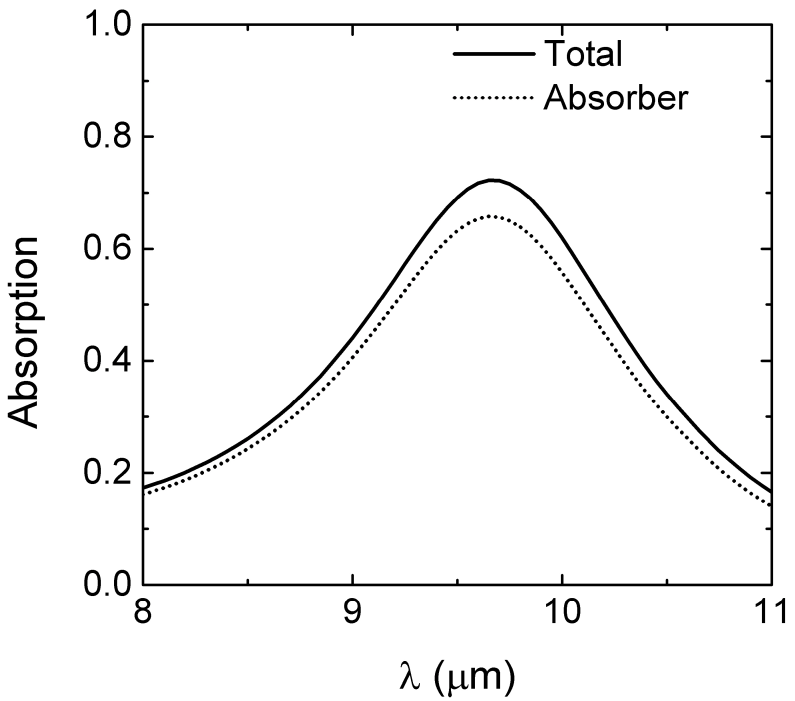
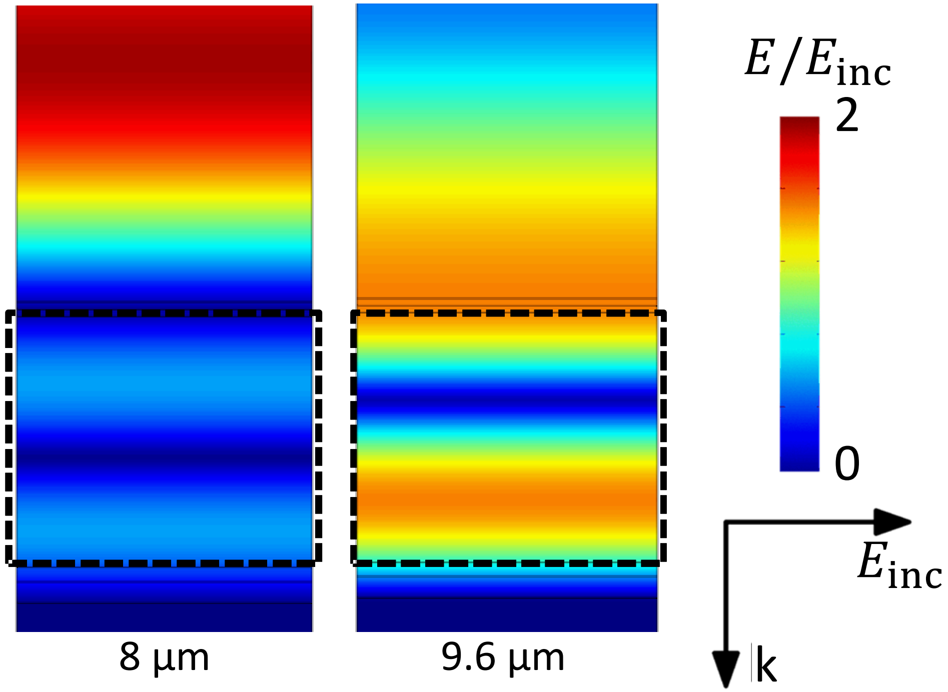
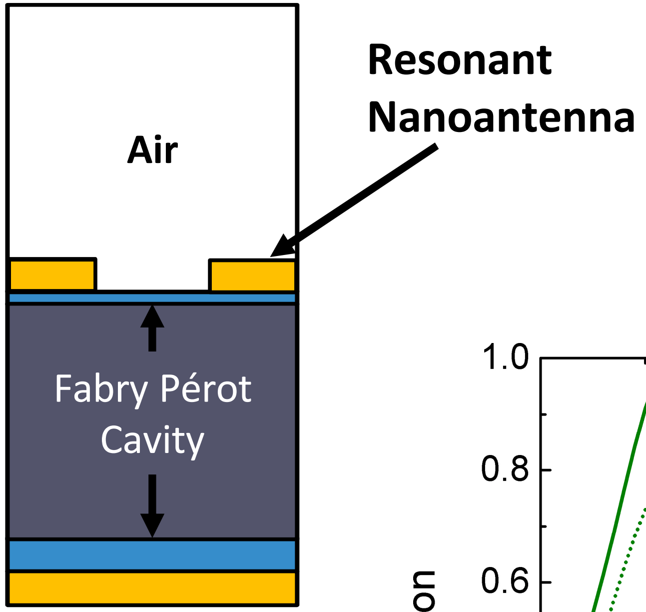
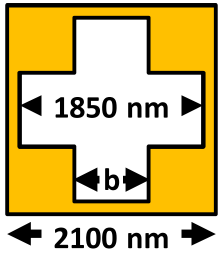
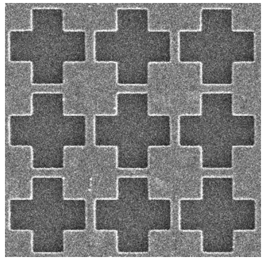


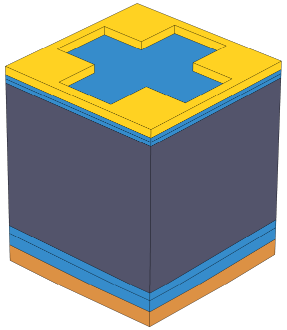


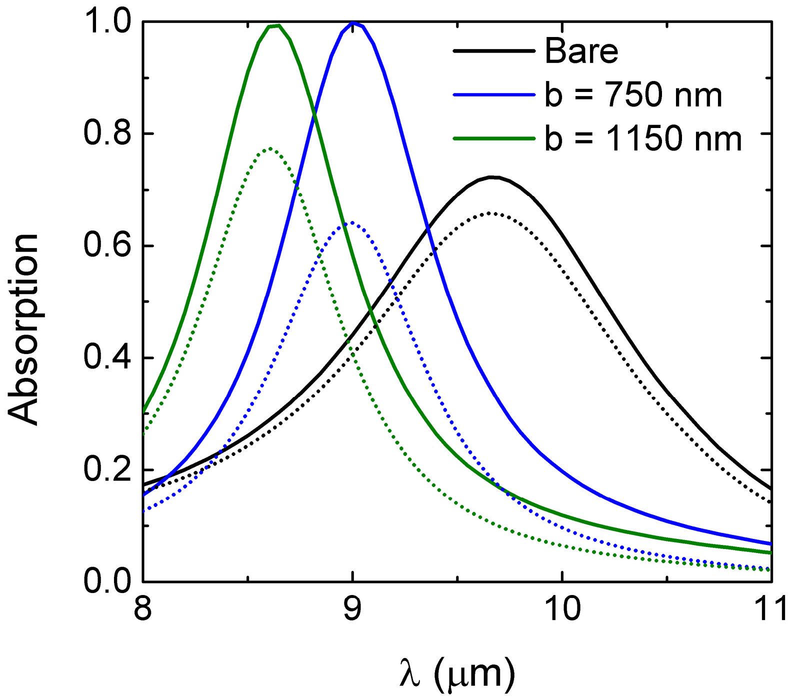
Coupled Resonances



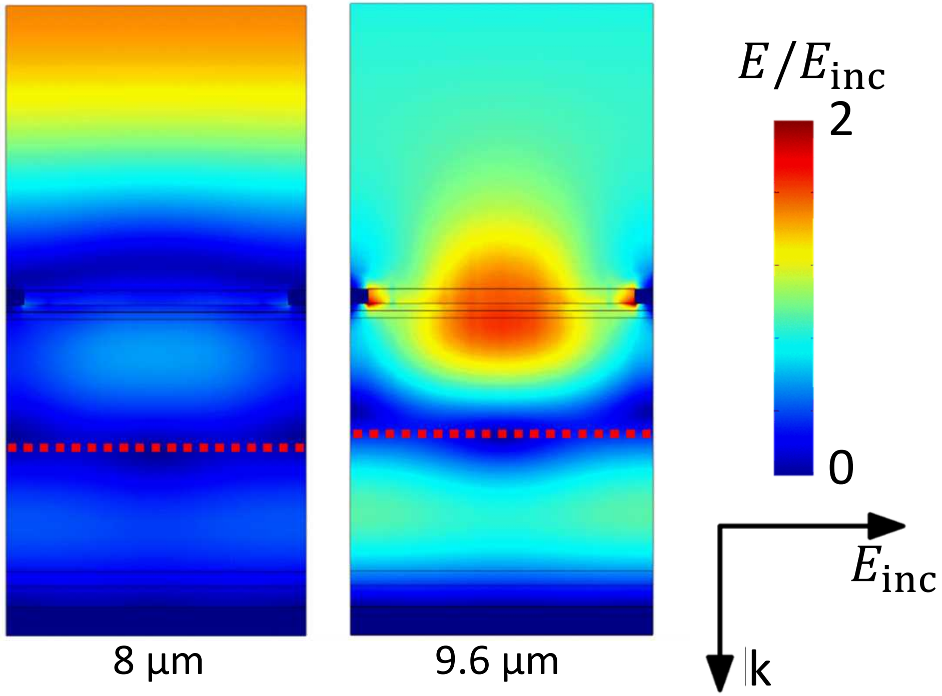




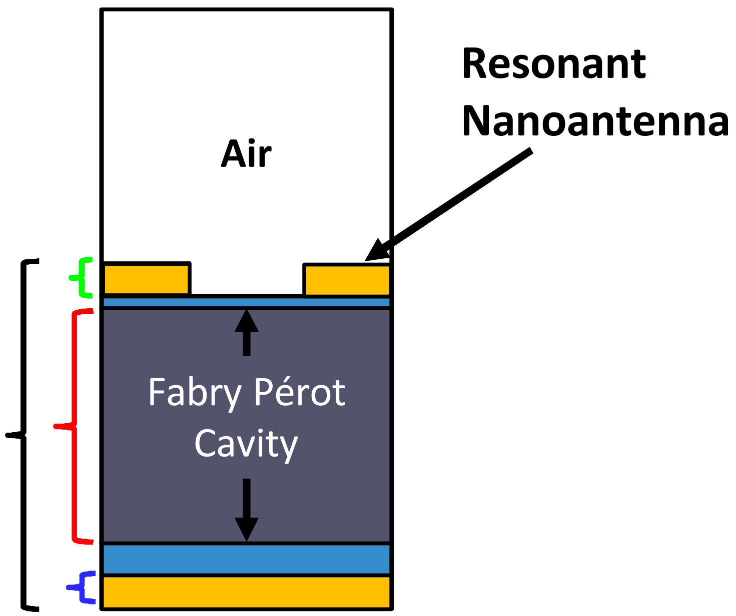


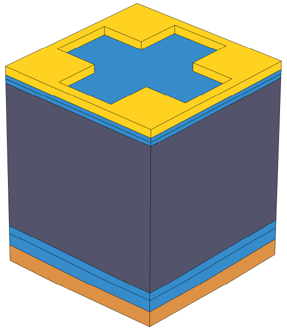


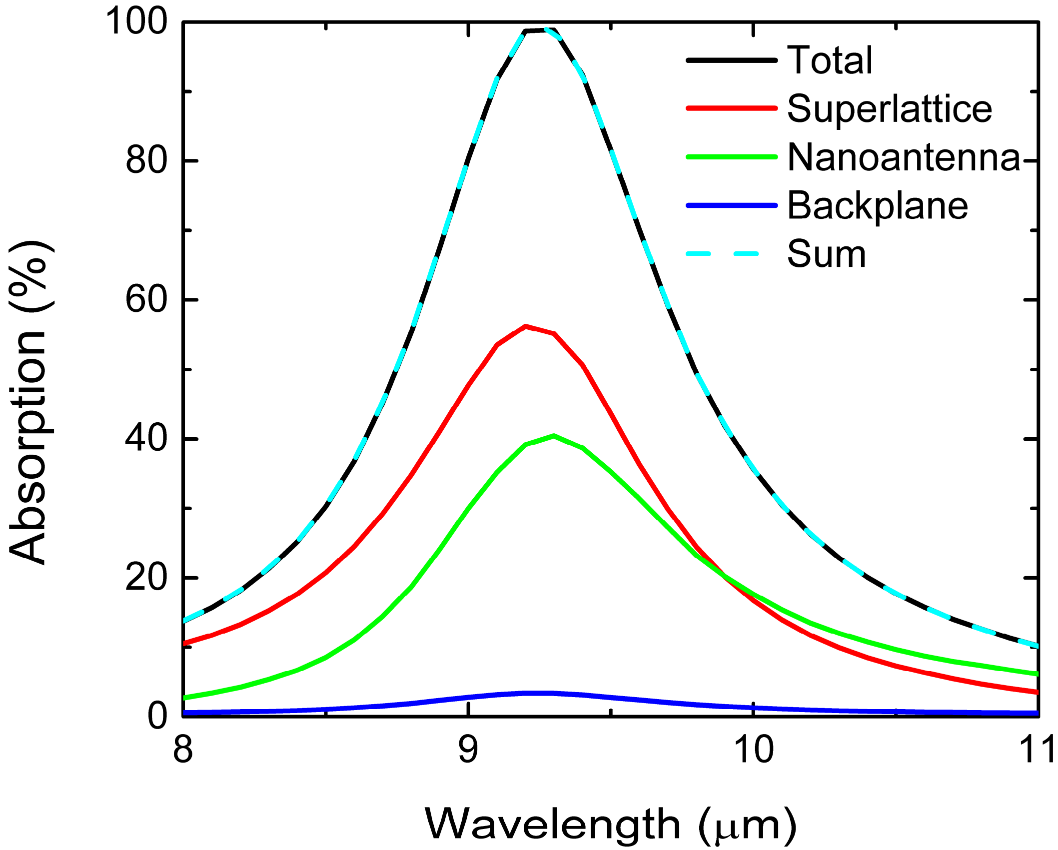
- Employ two coupled resonances: Fabry-Pérot cavity with metal nanoresonator.
- Variable response in fixed detector through variation of nanoantenna only.



Loss Mechanisms

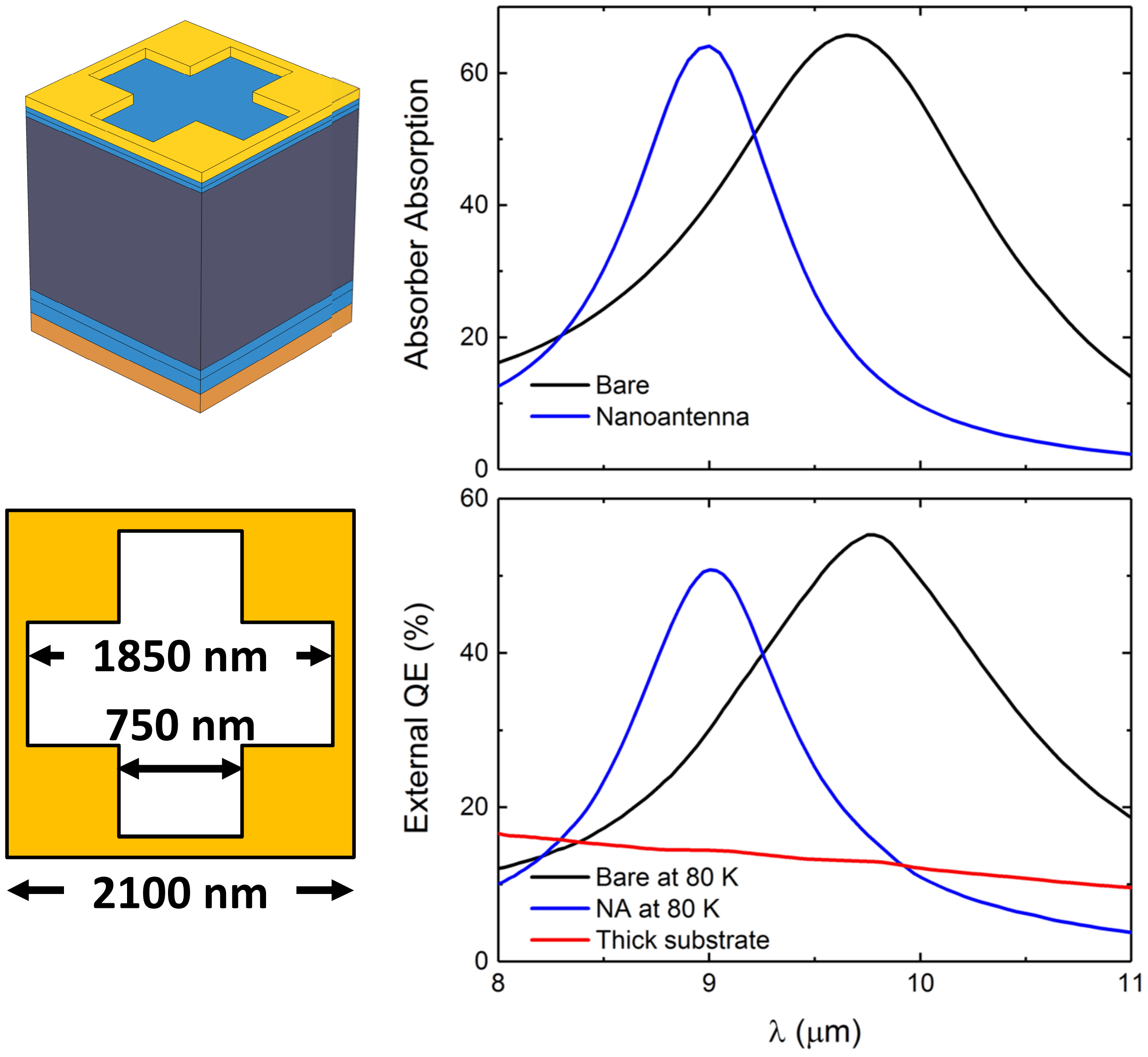




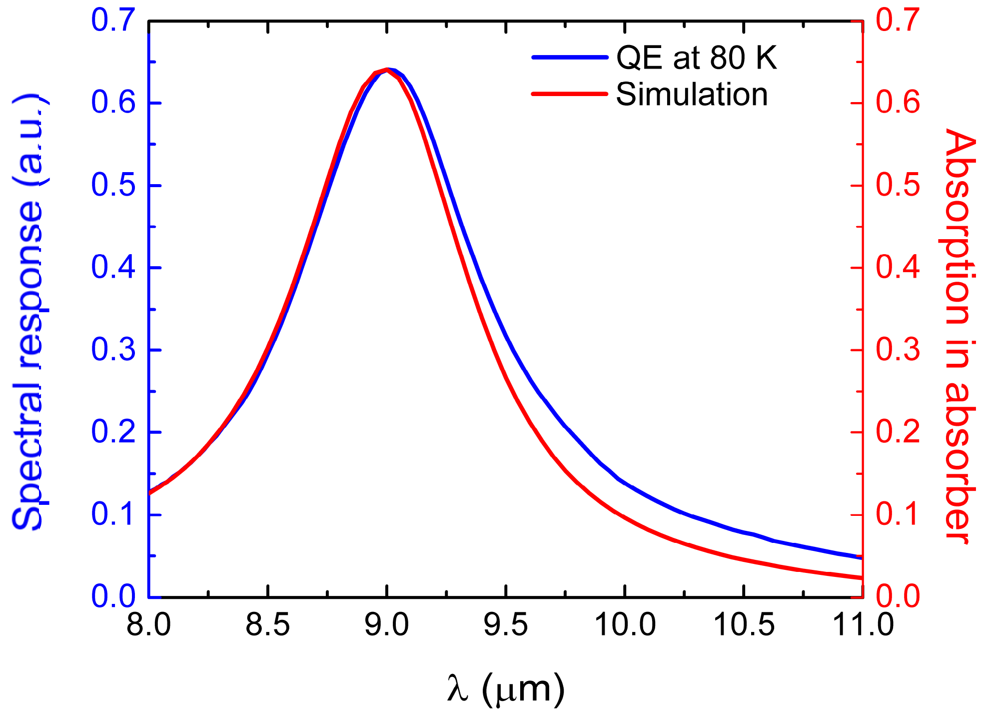


Majority of "lost" absorption is in the nanoantenna

Measured Quantum Efficiency

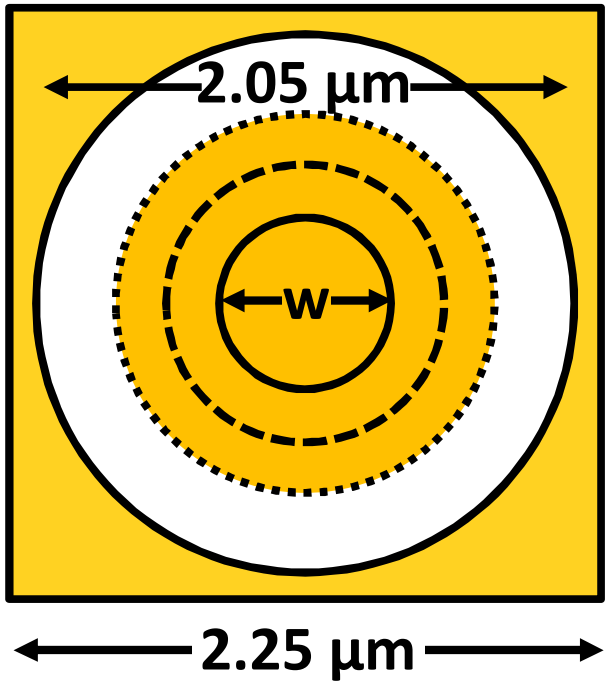


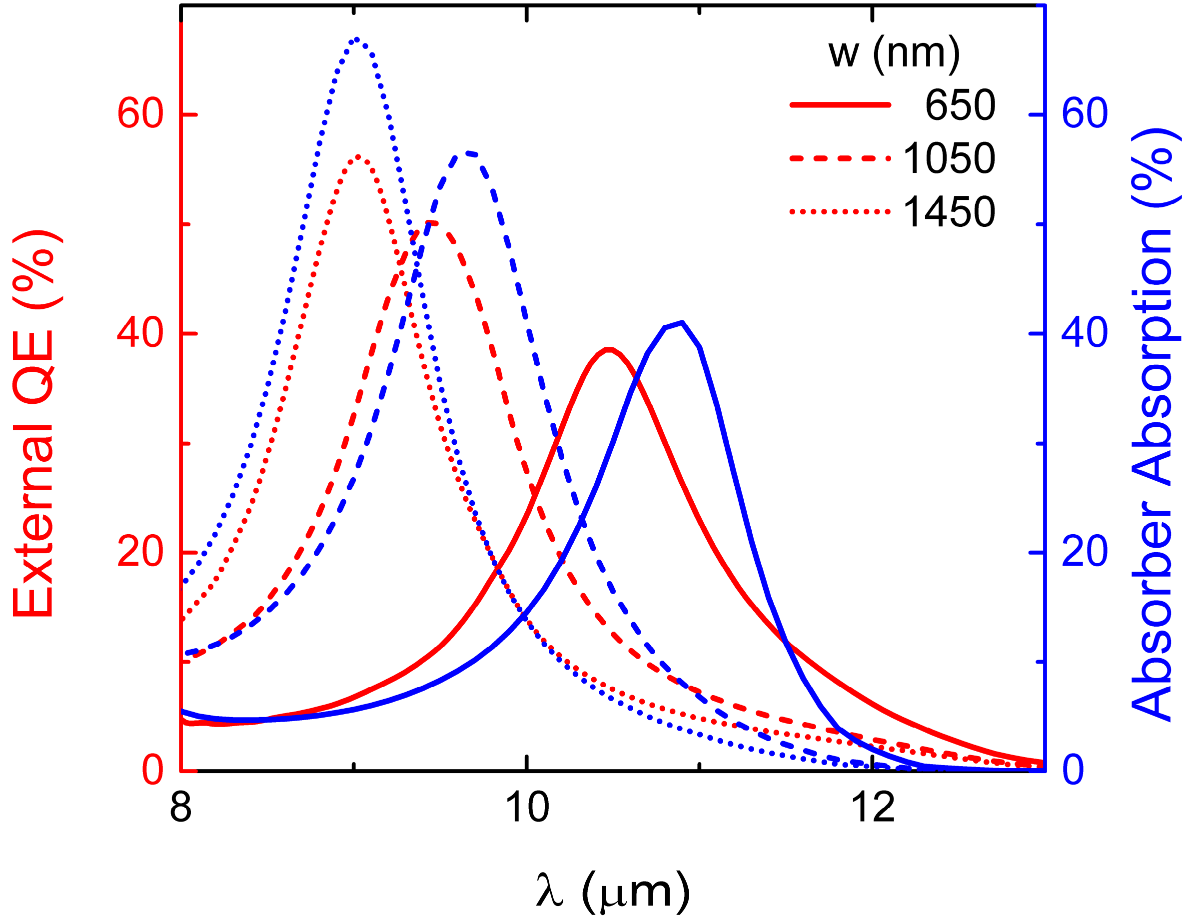
- QE>55%: 4-5x improvement compared to non-resonant detector.
- Temperature independent spectral response: lower cooling requirements.



Resonance Wavelength Modification

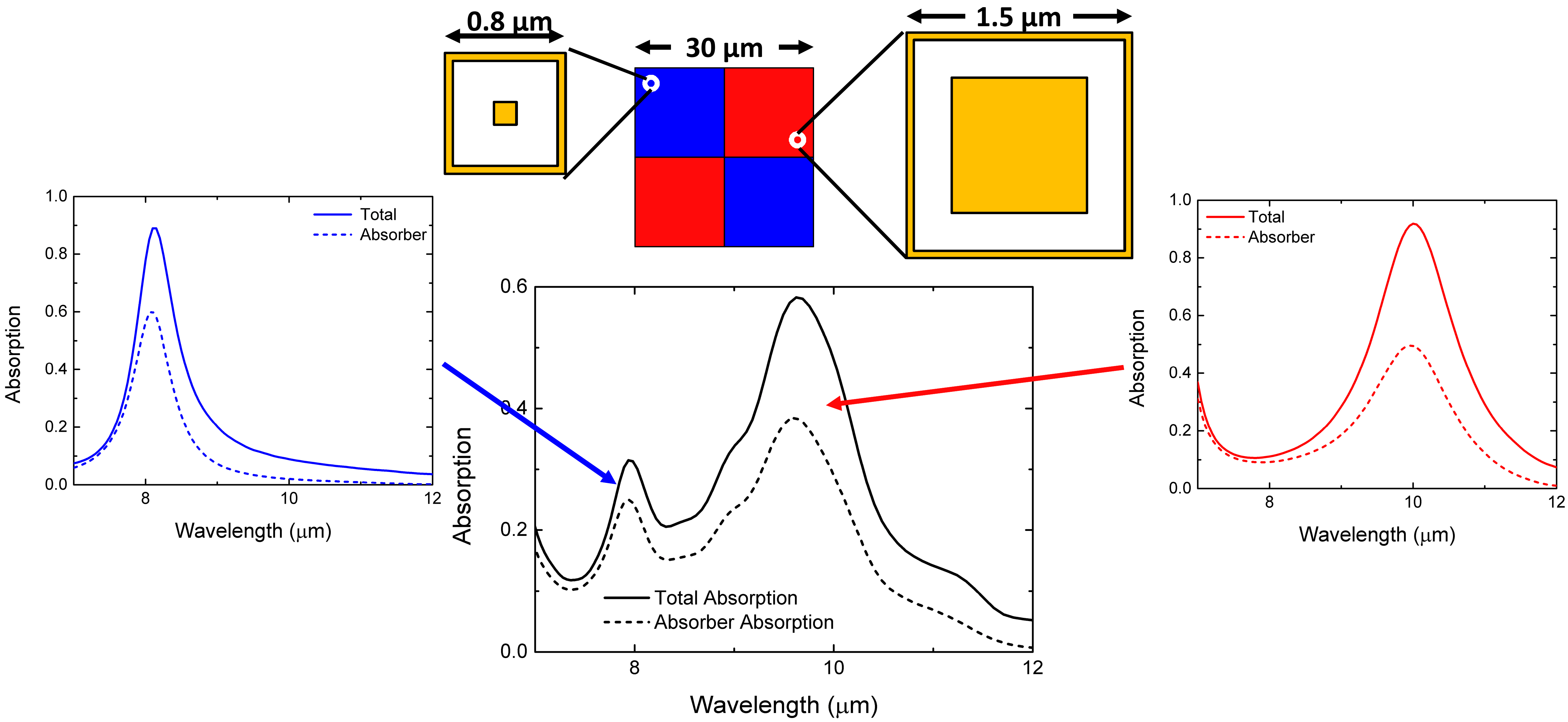
Sandia National Laboratories



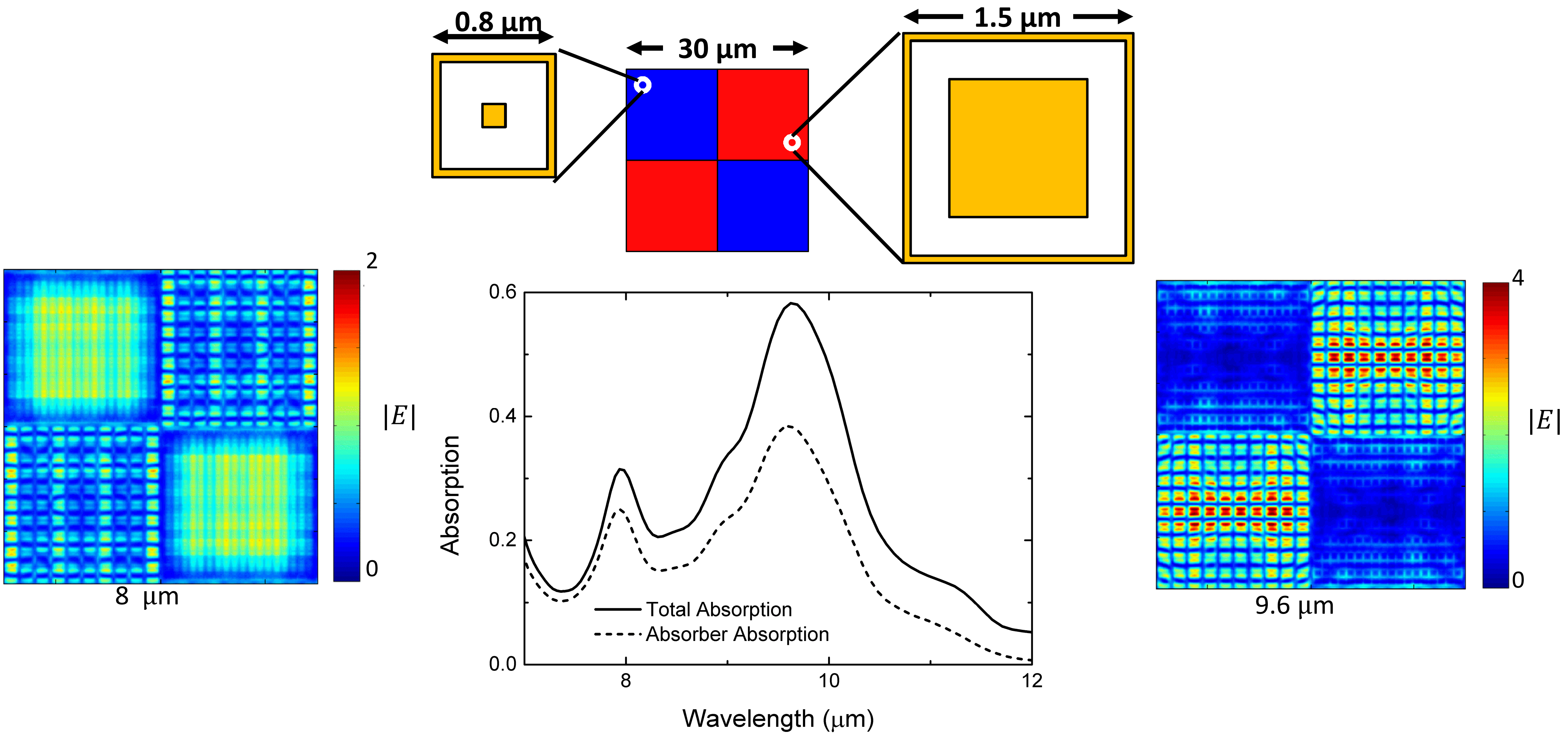


Nanoantennas enable a fixed detector stack to be resonant at multiple wavelengths without changing detector itself.

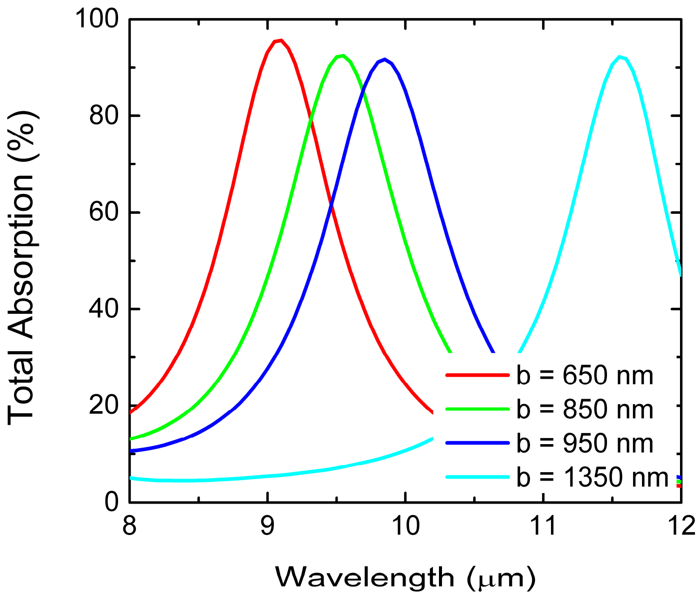
Two-Color Detections

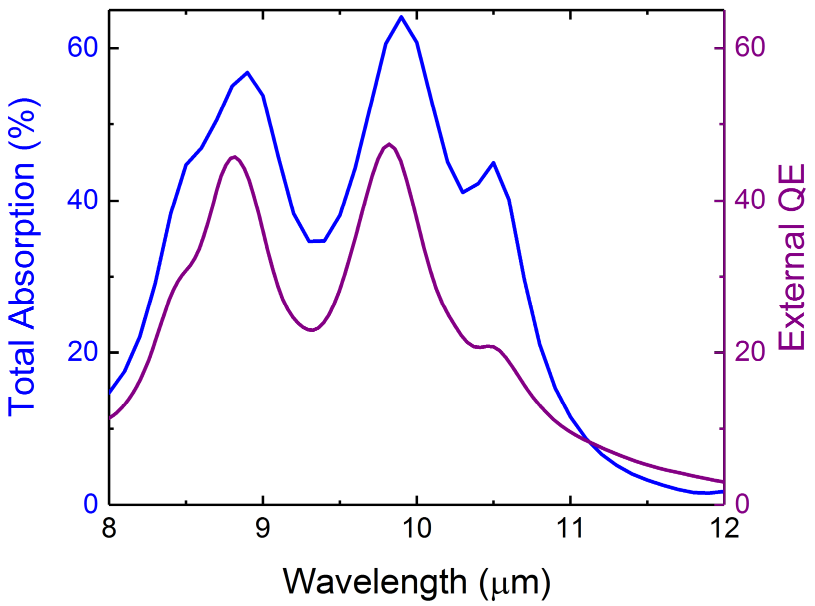


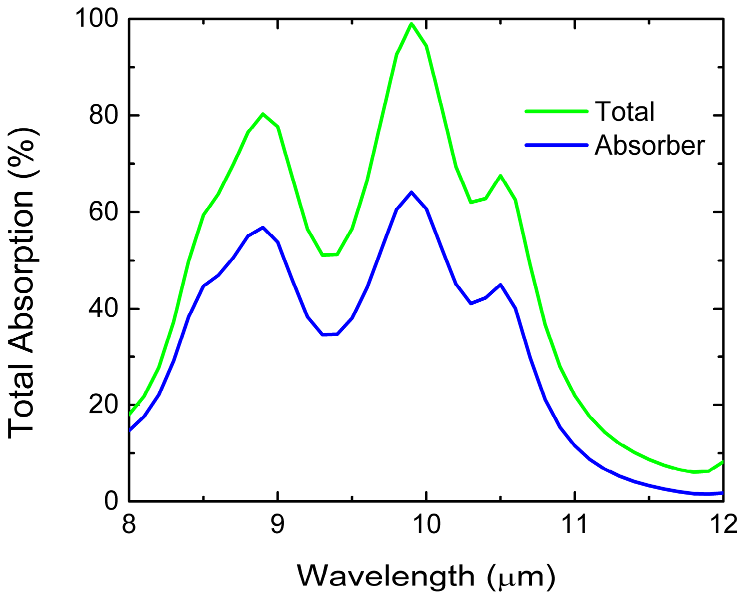
Electromagnetic Crosstalk Analysis

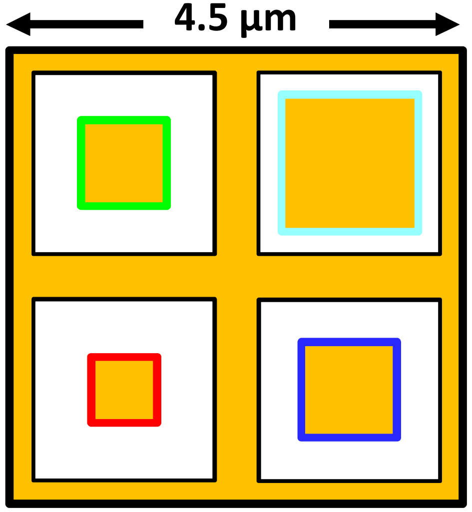


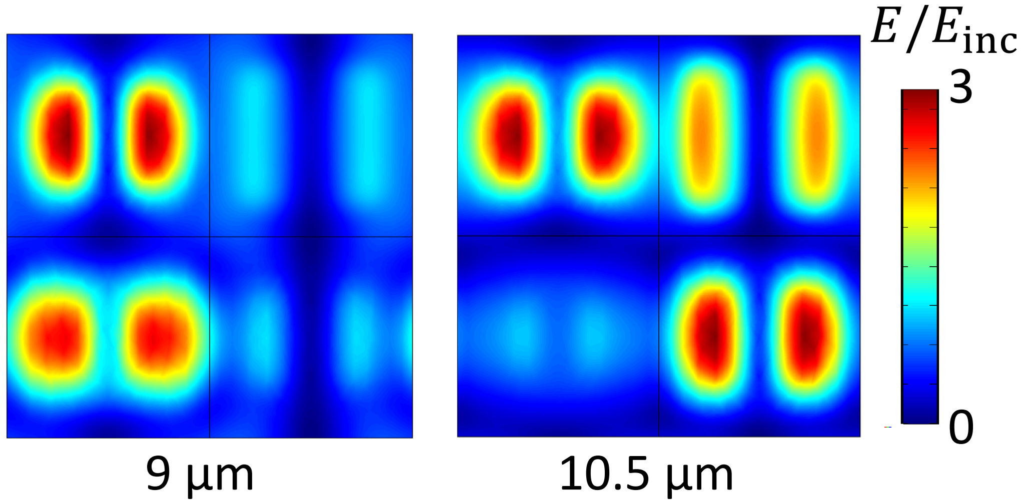
Supercell: Broadened Resonance







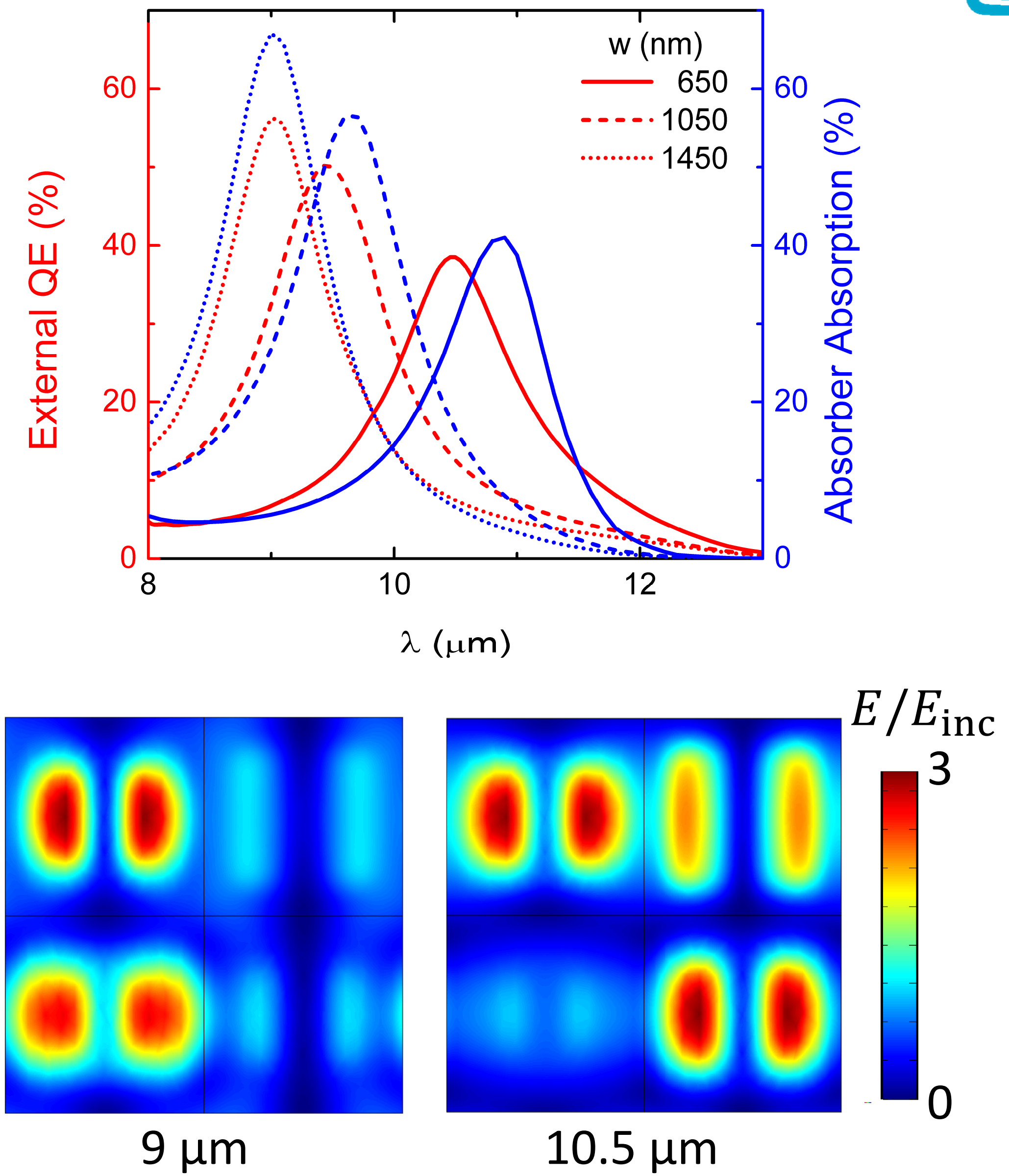




- Doubles FWHM of resonance.
- Enables improved QE over a broader range of frequencies.
- Polarization dependent response.

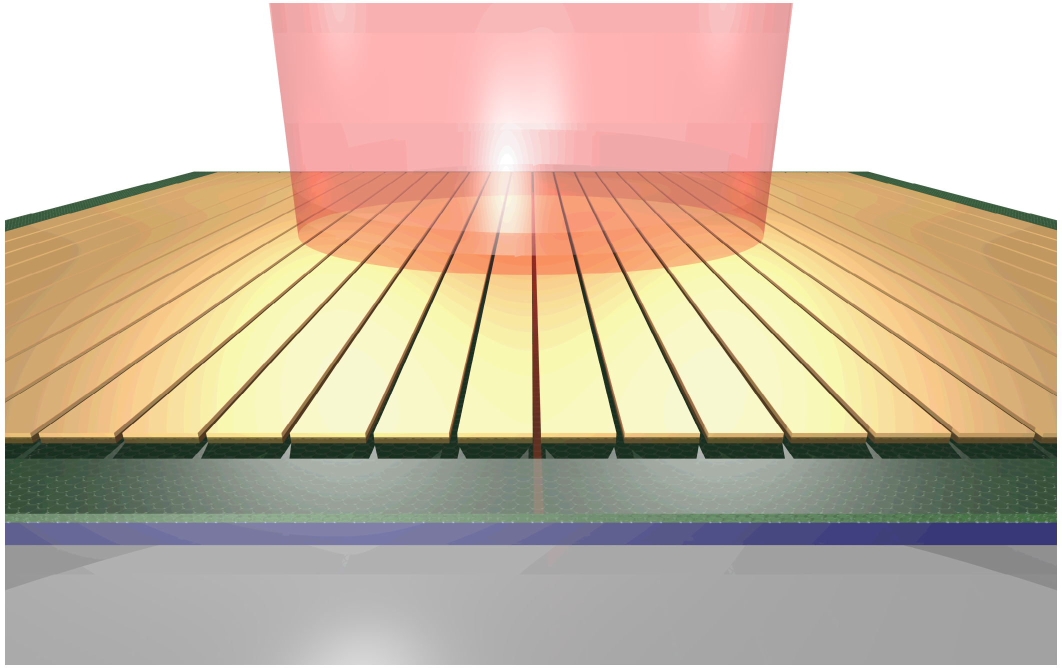
Conclusion

- Demonstrated significant gains in QE with reduction in absorbing volume.
- Control of detector response without changing detector itself.
- Broadband resonant response
- Examined two color detectors



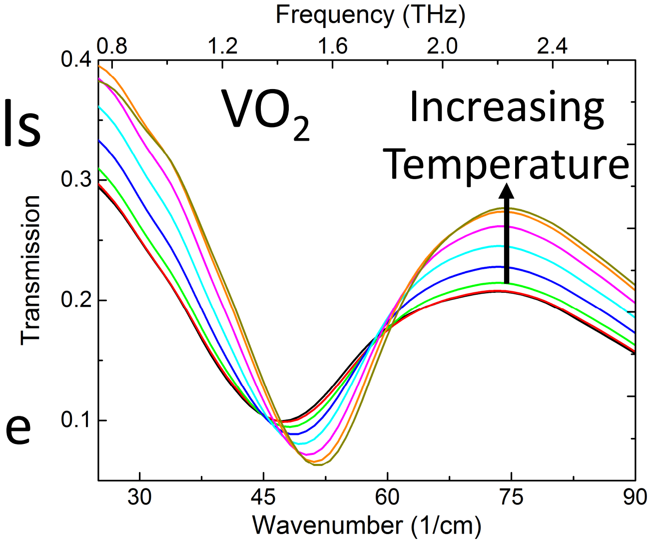
Outline

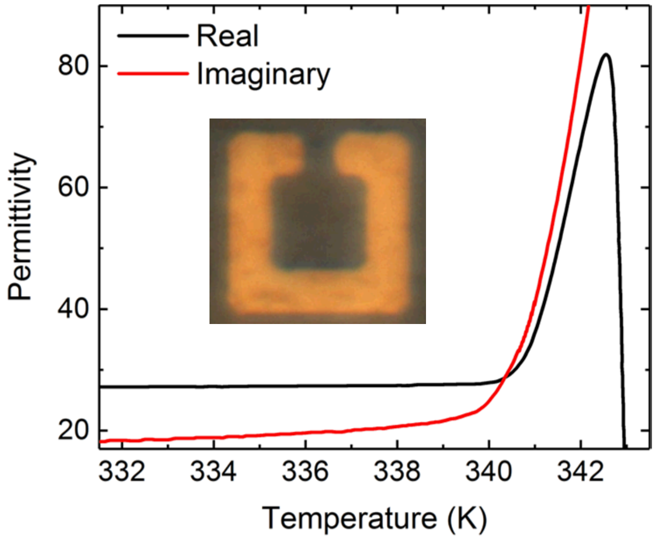
- Resonantly Enhance IR Detectors
  - Type-II Superlattices
  - Metallic nanostructures
- Tunable IR Filters
  - Graphene
  - Reflectance-mode Filter
- Summary

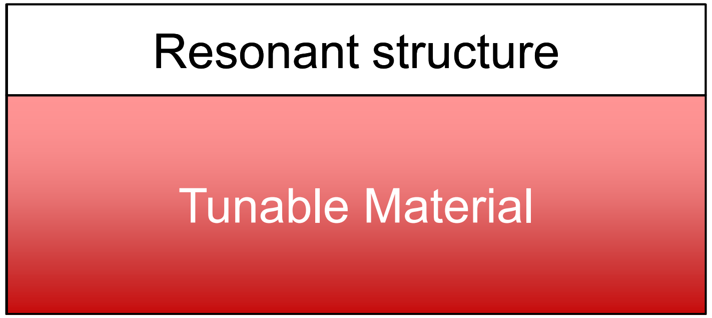


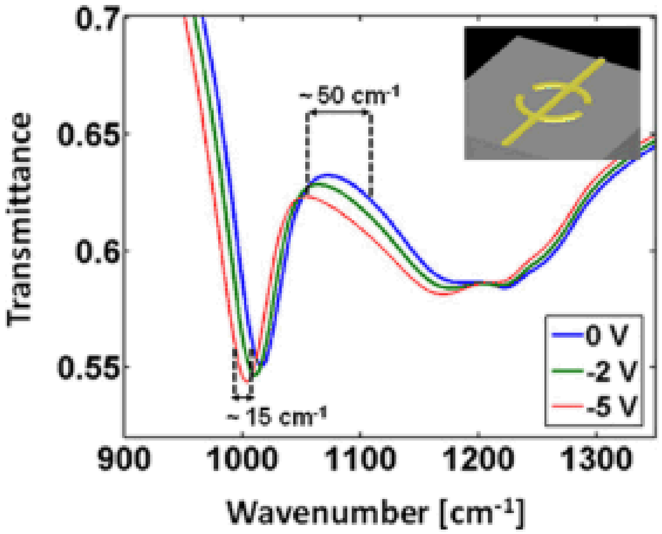
Tunable materials

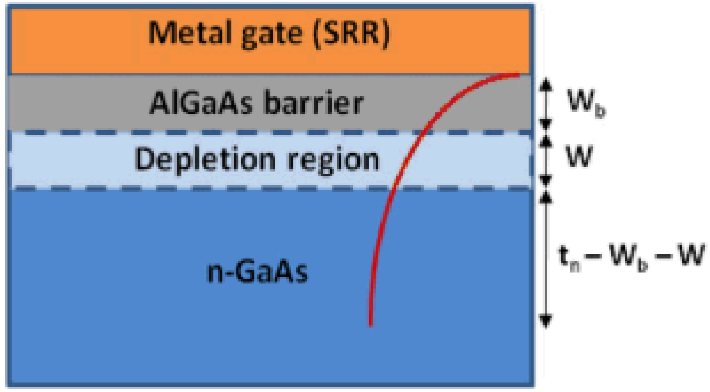
- Metal-Insulator transition materials
  - VO_2, V_2O_3, $NdNiO_3$
  - Thermally triggered
- Tunable bulk plasmonic materials
  - CdO, semiconductors, indium tin oxide
  - Electrically triggered







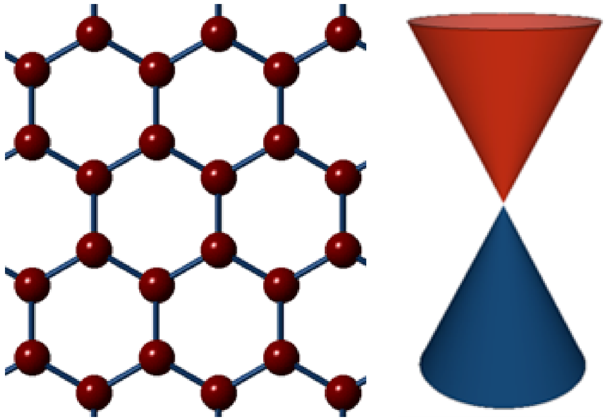


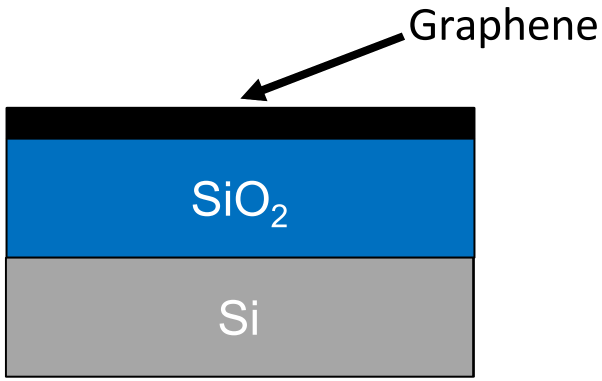


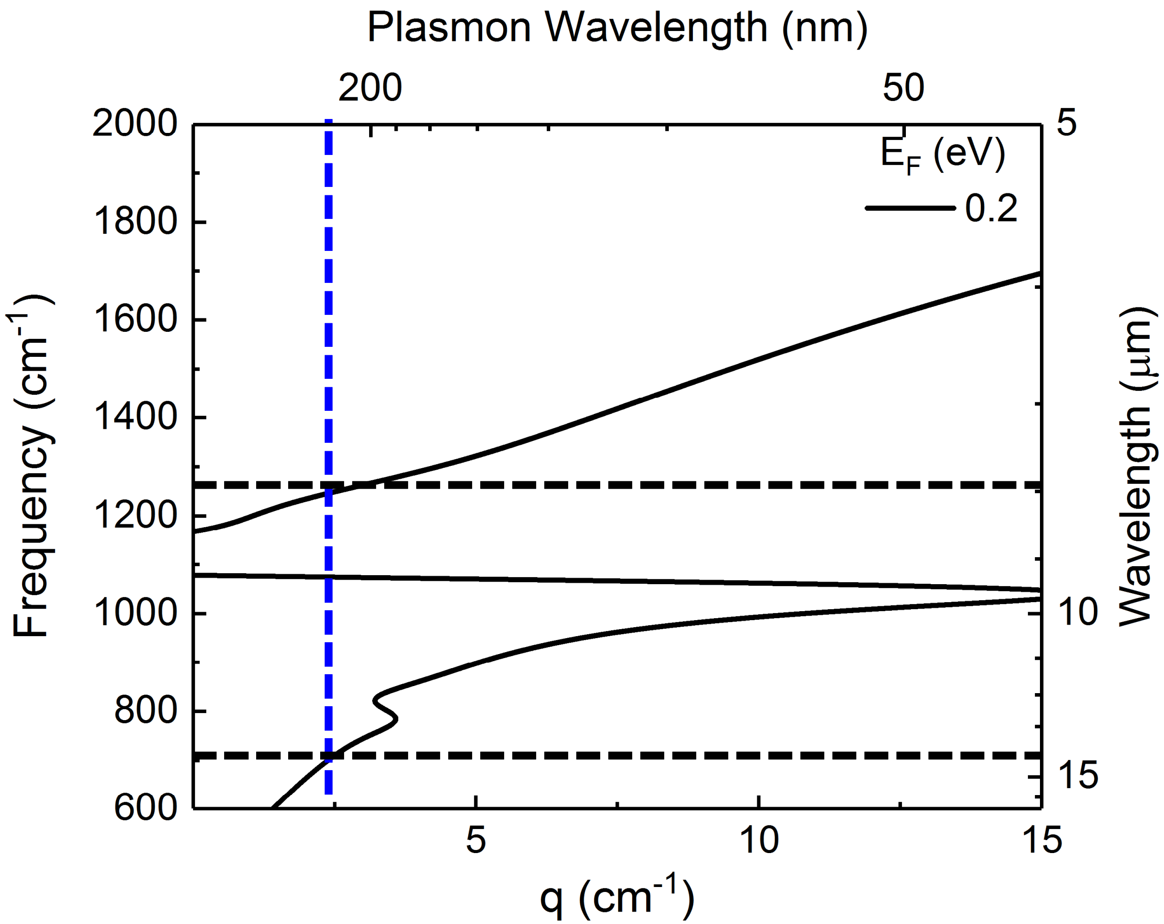
$$\omega_p \propto \sqrt{n}$$

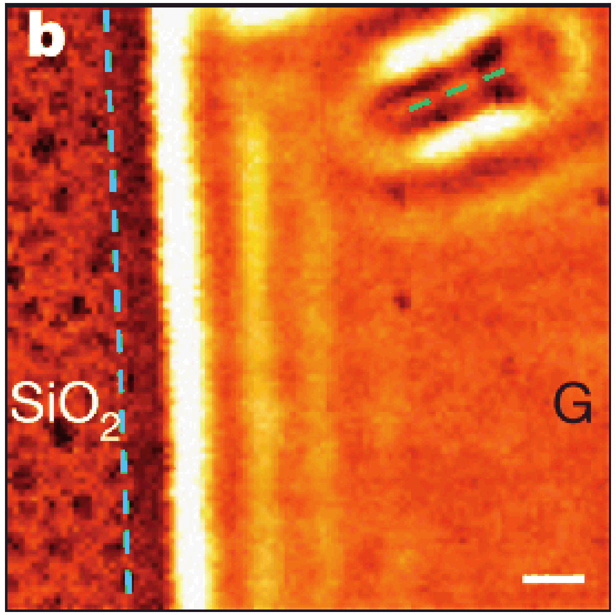
M. D. Goldflam, et al, Appl. Phys. Lett. 99 (4), 044103 (2011).
M. K. Stewart, et al, Phys. Rev. Lett. 107 (17), 176401 (2011).
T. Driscoll, et al, Appl. Phys. Lett. 93 (2), 024101 (2008).
Y. C. Jun and I. Brener, Journal of Optics 14 (11), 114013 (2012).
Y. W. Huang, et al, Nano Lett. (2016).

Plasmonic Tuning in Graphene









Plasmonic response easily tuned through carrier injection

Z. Fei, et al, Nano Lett. 2011, 11, (11), 4701-5.
J. Chen, et al, Nature 487 (7405), 77-81 (2012).
M. D. Goldflam et al, Nano Lett. 15 (8), 4859-4864 (2015).

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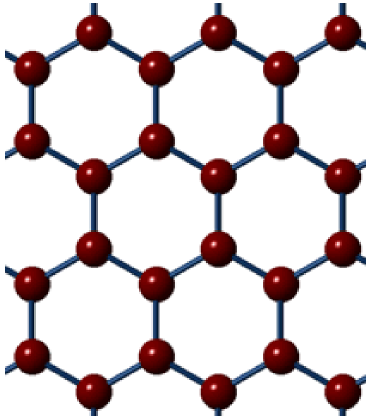

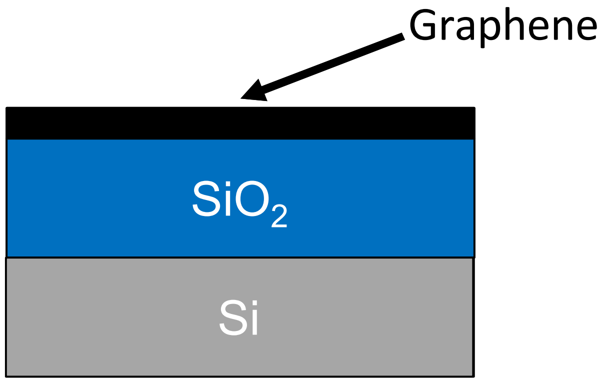

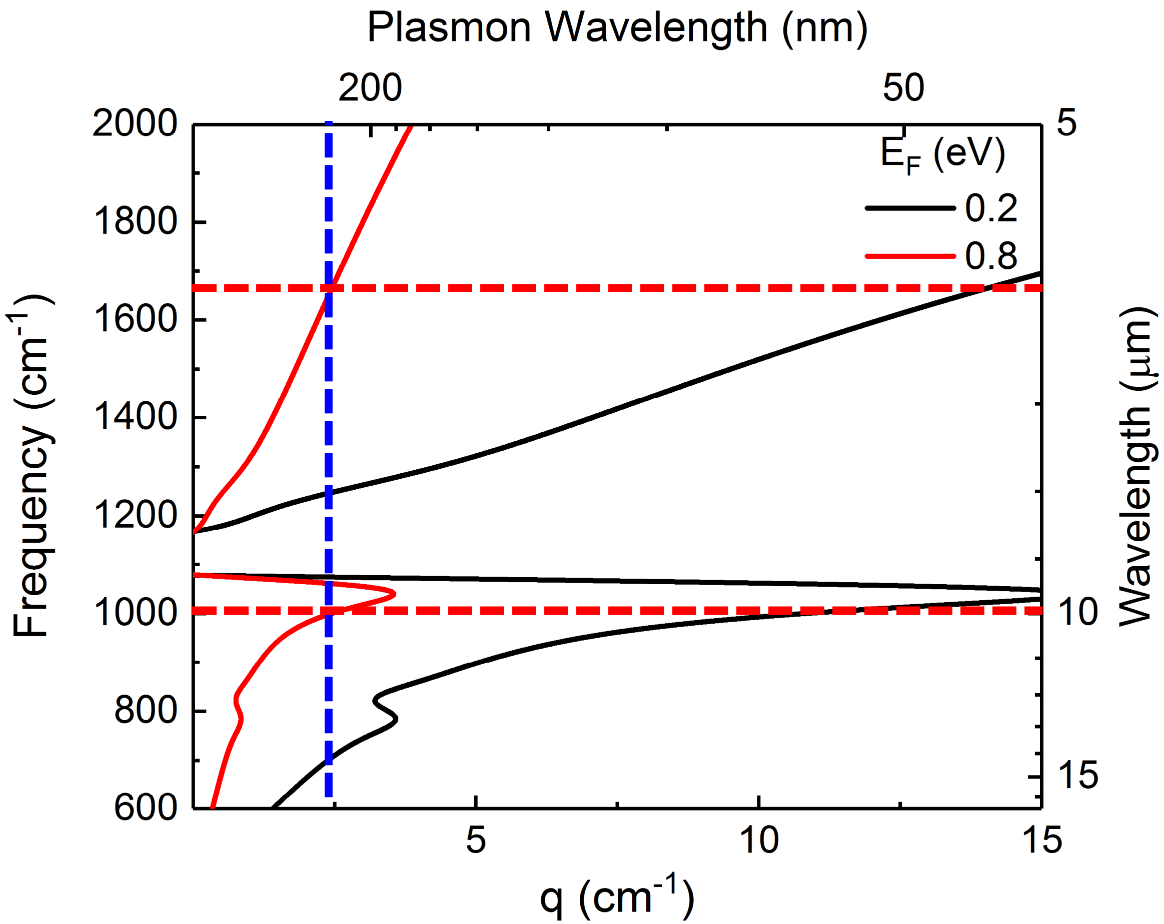

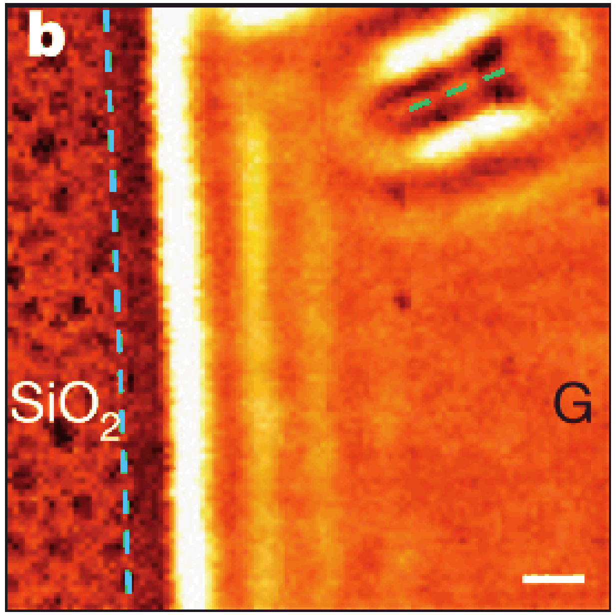

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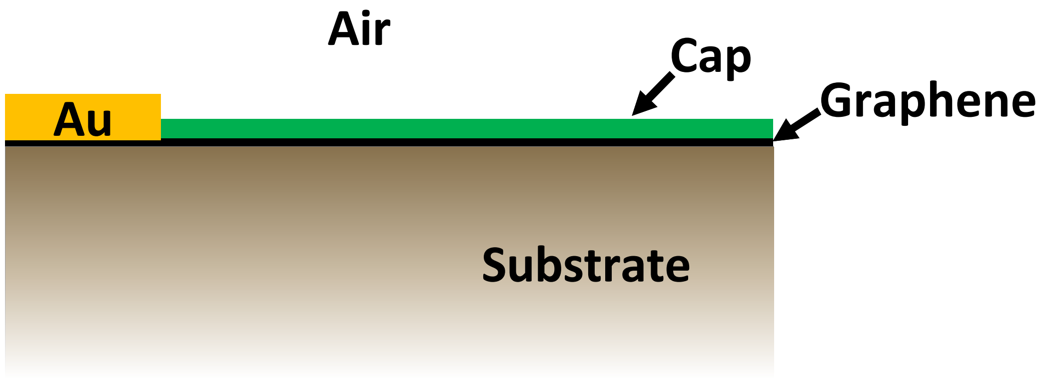
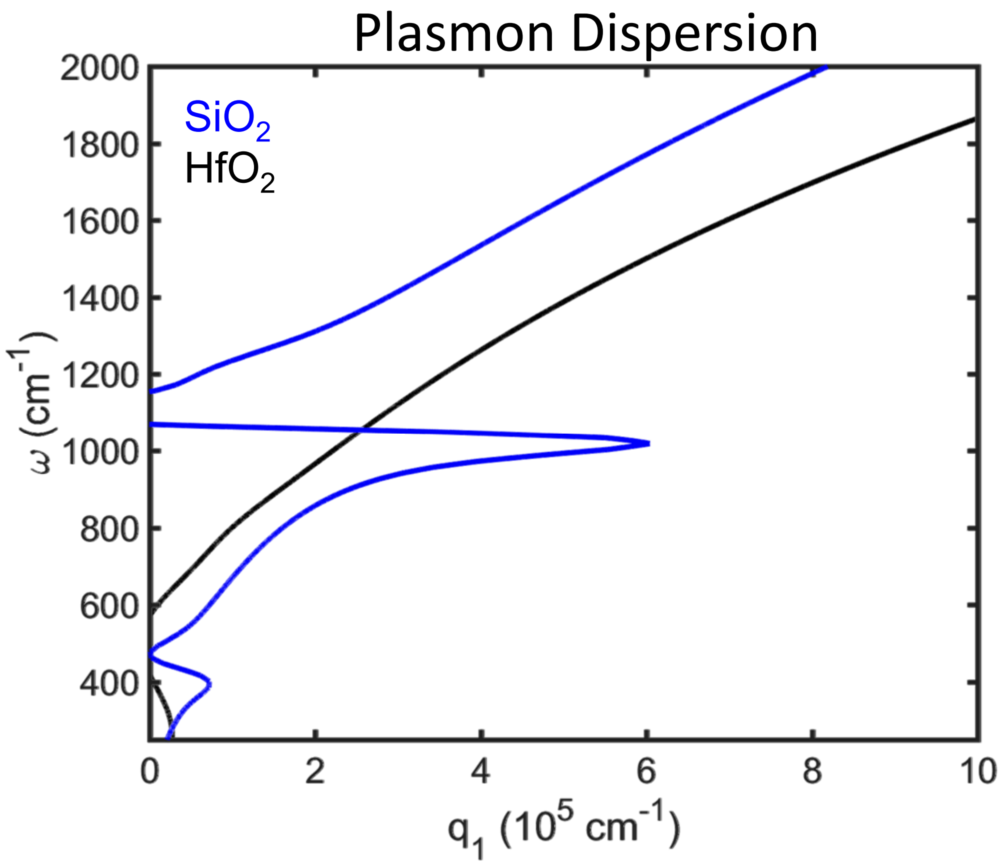
Limitations of Graphene

Graphene changed by environment and fabrication methods

- Fermi level pinning
- Environmental degradation
- Plasmon dispersion modification

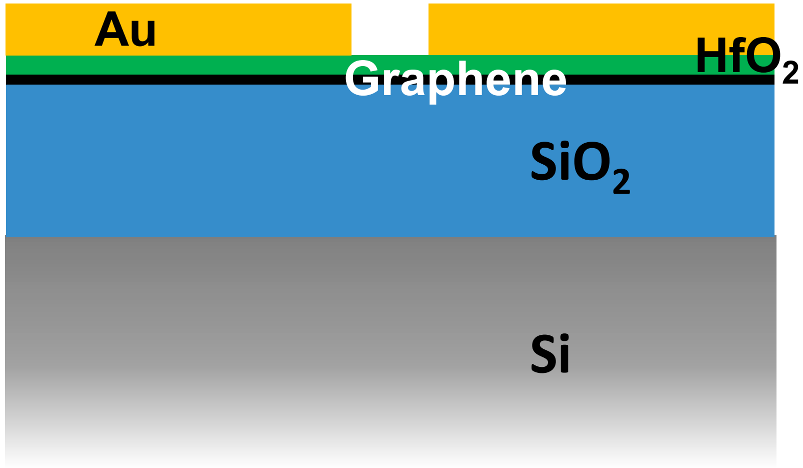


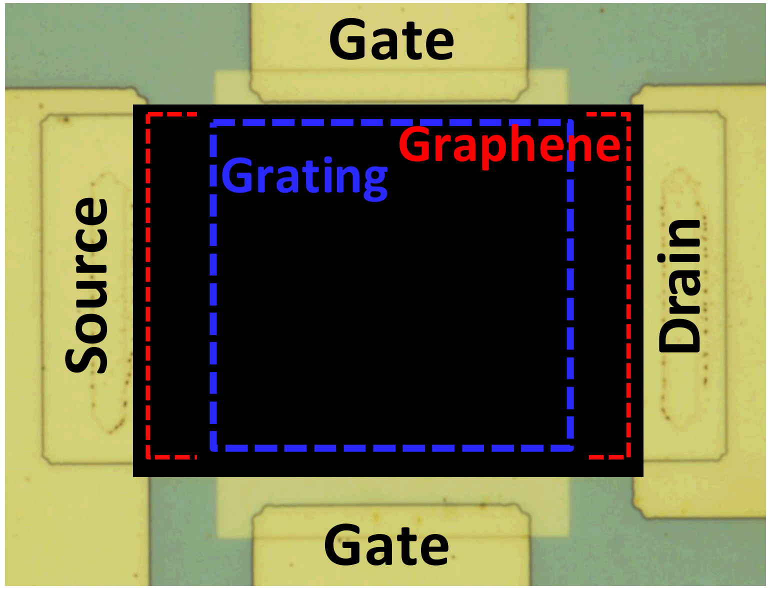


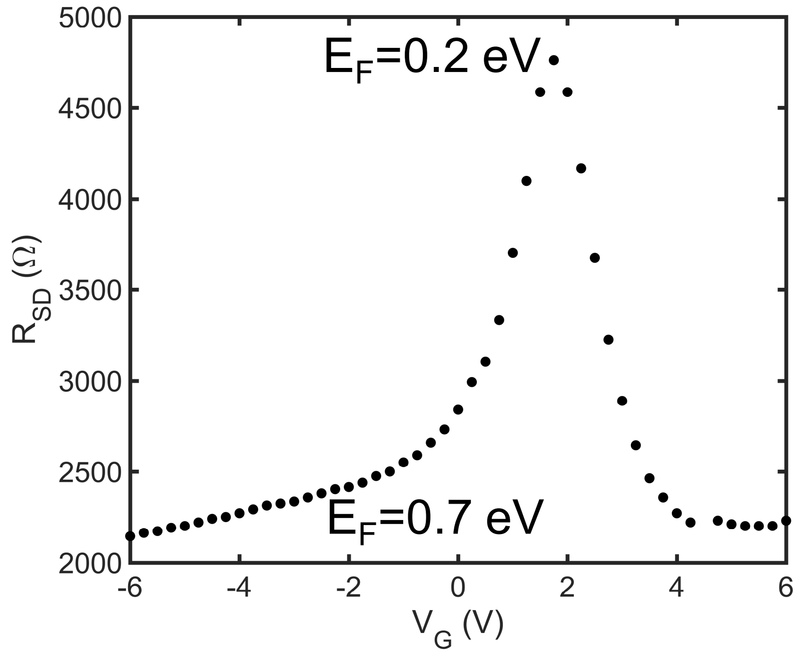
I. Ruiz, et al., Opt. Lett. 42 (14), 2850-2853 (2017).

Z. Fei, et al, Nano Lett. 2011, 11, (11), 4701-5.

Device Design



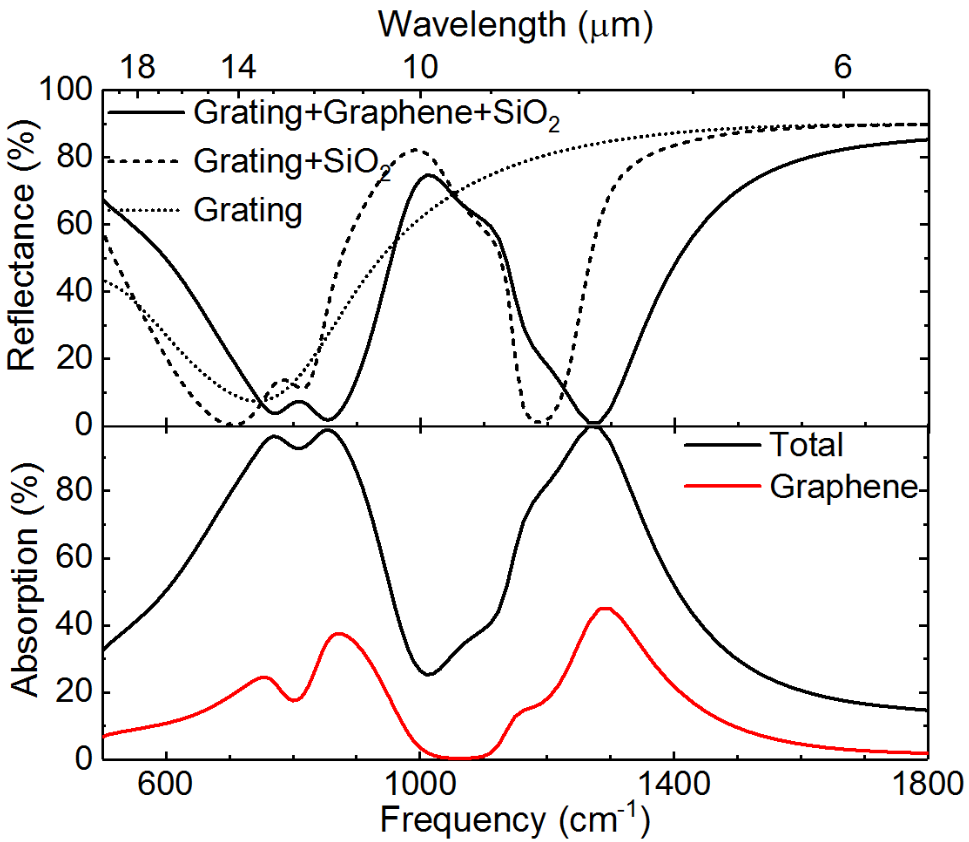


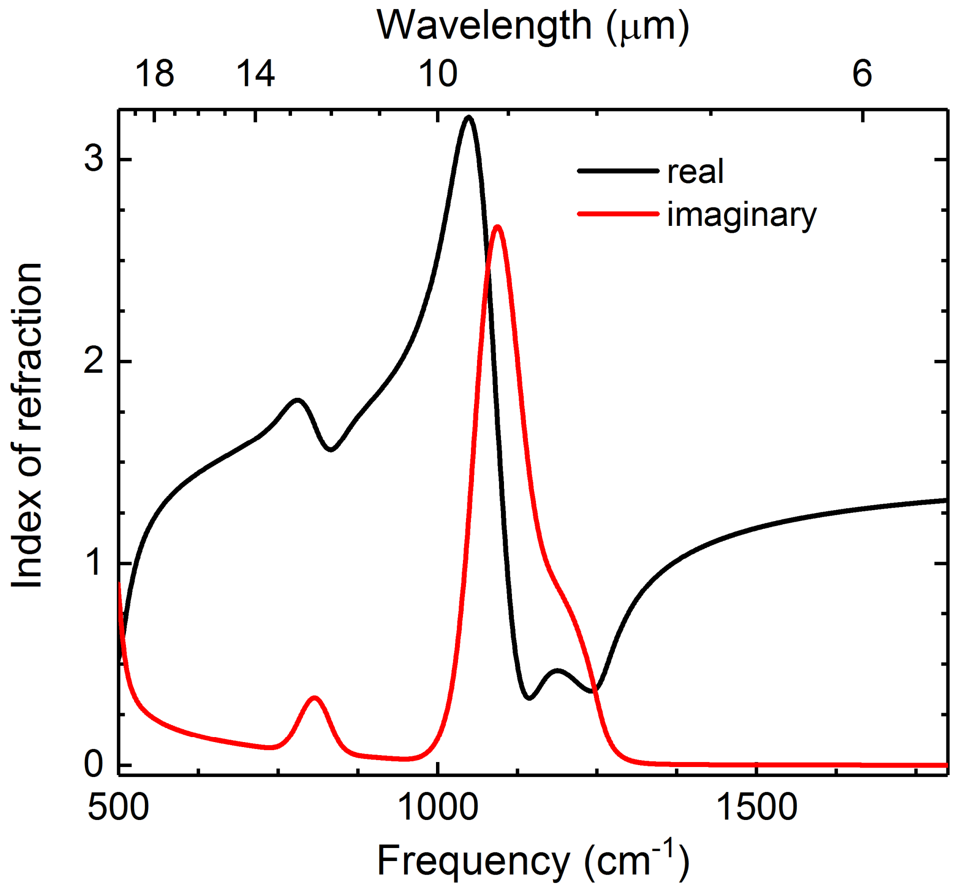


- Scalable (continuous and unpatterned large-area CVD graphene)
- Protected graphene (capping layer)
- Avoid metal-graphene contact

Goldflam et al, in preparation

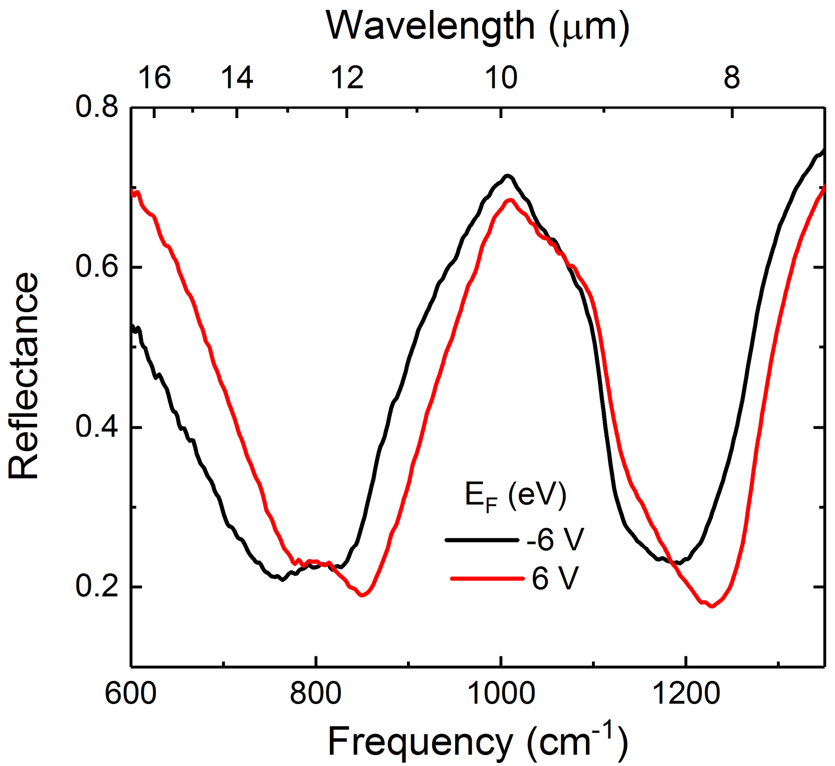
Building the Filter Response

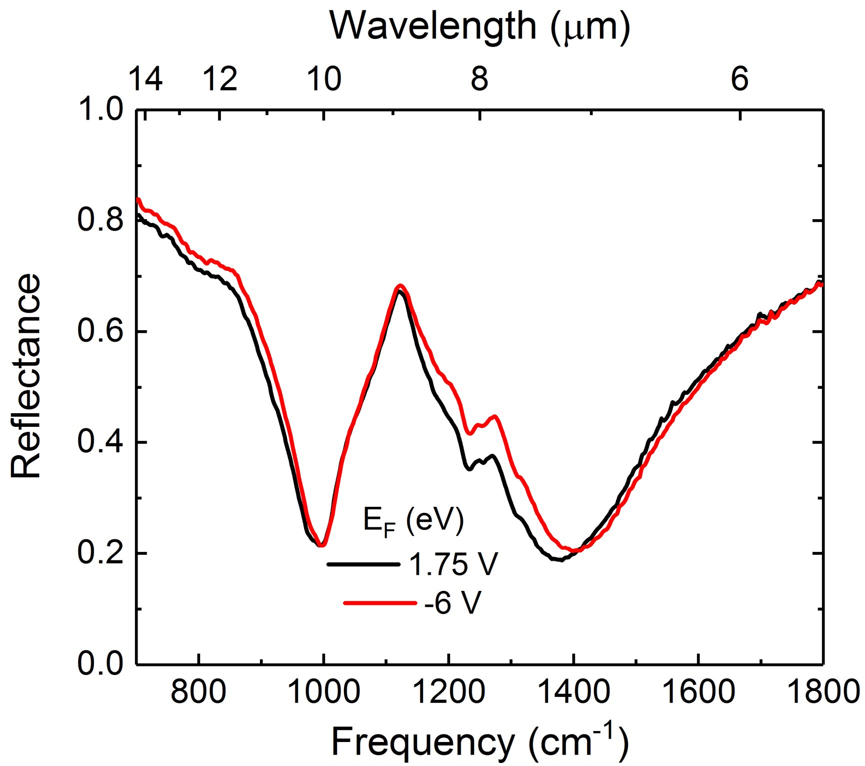


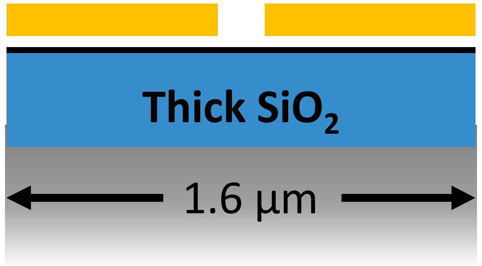


- Presence of SiO_2 increases resonance Q-factors
- Dielectrics can modify resonance location.

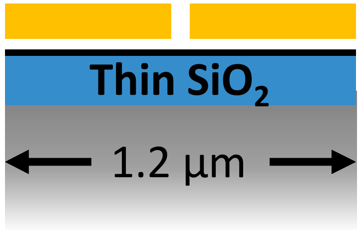
Measured Reflectance



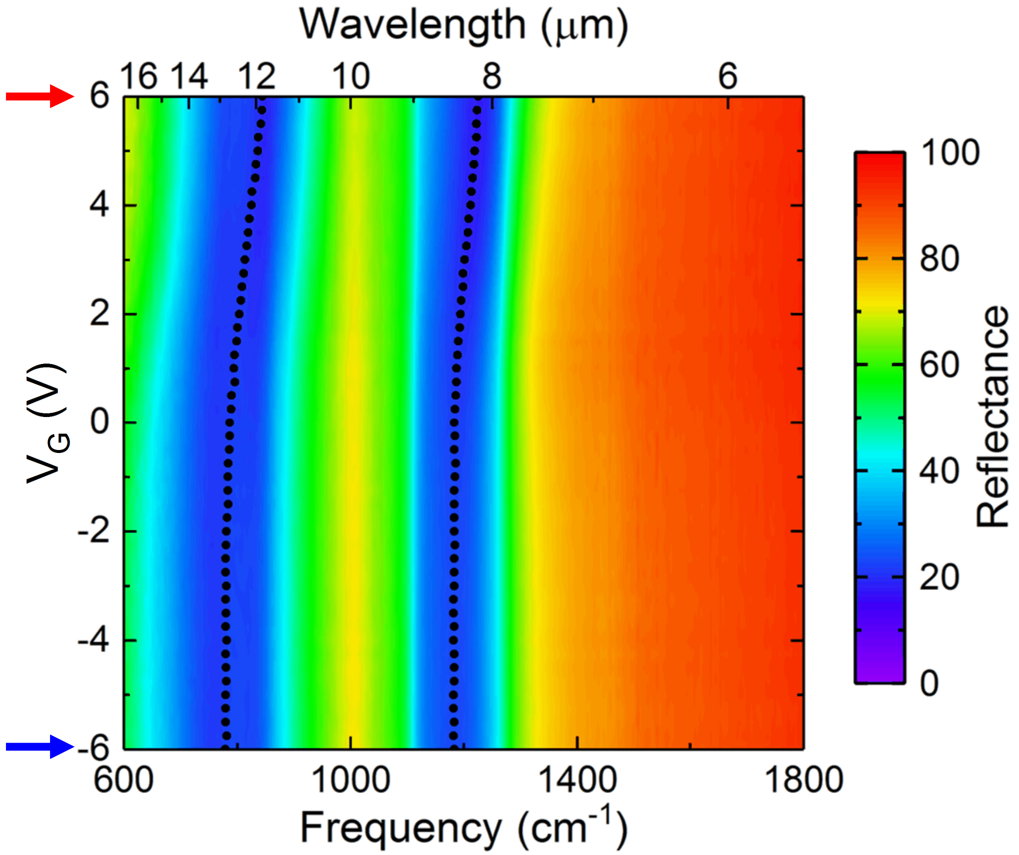


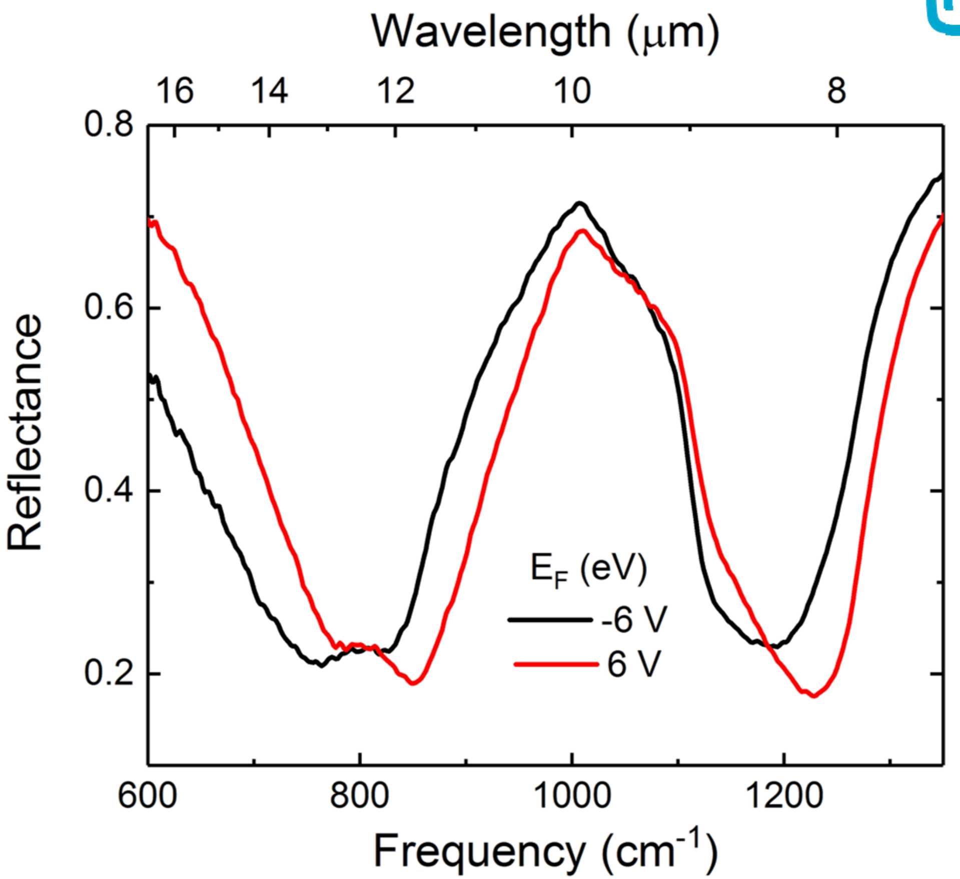


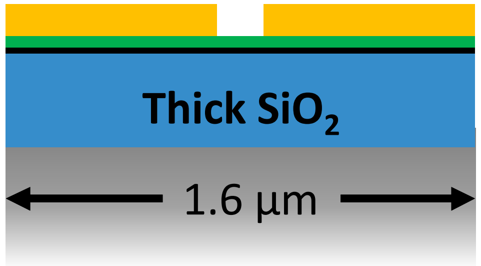
- Spectral shifts depend on geometry.
- Location and tuning amount can be designed.



Measured Reflectance

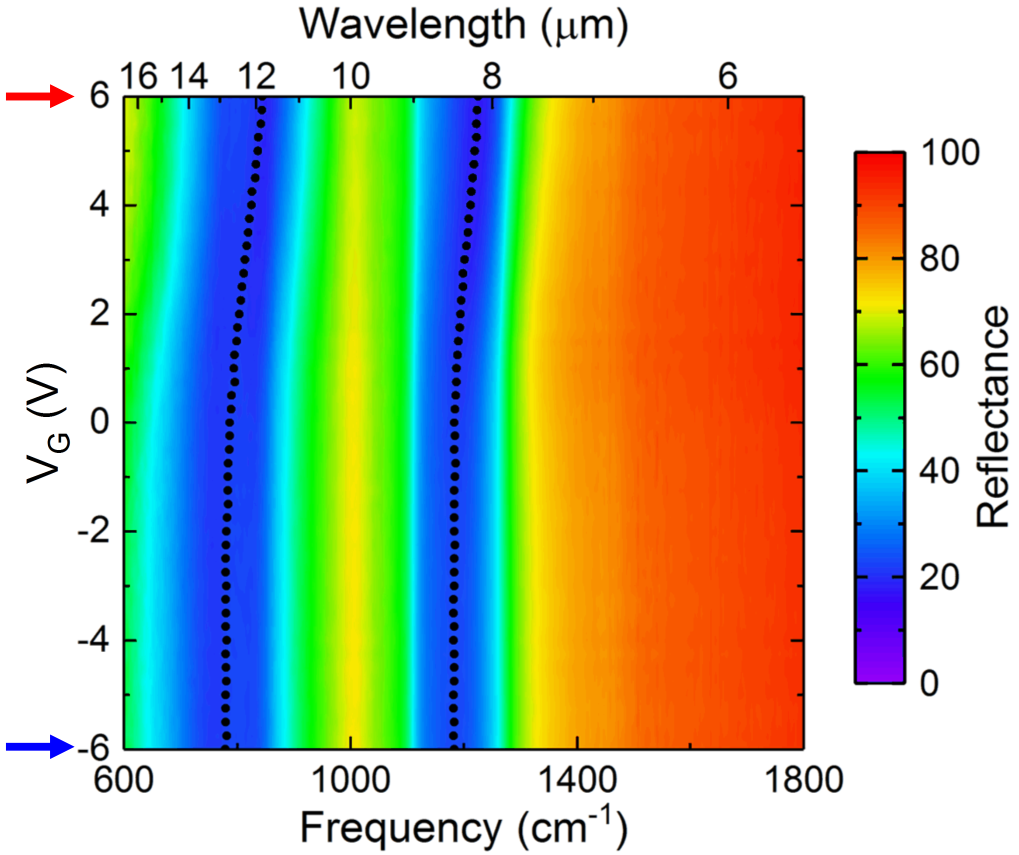


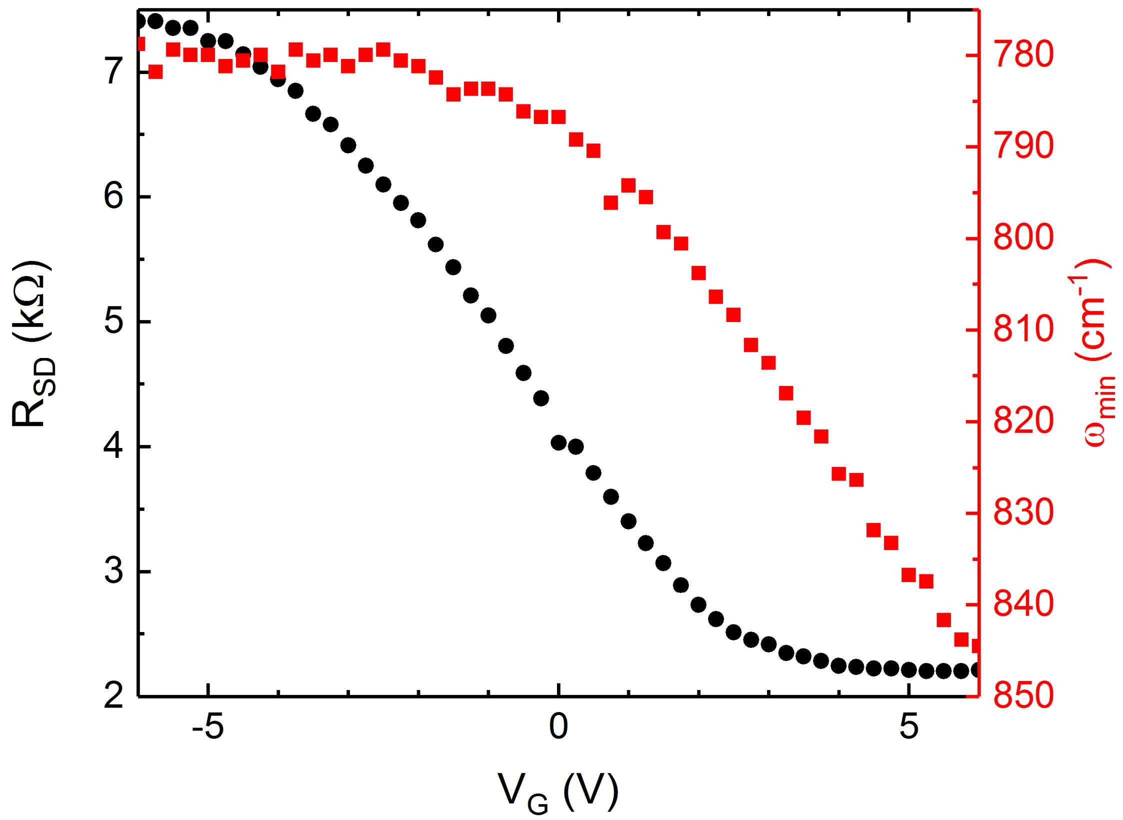


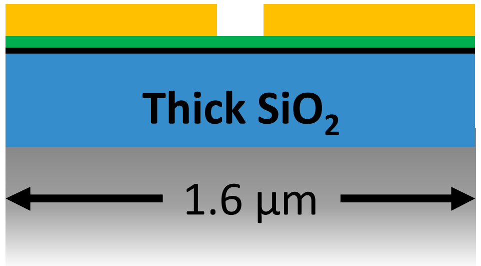


- Shift in position of two resonances simultaneously.
- Larger shifts at lower frequencies.
- Spectral shift depends on both grating design and SiO_2 thickness.

Measured Reflectance

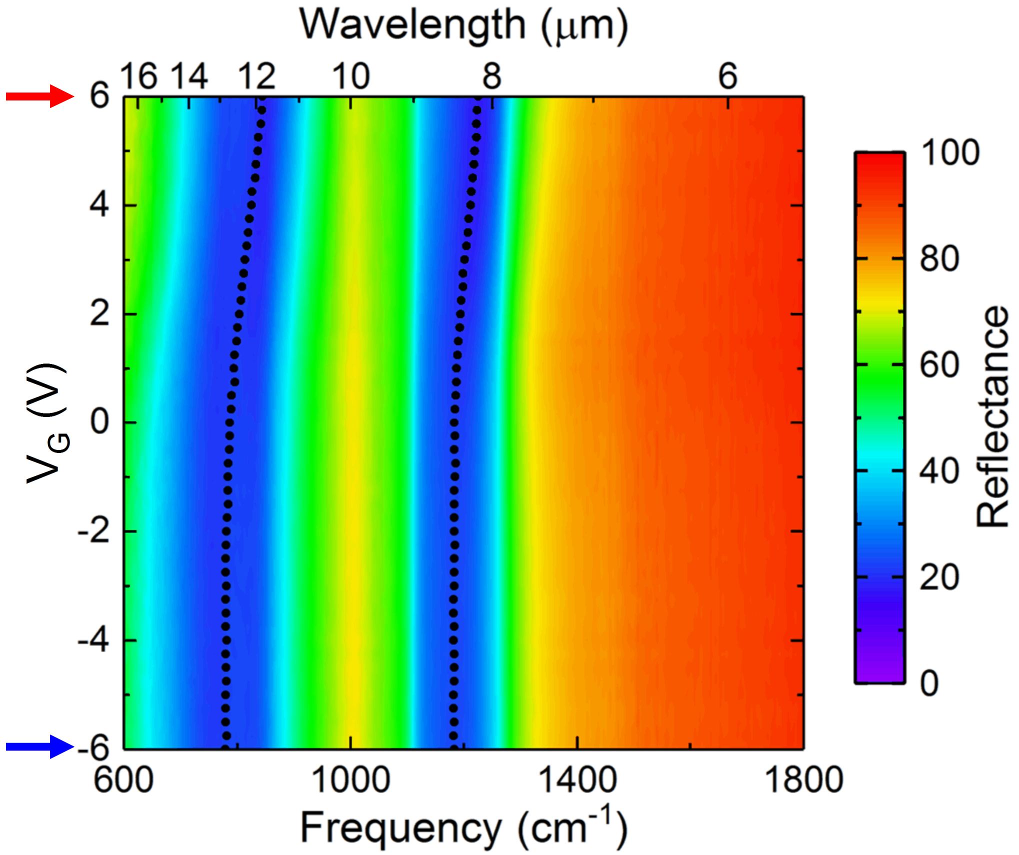


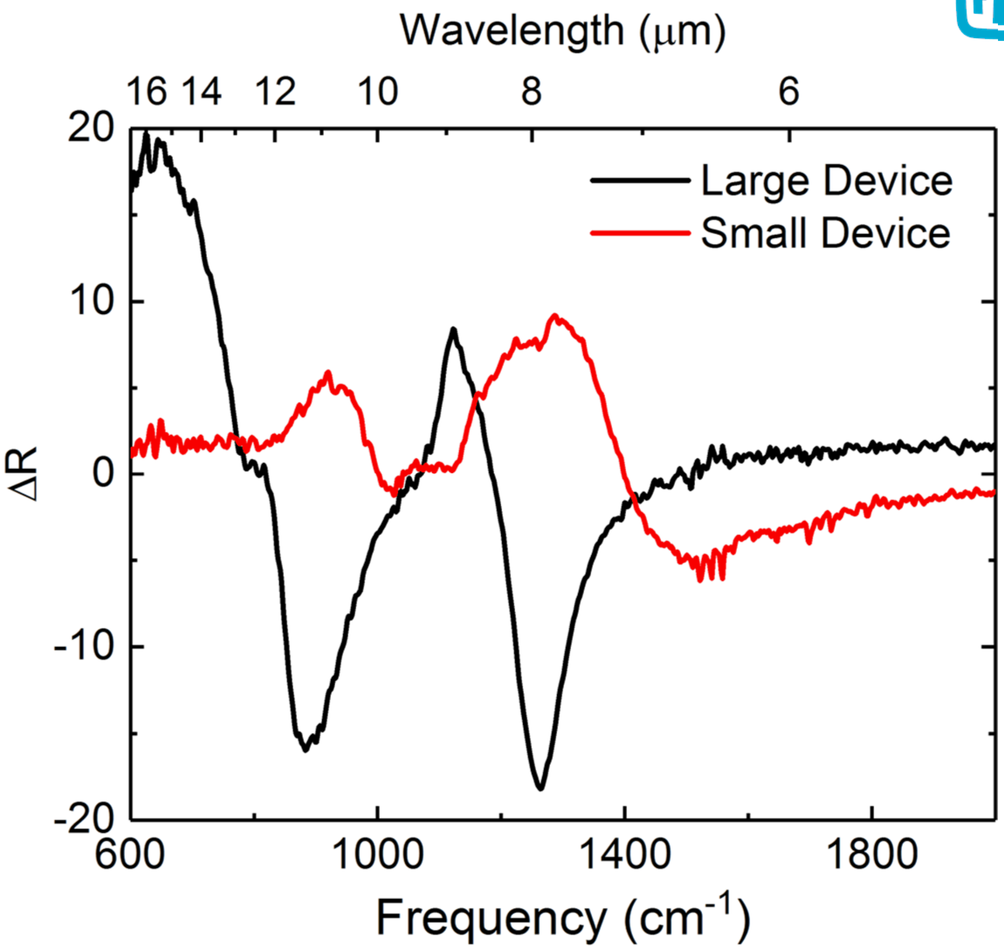


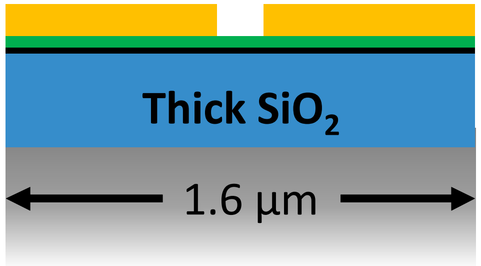


- Shift in position of two resonances simultaneously exceeding 50 cm^{-1}.
- Larger shifts at lower frequencies.
- Spectral shift depends on both grating design and SiO_2 thickness.

Measured Reflectance

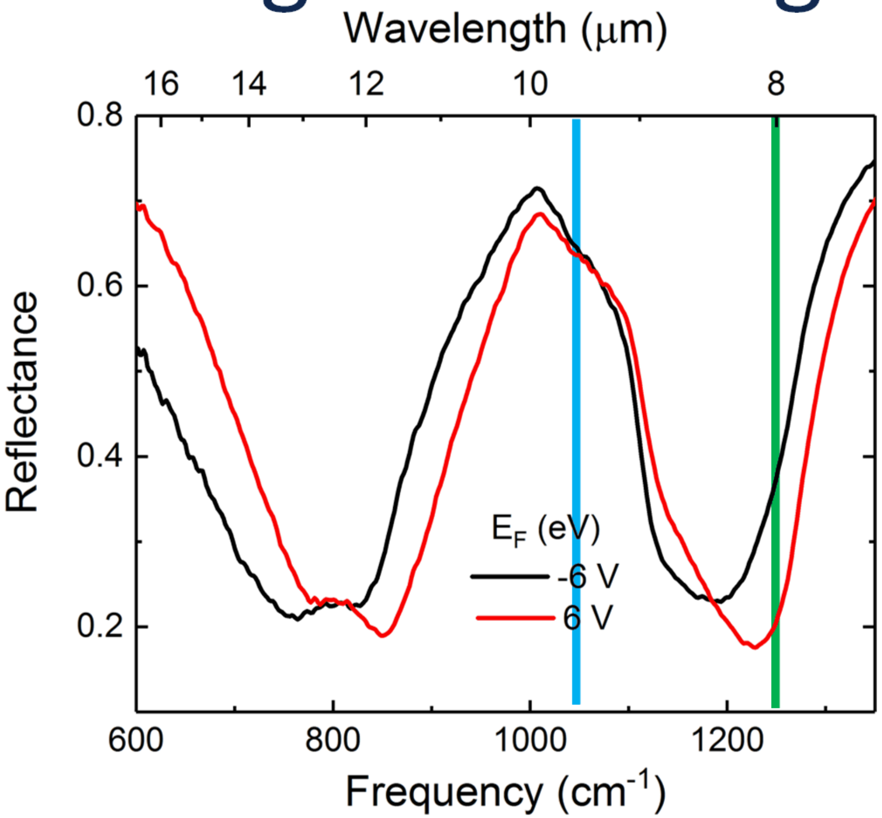


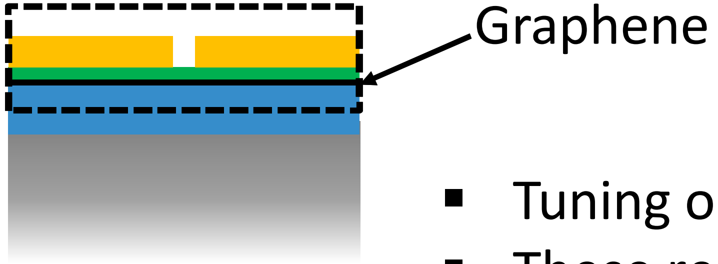


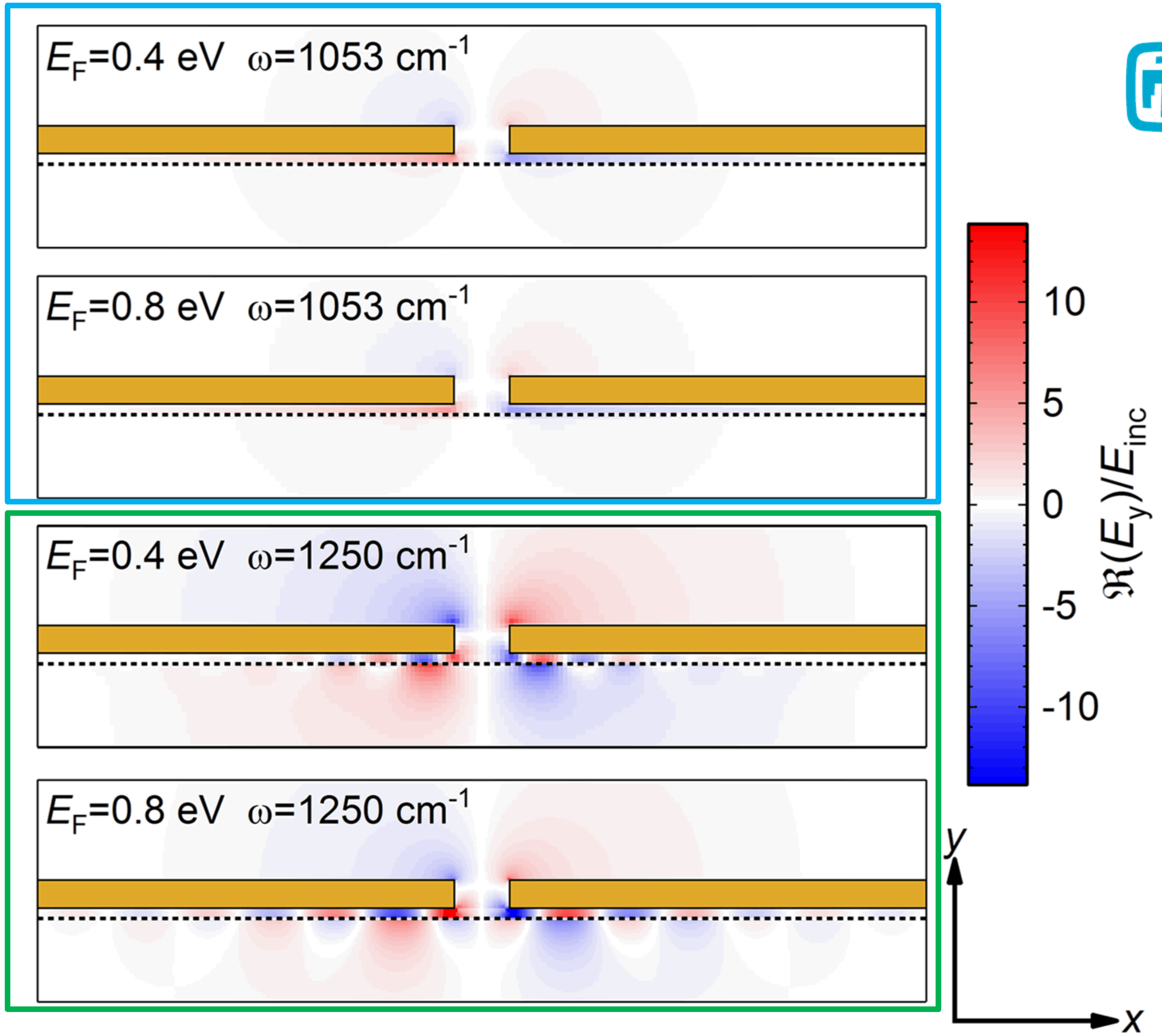


- Shift in position of two resonances simultaneously exceeding 50 cm^{-1}.
- Larger shifts at lower frequencies.
- Spectral shift depends on both grating design and SiO_2 thickness.
- Change in reflectance near 20%.

Origin of Tuning

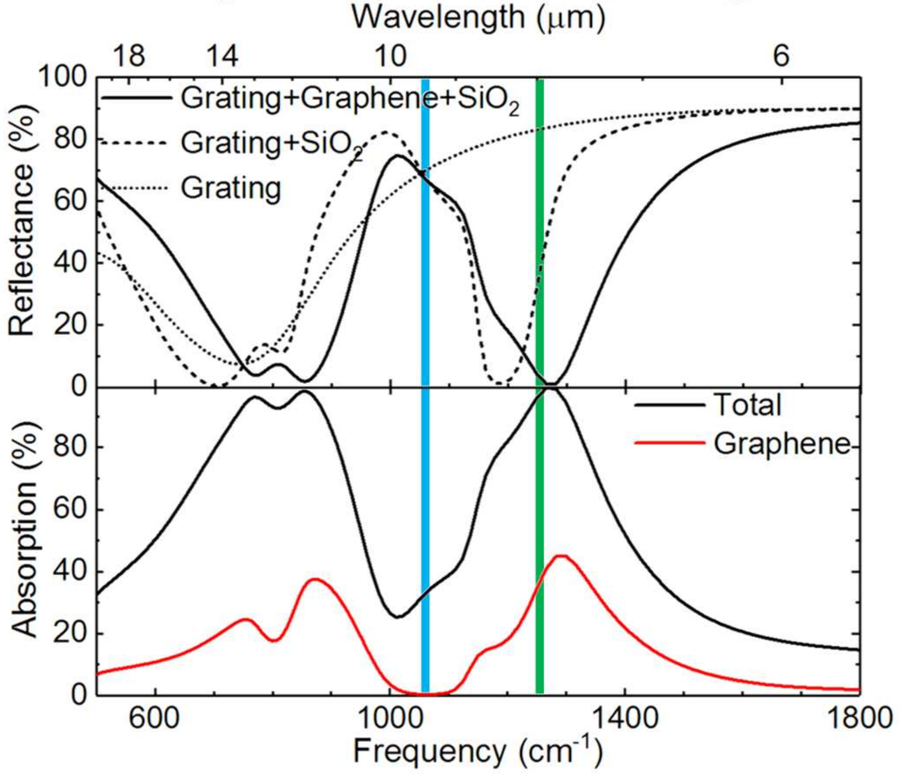


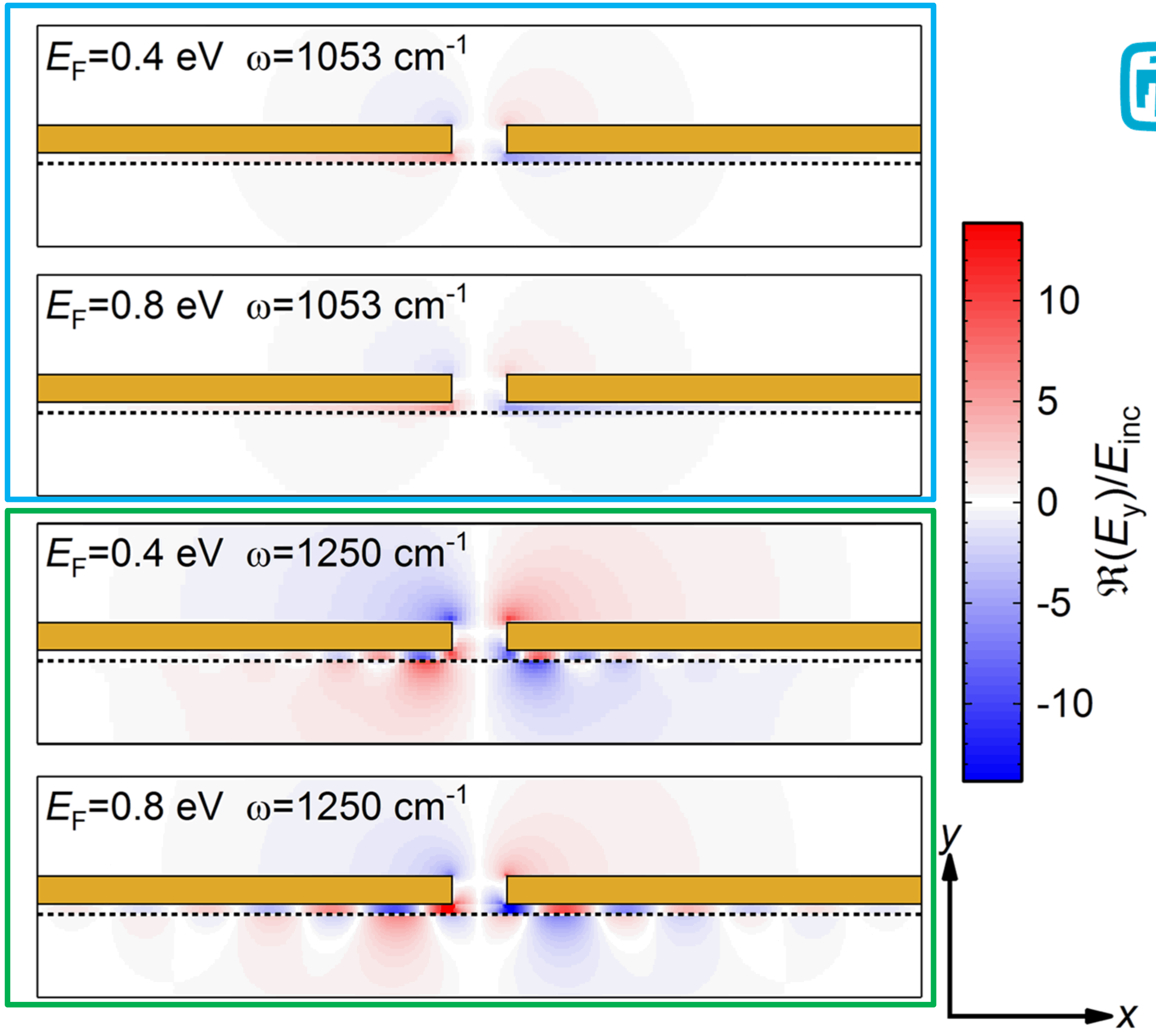


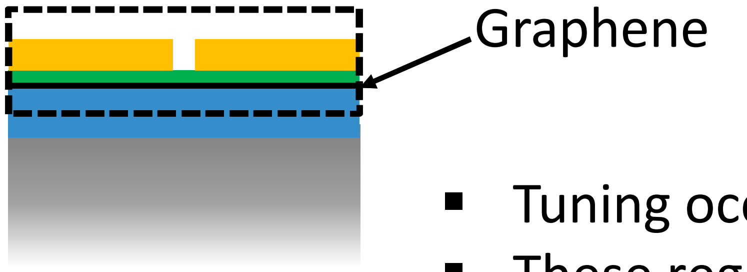


- Tuning occurs only where plasmon is excited and modified with Fermi energy.
- These regions are determined by dielectric cladding layers making them selectable.

Origin of Tuning

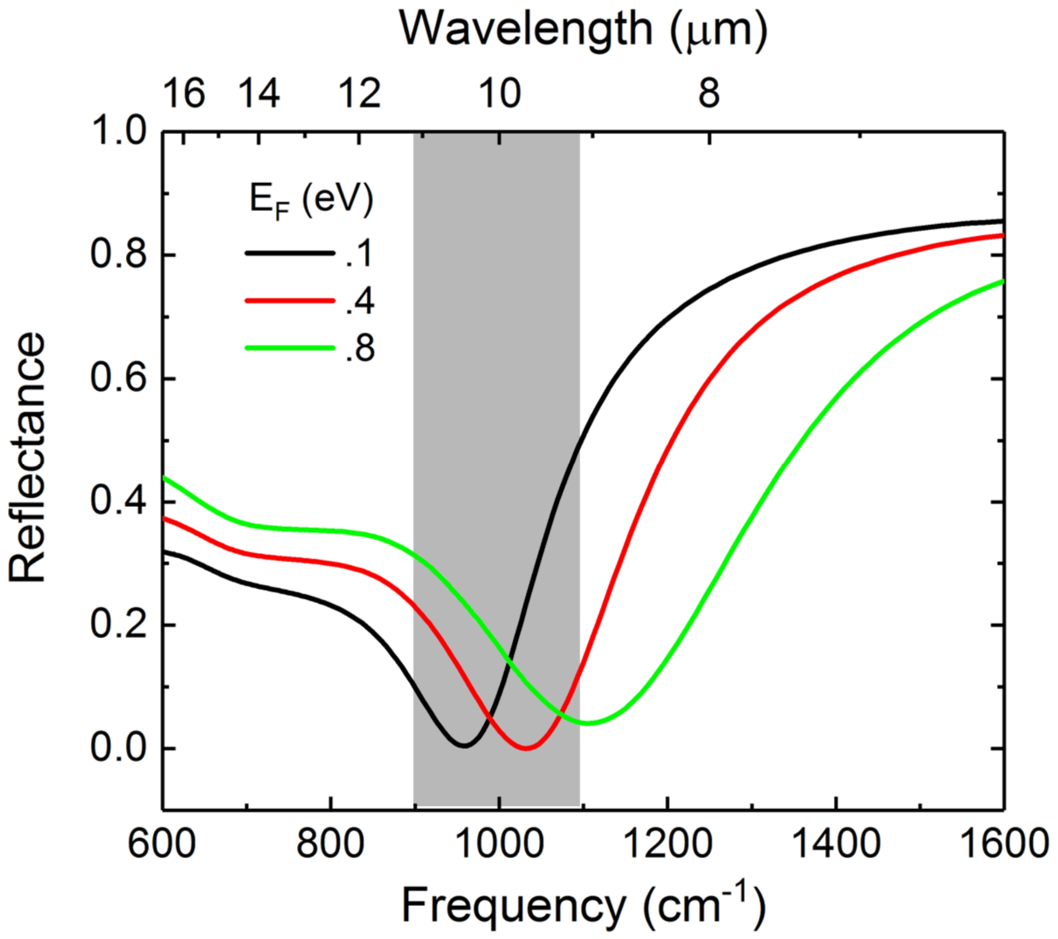


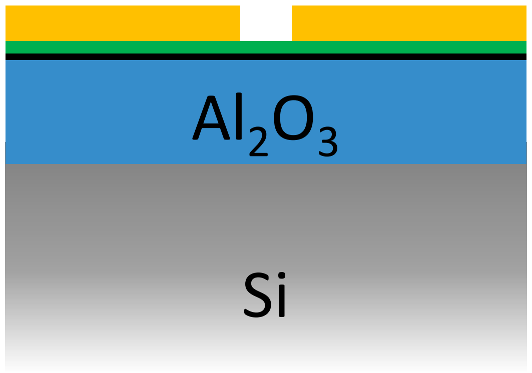


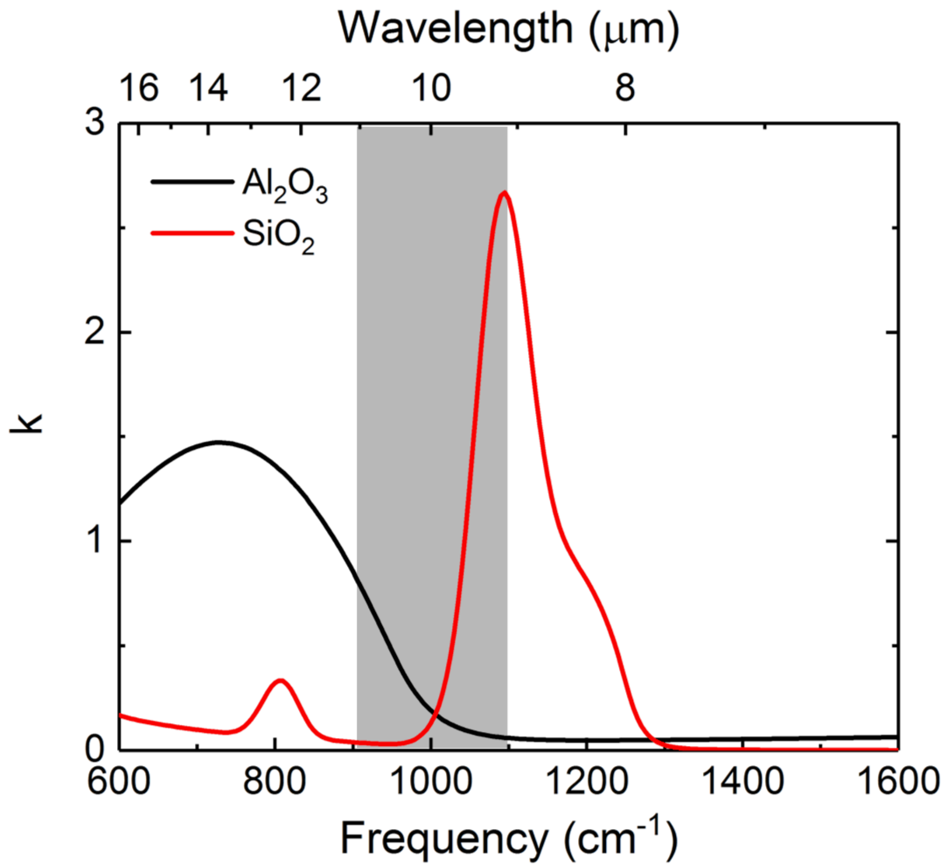


- Tuning occurs only where plasmon is excited and modified with Fermi energy.
- These regions are determined by dielectric cladding layers making them selectable.

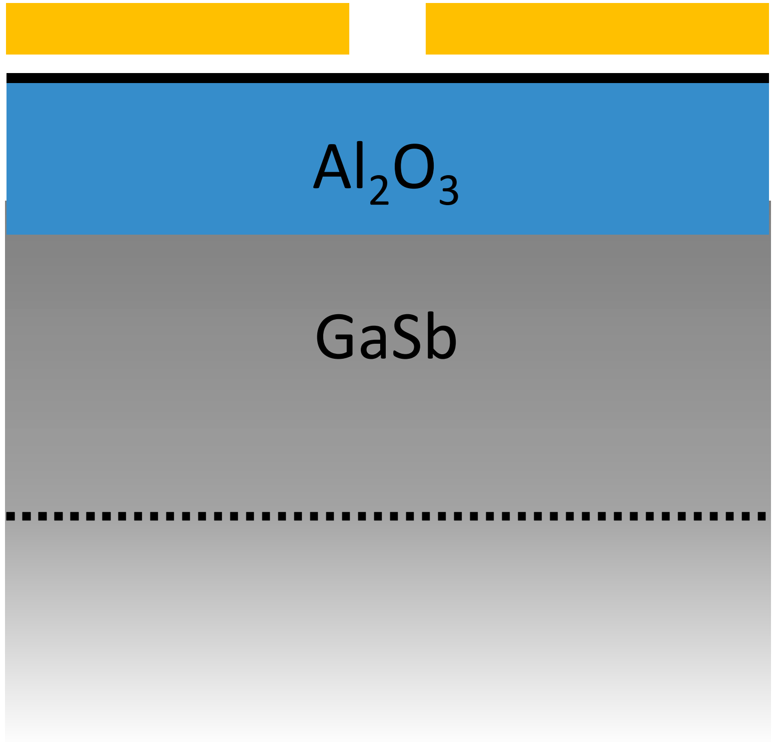
Wavelength Selection

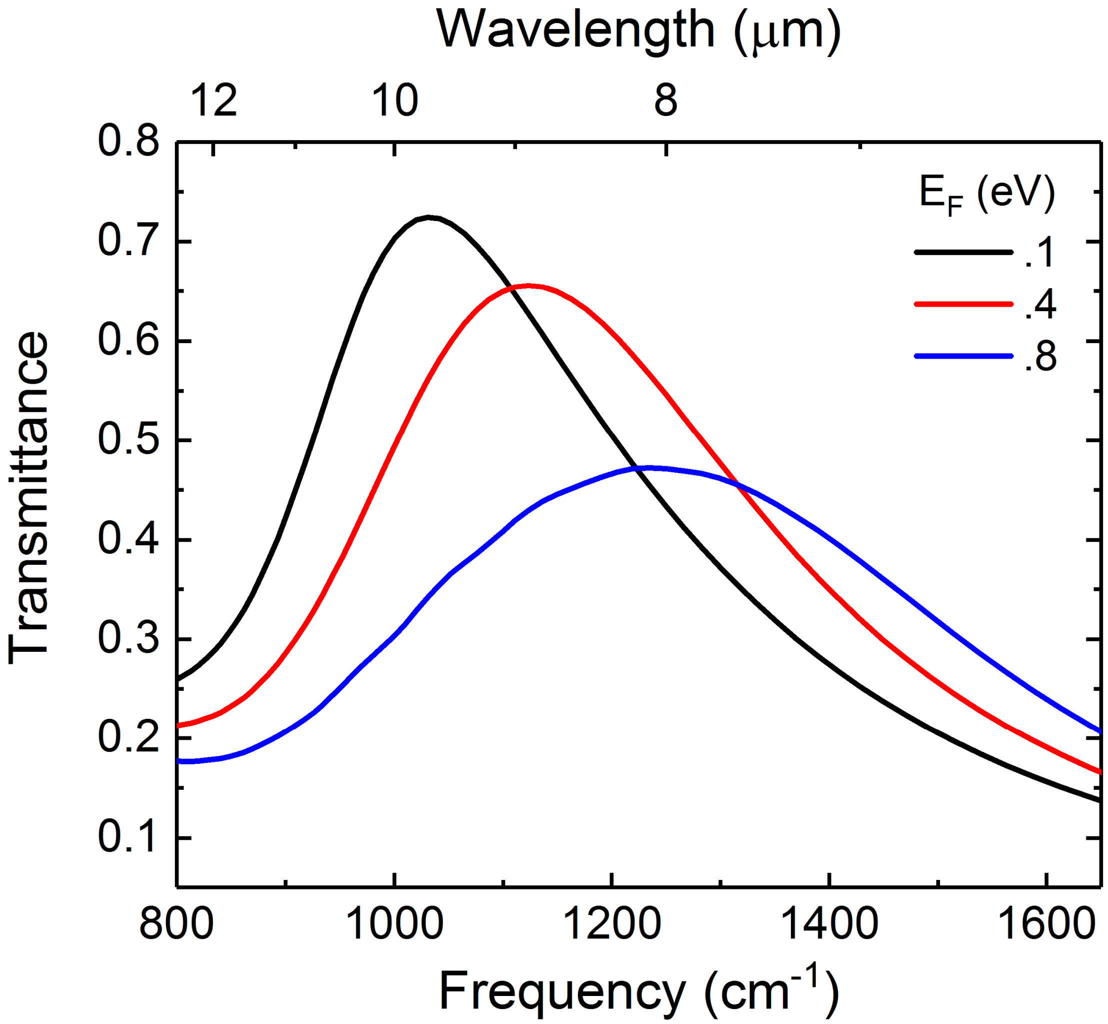






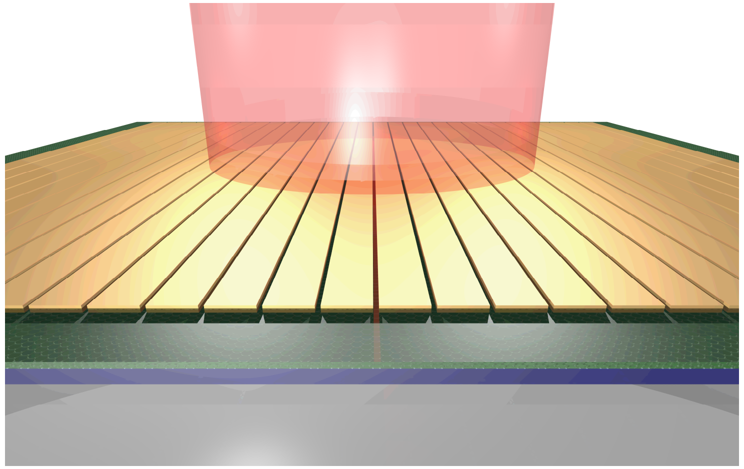
Transmittance-mode Filter

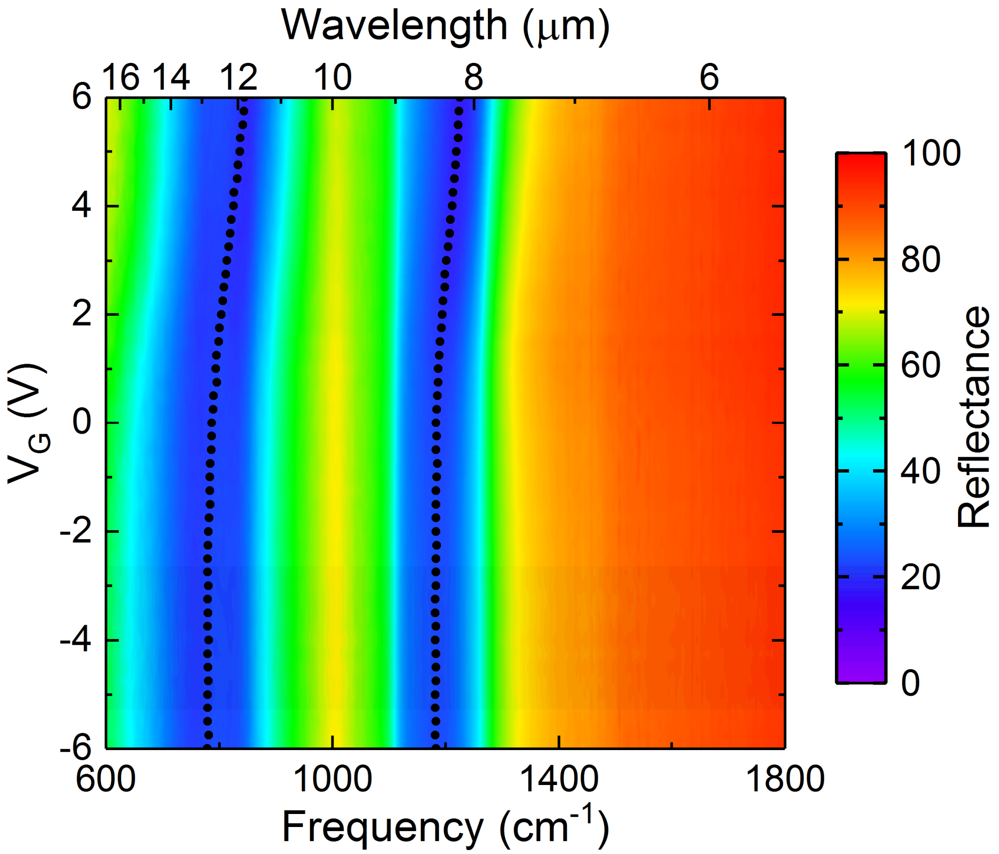


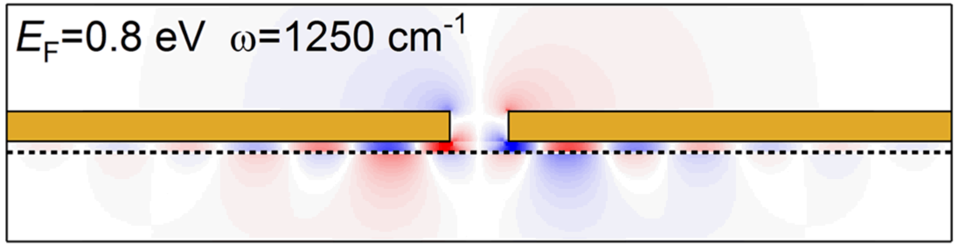


Conclusion

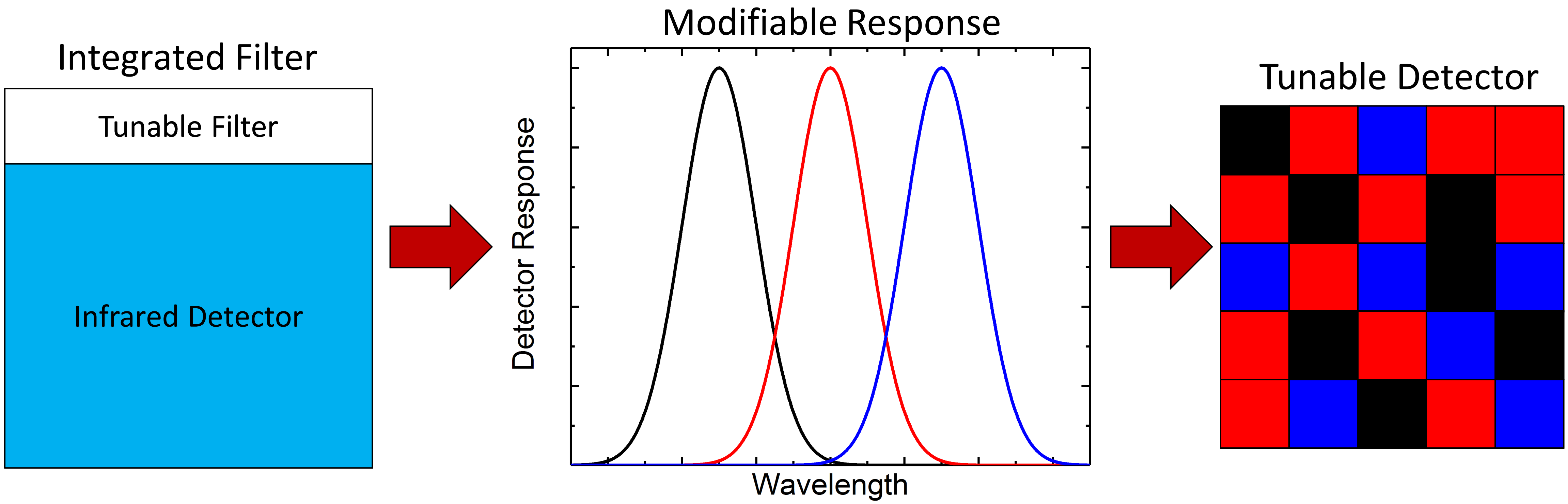
- Demonstrated scalable and tunable graphene-based IR filter.
- Enables modification of response in two bands simultaneously.
- Graphene is continuous and protected for device longevity.
- Mechnisms described here can be used to enable frequency-agile IR sensing.







Outlook


Integrated Filter
Tunable Filter
Infrared Detector
Modifiable Response
Detector Response
Wavelength
Tunable Detector

Technical Advances and Issued Patents

Sandia National Laboratories

Publications

- M.D. Goldflam, I Ruiz, S.W. Howell, J.R. Wendt, M.B. Sinclair, D.W. Peters, T.E. Beechem, “Tunable dual-band graphene-based infrared reflectance filter” in preparation.
- S.W. Howell, I. Ruiz, P. Davids, R. Harrison, S. Smith, M.D. Goldflam, J. Martin, N. Martinez, and T.E. Beechem "Graphene-Insulator-Semiconductor Junction for Hybrid Photodetection Modalities,“ Sci. Rep. Accepted 2017.
- I. Ruiz, M. D. Goldflam, T. E. Beechem, A. E. McDonald, B. L. Draper, and S. W. Howell, "Visibility of dielectrically passivated graphene films" Opt. Lett. 42 (14), 2850 (2017).
- Goldflam, M. D.; Campione, S.; Kadlec, E. A.; Hawkins, S. D.; Coon, W. T.; Fortune, T. R.; Parameswaran, S.; Keeler, G. A.; Klem, J. F.; Tauke-Pedretti, A.; Shaner, E. A.; Davids, P. S.; Warne, L. K.; Wendt, J. R.; Kim, J. K.; Peters, D. W., Next-generation infrared focal plane arrays for high-responsivity low-noise applications, 2017 IEEE Aerospace Conference, 4-11 March 2017, 2017; pp 1-7.
- Michael D. Goldflam, Zhe Fei, Isaac Ruiz, Stephen W. Howell, Paul S. Davids, David W. Peters, and Thomas E. Beechem, "Designing graphene absorption in a multispectral plasmon-enhanced infrared detector" Opt. Express 25 (11), 12400 (2017).
- F. Léonard, C. D. Spataru, M. Goldflam, D. W. Peters, and T. E. Beechem, "Dynamic Wavelength-Tunable Photodetector Using Subwavelength Graphene Field-Effect Transistors," Sci. Rep., 7, 45873 3 (2017).
- M. D. Goldflam, E. A. Kadlec, B. V. Olson, J. F. Klem, S. D. Hawkins, S. Parameswaran, W. T. Coon, G. A. Keeler, T. R. Fortune, A. Tauke-Pedretti, J. R. Wendt, E. A. Shaner, P. S. Davids, J. K. Kim, D. W. Peters, “Enhanced infrared detectors using resonant structures combined with thin type-II superlattice absorbers,” Appl. Phys. Lett., vol. 109, 251103, Dec. 2016.

Technical Advances and Patents

- SD 14080 Hybrid 2D Material/Absorber Structures for Broadband Tunable Detection
- SD 14291 Tunable Optics via Graphene Coupled to Static Resonances
- US 8,452,134 Frequency Selective Infrared Sensors
- US 8,750,653 Infrared Nanoantenna Apparatus and Method for the Manufacture Thereof