A Simulation of Extraordinary Optical Transmission Devices at Terahertz Frequencies

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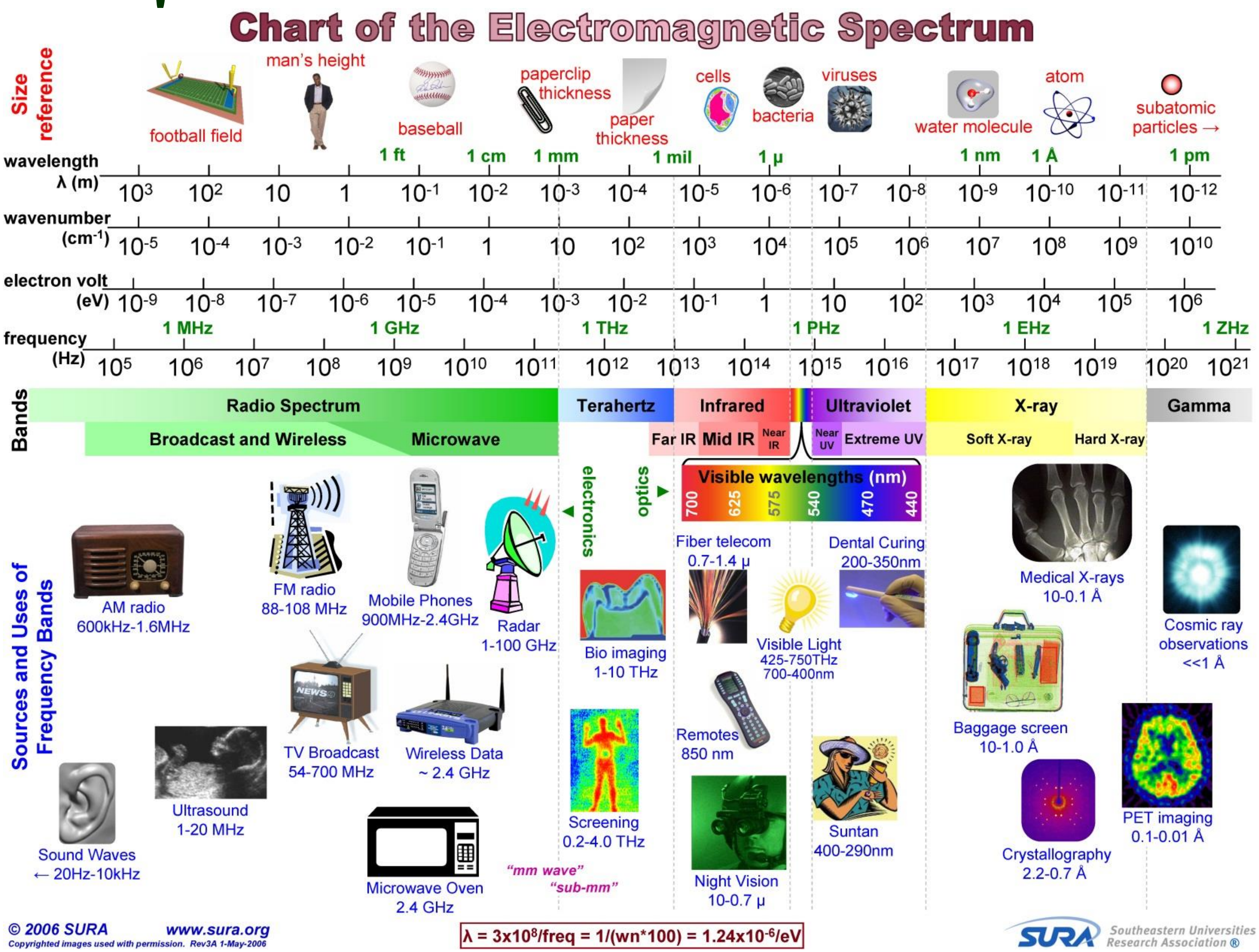
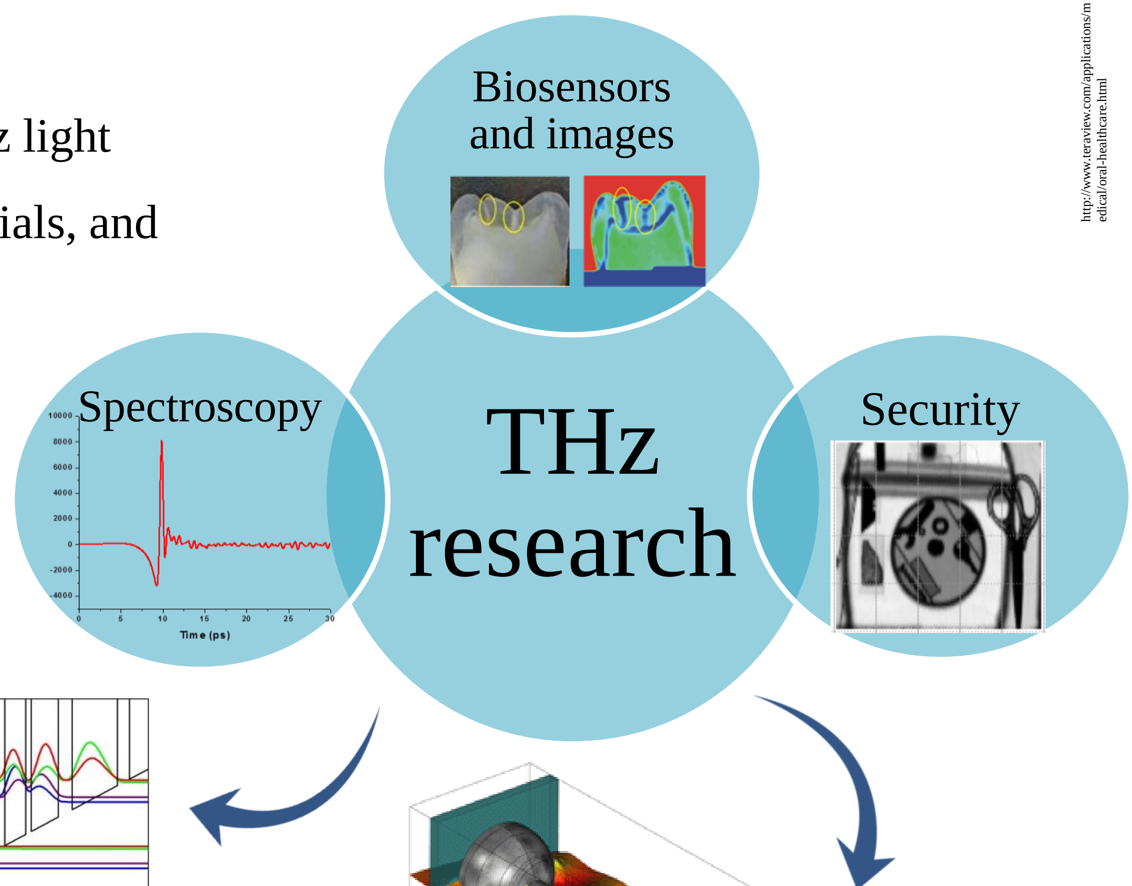
Introduction

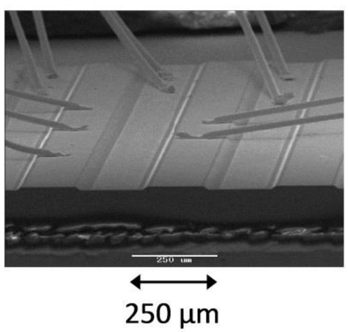


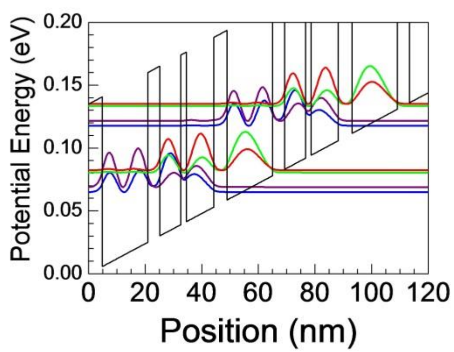
Introduction

Promising applications of terahertz light are driving phenomenology, materials, and device R&D.



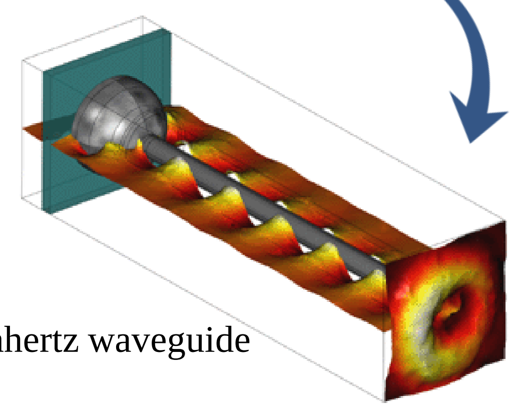
http://www.teraview.com/applications/medical/oral-healthcare.html





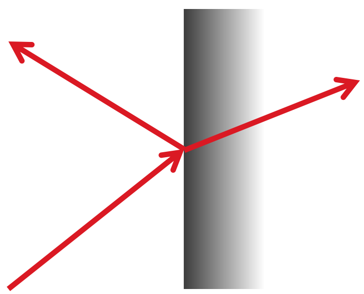
Quantum cascade laser

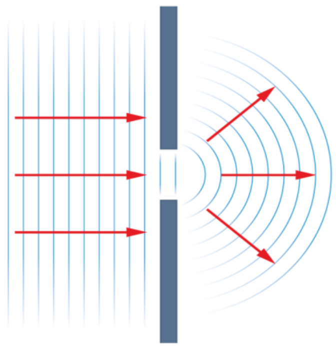
http://www.ruhr-uni-bochum.de/afp/thz/forschungzwei.html.de



Terahertz waveguide

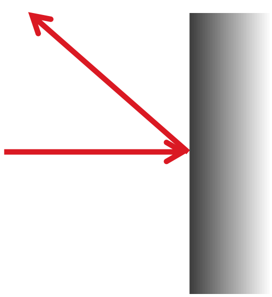
Extraordinary Optical Transmission

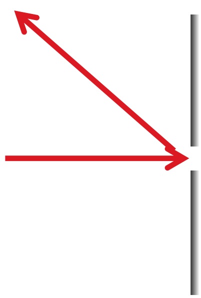




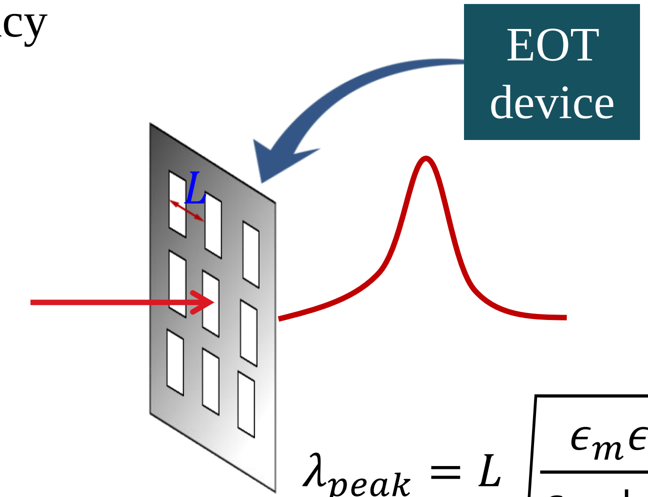
http://physics.taskermilward.org.uk/wave_behaviour_2.htm

Metals + low frequency





$$Transmission \propto \frac{1}{\lambda^4}$$



$$\lambda_{peak} = L\sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}}$$

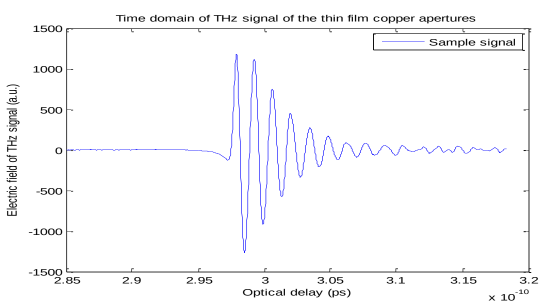
Resonant transmission

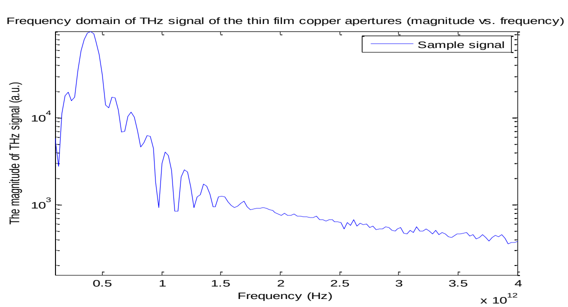
Time-of-flight Model

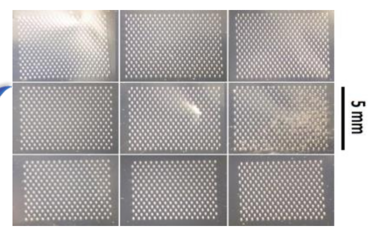
Incident polarized THz wave on 2-D apertures array on metallic thin film

An excited surface Plasmon polariton propagates along the edges

Recoupling into free space and recoupling on the aperture edges

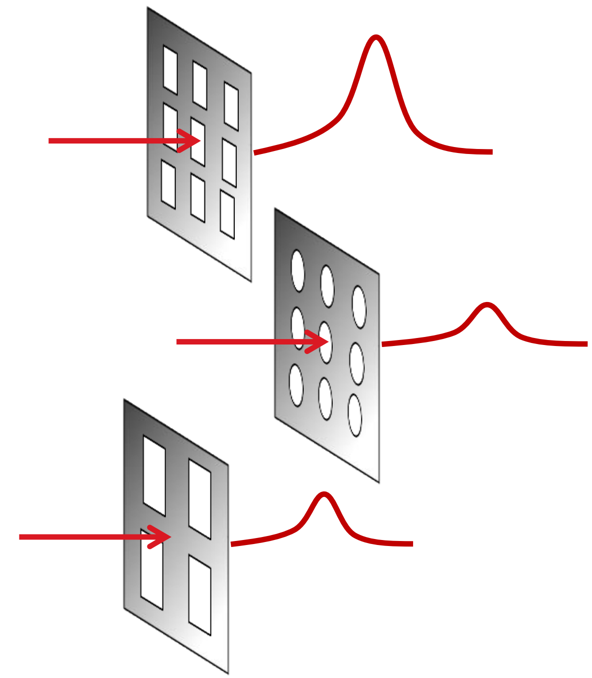






The Microscope Images of the Copper Film Apertures (EOT Device)

Niklas A. Characterization of structured nanomaterial using terahertz frequency radiation



Time-of-flight model takes ***apertures geometry*** and the ***polarization direction*** into account.

COMSOL Modeling
Geometry

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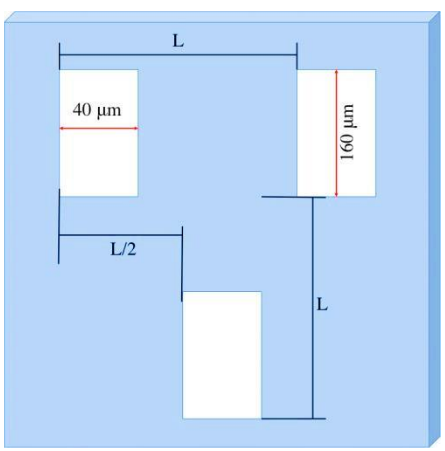
Experimental (literature)

- ✓ **Carbon nanotube (CNT) EOT on silicon substrate** with <u>*asymmetric*</u> aperture shape was studied.
- ✓ **Free standing CNT-based EOT** had higher enhanced transmission through <u>*symmetric*</u> apertures.
- ✓ **CNT-based EOT on silicon** substrate exhibited broadband transmission with <u>*symmetric*</u> apertures

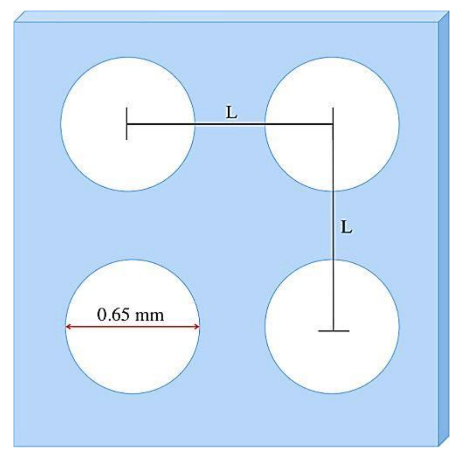
Computational (our work)

<u>Copper-Based EOT</u>



Aperture dimensions of the highest resonance suggested by Time-of-flight model work (2011).

<u>CNT-Based EOT</u>



Aperture dimensions of the CNT-based EOT

Materials

- ✓ Material properties for copper are assigned using COMSOL's library.
- ✓ Material properties of the CNT thin film are extracted from the experimental data.

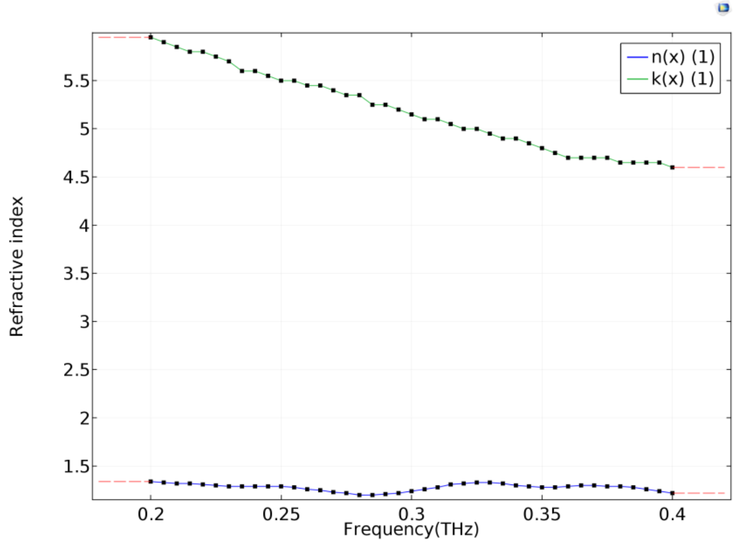
CNT-based EOT

- ✓ The dielectric constant is a function of the frequency dependent refractive index results…

$$\epsilon = (n^2 - k^2) + i(2nk)$$

- ✓ For simplicity, the conductivity of CNT is defined with a Drude conductivity model…

$$\sigma = \frac{\omega}{4\pi i}(\epsilon - 1)$$

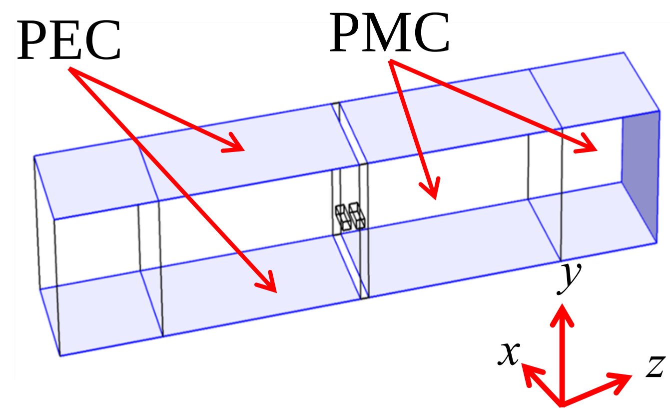


T. D. Nguyen, S. Liu, M. D. Lima, S. Fang, R. H. Baughman, A. Nahata, and Z. V. Vardeny, Terahertz surface plasmon polaritons on freestanding multi-walled carbon nanotube aerogel sheets, *Optical Materials Express*, **2**, 782-788 (2012).

COMSOL Modeling

Boundary Conditions

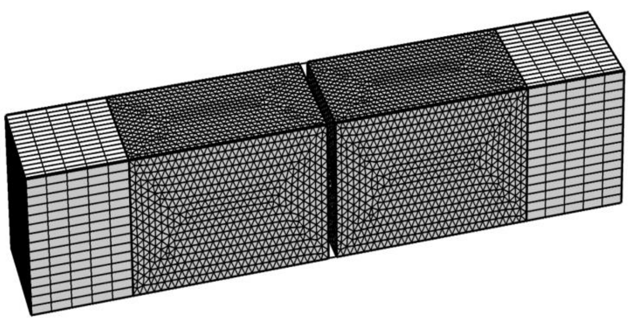
This configuration simulates an infinite xy plane wave and xy aperture device.



- ✓ Skin depth δ is much smaller than the thickness of the thin film d.

$$\delta = \frac{2}{\omega\mu_0\mu_r\sigma}$$

- ✓ The boundaries of the EOT device are assigned with the Impedance Boundary Condition.



Physics controlled mesh of maximum element size = $\frac{\lambda}{6}$

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Results

Copper-based EOT

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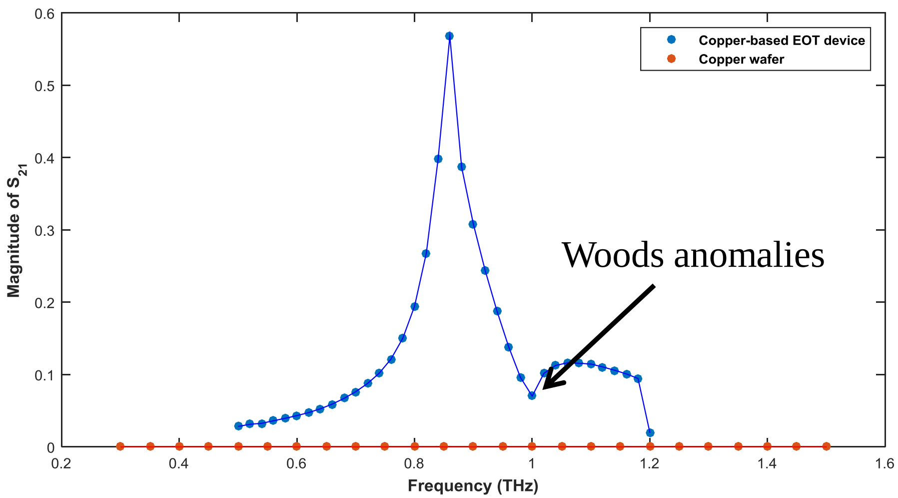
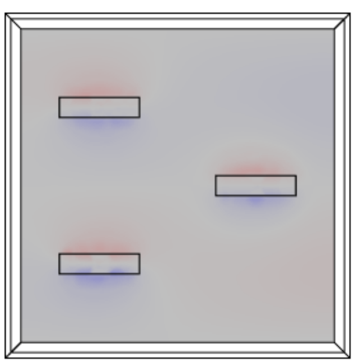
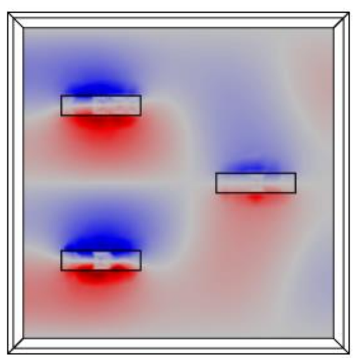
- The resonant frequency is located at 0.86 THz



The z-component of the electric field on the surface

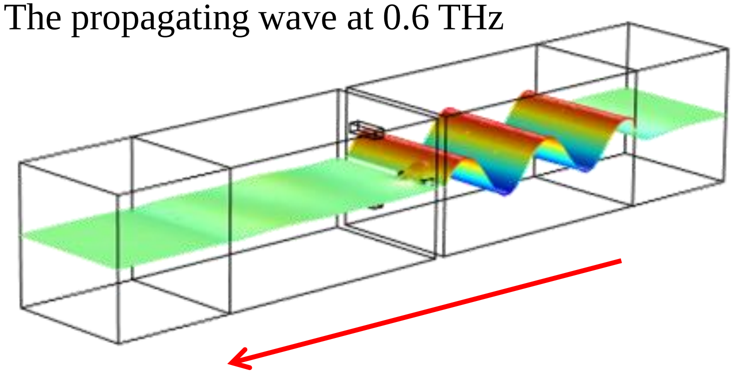


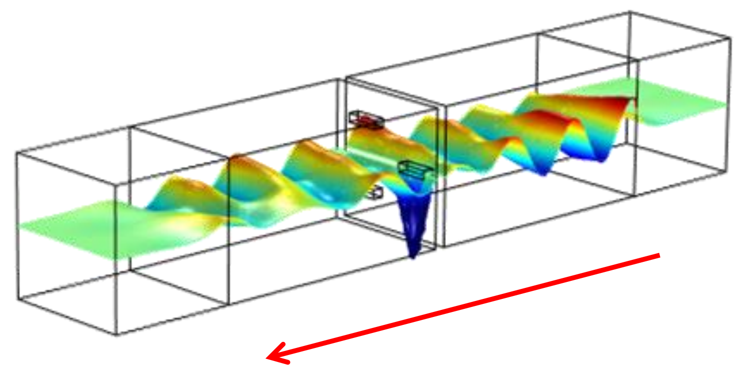
0.6 THz



0.86 THz (resonance)

The propagating wave at 0.6 THz



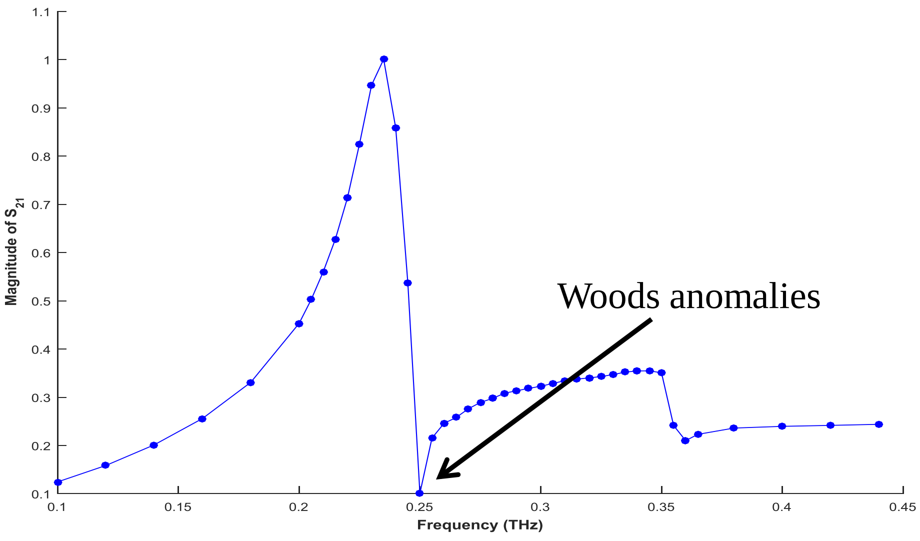


The propagating wave at 0.86 THz (resonance)

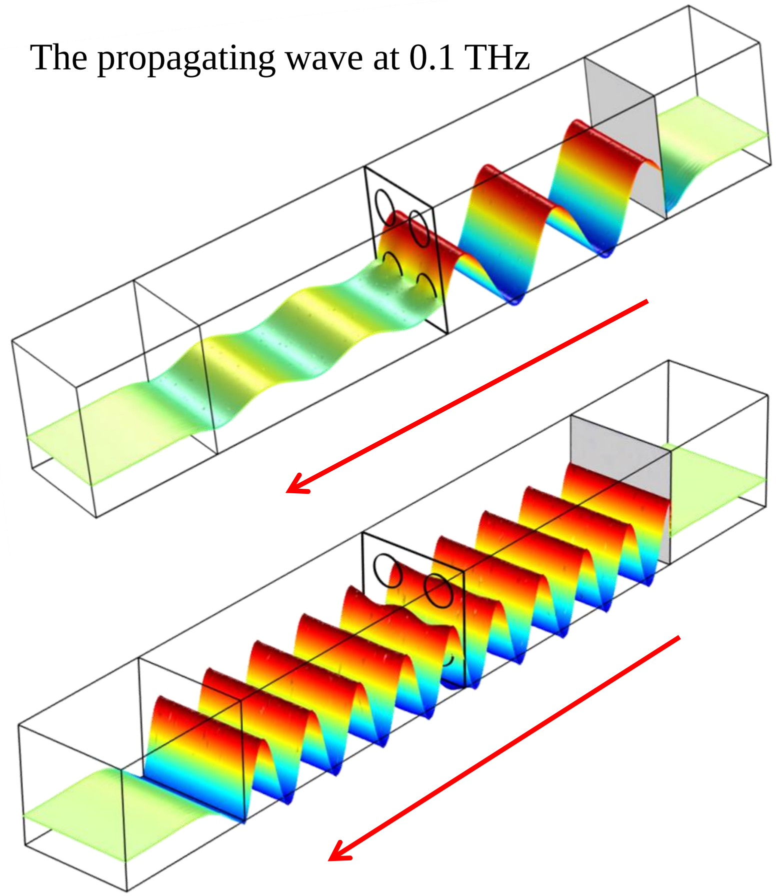
Results

CNT-based EOT

- The resonant frequency is located at 0.235 THz

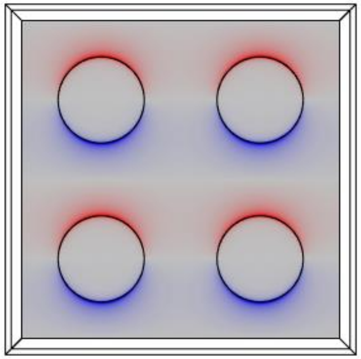


The propagating wave at 0.1 THz

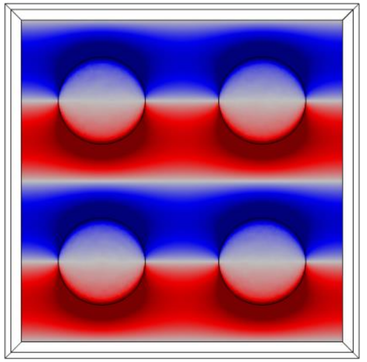


The propagating wave at 0.235 THz (resonance)

The z-component of the electric field on the surface



0.1 THz



0.235 THz (resonance)

Summary

- ✓ The simulation of the copper-based EOT device exhibits a red-shifted resonant transmission frequency that is red-shifted experimentally as well for a copper-based EOT device which has similar dimensions of its apertures.
- ✓ The simulated resonant frequency of the CNT-based EOT device shows good agreement with the experimental device results.
- ✓ Woods anomalies have been seen in simulations of both the copper and CNT EOT devices.
- ✓ The Drude-Lorentz could be used for CNT conductivity for more validation.
- ✓ More EOT-devices can be studied as a function of the materials' properties, aperture geometry, and polarization direction.

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References

1. D. Graham-Rowe, Terahertz takes to the stage, *Nature Photonics*, **1**, 75-77 (2007).
2. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio & P. A. Wolff, Extraordinary optical transmission through sub-wavelength hole arrays, *Nature*, **391**, 667-669 (1998).
3. H. F. Ghaemi, Tineke Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, Surface plasmons enhance optical transmission through subwavelength holes, *Phys. Rev. B*, **58**, 6779-6782 (1998).
4. A. Baragwanath, M.C. Rosamond, A.J. Gallant, J. M. Chamberlain, Time-of-Flight Model for the Extraordinary Transmission Through Periodic Arrays of Subwavelength Apertures at THz Frequencies, *Plasmonics*, **6**, 625-636 (2011).
5. Y. Wang, Y. Tong and X. Zhang, Transmission properties of terahertz waves through asymmetric rectangular aperture arrays on carbon nanotube films, *AIP Advances*, **6**, 045304 (2016).
6. T. D. Nguyen, S. Liu, M. D. Lima, S. Fang, R. H. Baughman, A. Nahata, and Z. V. Vardeny, Terahertz surface plasmon polaritons on freestanding multi-walled carbon nanotube aerogel sheets, *Optical Materials Express*, **2**, 782-788 (2012).
7. Y. Wang, X. Zhao, G. Duan, and X. Zhang, Broadband extraordinary terahertz transmission through super-aligned carbon nanotubes film, *Optics Express*, **24**, 15730-15741 (2016).
8. N. Ashcroft, N. Mermin, *Solid State Physics*, 17, Thomson Learning , United States (1976).

Thank you for your attention

Questions