A Simulation of Extraordinary Optical Transmission Devices at Terahertz Frequencies

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## Introduction

### Chart of the Electromagnetic Spectrum

<table>
<thead>
<tr>
<th>Wavelength (m)</th>
<th>10^3</th>
<th>10^2</th>
<th>10^1</th>
<th>10</th>
<th>10^-1</th>
<th>10^-2</th>
<th>10^-3</th>
<th>10^-4</th>
<th>10^-5</th>
<th>10^-6</th>
<th>10^-7</th>
<th>10^-8</th>
<th>10^-9</th>
<th>10^-10</th>
<th>10^-11</th>
<th>10^-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavenumber (cm^-1)</td>
<td>10^-5</td>
<td>10^-4</td>
<td>10^-3</td>
<td>10^-2</td>
<td>10^-1</td>
<td>1</td>
<td>10^2</td>
<td>10^3</td>
<td>10^4</td>
<td>10^5</td>
<td>10^6</td>
<td>10^7</td>
<td>10^8</td>
<td>10^9</td>
<td>10^10</td>
<td>10^11</td>
</tr>
<tr>
<td>Electron Volt (eV)</td>
<td>10^-9</td>
<td>10^-8</td>
<td>10^-7</td>
<td>10^-6</td>
<td>10^-5</td>
<td>10^-4</td>
<td>10^-3</td>
<td>10^-2</td>
<td>10^-1</td>
<td>1</td>
<td>10^1</td>
<td>10^2</td>
<td>10^3</td>
<td>10^4</td>
<td>10^5</td>
<td>10^6</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>1 MHz</td>
<td>1 GHz</td>
<td>1 THz</td>
<td>1 PHz</td>
<td>1 EHz</td>
<td>1 ZHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### Bands

- **Radio Spectrum**
  - Broadcast and Wireless
  - Microwave

- **Terahertz**

- **Infrared**
  - Far IR
  - Mid IR
  - Near IR

- **Ultraviolet**
  - Extreme UV
  - Soft X-ray
  - Hard X-ray

### Sources and Uses of Frequency Bands

- **AM radio**
  - 600kHz-1.6MHz

- **FM radio**
  - 88-108 MHz

- **Mobile Phones**
  - 900MHz-2.4GHz

- **Radar**
  - 1-100 GHz

- **Visible Light**
  - 425-750THz

- **Dental Curing**
  - 200-350nm

- **Medical X-rays**
  - 10-0.1 Å

- **Cosmic ray observations**
  - <<1 Å

### Equations

\[ \lambda = 3 \times 10^6 / \text{freq} = 1 / (\text{wn} \times 100) = 1.24 \times 10^{-6} / \text{eV} \]
Promising applications of terahertz light are driving phenomenology, materials, and device R&D.
Extraordinary Optical Transmission

Metals + low frequency

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

$\lambda_{peak} = L \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$

Resonant transmission

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

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

Niklas A. Characterization of structured nanomaterial using terahertz frequency radiation
**Experimental (literature)**

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

**Computational (our work)**

- Copper-Based EOT
- CNT-Based EOT

Aperture dimensions of the highest resonance suggested by Time-of-flight model work (2011).
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...
  \[ \sigma = \frac{\omega}{4\pi i} (\epsilon - 1) \]

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

- Skin depth $\delta$ 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 $= \frac{\lambda}{6}$
Results
Copper-based EOT

- The resonant frequency is located at 0.86 THz

The propagating wave at 0.6 THz

Woods anomalies

The z-component of the electric field on the surface

The propagating wave at 0.86 THz (resonance)
The resonant frequency is located at 0.235 THz.

Woods anomalies

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)
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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Thank you for your attention

Questions