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Light Scattering From Periodic Conducting Nanostructures

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Scattering of Light From Periodic Conducting Nanostructures

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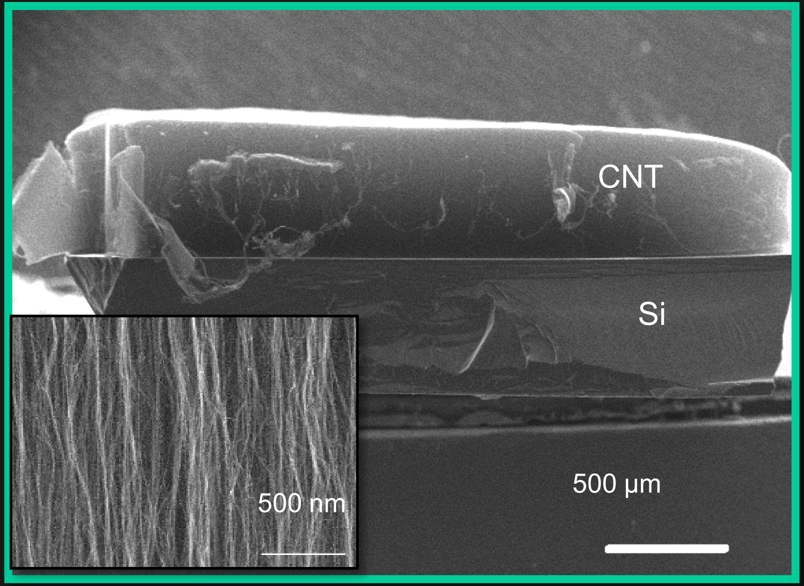
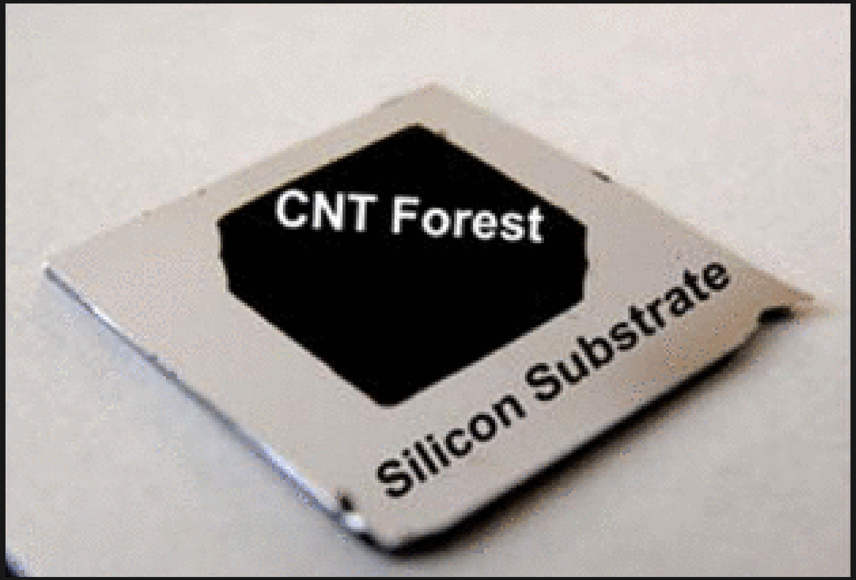


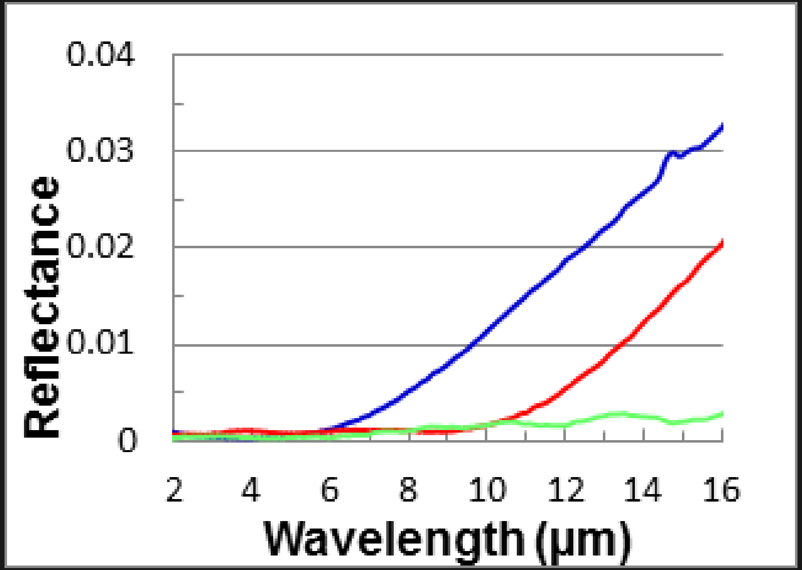


Appl. Phys. Lett. 101, 061913 (2012)

Carbon Nanotubes (CNTs)

Used in optical calibration, energy conversion, antireflection, and radiometry.

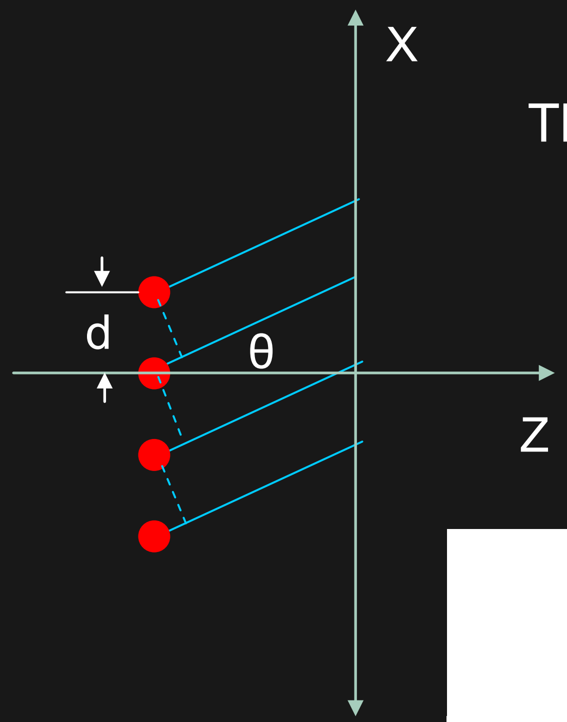
- Why are CNT forests dark?
- Why does the reflection rise after a certain wavelength?
- What can be done to extend the absorption range?



Interference from a line of coherent point sources

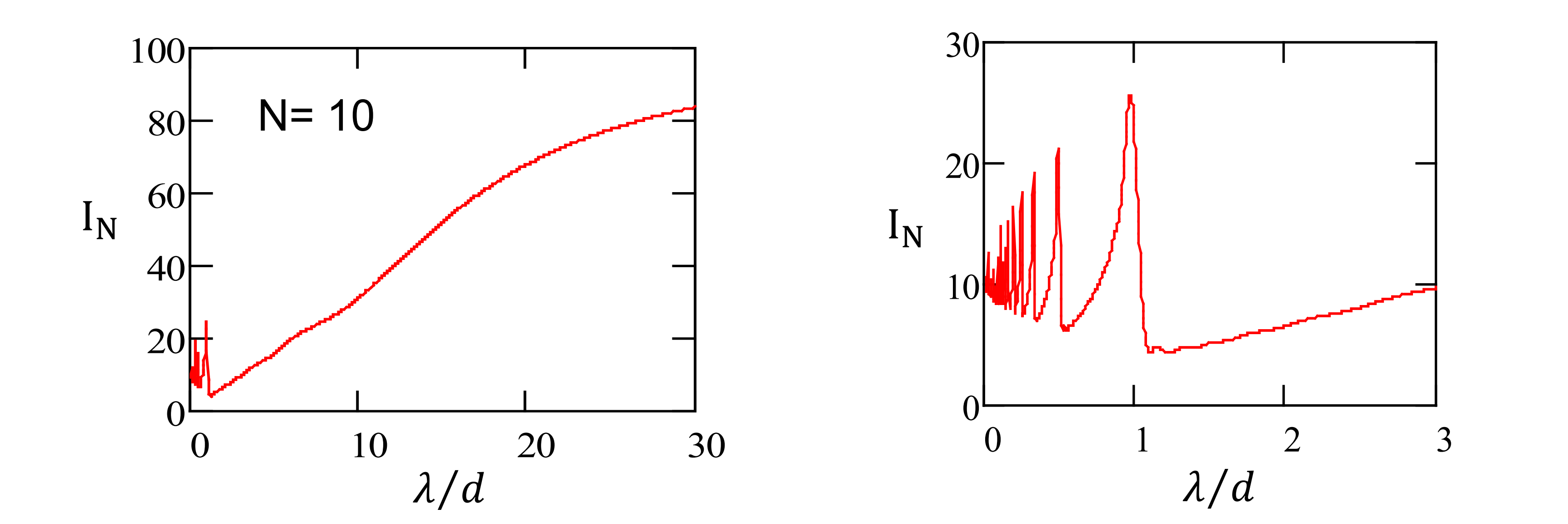
Far field of N cylindrical waves:

$$E_{total}(\theta) = \frac{A_0}{\sqrt{r}} e^{i(kr-\omega t)} e^{i(N-1)\alpha/2} \left(\frac{\sin\frac{N\alpha}{2}}{\sin\frac{\alpha}{2}} \right) \qquad \alpha = kd\sin\theta = \frac{2\pi \sin\theta}{\lambda/d}$$



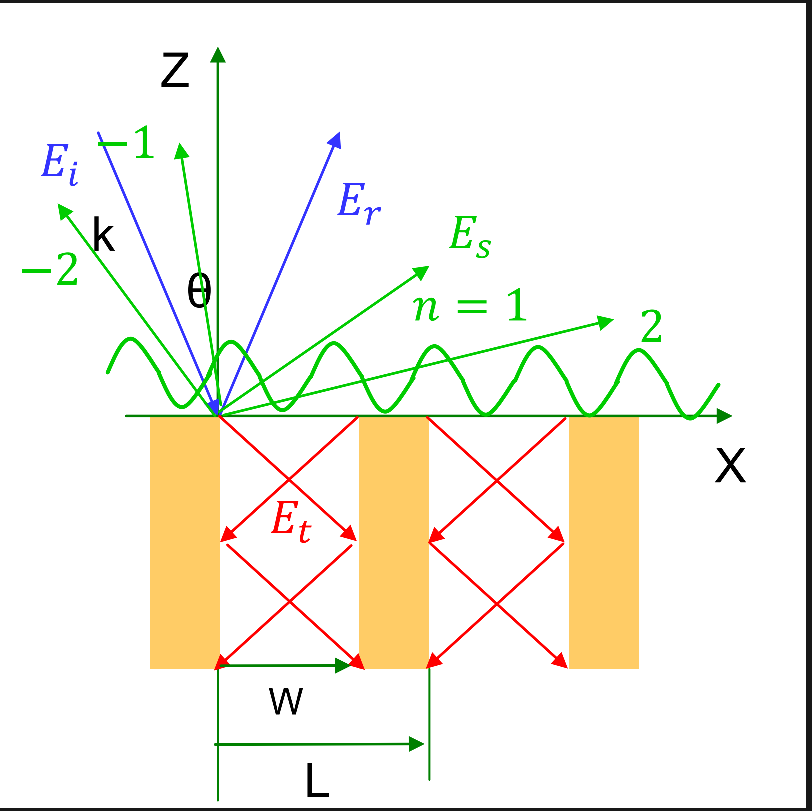
The total energy flux across an infinite plane in the z-direction:

$$I_N = \frac{C}{2} A_0{}^2 \int_{-\pi/2}^{\pi/2} \left(\frac{\sin\frac{N\alpha}{2}}{\sin\frac{\alpha}{2}} \right)^2 d\theta \qquad \begin{cases} I_N = N\, I_1 & \lambda/d \ll 1 \\ I_N = N^2 I_1\,, & \lambda/d \gg 1 \end{cases}$$



Scattering from 1D periodic metallic grating

TE mode



Incident wave $E_{iy} = A_0 e^{-j\beta x + jqz}$

Reflected wave $E_{ry} = -A_0 e^{-j\beta x + jqz}$

$$H_x = \frac{-j}{\omega\mu}\partial_z E_y$$

$$H_z = \frac{j}{\omega\mu}\partial_x E_y$$

Scattered wave $E_{sy} = \sum_{n=-\infty}^{\infty} B_n\, e^{-j\beta_n x - jq_n z}$ ⬅ Floquet theorem

Transmitted wave

$$E_{ty} = \begin{cases} \sum_{m=1}^{\infty} C_m\, e^{-jp_m z} \sin\frac{m\pi x}{W}, & 0 < x < W \\ 0, & W \le x \le L \end{cases}$$

$$p_m = \sqrt{k^2 - (m\pi/W)^2}$$

$$\beta = k\, sin\theta \qquad \beta_n = \beta + \frac{2\pi n}{L}$$

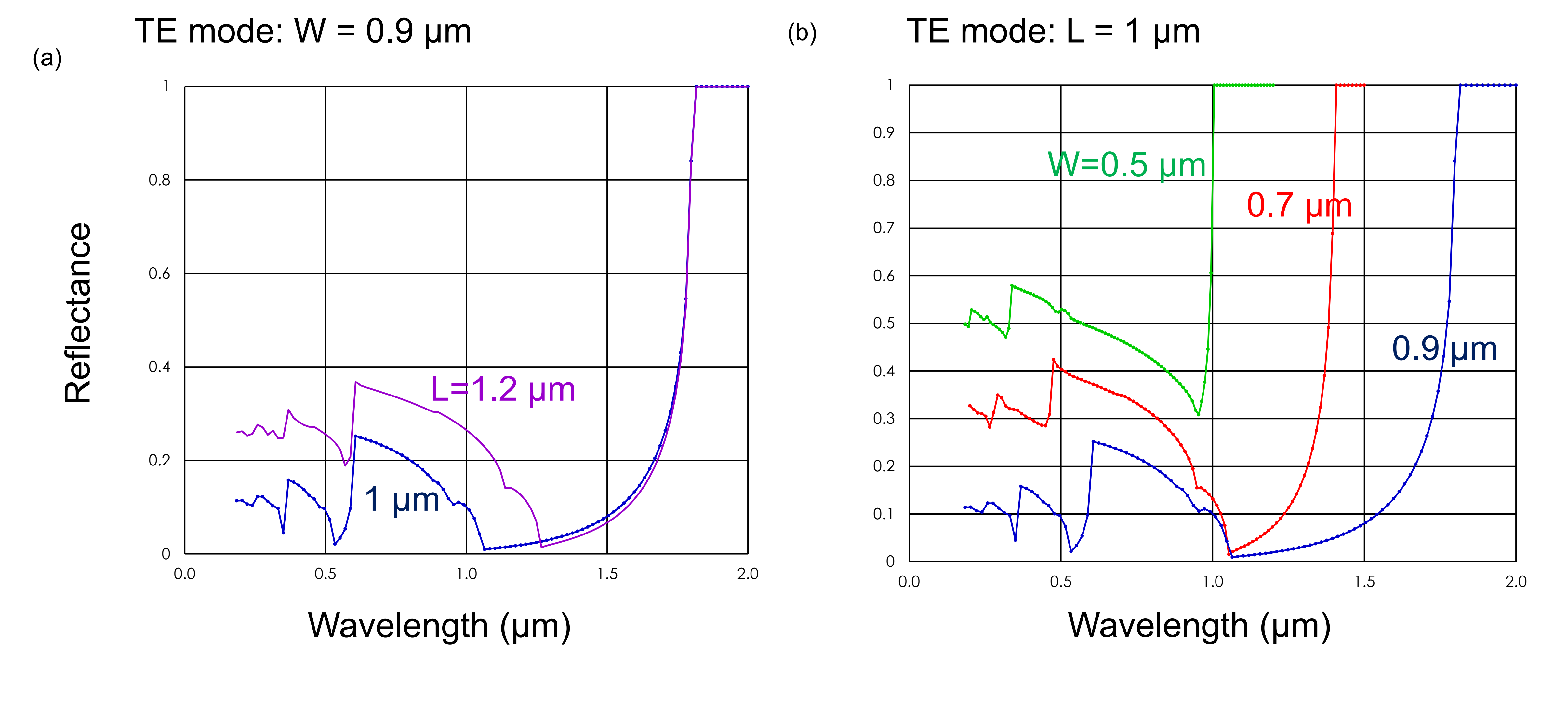
$$q = k\, cos\theta \qquad q_n = \sqrt{k^2 - \beta_n^2}$$

Boundary conditions

$$E_{iy} + E_{ry} + E_{sy} = E_{ty}$$

$$H_{ix} + H_{rx} + H_{sx} = H_{tx}$$

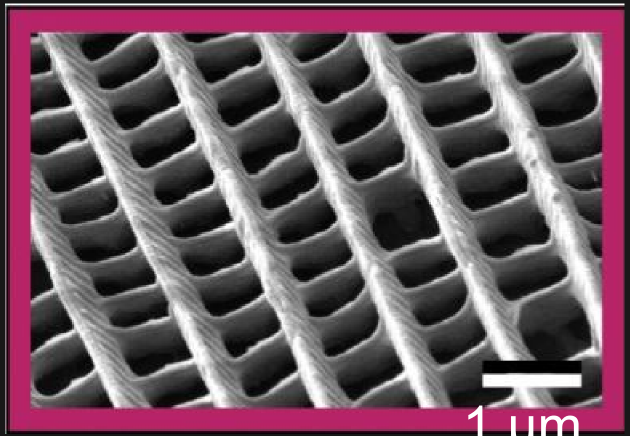
1D metallic grating results

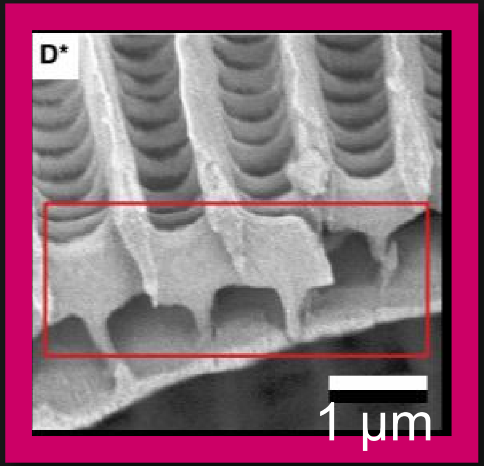


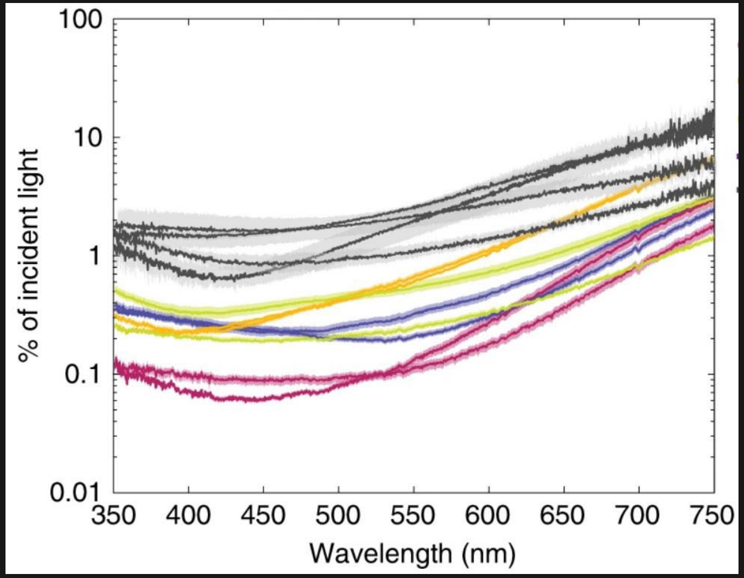
Reflectance: $R = P_{zr}/P_{zi}$

Broadband absorption cellular structures

Butterfly wings

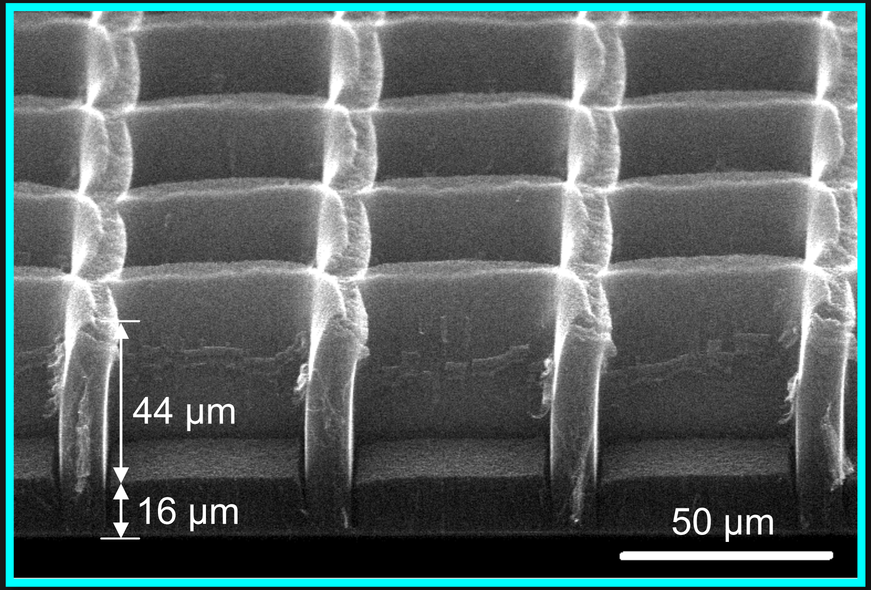






Nature Comm. 11, 1294 (2020)

Fabricated CNT forest



Fe398A_20

Cell: Co (1 nm) /AlO_x (30 nm)/Si

Grid: Fe(2 nm)Co (1 nm)/AlO_x (30 nm)/Si

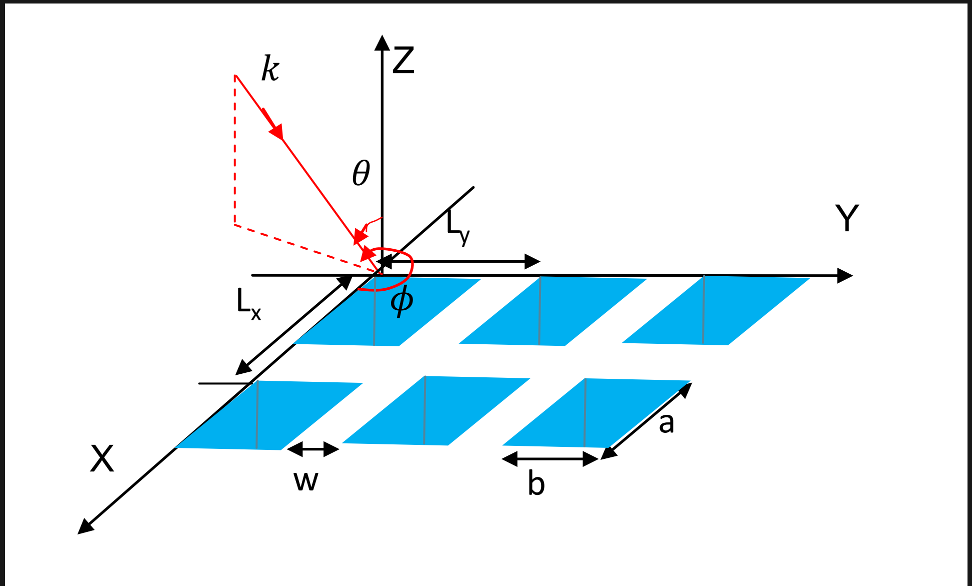
C_2H_4:H_2:Ar=50:250:200 sccm

CVD: 800 ºC, 30 min

Carbon Trends 4, 100070 (2021)

Scattering from 2D metallic grids

TE mode



$$\tilde{E}_i = (\hat{x}sin\phi - \hat{y}cos\phi)A_0 e^{-j\vec{k}_i\cdot\vec{r}}$$

$$\tilde{E}_r = (-\hat{x}sin\phi + \hat{y}cos\phi)A_0 e^{-j\vec{k}_r\cdot\vec{r}}$$

$$E_{sx} = \sum_{m,n=-\infty}^{\infty} B_{mn}\, e^{-jk_{xm}x-jk_{yn}y-jq_{mn}z}$$

$$E_{sy} = \sum_{m,n=-\infty}^{\infty} C_{mn}\, e^{-jk_{xm}x-jk_{yn}y-jq_{mn}z}$$

Boundary conditions

$$H_{ix} + H_{rx} + H_{sx} = H_{tx}$$

$$E_{sy} = E_{ty}$$

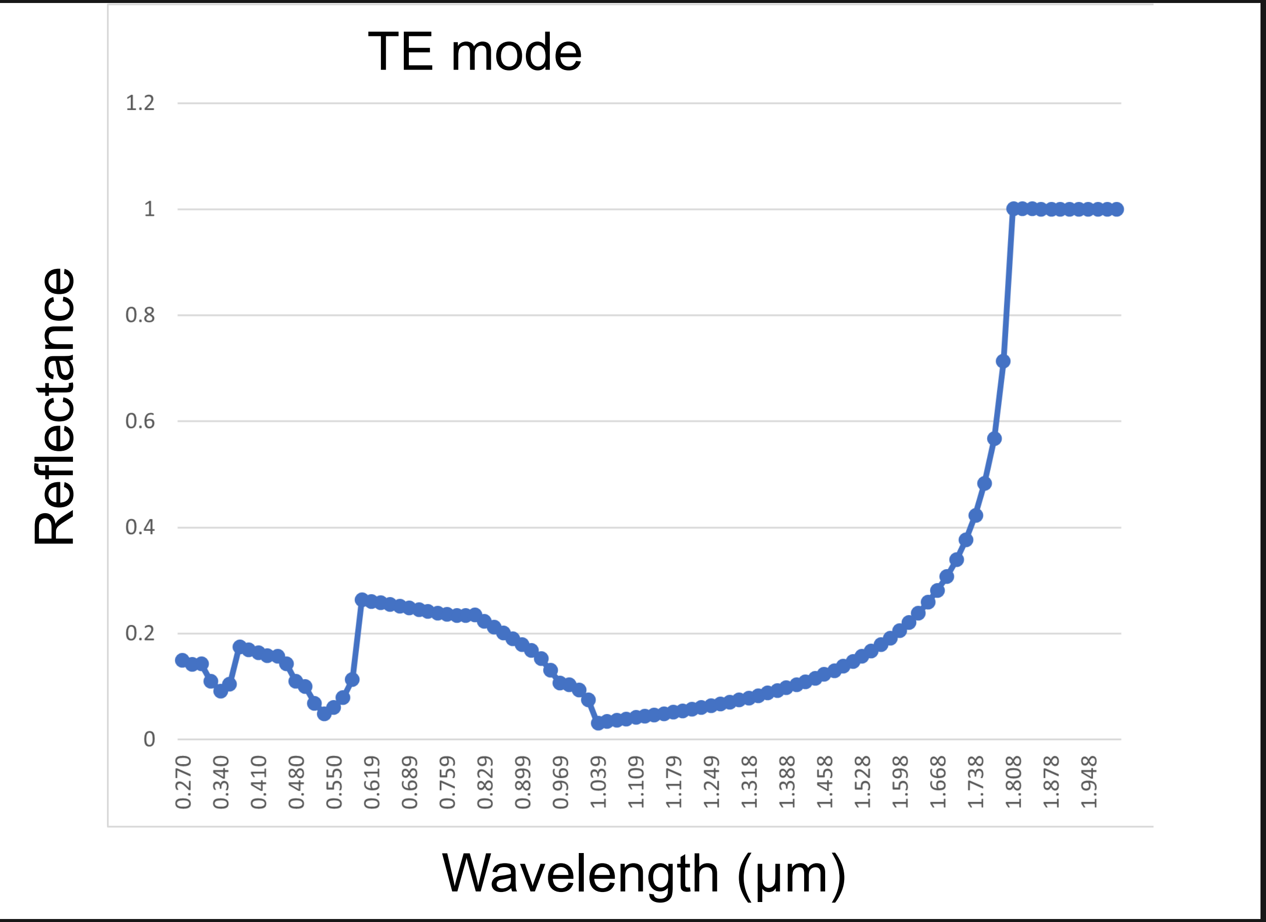
$$H_{iy} + H_{ry} + H_{sy} = H_{ty}$$

$$E_{sx} = E_{tx}$$

$$E_{tx} = \frac{j\omega\mu\pi}{b} \sum_{\substack{r,s=0 \\ no\ (0,0)}}^{\infty} \frac{sD_{rs}}{K_{rs}^2} cos\frac{r\pi x}{a} sin\frac{s\pi y}{b} e^{jp_{rs}z}$$

$$E_{ty} = \frac{-j\omega\mu\pi}{a} \sum_{\substack{r,s=0 \\ no\ (0,0)}}^{\infty} \frac{rD_{rs}}{K_{rs}^2} sin\frac{r\pi x}{a} cos\frac{s\pi y}{b} e^{jp_{rs}z}$$

2D metallic grating results



Reflectance: $R = P_{zr}/P_{zi}$

a = b = 900 nm

Lx = Ly = 1000 nm

Φ = 45°, θ = 3°

Good:

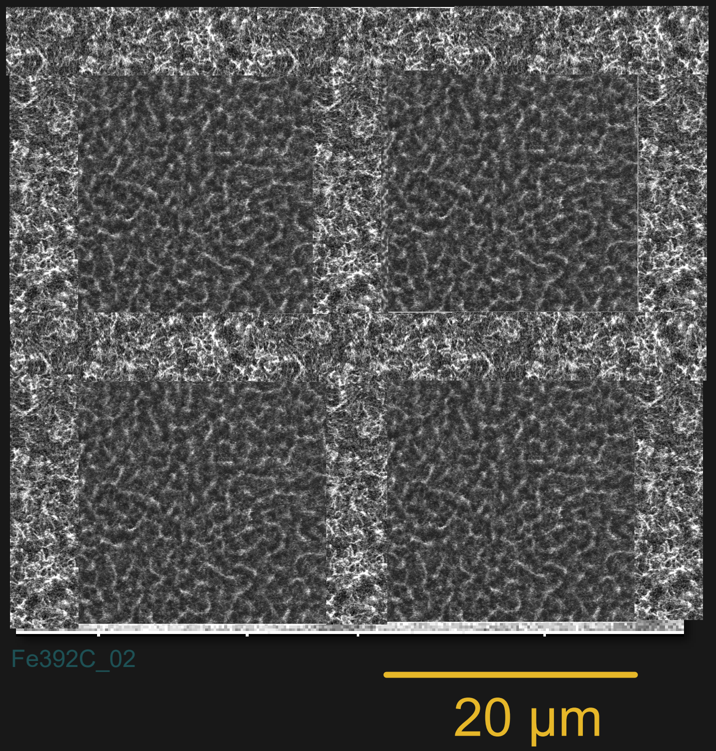
- Low-wavelength geometric limit
- Cutoff at λ=2a

Challenges:

- *D* coefficients are transposed for E_{ty} versus E_{tx}
- Information lost in solving process? Need alternative method?

Conclusions

- Deep, wide cellular structures extend absorption range.
- Thin walls create less reflection and stronger interference.
- Cellular CNT forest structures have the potential to extend the absorption range beyond the mid-IR region.



Acknowledgement

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