Design of Photonic Crystal Wave Guide for Light Confinement in Carbon Nanotube based Infrared Sensors

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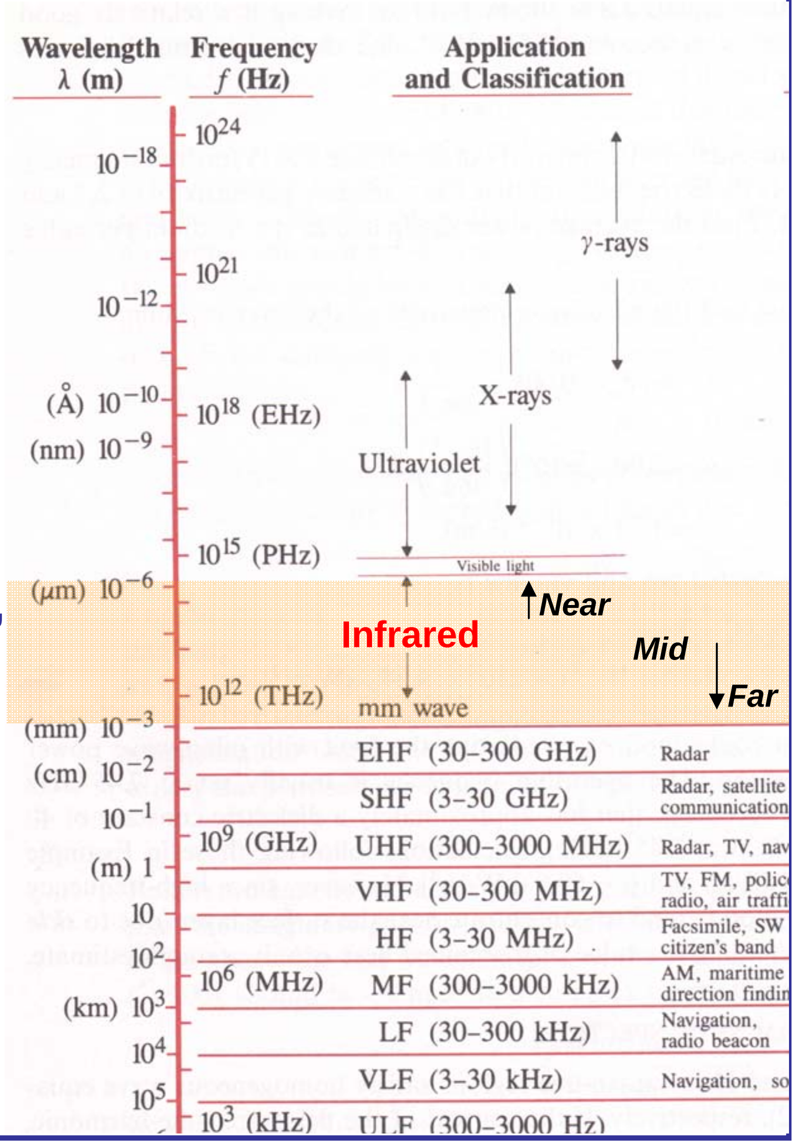
Content

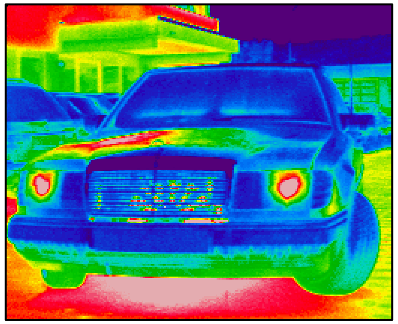
- Background of IR Detector
- Principle of IR Detector and Photonic Crystal
- Design for Photonic Crystal
- Inverse Problems
- Band Diagram
- Conclusion

Background of IR Detector

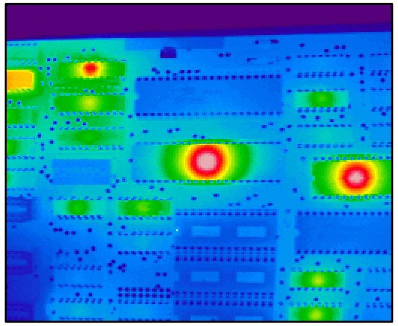
- Electromagnetic waves with wavelength longer than visible light and shorter than microwaves (~ 750 nm to 1mm)
- Shorter wavelengths for telecommunication
- Longer wavelengths are 'thermal'
- 8 - 14 μm is useful range for 'thermal imaging'
- Sensing 3 – 5 μm is difficult



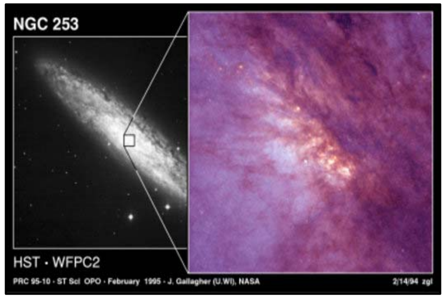
Application of IR Detector - Infrared Camera



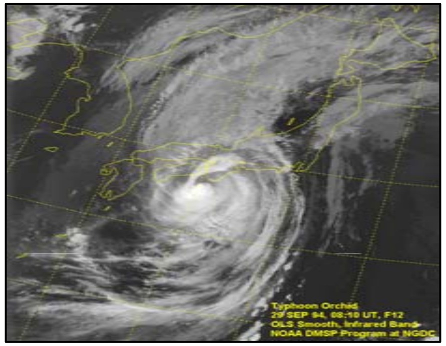
•Automotive Industry



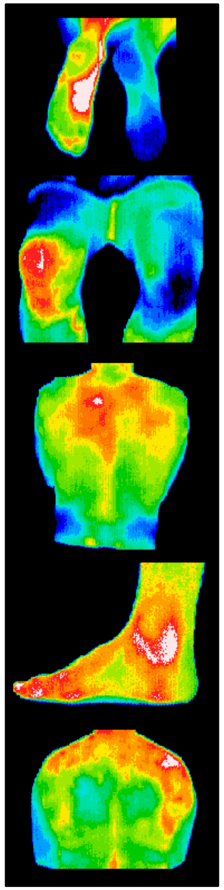
•Electronics

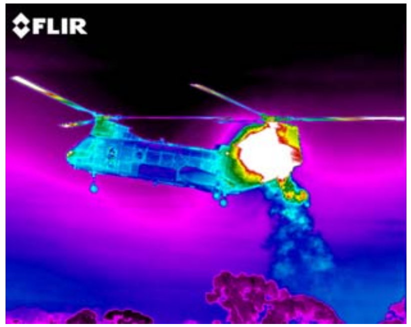


•Astronomy



•Weather Forecasting





Industrial (MWIR)&(LWIR)

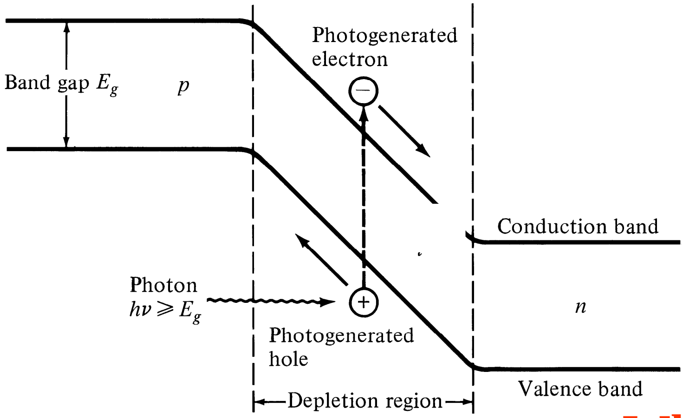
Space (MWIR,LWIR, &VLWIR)

Medical (LWIR)

Security (MWIR & LWIR)

Working principle

- Photodiodes convert optical signal (light) to electrical signal (current/voltage)
- Cut off wavelength depends on the bandgap energy of the material



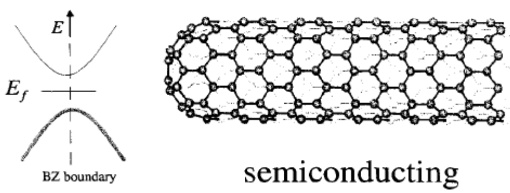
$$\lambda_c = \frac{hc}{E_g}$$

h is Planck's constant
c is the speed of light

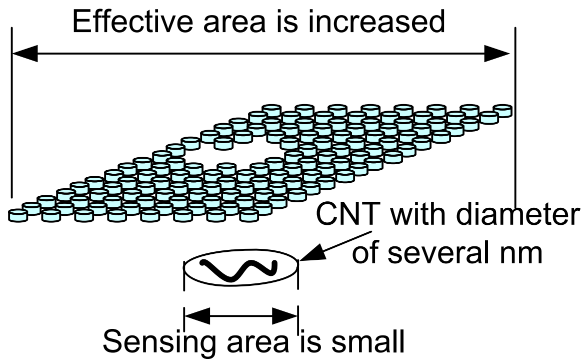
Material	Eg (eV)	λ cutoff (μm)
Si	1.17	1.06
GaAs	1.424	0.87
InSb	0.36	3.4

Why Single CNT?

- The 1D character of CNTs drastically reduces the scattering probability – low thermal noise
- Adjustable band gap for color detectors



Pau L. McEuen, et. al., *IEEE Transactions on Nanotechnology*, VOL. 1, NO. 1, 2002



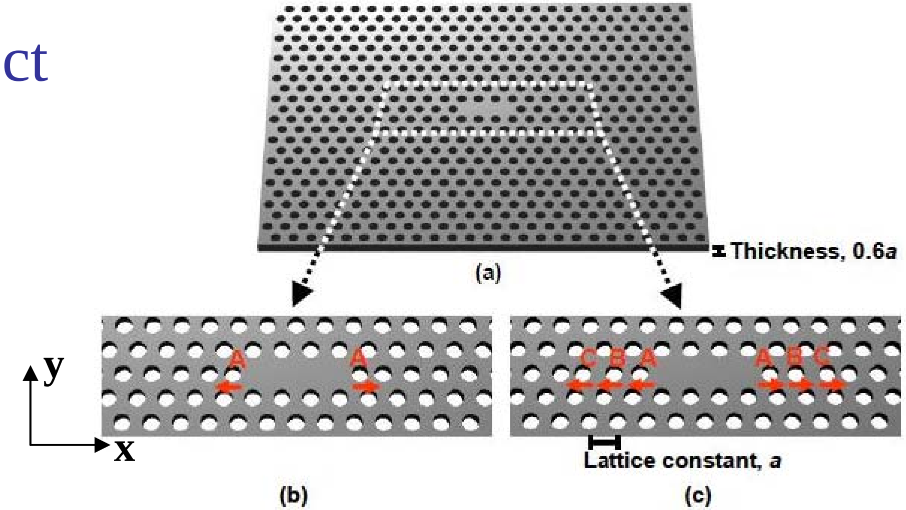
Single CNT is a promising material for non-cryogenic cooled MWIR sensors

⇒ ***Problem:** IR response of CNT sensors is small due to the low incoming electric field and small sensing area*

⇒ ***Approach:** Design a structure to enhance the field intensity at the sensing region*

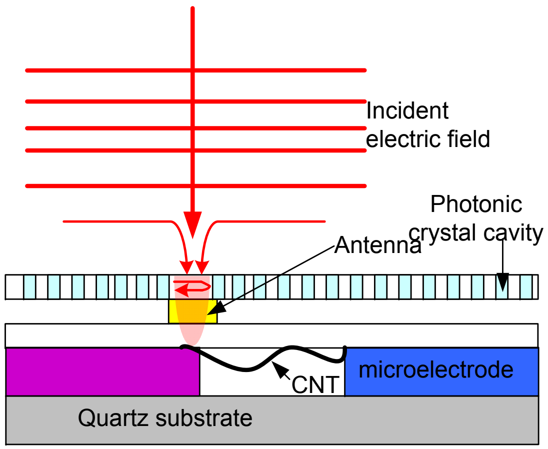
Photonic Crystal Wave Guide for Light Confinement

- Light control and confinement with photonic crystal
- Line defect and point defect

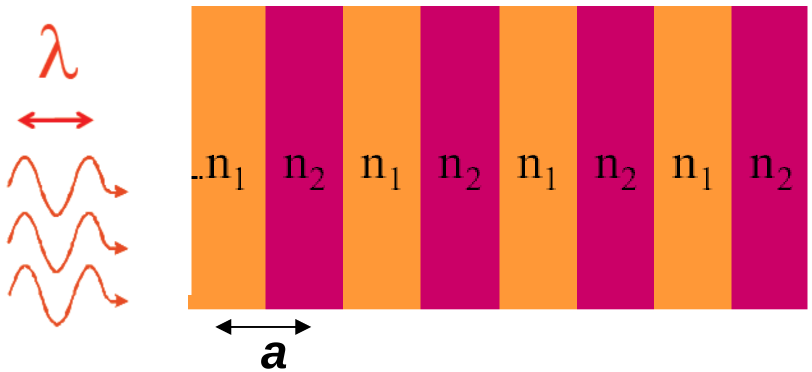


Yoshihiro Akahane, et. al., *Nature*, VOL. 425 (30), 2003

Photonic crystal cavity:
2D periodic structure to totally **localize** the incoming radiation in the cavity

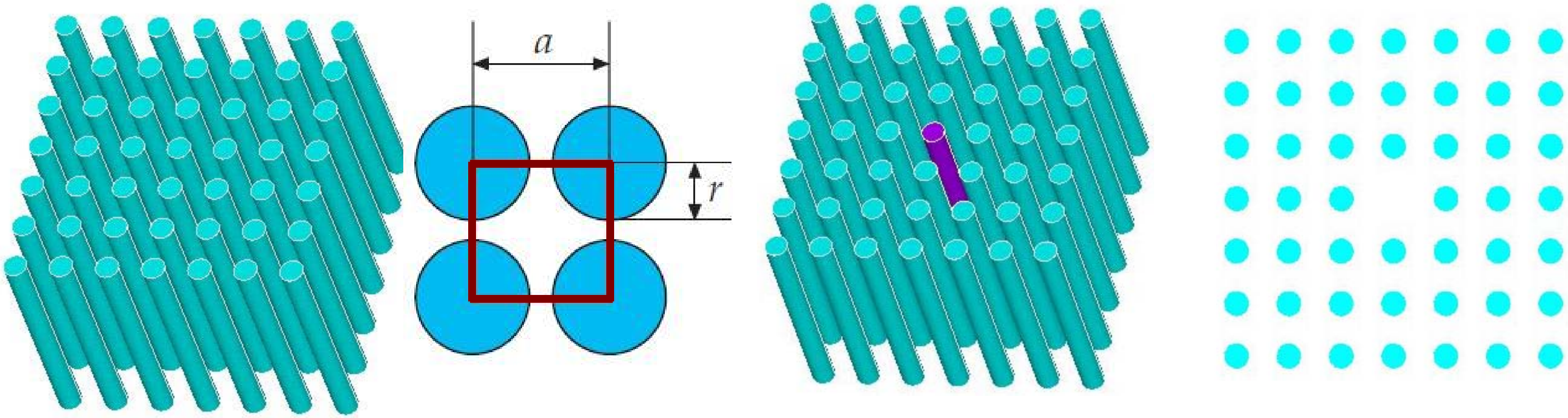


scale *a* ≈ wavelength of light *λ*

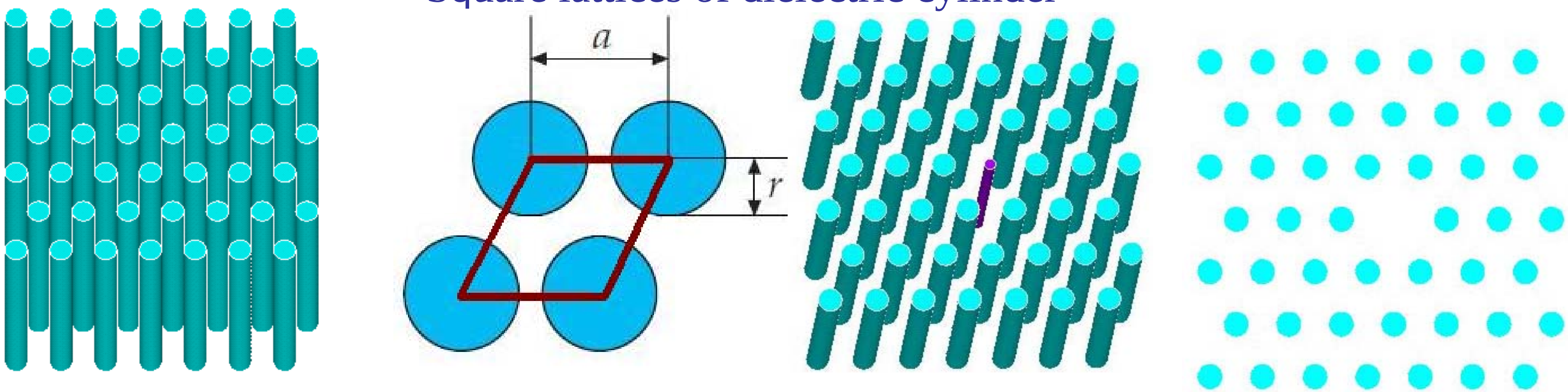


Possible designs of photonic crystal

- Array of high dielectric rods in air



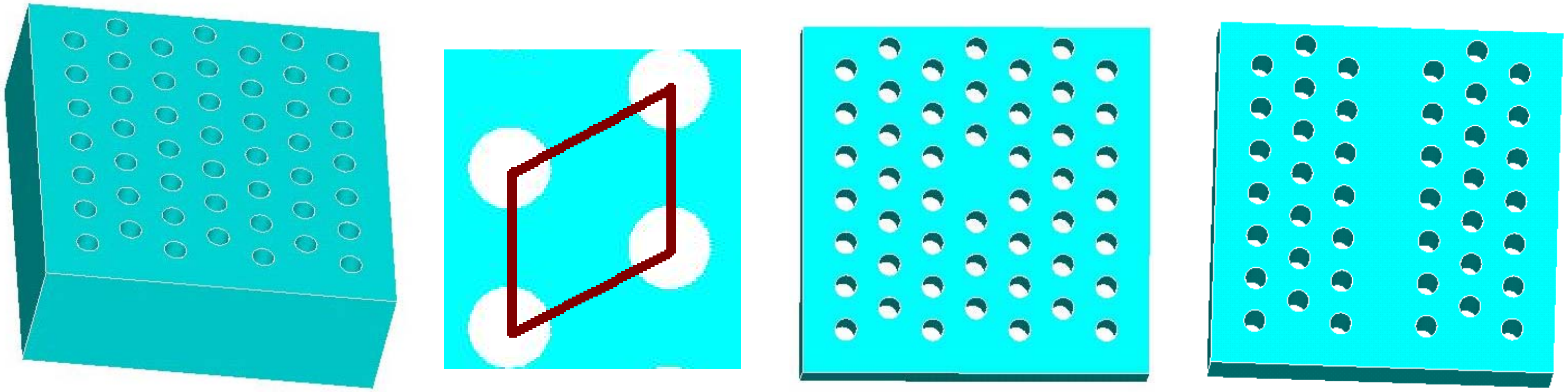
Square lattices of dielectric cylinder



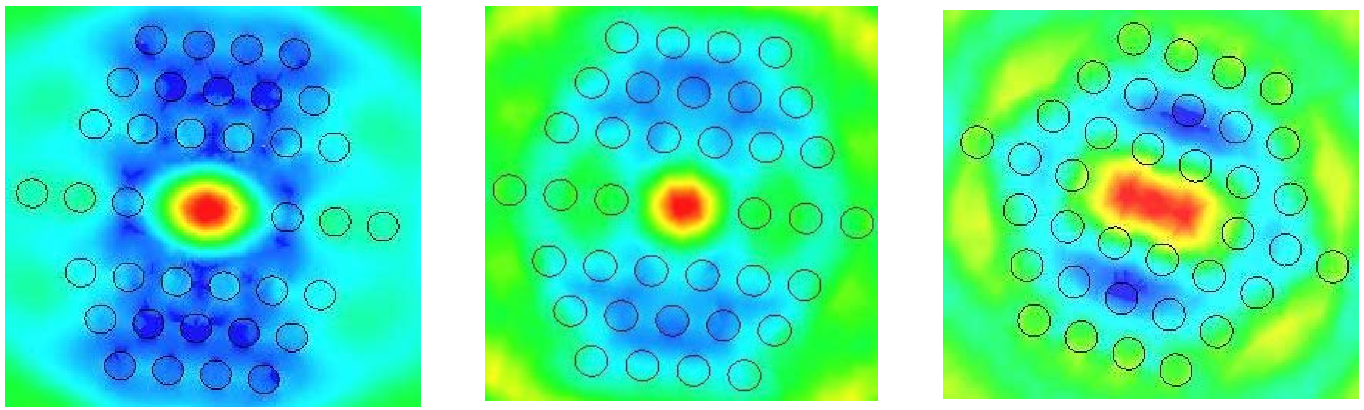
Hexagonal lattices of dielectric cylinder

Possible designs of photonic crystal

- Air holes in high dielectric substrate



Hexagonal lattices of air hole in dielectric substrate

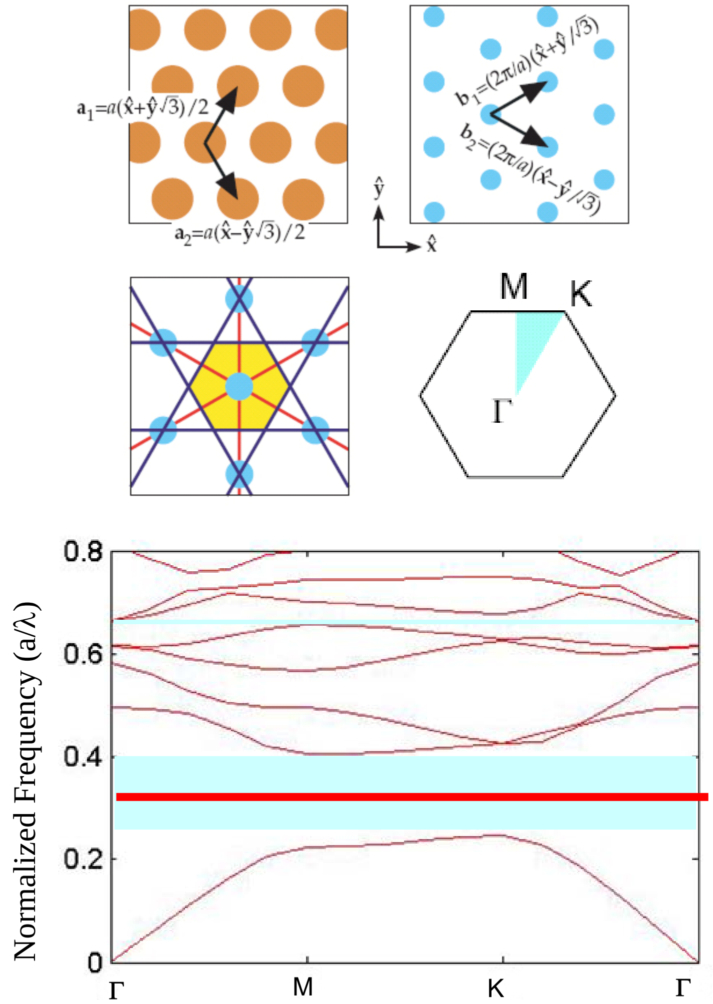


Light confinement (point defect with air hole in dielectric substrate)

Inverse Problems

- The forward problem
  - Finding the maximum output electric field ***E*** and resonant frequency ***ω*** as a function of radius ***r***, periodic distance ***a***, dielectric constant ***ε***

- The inverse problem
  - Find ***r***, ***a*** and specific frequency ***ω*** from the band diagram



Basic Theory

- Electromagnetic principle
  - Maxwell equations

$$\nabla \cdot H(r,t) = 0, \qquad \nabla \times E(r,t) + \mu_0 \frac{\partial H(r,t)}{\partial t} = 0$$

$$\nabla \cdot [\varepsilon(r) E(r,t)] = 0, \qquad \nabla \times H(r,t) - \varepsilon_0 \varepsilon(r) \frac{\partial E(r,t)}{\partial t} = 0$$

$$H(r,t) = H(r) e^{-i\omega t}$$

$$E(r,t) = E(r) e^{-i\omega t}$$

  - Master equation

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r)$$

$$\mathrm{E(r)} = \frac{\mathrm{i}}{\omega \varepsilon_0 \varepsilon(r)} \nabla \times H(r)$$

- Schrödinger’s equation
  - Hamiltonian of a system of electrons

$$H = \frac{1}{2m_e} \left(\hat{\mathrm{P}} + \frac{e}{c} \mathrm{A} \right)^2 + V(r)$$

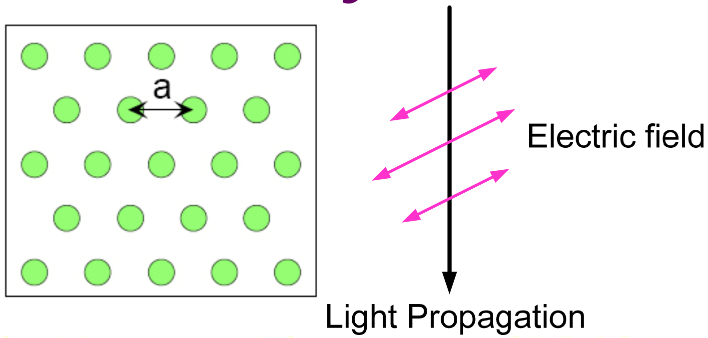
  - Quantum conductivity and dielectric function

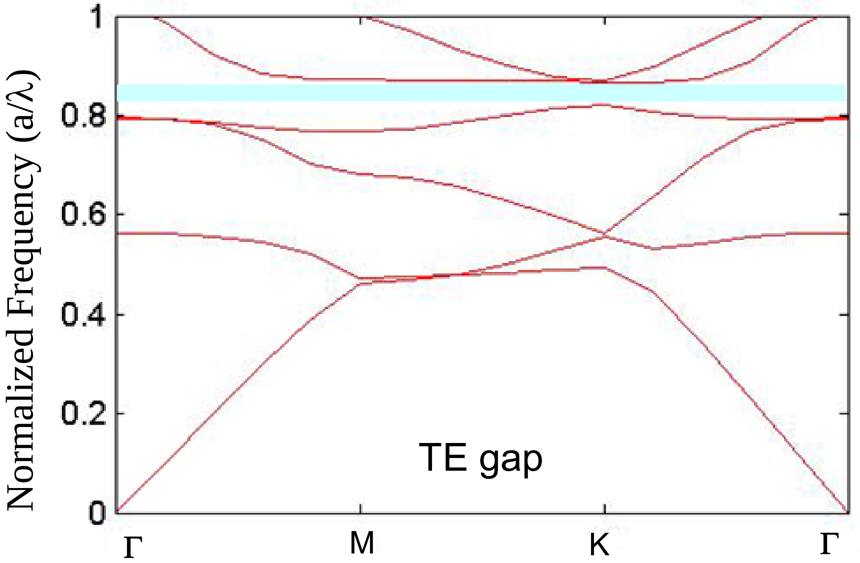
$$\sigma(\omega) = -j \frac{e^2 E_F}{\pi \hbar^2 (\omega - j\upsilon)}$$

$$\varepsilon(\omega) = 1 + i4\pi\sigma(\omega)/\omega$$

Band Diagram for Photonic Crystal

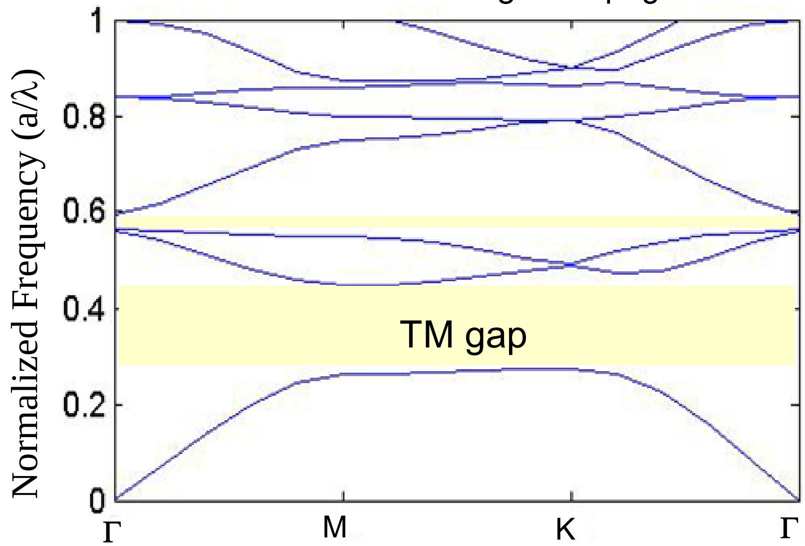
- High dielectric: <u>Silicon</u> (*ε=12*) rods in air
- Radius of the dielectric rod ***r****=0.2a*





TE polarization

<u>Gap from band 4 (0.822) to band 5 (0.864), 5.1%</u>

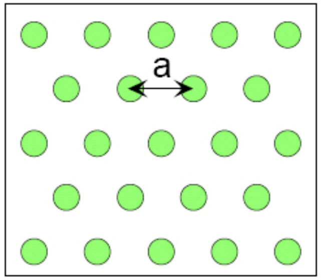


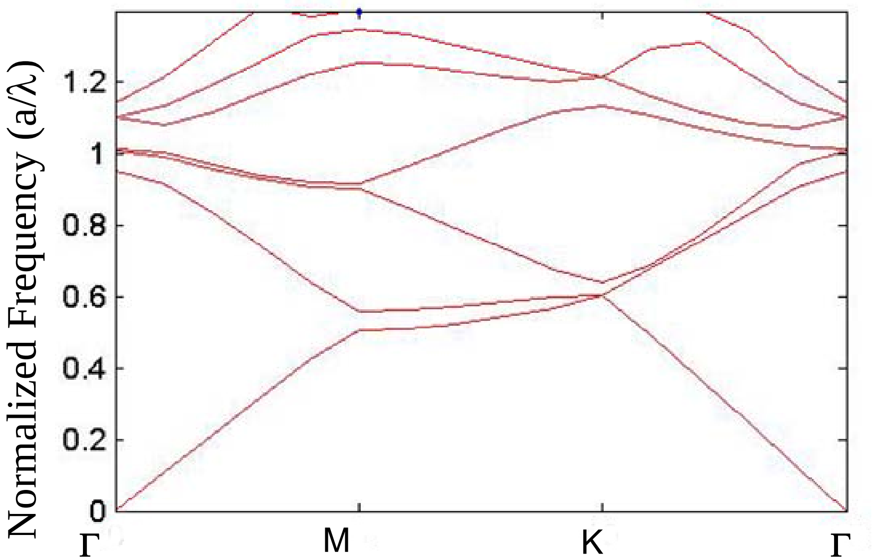
TM polarization

<u>Gap from band 1 (0.275) to band 2 (0.446), 47.5%</u>
<u>Gap from band 3 (0.564) to band 4 (0.5934), 5.1%</u>

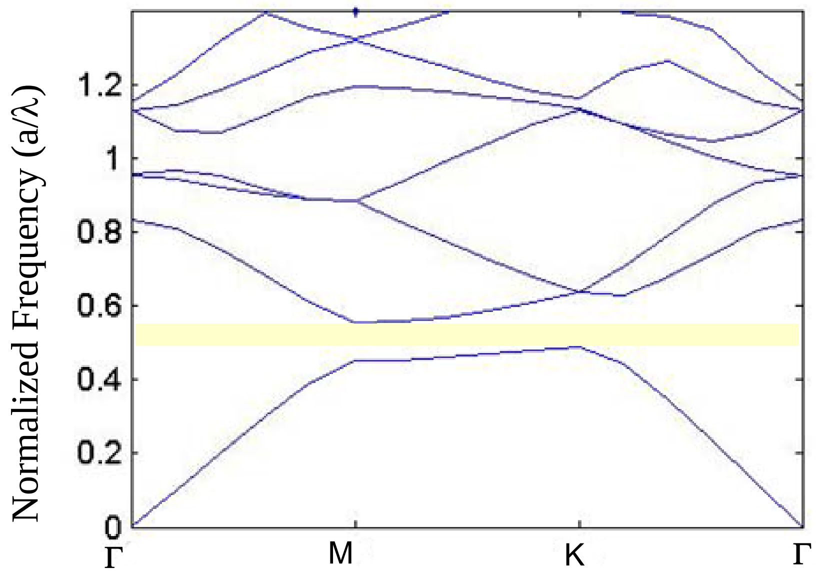
Band Diagram for Photonic Crystal

- High dielectric: <u>Parylene</u> (ε=3.1) rods in air
- Radius of the dielectric rod $\boldsymbol{r}$=$0.2a$





TE polarization



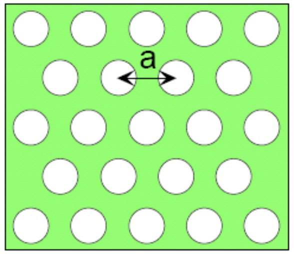
TM polarization

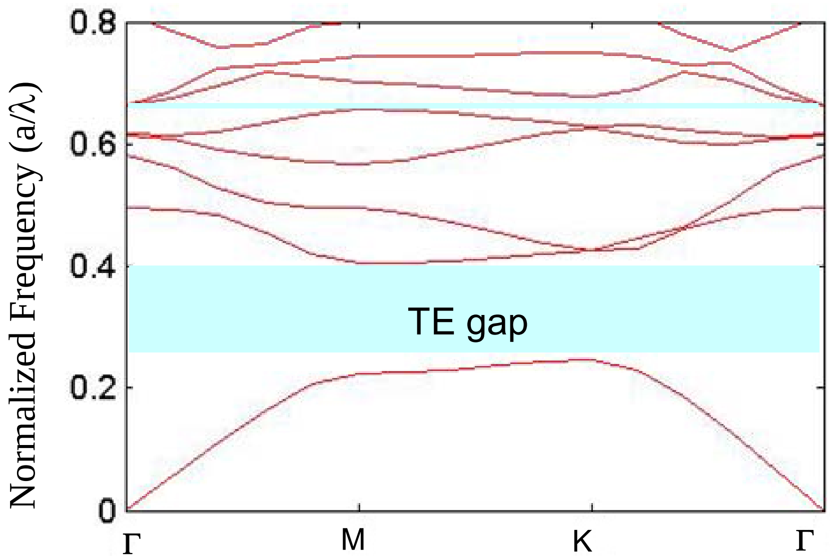
<u>No bandgap</u>

<u>Gap from band 1 (0.488) to band 2 (0.554), 12.7%</u>

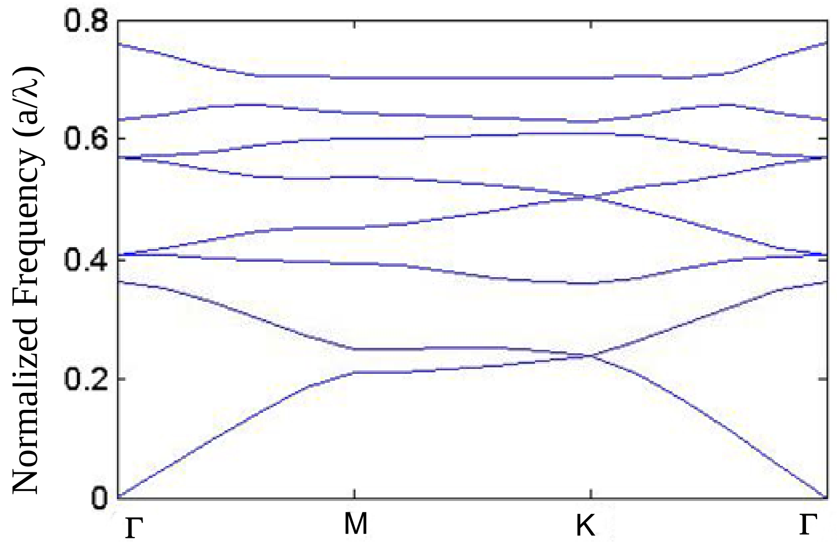
Band Diagram for Photonic Crystal

- Air holes in dielectric: Silicon (ε=12)
- Radius of the hole ***r*=*0.4a***





TE polarization



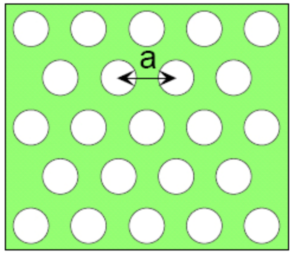
TM polarization

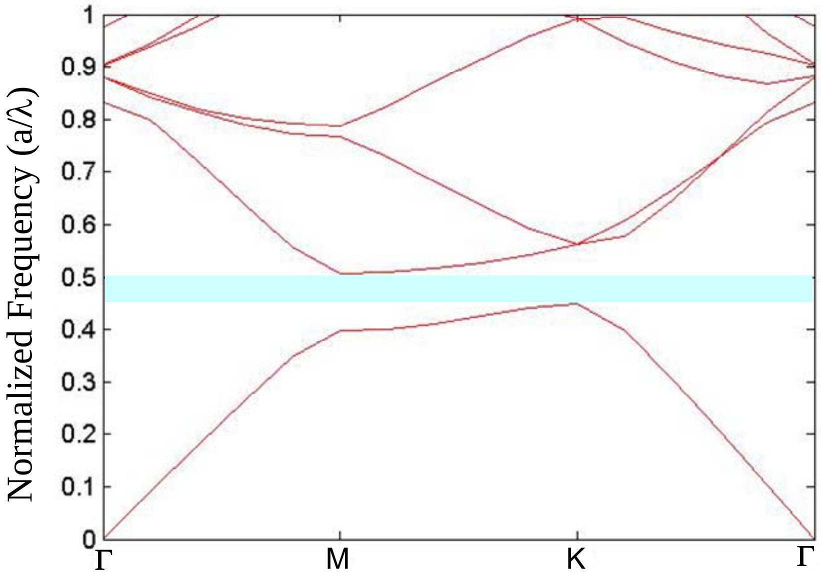
Gap from band 1 (0.246) to band 2 (0.405), 48.8%
Gap from band 5 (0.657) to band 6 (0.661), 0.71%
Gap from band 7 (0.749) to band 8 (0.752), 0.38%

Gap from band 5 (0.569) to band 6 (0.570), 0.15%
Gap from band 6 (0.61) to band 7 (0.63), 3.3%
Gap from band 7 (0.657) to band 8 (0.702), 6.6%

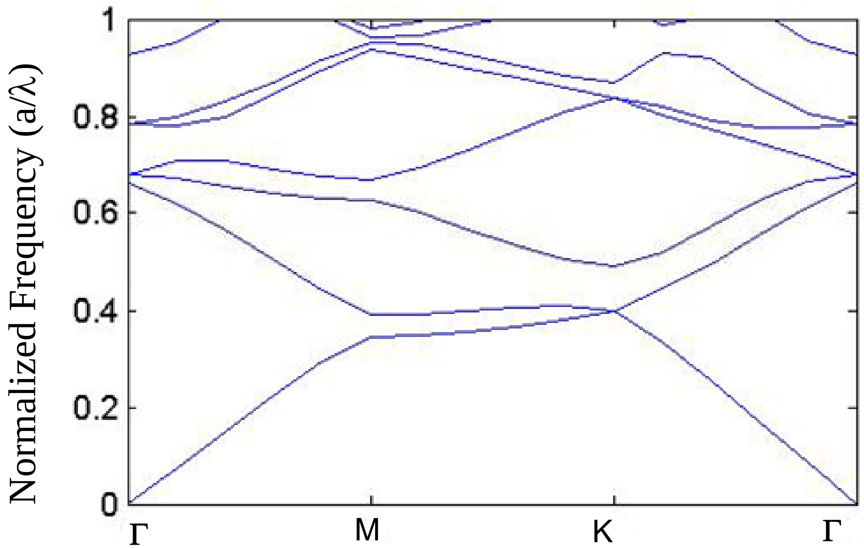
Band Diagram for Photonic Crystal

- Air holes in dielectric: Parylene (ε=*3.1*)
- Radius of the hole ***r****=0.4a*





TE polarization

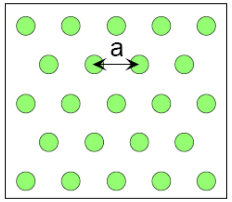


TM polarization

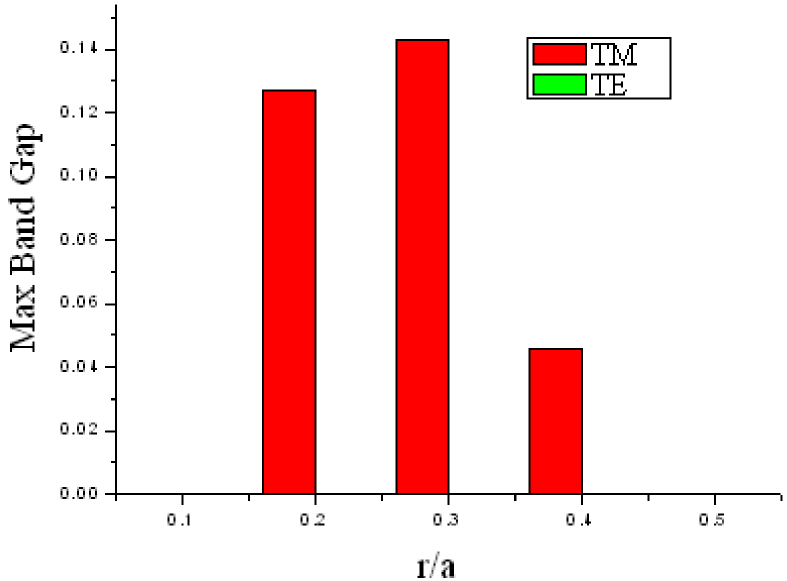
Gap from band 1 (0.449) to band 2 (0.507), 12.2%

Gap from band 7 (1.161) to band 8 (1.181), 1.74%

Band Diagram for Photonic Crystal

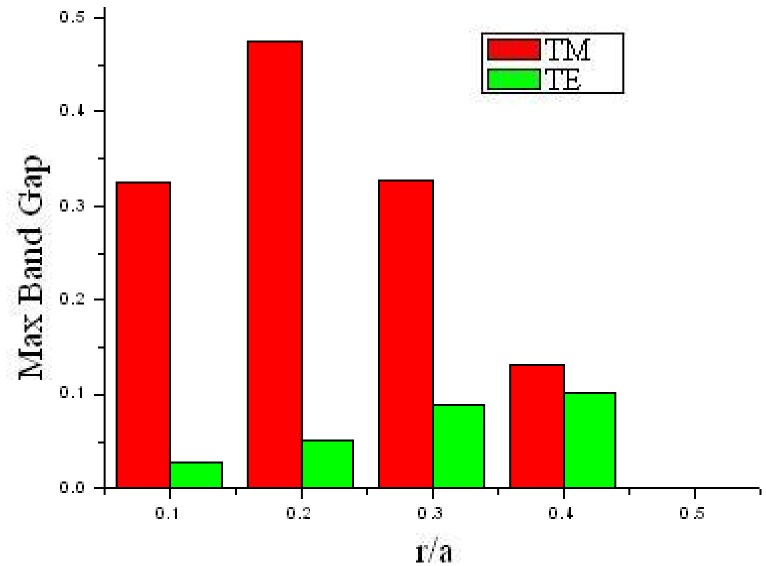


Parylene: Dielectric constant ε=3.1



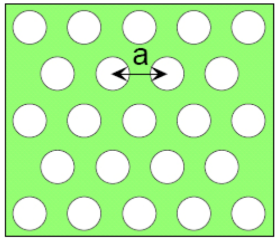
- Max. band gap for TM wave: 14.4%
- TE wave: no band gap

Silicon: Dielectric constant ε=12

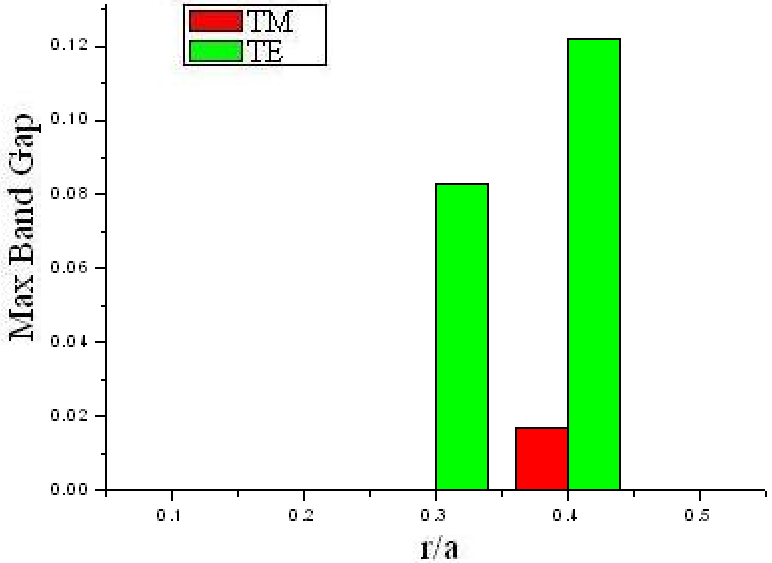


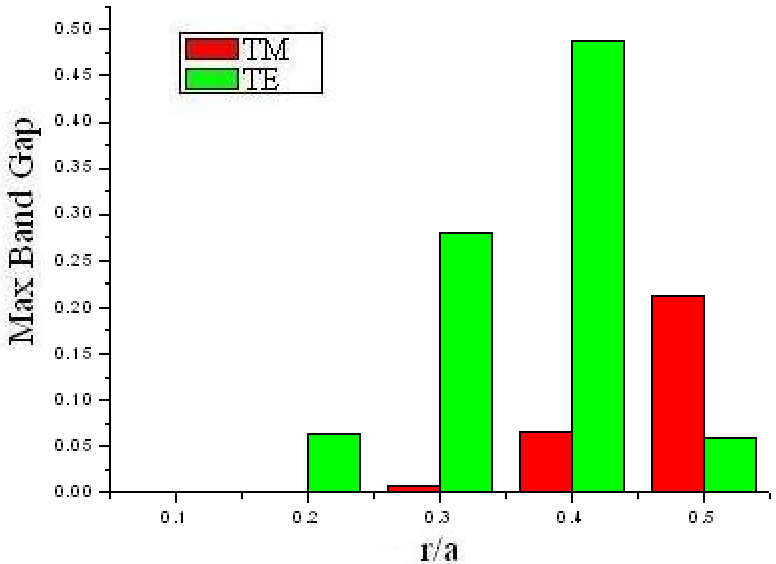
- Max. band gap for TM wave: 47.5%
- Max. band gap for TE wave: 10.3%

Band Diagram for Photonic Crystal



Parylene: Dielectric constant ε=3.1	Silicon: Dielectric constant ε=12



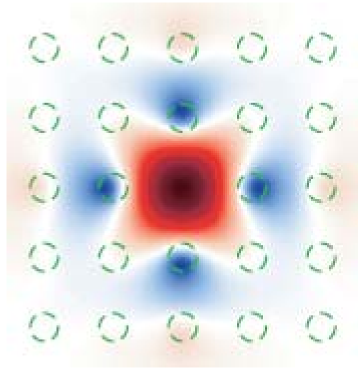


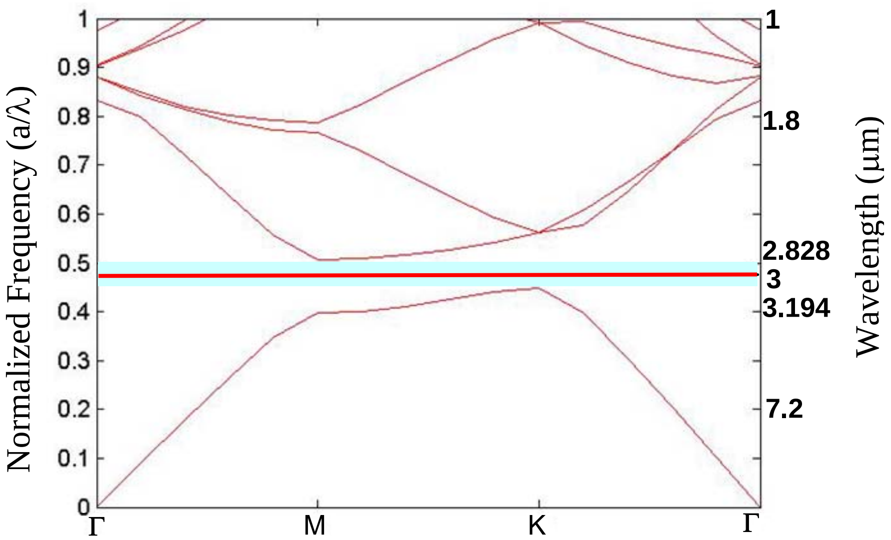
- Max. band gap for TM wave: 1.74%
- TE wave: 12.2%

- Max. band gap for TM wave: 21.3%
- Max. band gap for TE wave: 48.8%

Band Diagram for Photonic Crystal

- Light confinement with point defect
  - Air hole in dielectric substrate
  - Point defect in the center
  - Incident light frequency:
    mid-frequency of band gap
  - Electric field intensity: confine at defect position





Midgap=0.478
When ***λ=3μm***
⇨***a=0.478*3=1.434μm*** *(r=0.5736μm)*
⇨bandgap *λ* from ***2.828μm*** to ***3.194μm***

Conclusion

- Infrared sensors enable many potential applications
- Single CNT is a promising material for non-cryogenic cooled IR sensors
- Photonic crystal cavity to confine and enhance the electric field at the sensor
- Band diagram for different photonic crystal structures
- Find the optimized design based on the band diagram

Thank you