Accuracy requirements in the mechanical assembly of photonic crystals

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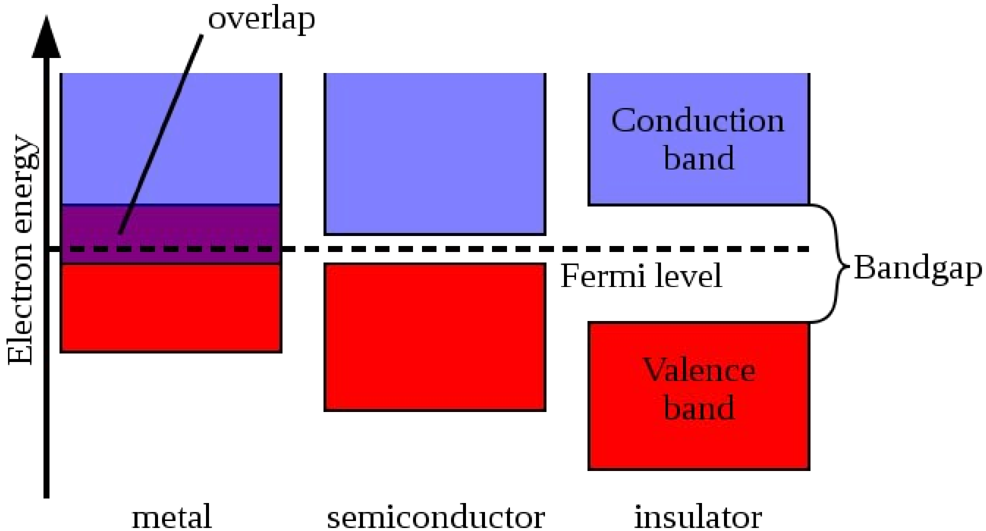
Agenda

- Introduction to photonic crystals: theory, background, applications
- Photonic crystal fabrication: state-of-the-art techniques to manufacture photonic crystals
- Application: influence of a misalignment in the 3D structure on the band gap – simulation results

Introduction

Photonic crystals are to Optics what semiconductors are to electronics

Semiconductors = material that has a conductivity between that of isolator and conductor



Theory

Maxwell equation

$$\nabla \cdot \mathrm{B} = 0 \quad \nabla \times \mathrm{E} + \frac{\partial \mathrm{B}}{\partial t} = 0$$

$$\nabla \cdot \mathrm{D} = \rho \quad \nabla \times \mathrm{H} - \frac{\partial \mathrm{D}}{\partial t} = \mathrm{J}$$

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

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

$$\rightarrow$$

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

Bloch theorem

<u>If the system has a periodic permittivity:</u>

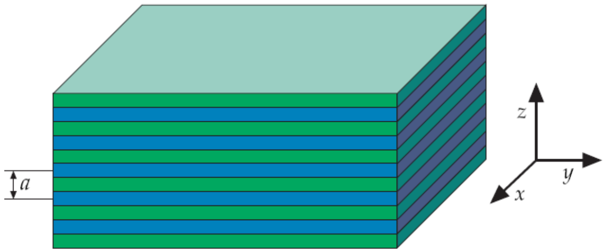
$$\mathrm{H}_{\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} \mathbf{u}_{\mathbf{k}}(\mathbf{r}), \quad \mathbf{u}_{\mathbf{k}}(\mathbf{r}) = \mathbf{u}_{\mathbf{k}}(\mathbf{r} + \mathbf{R})$$

$$\begin{cases} \hat{\Theta}\mathrm{H}(\mathbf{r}) = \left(\frac{\omega}{c} \right)^2 \mathrm{H}(\mathbf{r}). \\ \hat{\Theta}\mathrm{H}(\mathbf{r}) \triangleq \nabla \times \left(\frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathrm{H}(\mathbf{r}) \right). \end{cases}$$

becomes

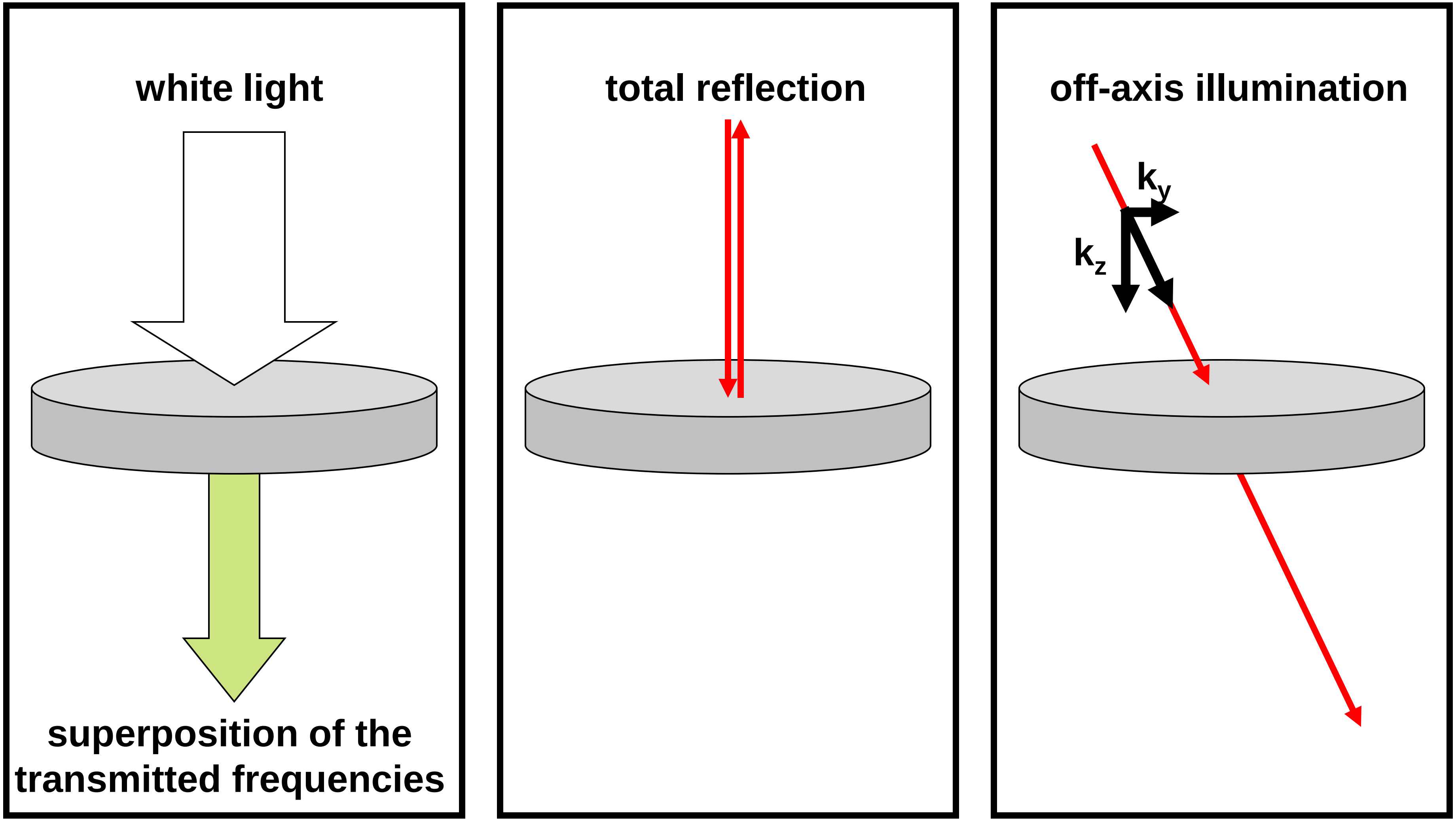
$$\boxed{\begin{cases} \hat{\Theta}_{\mathbf{k}} \mathbf{u}_{\mathbf{k}}(\mathbf{r}) = (\omega(\mathbf{k})/c)^2 \mathbf{u}_{\mathbf{k}}(\mathbf{r}). \ (\mathbf{r}). \\ \hat{\Theta}_{\mathbf{k}} \triangleq (i\mathbf{k} + \nabla) \times \frac{1}{\varepsilon(\mathbf{r})} (i\mathbf{k} + \nabla) \times . \end{cases}} \quad .$$

Dispersion relation

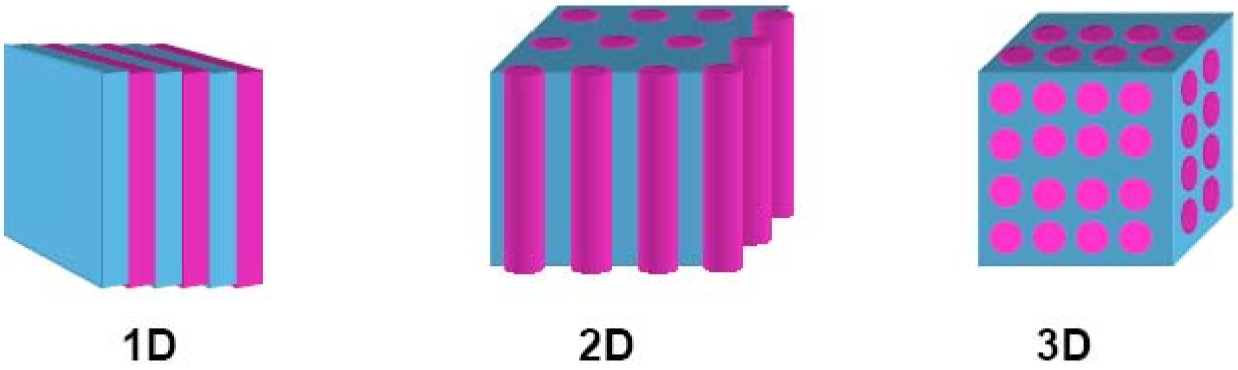


Source: J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic crystals: molding the flow of light* (Princeton university press, Princeton, 1995).

Because there's nothing better than a little experiment…



From 1D to 3D crystals



Source: J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic crystals: molding the flow of light* (Princeton university press, Princeton, 1995).

Application of photonic crystals

Filters

Mirrors

Wave guides

Cavities

Light shaping

3D Photonic crystal: fabrication

- Full 3d fabrication

- Point by point fabrication

- Layer-by-layer approach

3D Photonic crystal: fabrication

•**Full 3d fabrication**
•Point by point fabrication
•Layer-by-layer approach

Colloidal particles

Self-assembly or
micromanipulation of spheres

Please see Fig. 2 in Garcia-Santamaria, F., et al. "Opal-like Photonic Crystal With Diamond Lattice." *Applied Physics Letters* 79 (October 2001): 2309-2311.
Fig. 2 in Vlasov, Yurii A., et al. "On-chip Natural Assembly of Silicon Photonic Bandgap Crystals." *Nature* 414 (November 15, 2001): 289-293.

Opal-like photonic crystal with diamond lattice
F. Garcia-Santamaria, et al.
2001 American Institute of Physics.

On-chip natural assembly of silicon photonic bandgap crystals
Y. A. Vlasov *et al., Nature 414, 289 (2001).*

3D Photonic crystal: fabrication

- **Full 3d fabrication**
- Point by point fabrication
- Layer-by-layer approach

Holographic lithography

Four laser beams interfere to create a 3d interference pattern that exposes a photoresist.

Fabrication of photonic crystals for the visible spectrum by holographic lithography
M. Campbell et al.
Nature, vol 404, 2000

3D Photonic crystal: fabrication

- Full 3d fabrication
- **Point by point fabrication**
- Layer-by-layer approach

Multi-photon polymerization

Photoresist exposed with laser light below the single-photon polymerization threshold. At a tight focus point, multi-photon polymerization may occur.

Best resolution achieved: 120nm.

Can be combined with holographic lithography.

Image removed due to copyright restrictions.
Please see Fig. 1 in Deubel, Markus, et al. "Direct Laser Writing of Three-dimensional Photonic-crystal Templates for Telecommunications." *Nature Materials* 3 (July 2004): 444-447.

Direct laser writing of three-dimensional photonic-crystal templates for telecommunications
MARKUS DEUBEL et al.
Nature, 2004

3D Photonic crystal: fabrication

- Full 3d fabrication
- Point by point fabrication
- **Layer-by-layer approach**

The woodpile structure

Image removed due to copyright restrictions. Please see Fig. 2 in Lin, S. Y., et al. "A Three-dimensional Photonic Crystal Operating at Infrared Wavelengths." *Nature* 394 (July 16, 1998): 251-253.

A three-dimensional photonic crystal operating at infrared wavelengths

S. Y. Lin et al.

Nature, 1998

3D Photonic crystal: fabrication

- Full 3d fabrication
- Point by point fabrication
- **Layer-by-layer approach**

Holes-rods structure

diamond lattice

A three-dimensional optical photonic crystal with designed point defects
Minghao Qi et. al
Nature, 2004

3D Photonic crystal: fabrication

- Full 3d fabrication
- Point by point fabrication
- **Layer-by-layer approach**

Membrane stacking

Three-dimensional photonic crystals for optical wavelengths assembled by micromanipulation
Kanna Aoki et al.
Applied Physics Letters, 2002

3D Photonic crystal: fabrication

- Full 3d fabrication
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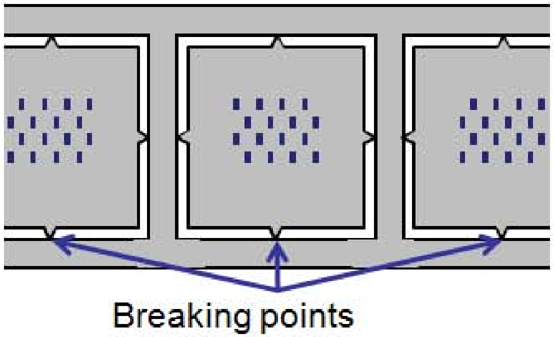
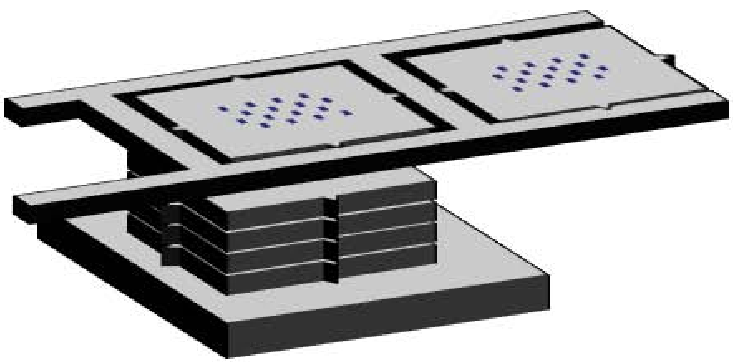
- **Layer-by-layer approach**

Membrane stacking

Membrane segments are held to the frame via flexures that fracture upon removal of frame. Nanomagnets patterned on the segments self-align the membrane to the 3D stack.



Top: membranes are patterned to break at determined points. The frame carries multiple membranes for a repeatable and automated process.



Side: One after the other the membranes align and snap to matching magnets arrays on the growing 3D patterned stack.

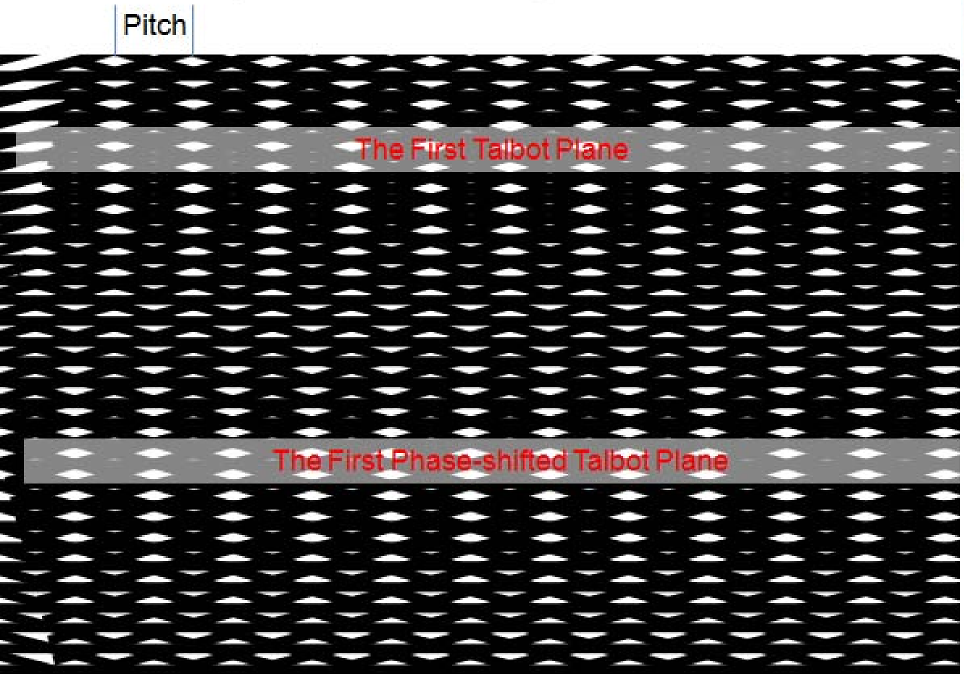
3D Photonic crystal: fabrication

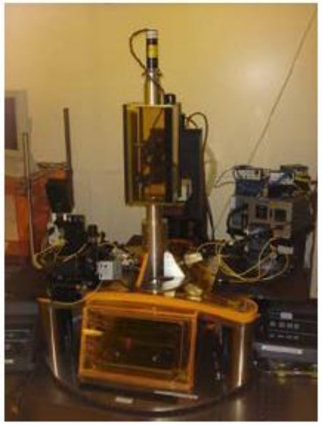
- •Full 3d fabrication
- •Point by point fabrication
- **•Layer-by-layer approach**

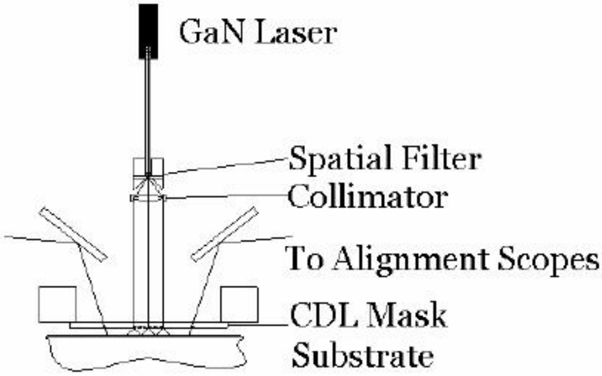
layer fabrication

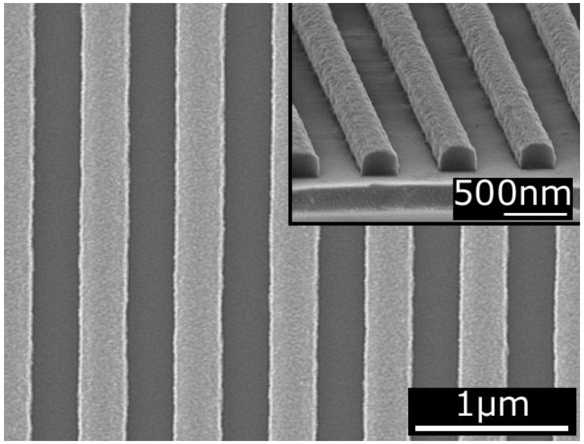
Coherent Diffraction Lithography

Beyond the amplitude mask









3D Photonic crystal: Diamond Lattice

This Diamond Lattice:

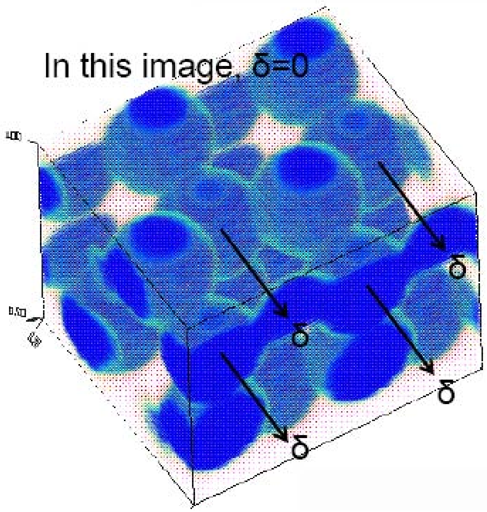
•Face-center cubic (ε_r = 1) unit cell - volume a^3

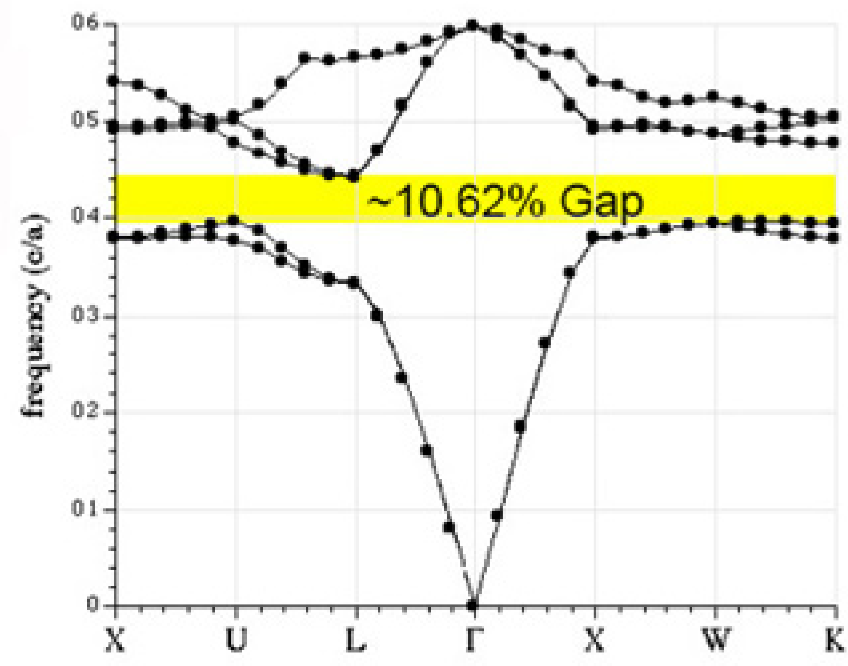
•2 spherical elements (ε_r = 11.56) per unit cell

•Each sphere has radius 0.25*a

•One is centered at (1/8,1/8,1/8)

•The other centered at (-1/8+δ,-1/8,-1/8)





•The band gap is centered about: $0.42 \cdot 3\times10^8$ [m/s]/lattice-size[m]

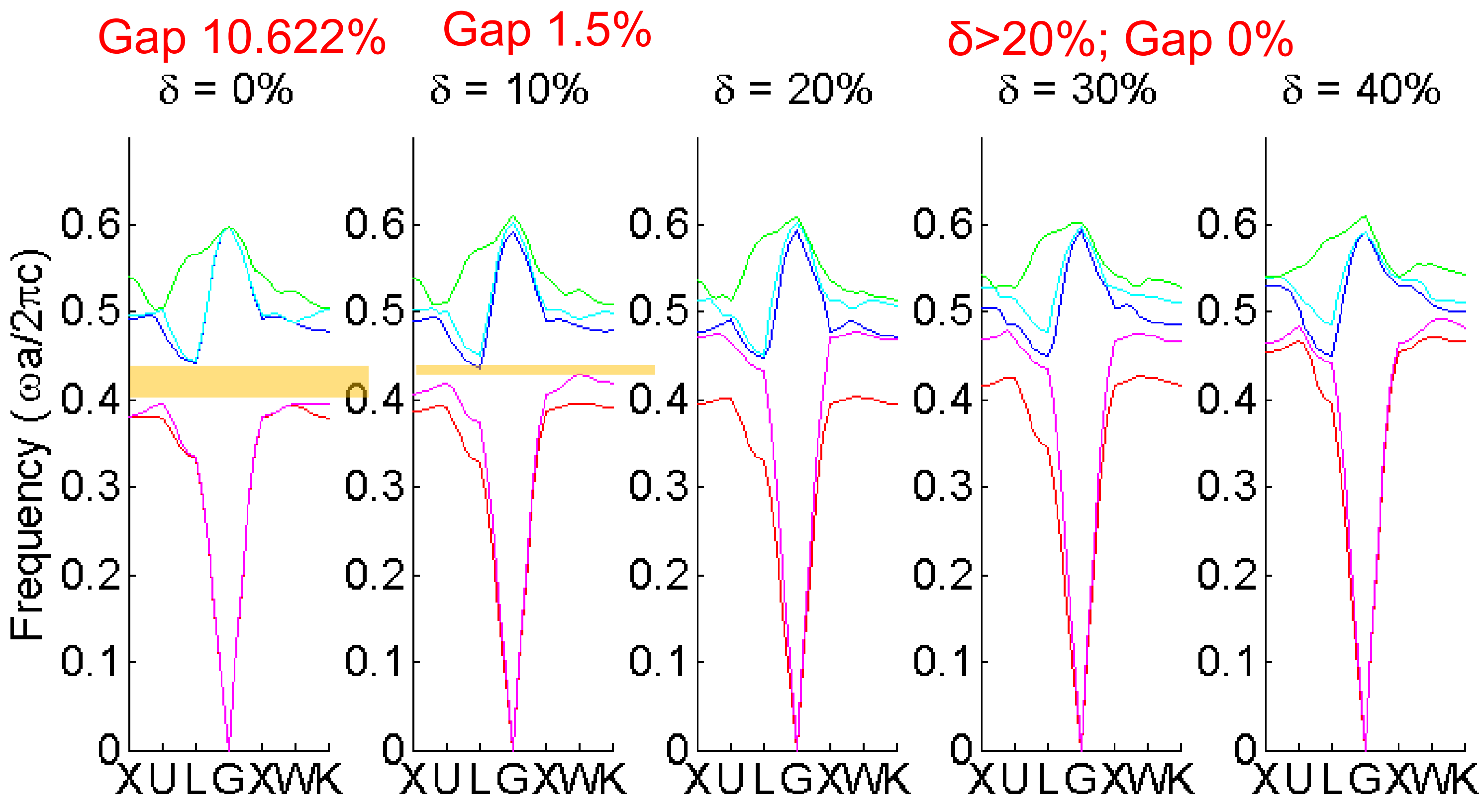
•Gap is defined as $\Delta\omega/\omega_{middle}$

Images from MPB documentation: http://ab-initio.mit.edu/wiki/index.php/MPB_Data_Analysis_Tutorial

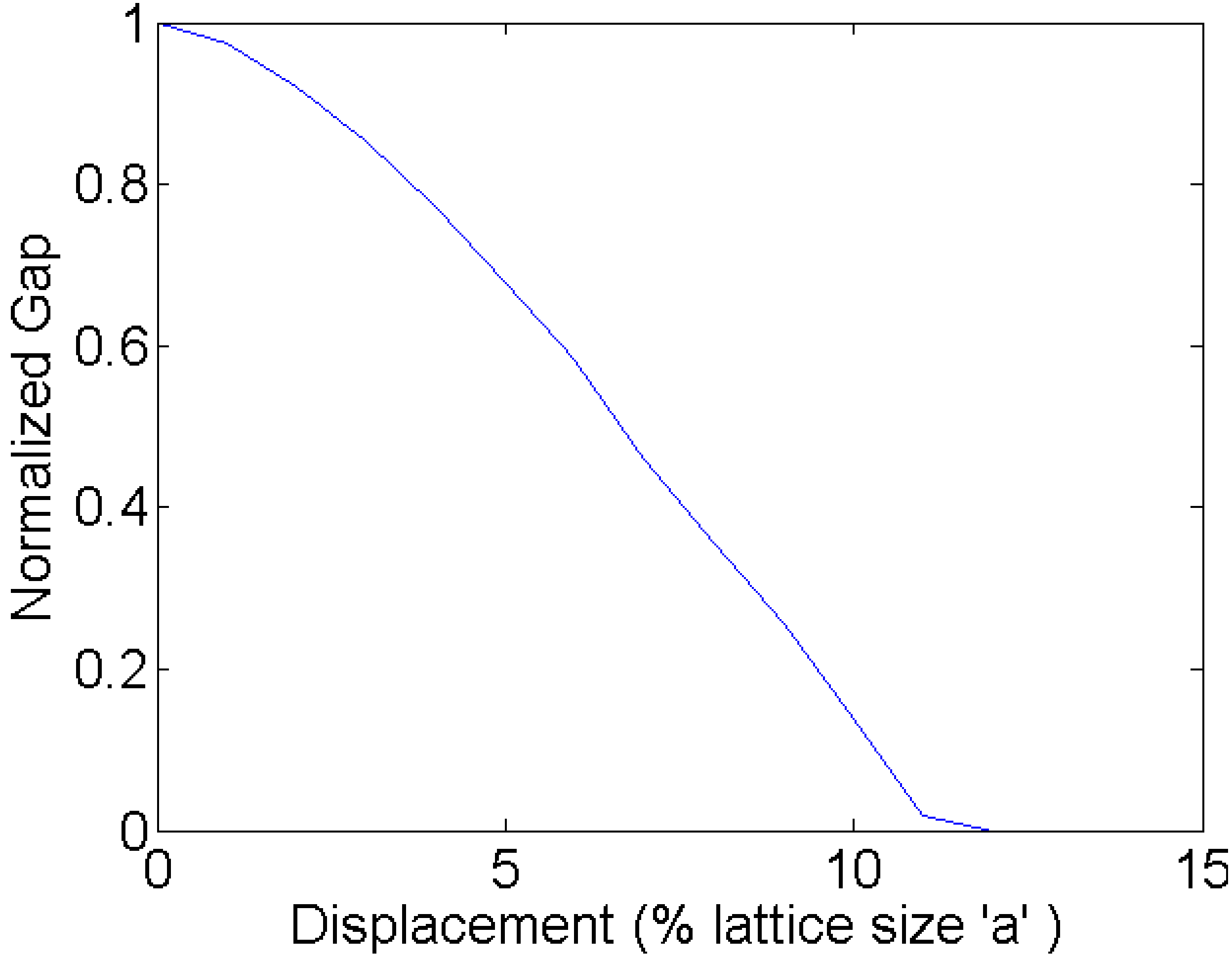
Evolution of the Displaced Sphere

- If a translation of δ is applied to the lower sphere, how does the dispersion relationship and Gap-width change

δ describes a lateral misalignment relative to the normalized lattice-size ‘a’.



The Gap as a function of δ



What does it mean?

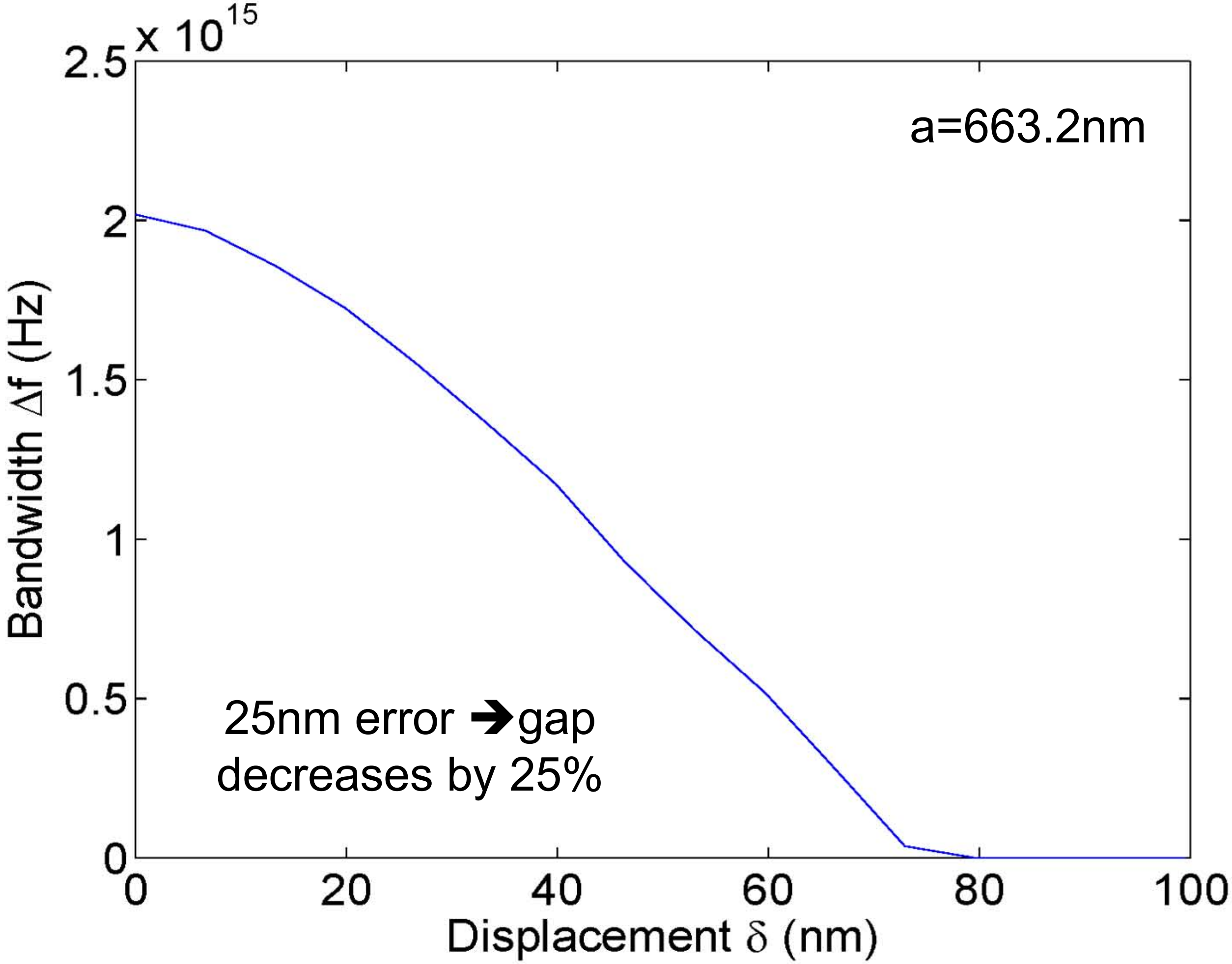
- Suppose the lattice-size was 500nm then a 25nm error (5% displacement) in pattern placement would correspond to a band gap that is 67% of the band-gap at no displacement.
- If the original band-gap at no displacement was 10.622% then
  - the new band-gap at 5% alignment error reduces to 7.2%
  - the new band-gap at 10% alignment error reduces to 1.5%
  - To remain above 10% (0.95 normalized gap) the alignment error must be less than 2%

A telecom example

Suppose λ=1.55μm & f=1.9e14 Hz

Suppose the band gap center is c/a=0.42

Then at centering the band-gap at f, the lattice size becomes:



2.71 / 2.710 Optics
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