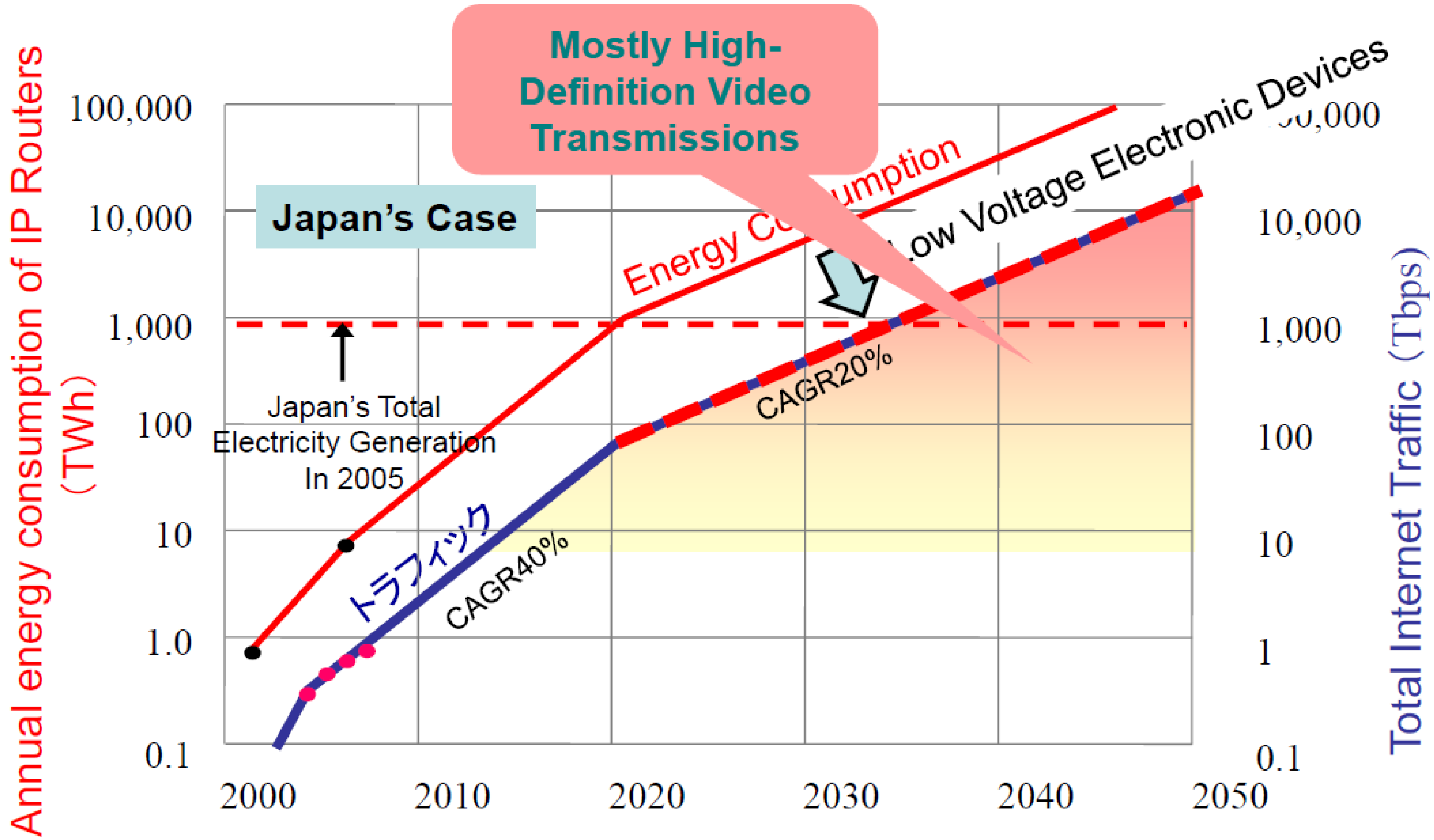
Stop and Frozen light

Why to use photons instead of electrons?

How to control the propagation of light?

How to slow and stop light?

Motivation: Energy consumption



- The current technologies can't scale to the increasing traffic in future.
- 3-4 digit energy saving is necessary, which means we need a new paradigm.

S. Namiki et al., OECC2009, FT2, Hong Kong

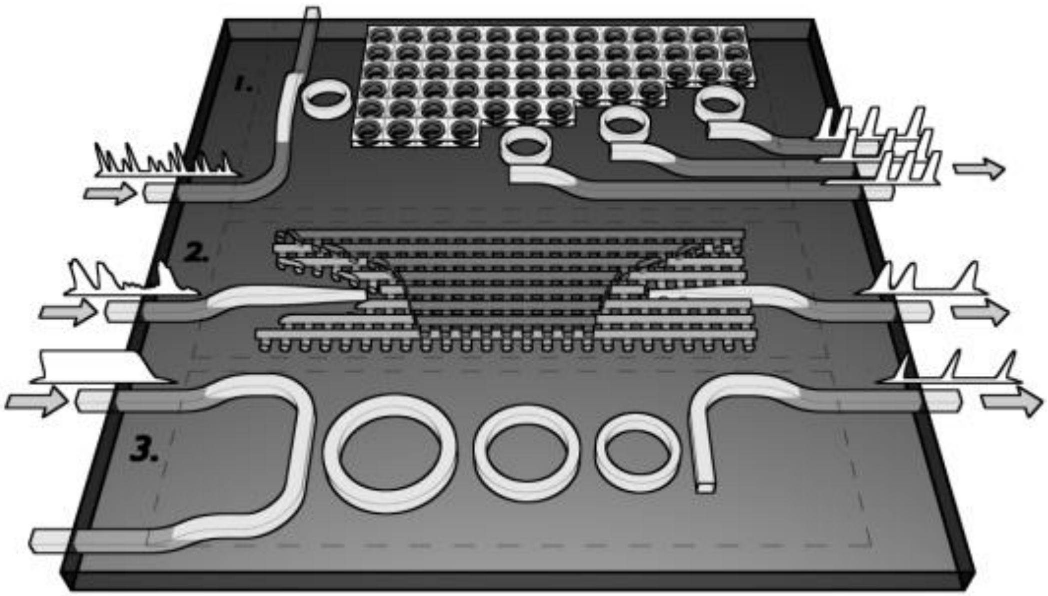
http://www.aist.go.jp

Why using photons instead of electrons?

- The photons travel in the speed of light.
- Photons are a massless entities.
- Each optical channel (or colour) can carry up to 1,000 Tbps

Cudos vision

To create photonic integration "platform"



Processing building blocks:

1. Logical operation
2. Storage
3. Input/output

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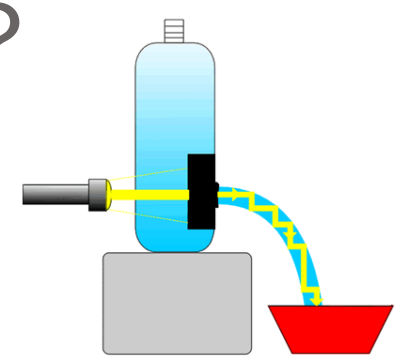
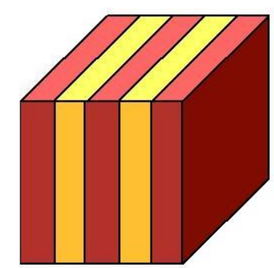
How to confine and guide light?



- Optical fibre: total internal reflection:
  - For a range of angles light is reflected from a dielectric interface without loss.
- Forbidden energy gap materials
  - The forbidden electron gap in crystals govern whether the material will be conductor or insulators.
  - By creating periodic optical material forbidden energy band for photons can emerge



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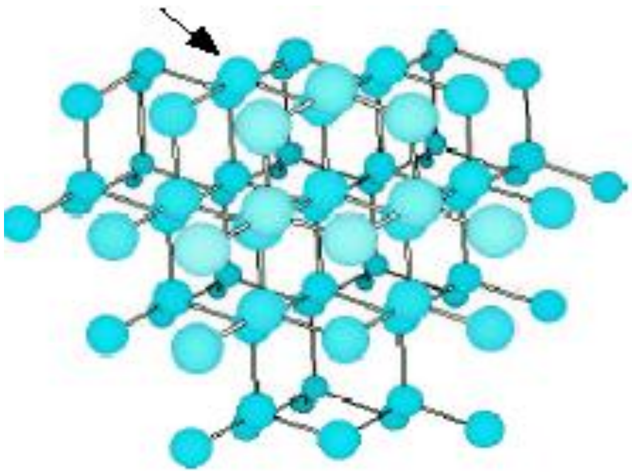
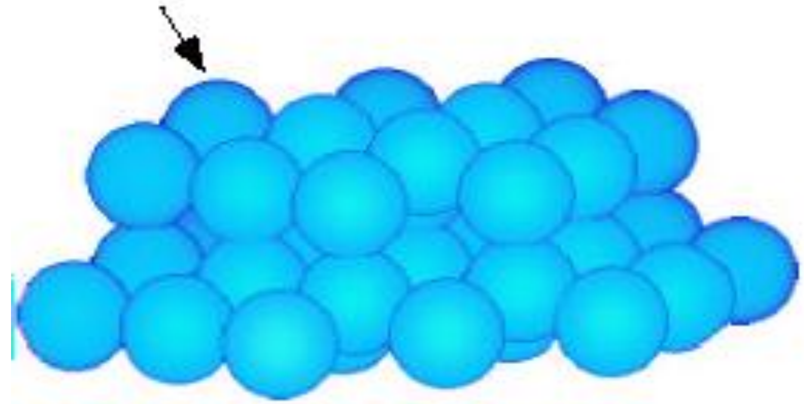
Electronic and Photonic Crystals

Periodic Medium

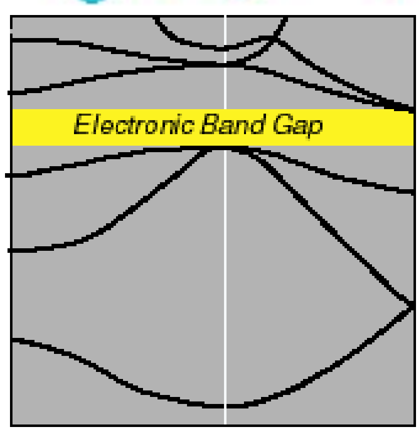
atoms in diamond structure

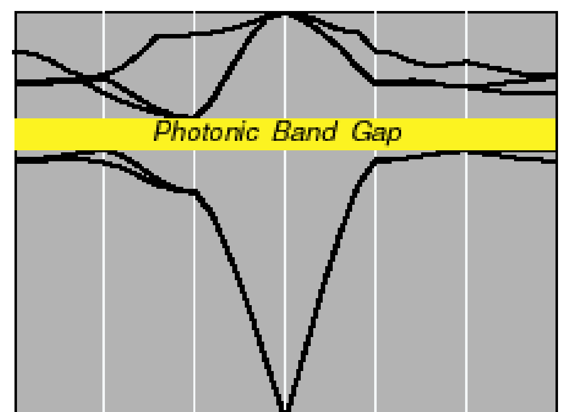


dielectric spheres, diamond lattice

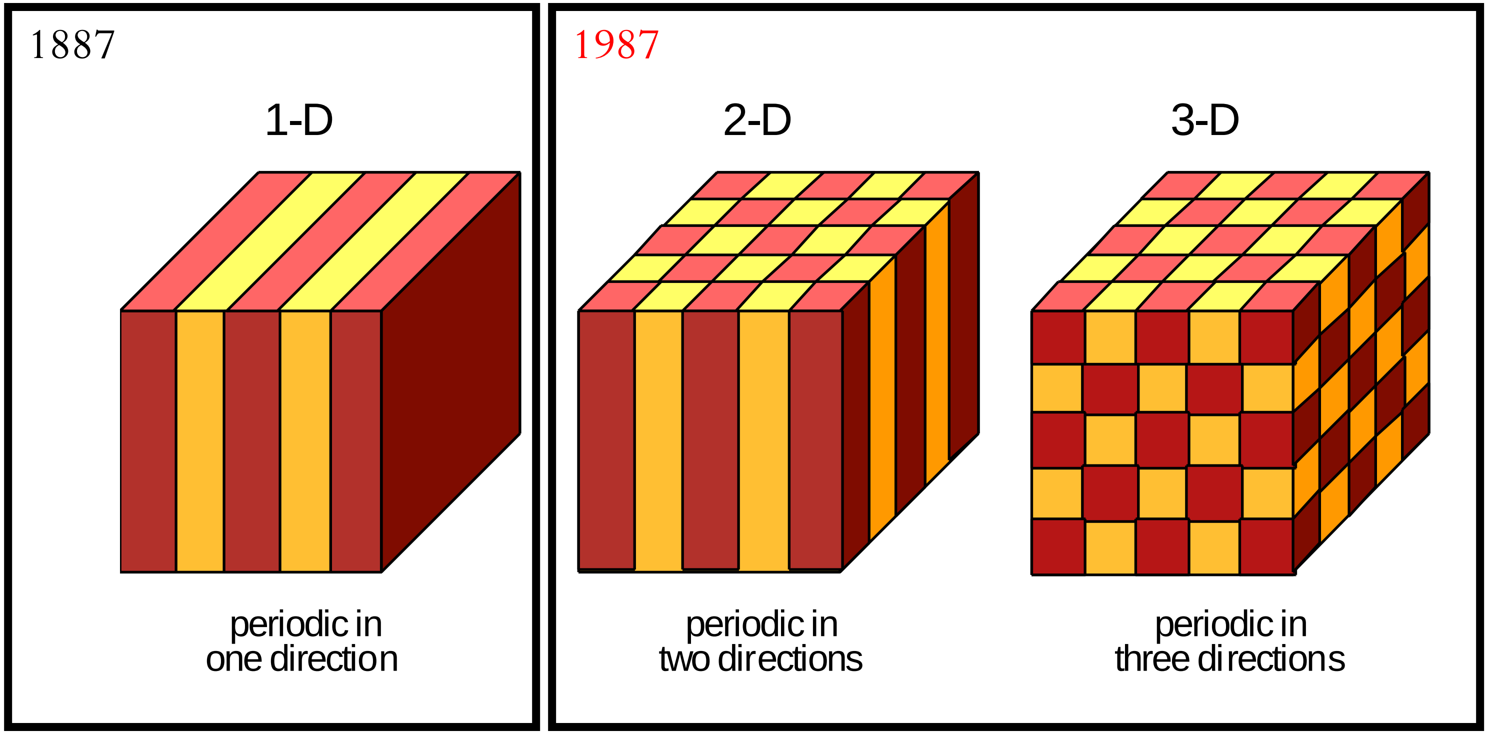


Bloch waves: Band Diagram





Photonic crystals: periodic electromagnetic media

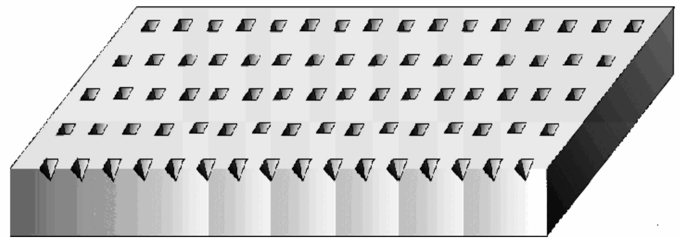


optical "insulators"

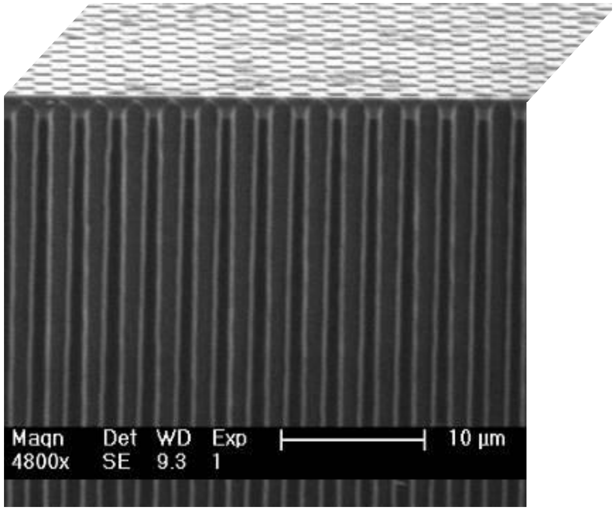
How to create photonic crystals?

- Wet etching of Silicon.

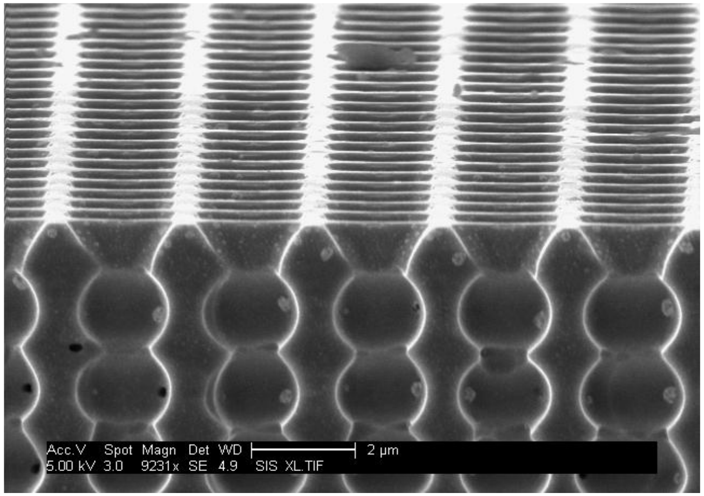
Define your substrate with lithography



2D Photonic Crystals

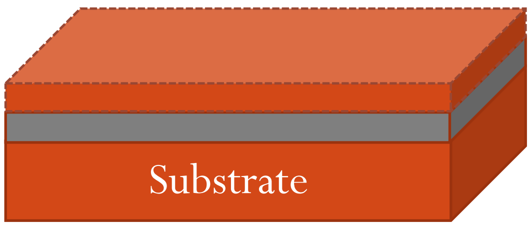


3D Photonic Crystals

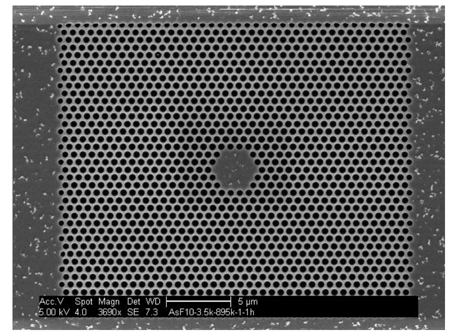


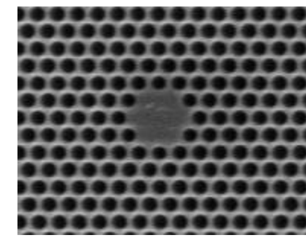
How to create photonic crystals?

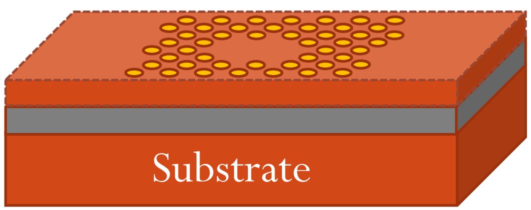
- Dry etching of Silicon.



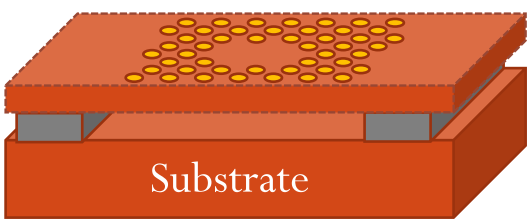
Buried oxide
Silicon on insulator:



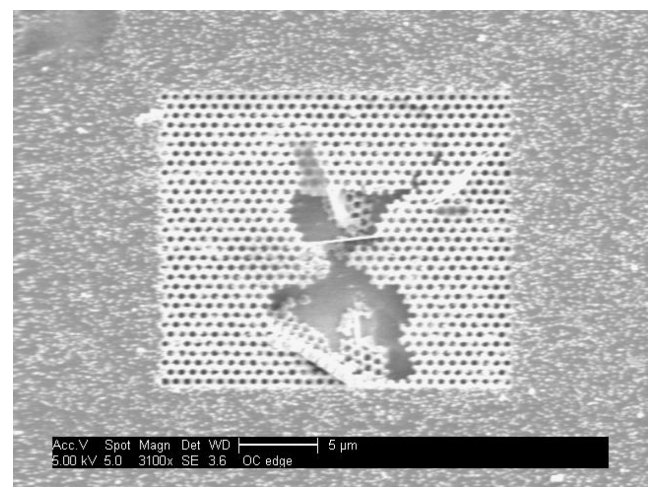




eBeam lithography
using Cr mask

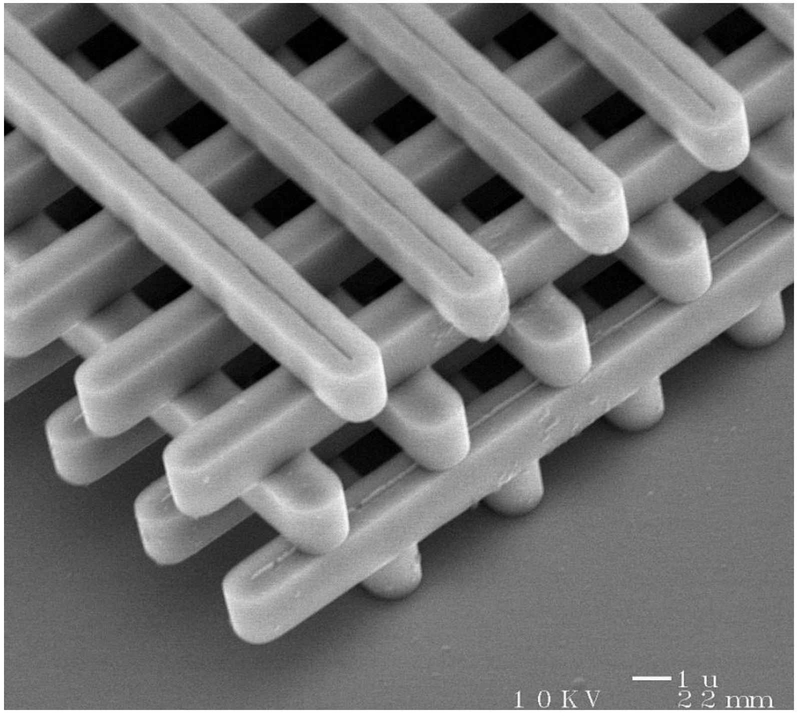


Oxide etch
using buffer oxide



How to create photonic crystals?

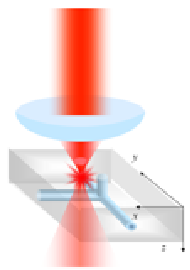
- Layer by layer deposition of amorphous materilas

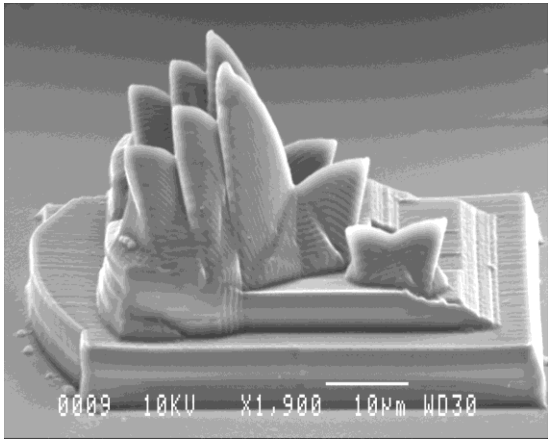


[S.Y. Lin *et al.*, *Nature* **394**, 251 (1998)]

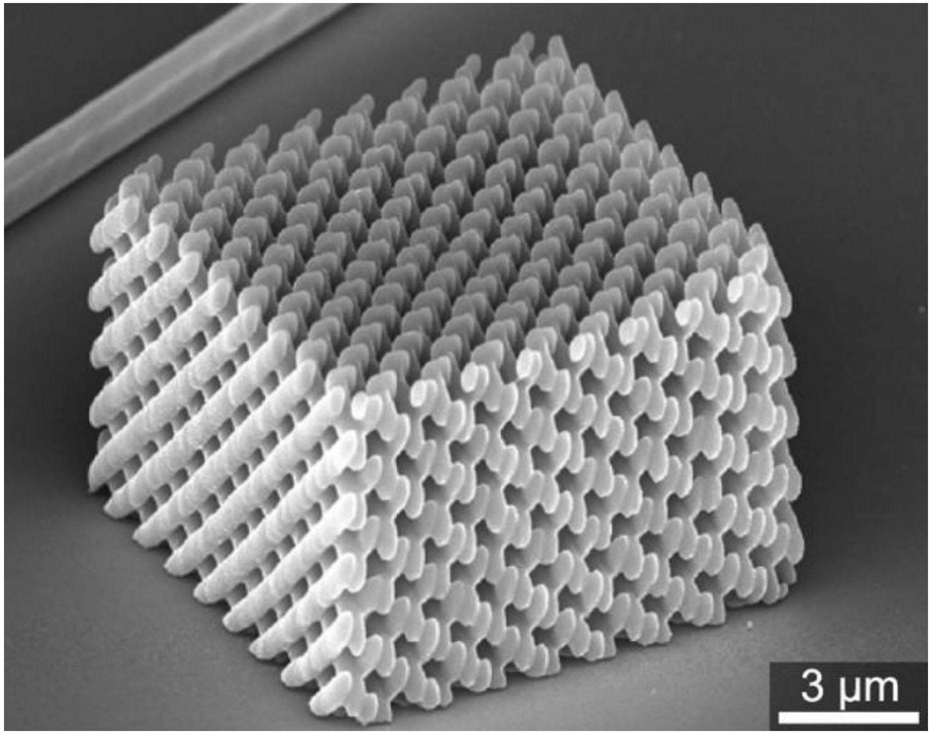
How to create photonic crystals?

- Direct laser writing and two photons absorption.





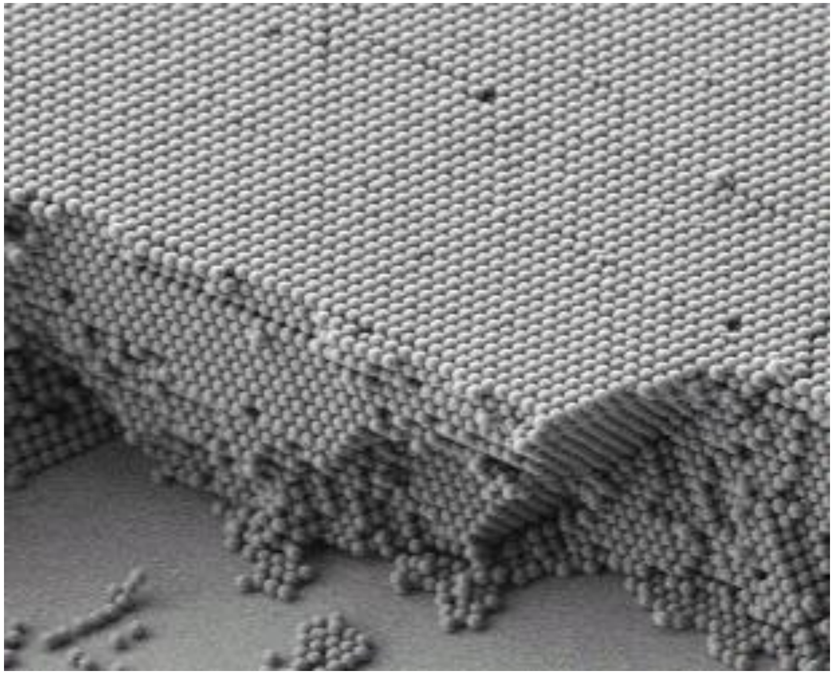
[From the group of Prof. Min Gu in Swinburne University]



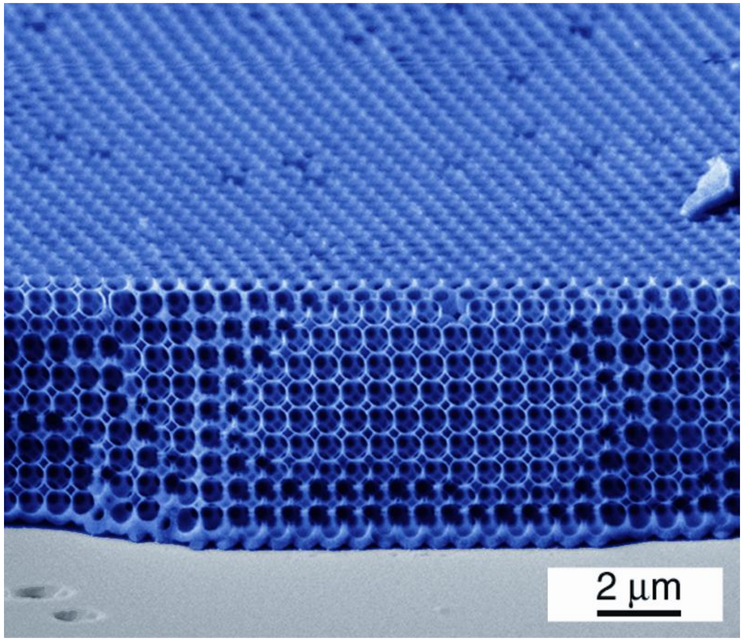
[Nanoscribe Ltd.]

How to create photonic crystals?

- Opal and inverse opal



[Colvin et al., Chem. Mater. (1999)]



[Y. A. Vlasov *et al.*, *Nature* **414**, 289 (2001)]

Maxwell's equations

$$\int \vec{E} \cdot d\vec{S} = \frac{1}{\varepsilon_0} \int \rho dV$$

$$\int \vec{B} \cdot d\vec{S} = 0$$

$$\oint \vec{E} \cdot d\vec{l} = -\int \frac{d\vec{B}}{dt} \cdot d\vec{S}$$

$$\oint \vec{B} \cdot d\vec{l} = -\mu_0 \int \vec{j} \cdot d\vec{S} + \varepsilon_0 \mu_0 \int \frac{d\vec{E}}{dt} \cdot d\vec{S}$$

Solutions:
what are the fields and their time dependence?

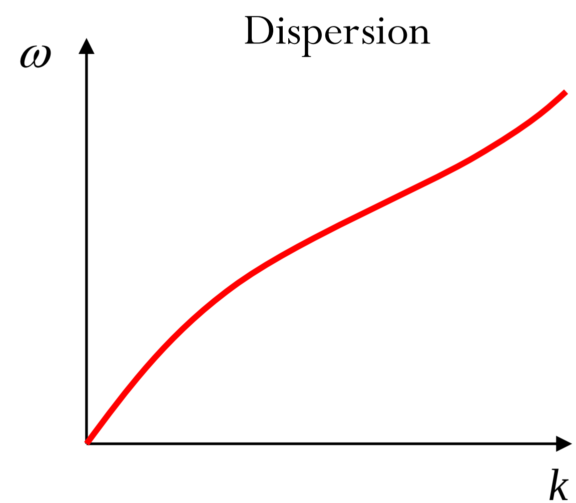
$$H(x, y, z, t) = ?$$

$$E(x, y, z, t) = ?$$

A more simple problem

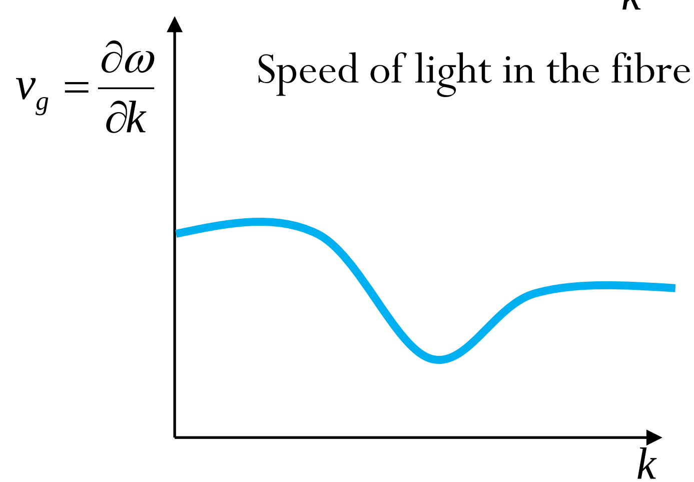
A regular optical fibre

$n_2 < n_1$



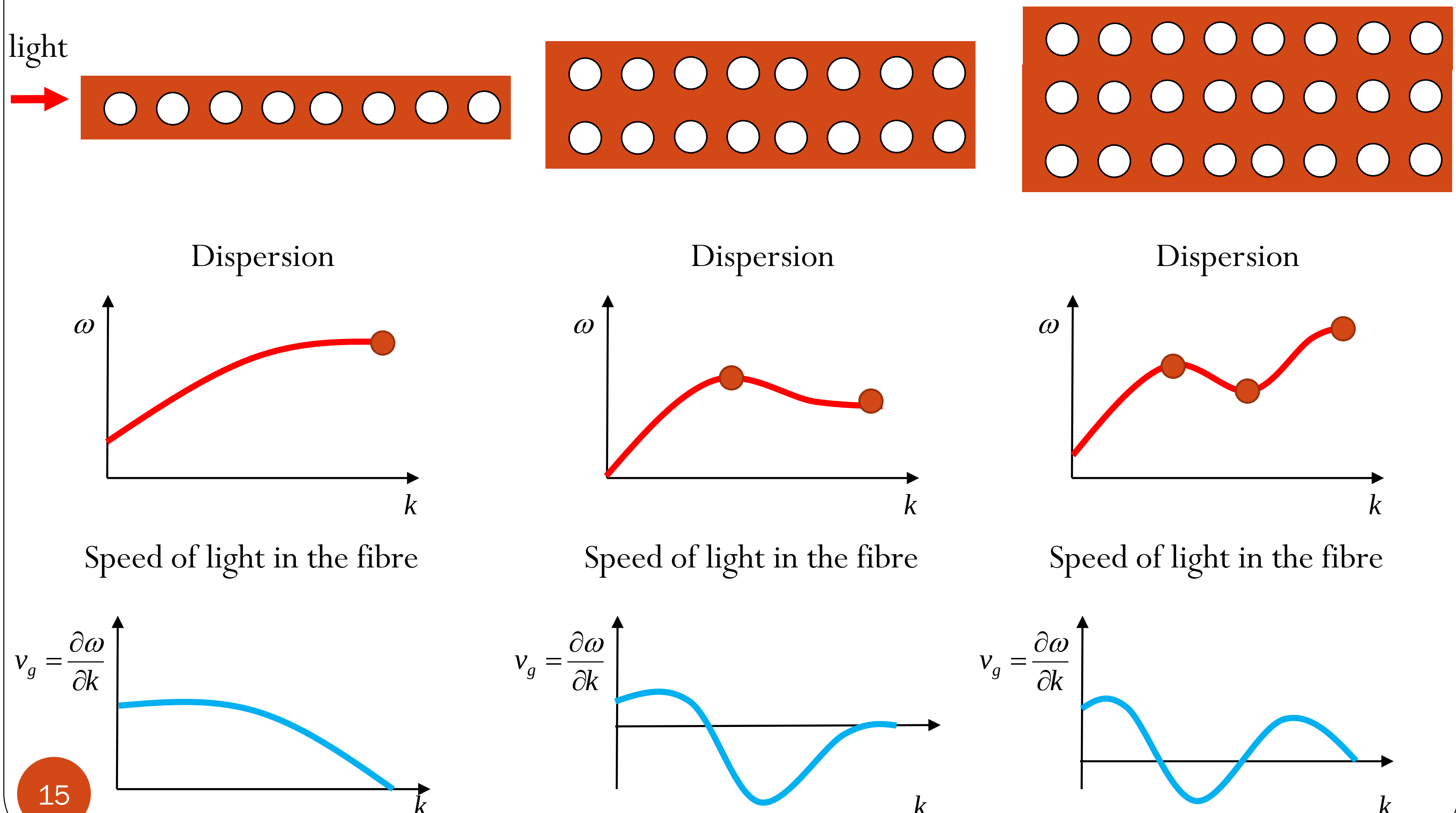
A guess "Ansatz" solution

$$\mathbf{H}(z,t) = \mathbf{H}_k e^{i(kz-\omega t)}$$



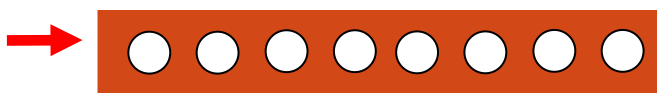
Photonic crystals: Bloch function

$$\mathbf{H}_z(z,t) = \mathbf{H}_z^k(z)\, e^{i(kz-\omega t)}$$



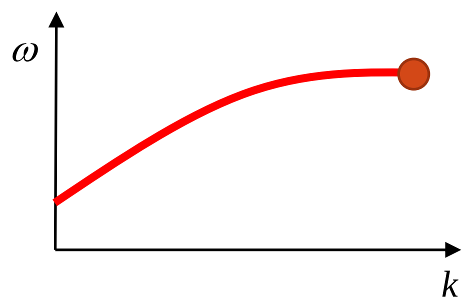
Slow light

light



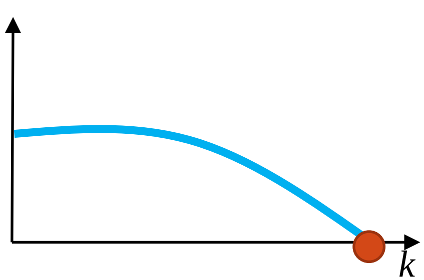
Quadratic band edge: $\omega \propto k^2$

Dispersion

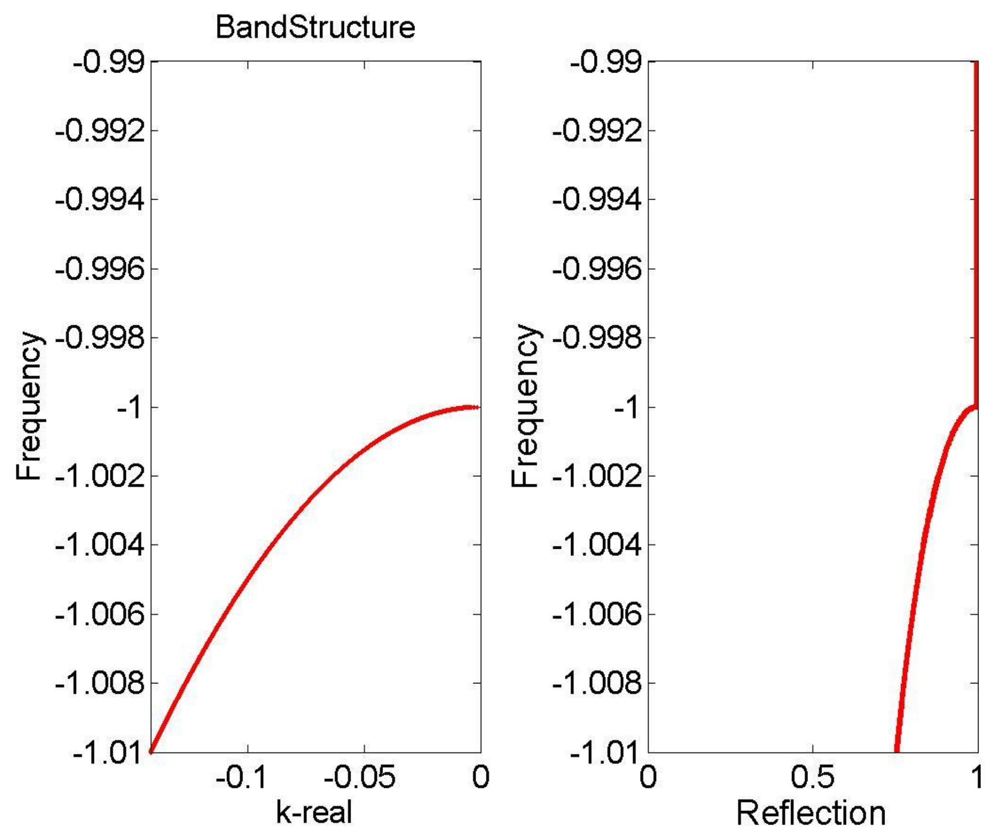


Speed of light in the fibre

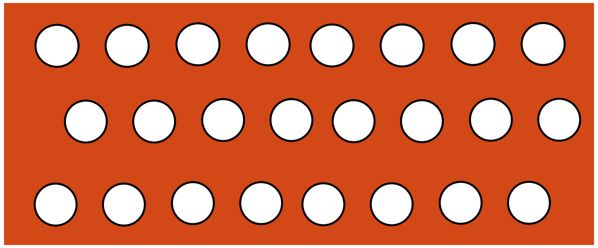
$v_g = \frac{\partial \omega}{\partial k}$



All the light is reflected back at the zero group velocity point



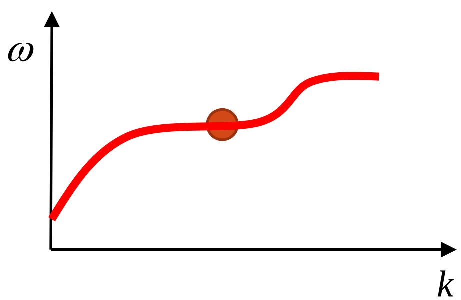
Inflection points-Frozen light



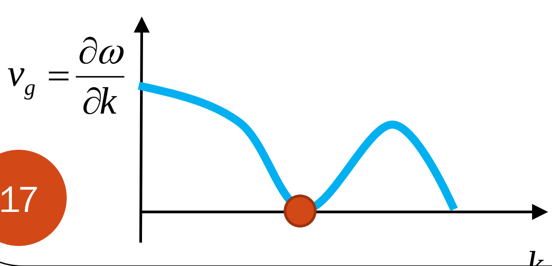
Most of the light is coupled to a light with zero group velocity-zero speed.

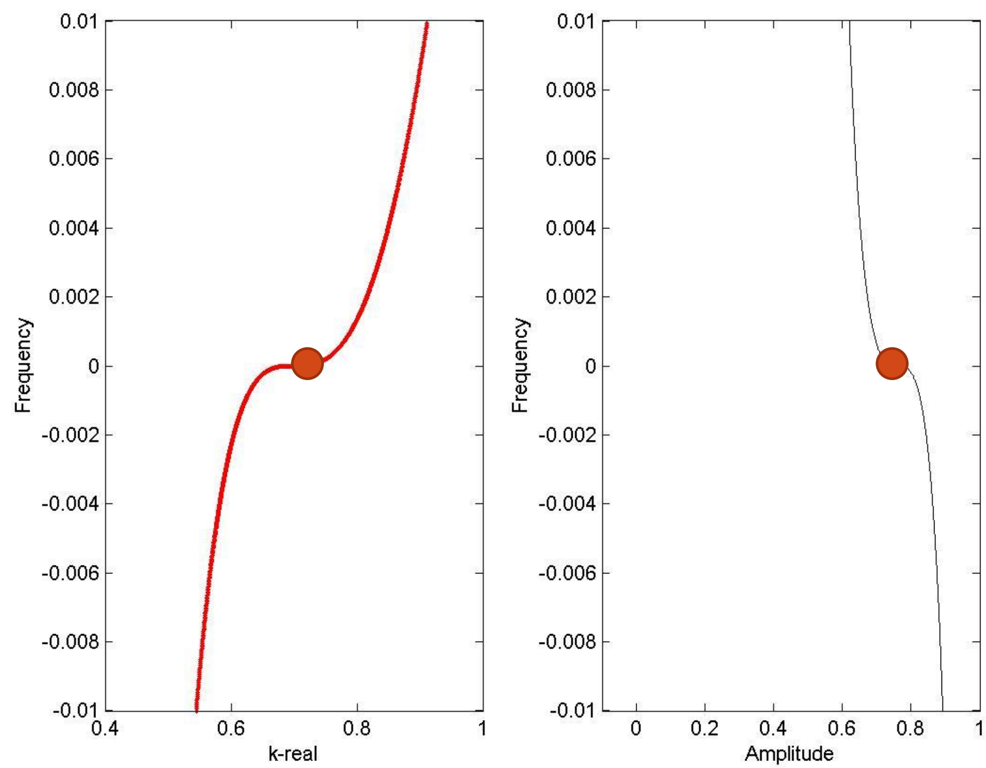
Cubic infliction point: $\omega \propto k^3$

Dispersion



Speed of light in the fibre

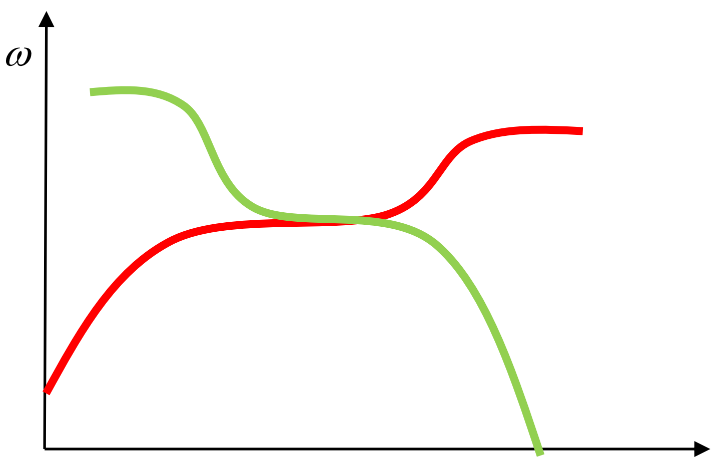




The reason for frozen light.

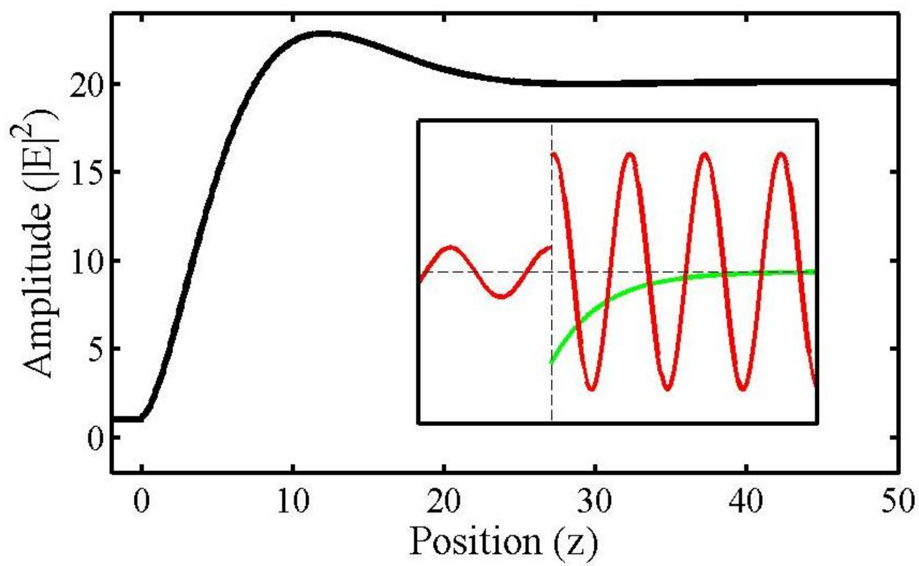
Complex dispersion

The field inside the frozen light waveguide is composed of two waves: one propagating and one decay



k-real

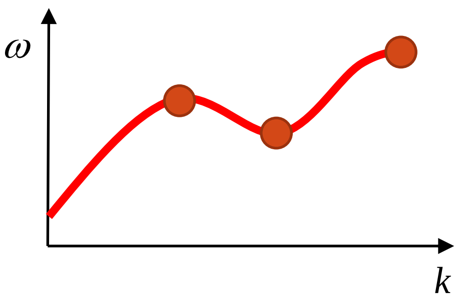
k-imaginary

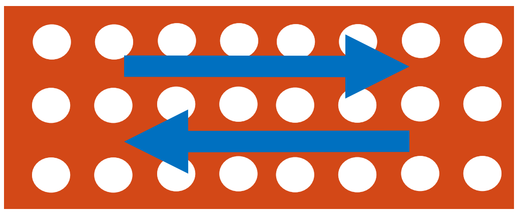


The nature of frozen light

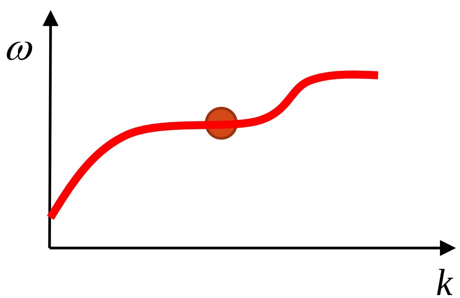
- **Vortices in periodic waveguides**

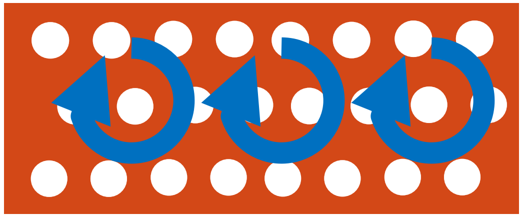
Dispersion

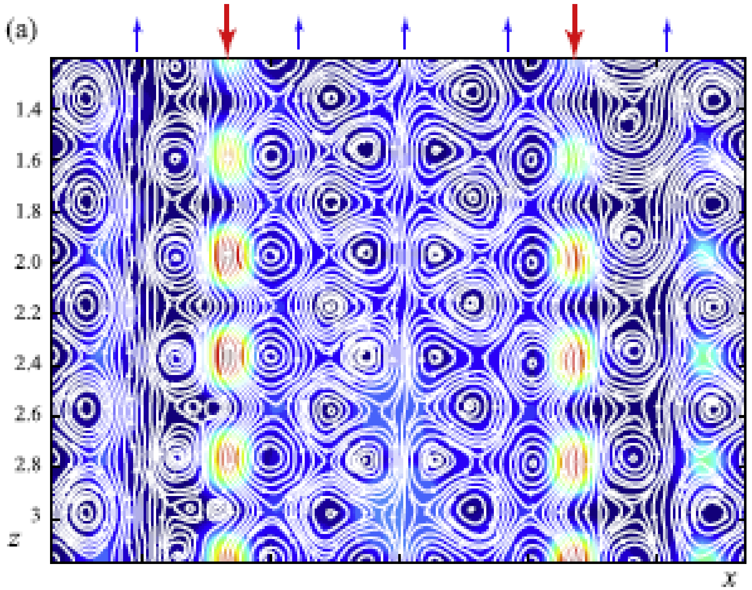




Dispersion







[A.A. Sukhorukov J. Opt. A: Pure Appl. Opt. 11 (2009) 094016]

k

How to solve the equations?

- Eigen values problem of the master equations

$$\nabla \times \frac{1}{\varepsilon(x,y,z)} \nabla \times \vec{H}(x,y,z,t) = \frac{1}{c^2} \frac{\partial^2 \vec{H}(x,y,z,t)}{\partial t^2}$$

- Solving for a single frequency

$$\vec{H}(x,y,z,\omega_o)$$

- Using perturbation theory we find the solution close to the given frequency.

$$\vec{H}(x,y,z,\omega_o) + \Delta\vec{H}(x,y,z,\omega_o)$$