Presented at the COMSOL Conference 2010 India

Engineering Light

Photonics, Plasmonics and Meta-materials

Anil Prabhakar

Experimental Optics Group
Dept. of Elec. Engg.,
IIT-Madras

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At IIT-Madras

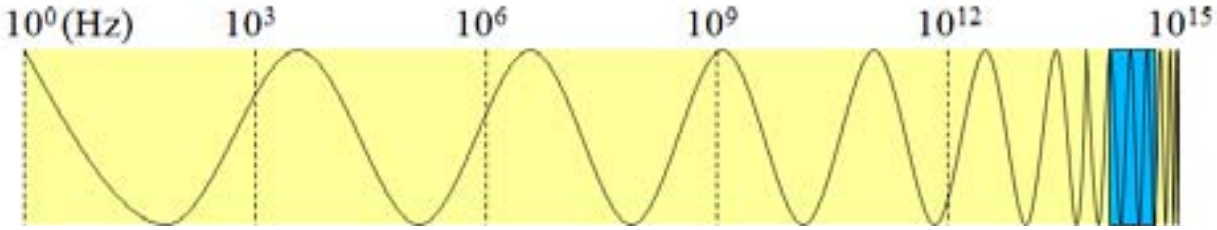
Capabilities

- Optoelectronics (pulsed current drivers, detection systems)
- Telecommunications - Fibre optics
- Metrology - instruments, sensors, lasers

People

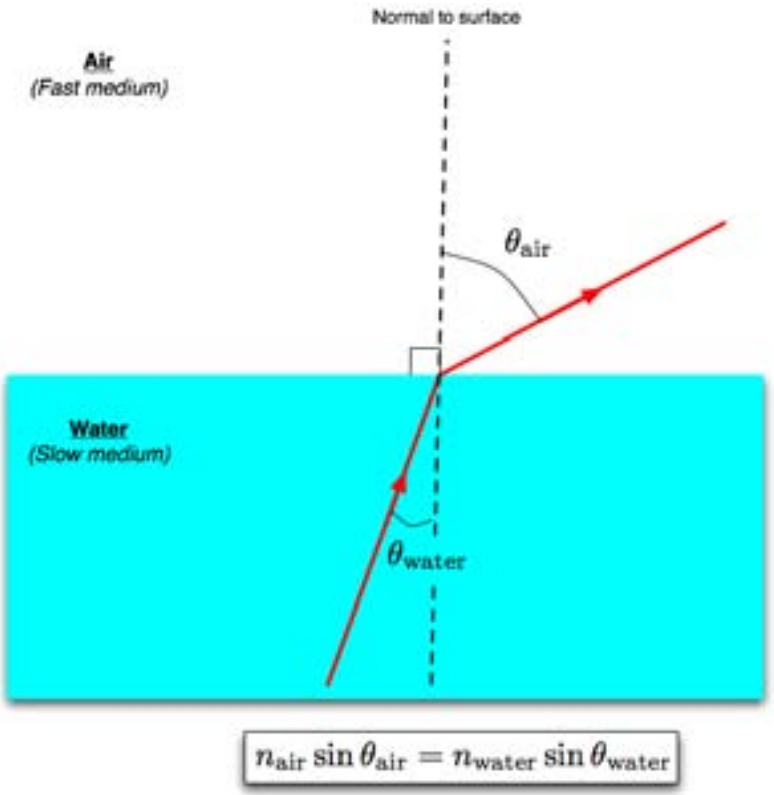
- 8 faculty in EE, 13 in IIT-M
- 15+ students
- 15+ project staff
- Active collaborations in lots and lots of projects

Electromagnetics

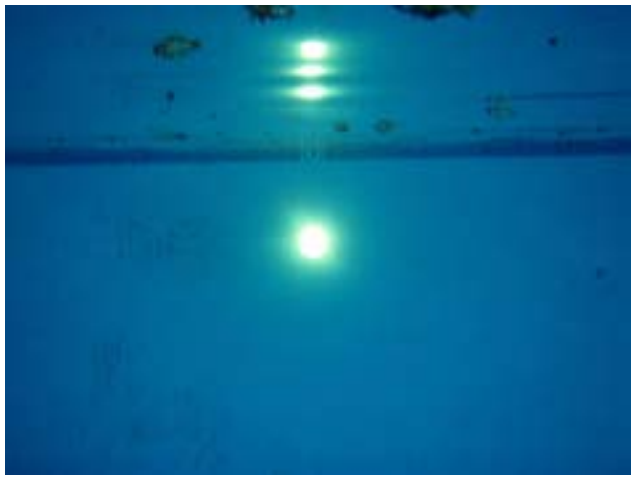


- Lots of room in the electromagnetic spectrum
  - Nd:YAG ($1.06\,\mu$m) is very popular
  - Infra-red ($1.55\,\mu$m)is the choice for telecommunications
  - Tm:YAG ($2.0\,\mu$m) is eye-safe for LIDAR
  - Er:YAG ($2.94\,\mu$m) is good for dentistry
- Visible optics is our first introduction
  - Why is the sky blue?
  - Snell's law: Reflection and Refraction
  - Glass prizm: Colors of the rainbow

Refraction

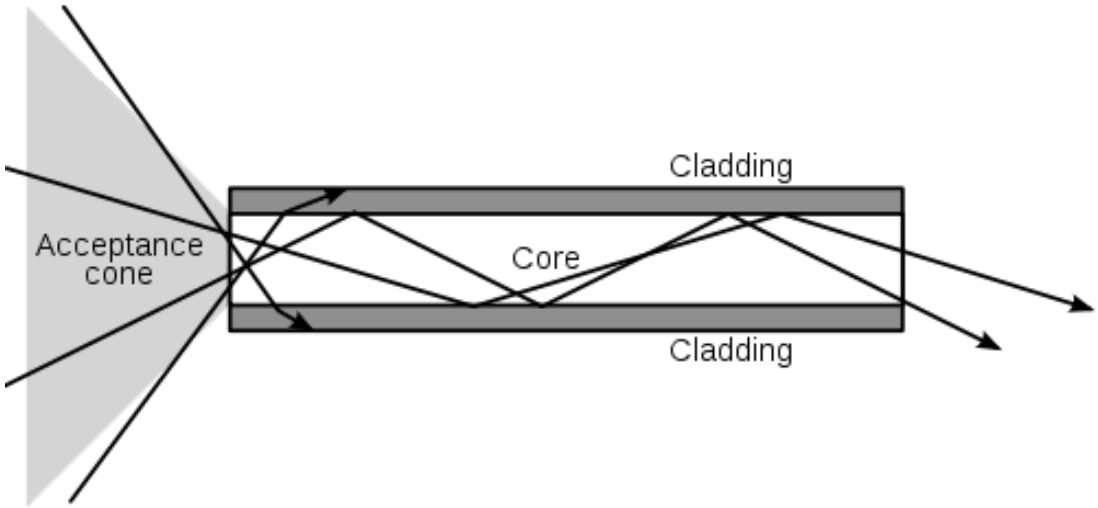


Total internal reflection in a swimming pool



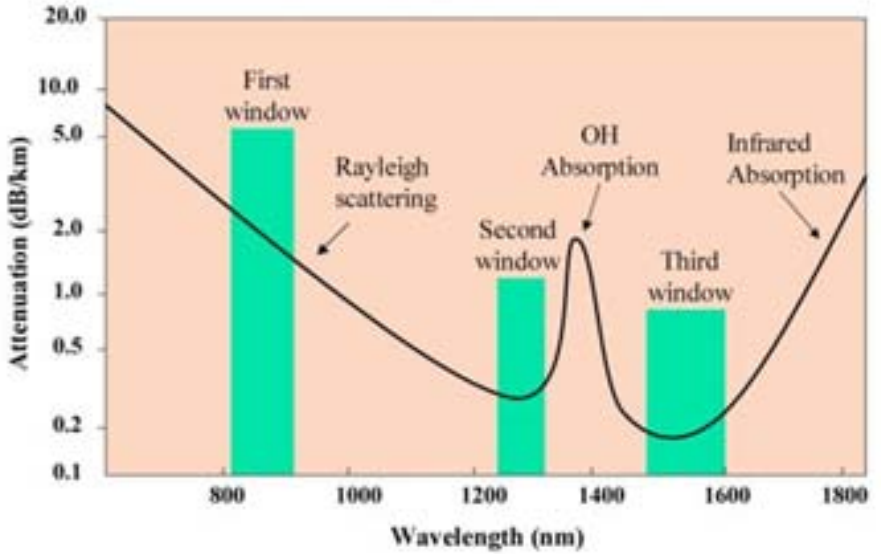
- Light bends when it goes from one medium to another
- Snell's law relates angles of incidence and transmission
- Critical angle beyond which we have total internal reflection

Fibre Optics



- High refractive index core
- Low refractive index cladding
- Light is guided along by total internal reflection
- Cone angle of acceptance to couple light into the fibre
  - Apply Snell's law at the input air-core interface
  - Require incidence at critical angle at core-clad interface

Telecommunications

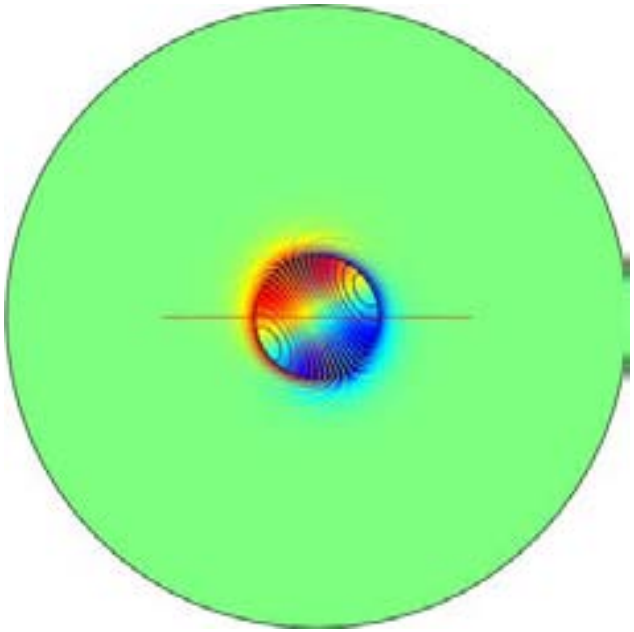


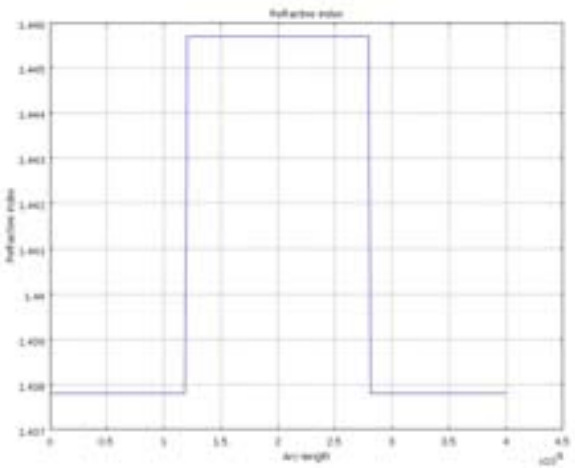
- Rayleigh scattering causes attenuation (loss)
  - Why is the sky blue, but red at sunrise or sunset?
- Pure silica has low loss in the infra-red
- Kao shares the Physics Nobel Prize in 2009

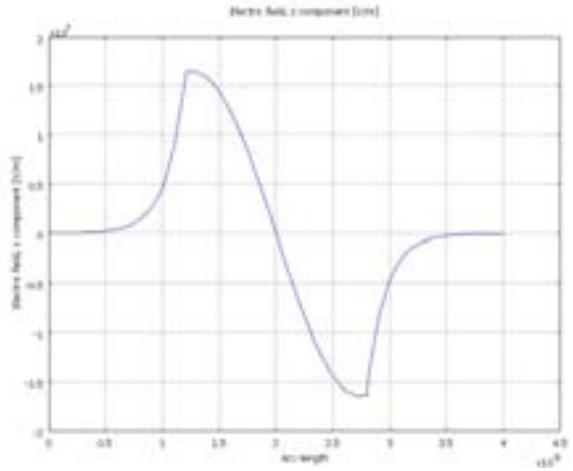
Fibre Deployment

Early Reliance network.
Redundancy and Aggregation.

Cross-section of an optical fibre

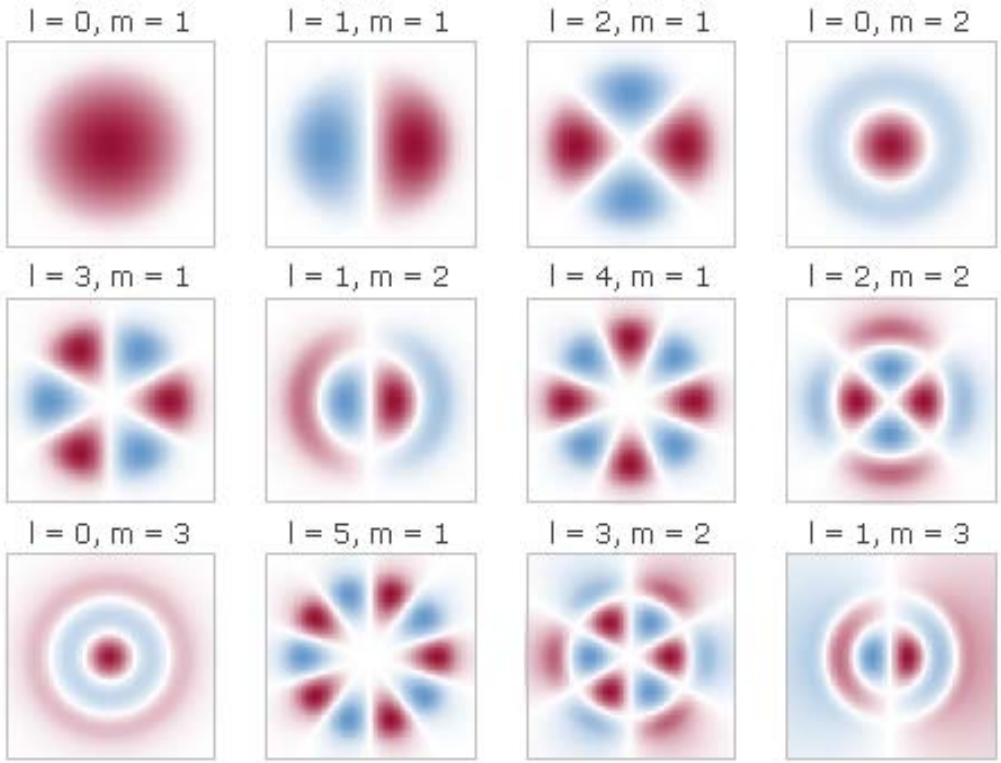






- Comsol model library - step index fibre
- Aspect ratio - 100 μm versus 100 km
- Idealized system - invariant along the length of the fibre

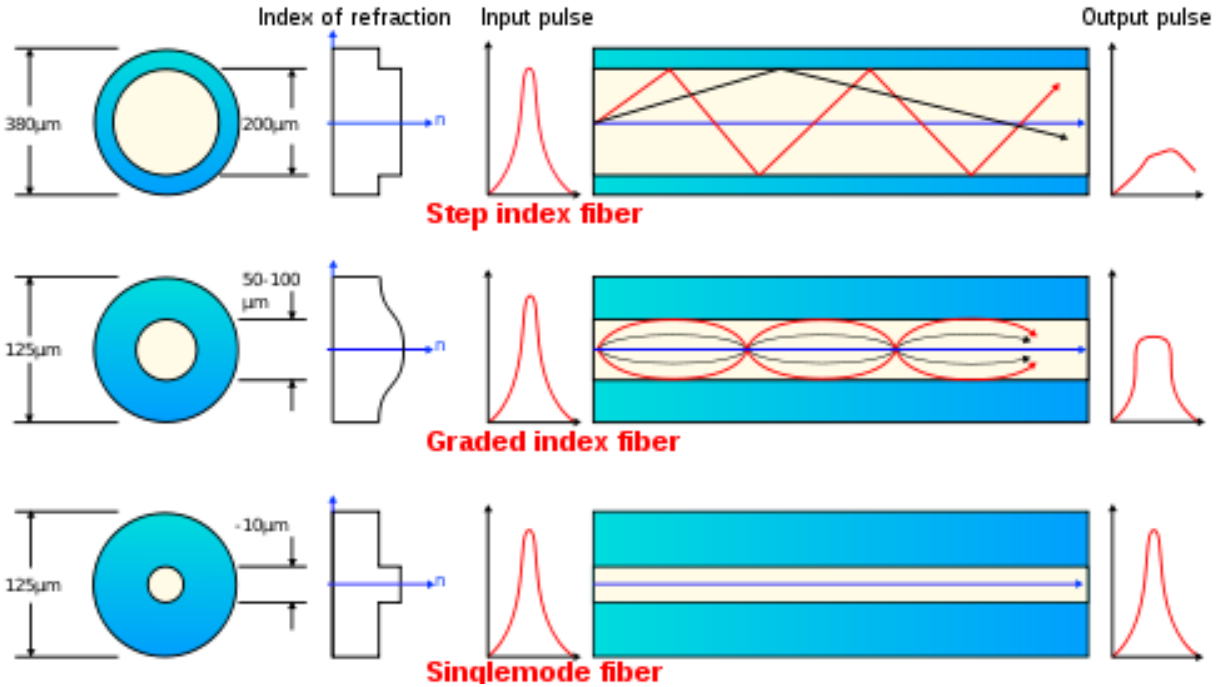
Propagation modes



- Think now of the surface of a drum - transverse modes
- Optical intensity in a multi-mode fibre is not uniform

Images:RP Photonics

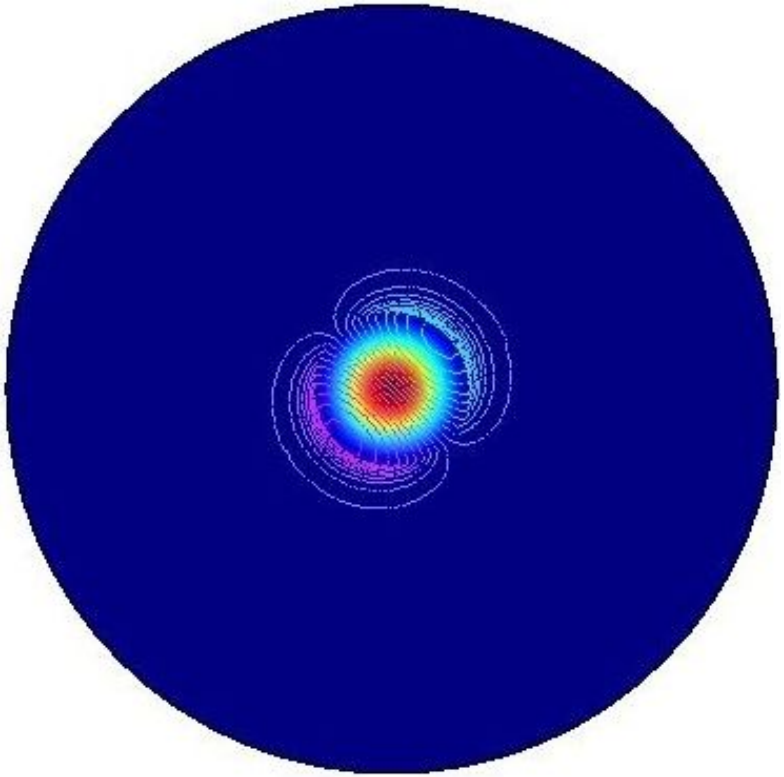
Types of Optical Fibres

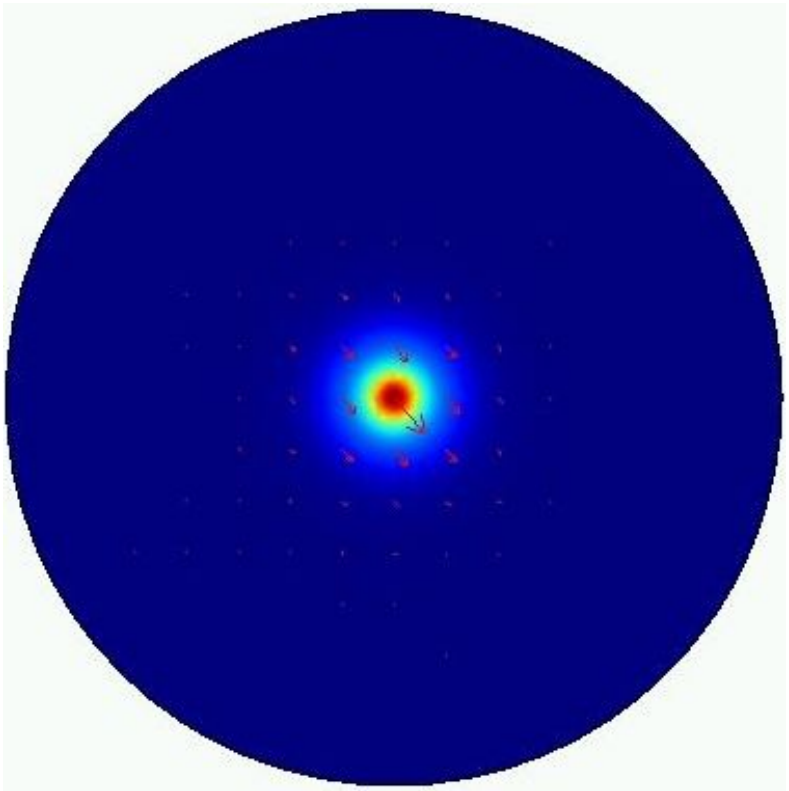


- Different modes travel different distances (ray diagram)
- Telecommunication uses single mode fibres
- Multimode fibres used in imaging have dispersion

Images: wikipedia

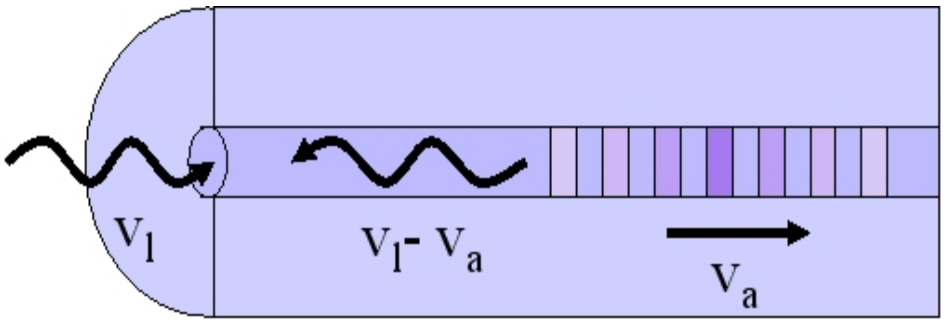
Eigenmode Analysis

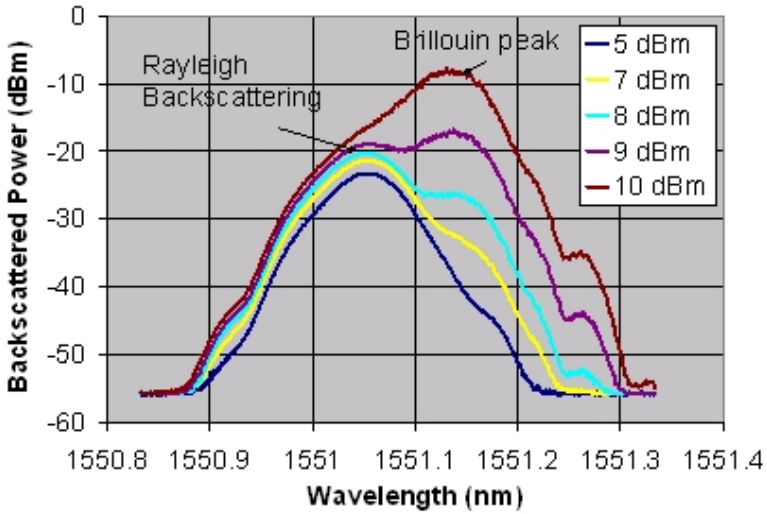




- Graded index: $n_1 = 1.455 + 0.005e^{-(r/5)^{12}}$
- Annular index:
  $n = n_1 + .002 \tanh[10(r-6)] - \tanh[10(r-8)]$
- Retain the basic optical mode shape

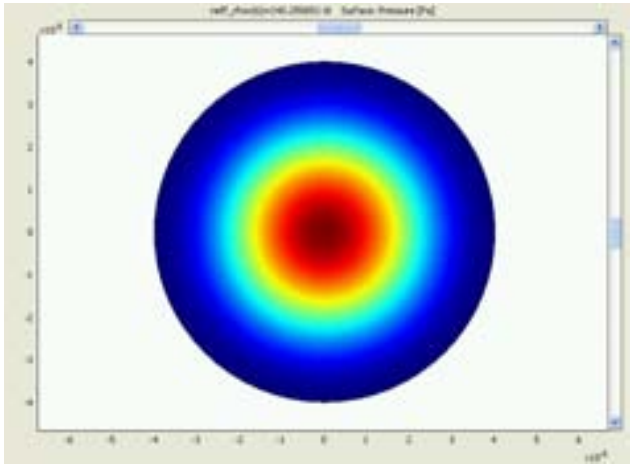
Brillouin Scattering

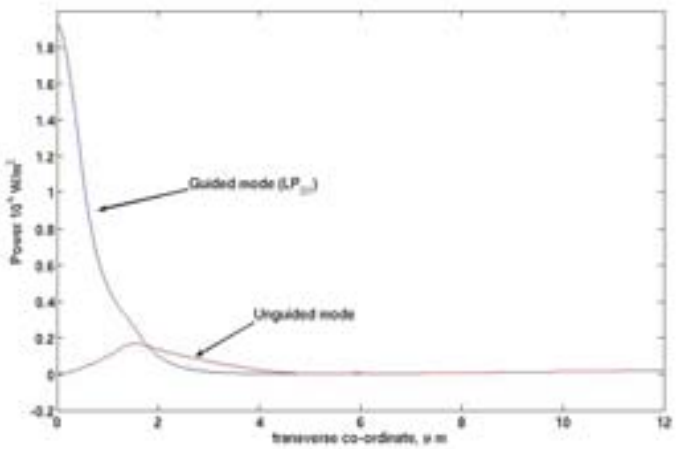


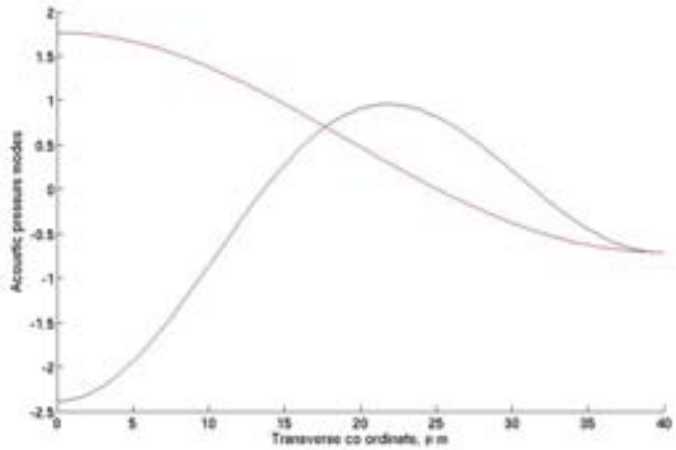


- Energy transferred from photons to phonons
- Doppler effect: Reflected power is shifted to a lower frequency
- Want to minimize acoustic waves ... multiphysics modelling

Acoustic Mode

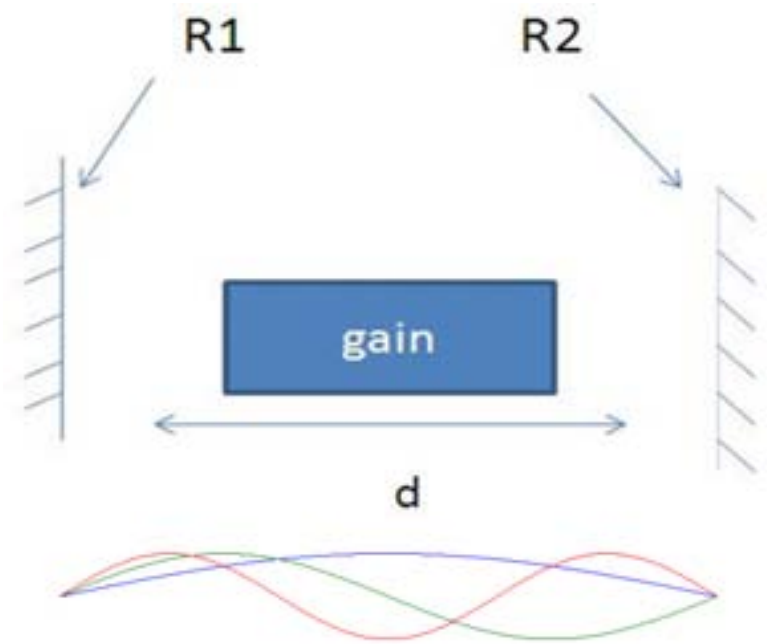






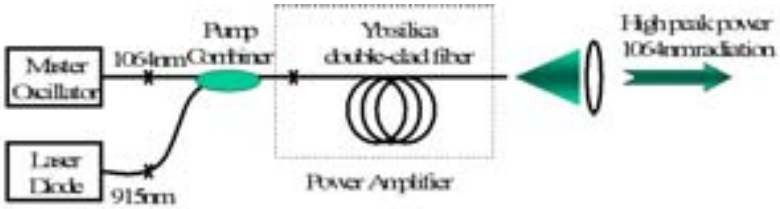
- Acoustic modes also depend on refractive index
- Optimize $n(r)$ to minimize coupling between photons and phonons.

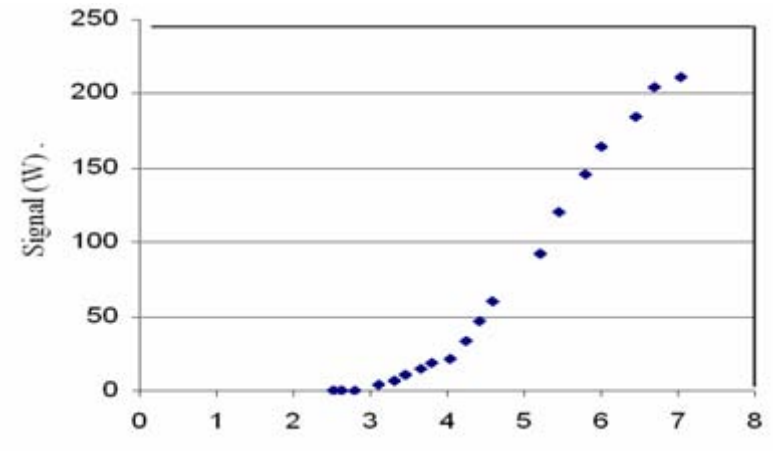
Laser cavity



- Gain medium between two reflecting surfaces
- Longitudinal modes in the cavity

High power fibre laser



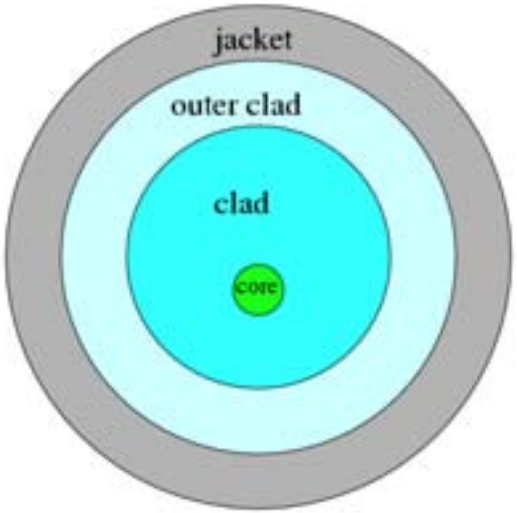


- 10's of watts of continuous power, kW's of pulsed power
- Fibre lasers to replace Nd-YAG lasers in all industrial/defense applications.

Double Clad Fibres

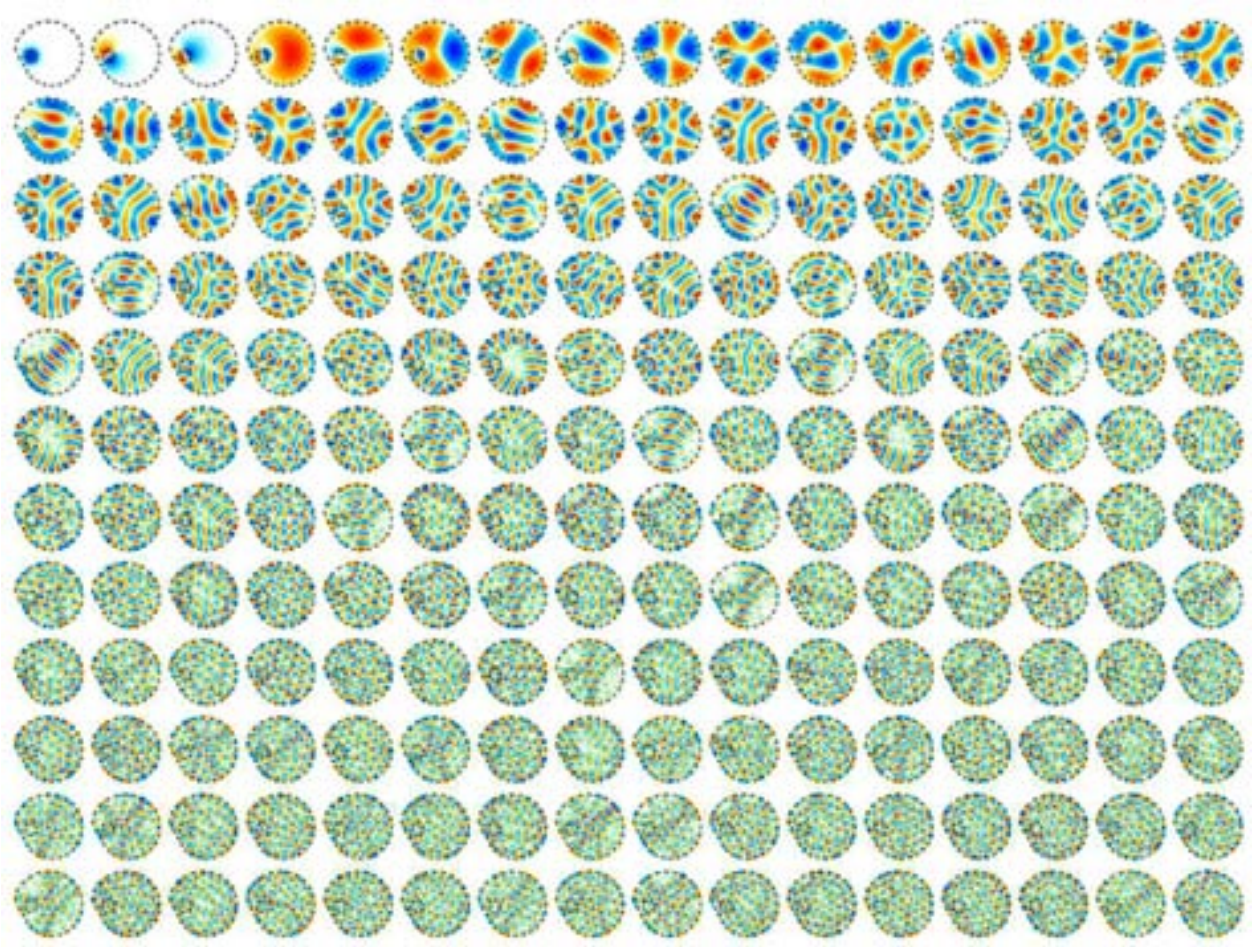
Why are fibre lasers efficient?

- Take the glass rod and stretch it
- Same volume of gain medium, more surface area
- Pump it from the side, along the fibre length
- No dust particles.
- Beam quality is very good.



Notice that the core is not at the centre

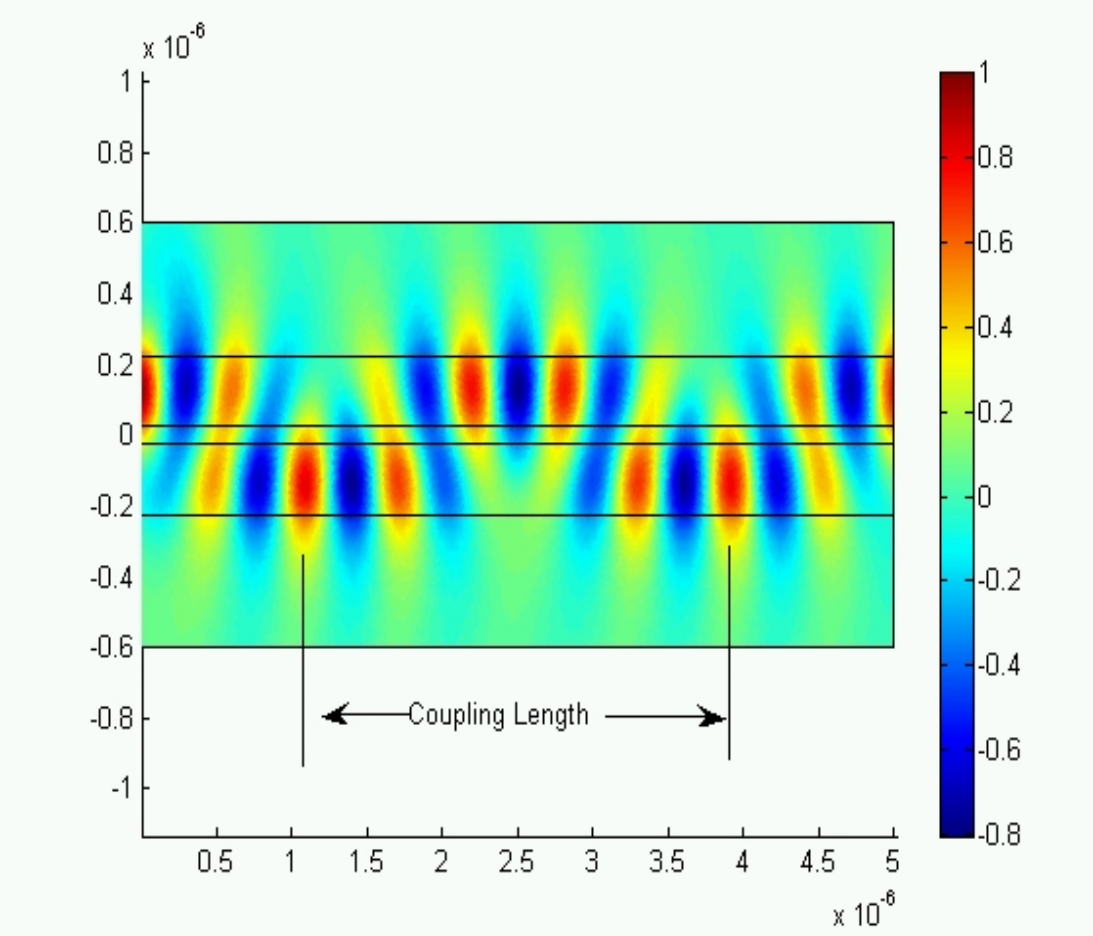
Modes in Double Clad Fibres



Off-centre core allows better pumping of the gain medium

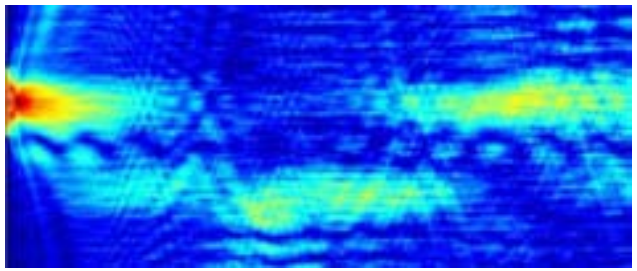
Kouznetsov, D.; Moloney, J.V. (JOSA B, 2003)

Coupled Mode Theory

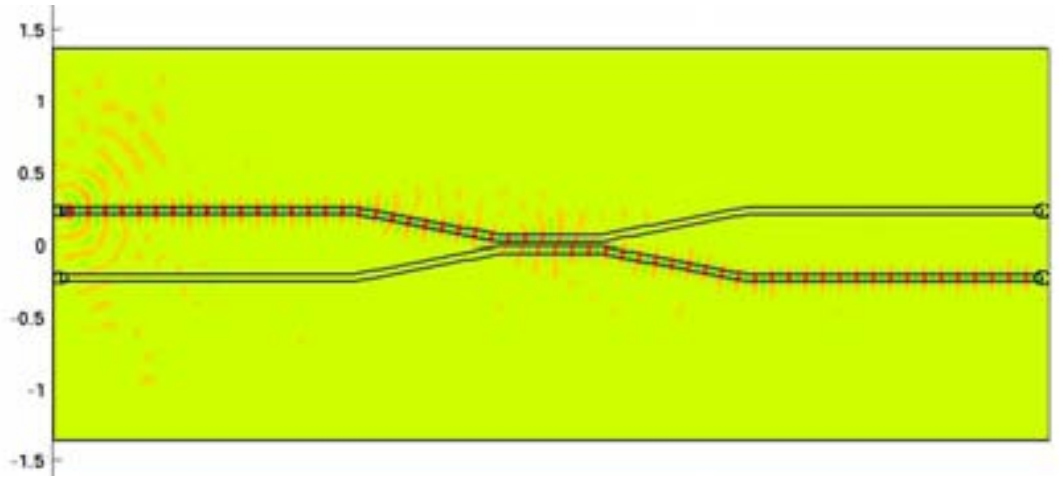


Non-reflecting (NR) boundaries allow us to solve a smaller problem.

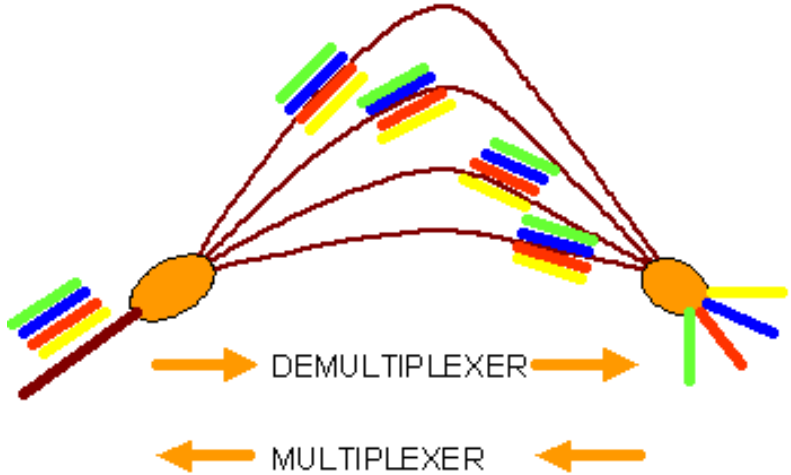
- Tail of the wave in one waveguide leaks into another
- Degenerate waveguides
  $A(z) = \cos(\kappa z)$
  $B(z) = -j \sin(\kappa z)$
- Vary device length to get desired power transfer



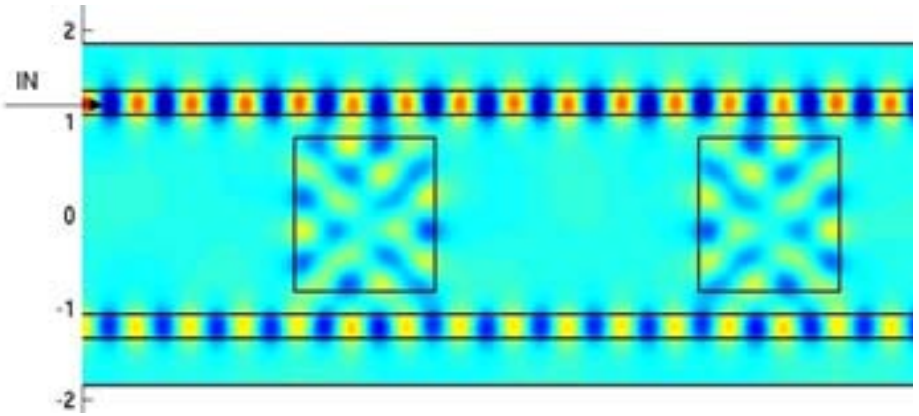
Directional Coupler

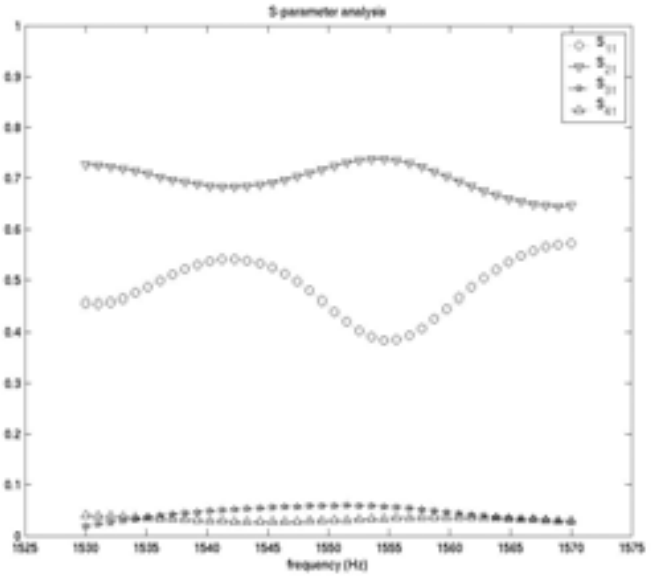


Imagine routing different wavelengths to different cities!!



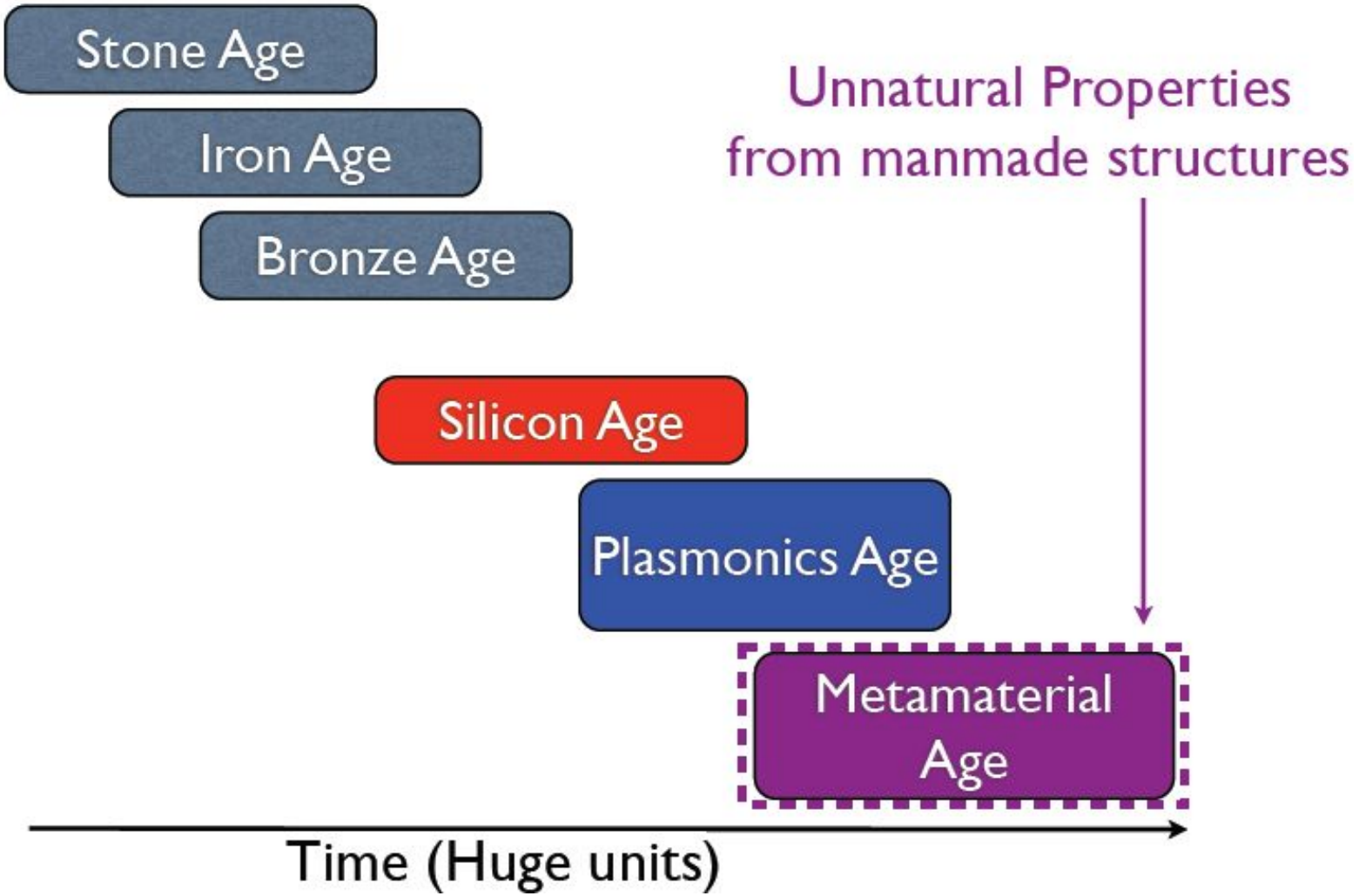
Optical Add-Drop Multiplexer (OADM)



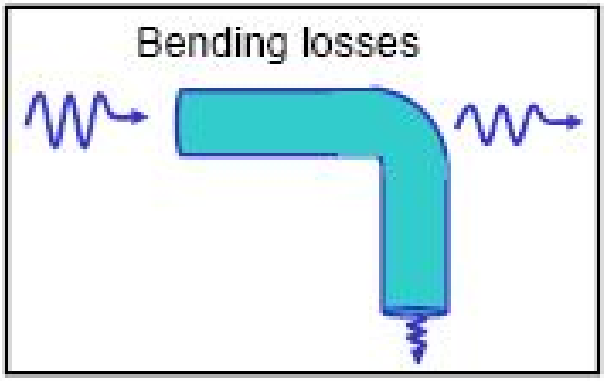


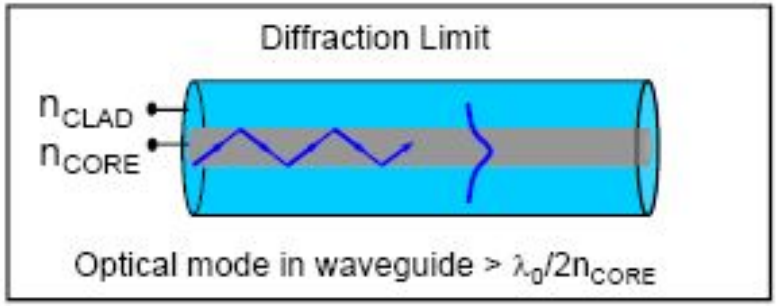
- Resonant structures improve efficiency.
- Transmission characteristics depend on frequency.
- Needs less than $1\,\mu$m lithography.

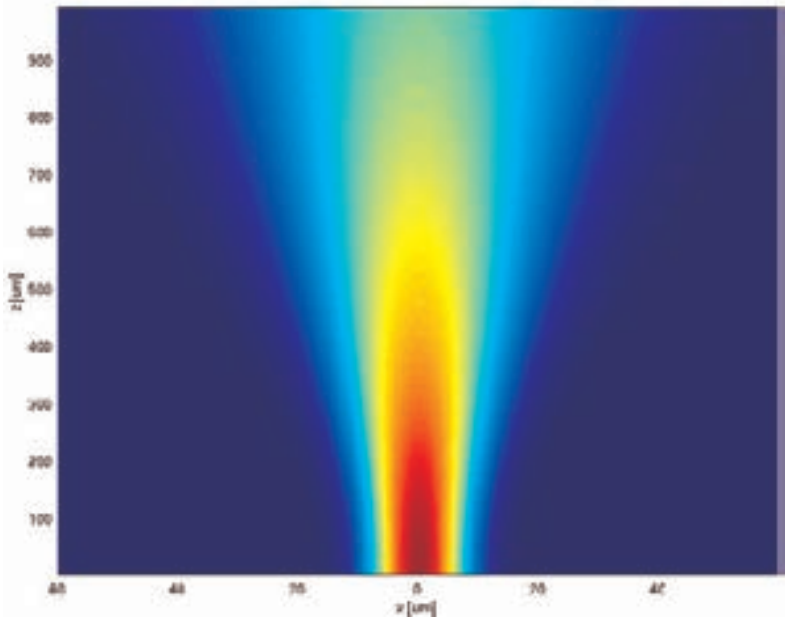
Material - Civilization



Problems with dielectric materials



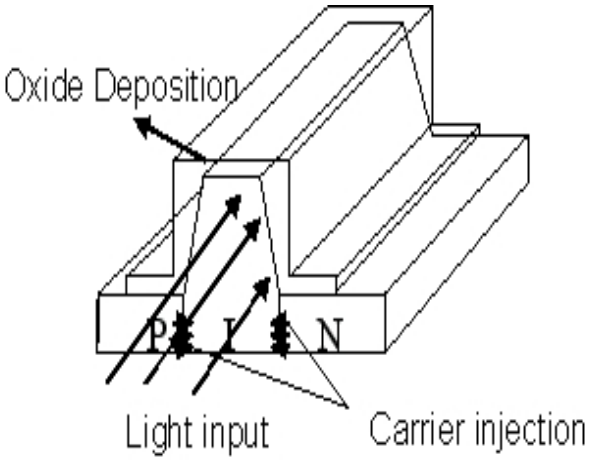


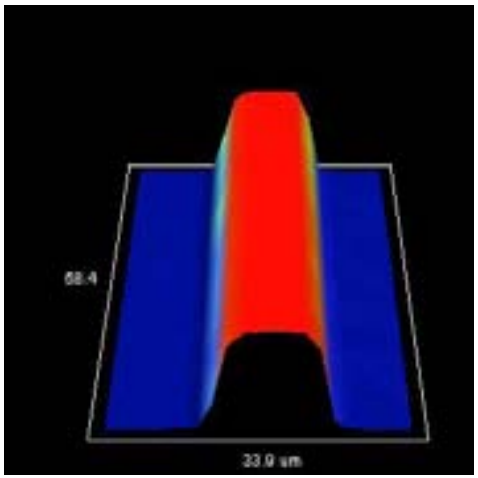


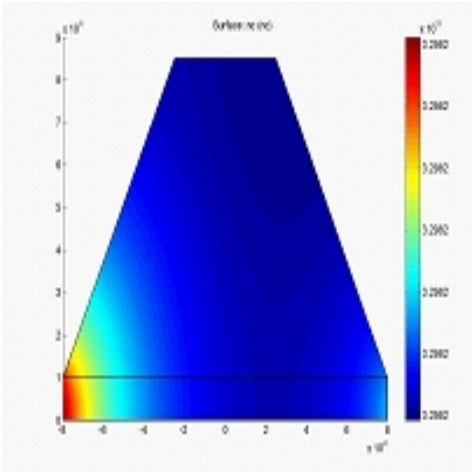
- High speed, high bandwidth
- Do not integrate well with Silicon

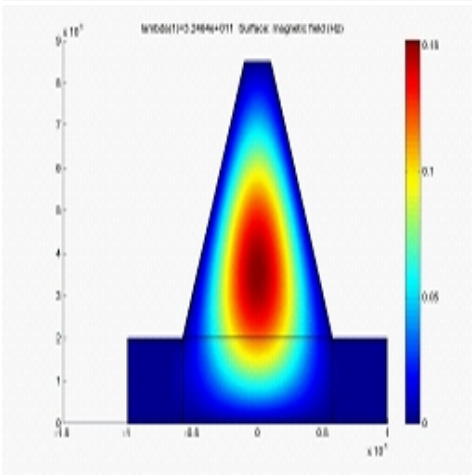
Silicon Optics - Multiphysics

- Corporate champion - Intel
- Variable optical attenuators and phase modulators



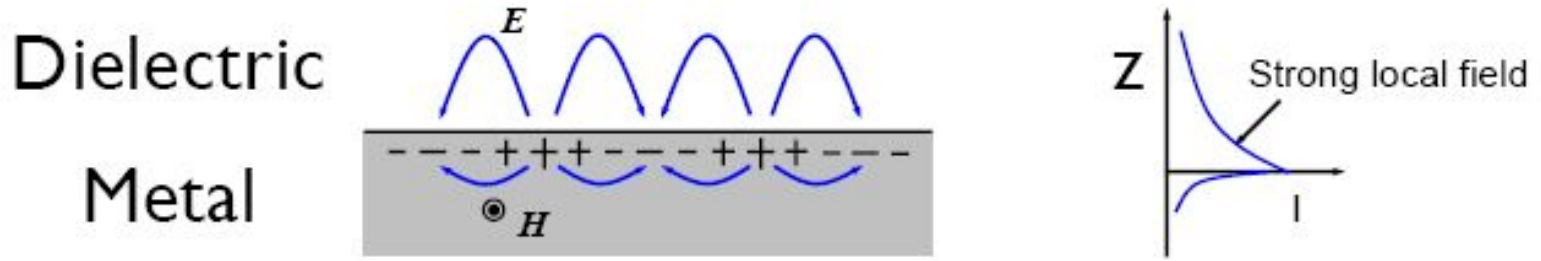




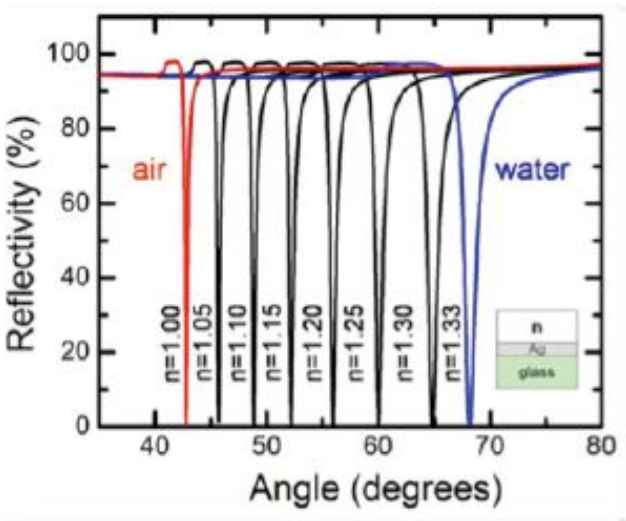


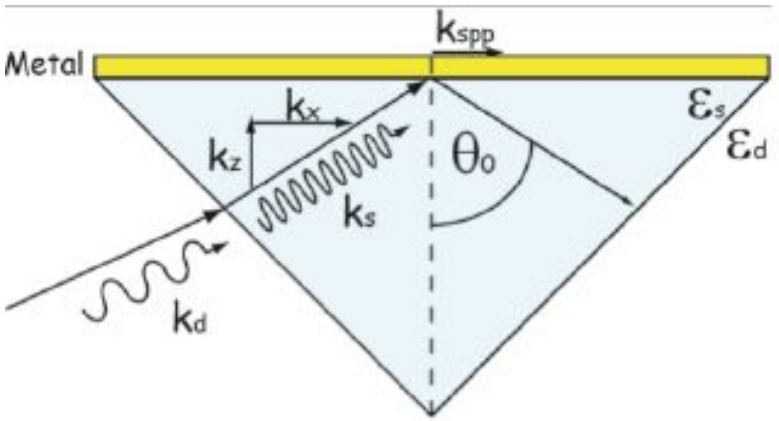
- Minimum ridge height for electronic control
- Maximum ridge height for optical confinement

Surface Plasmons

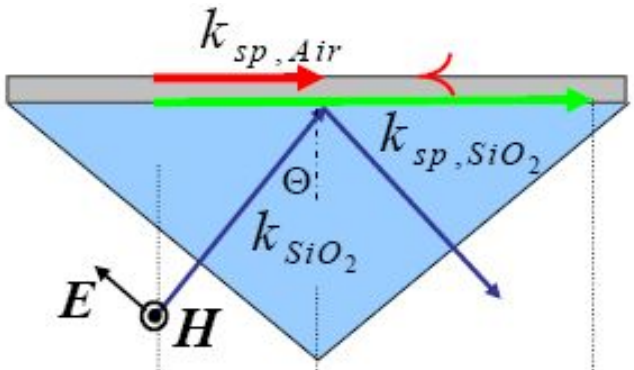


- Electron charge distribution at the metal-dielectric interface
- Strongly localized electric field

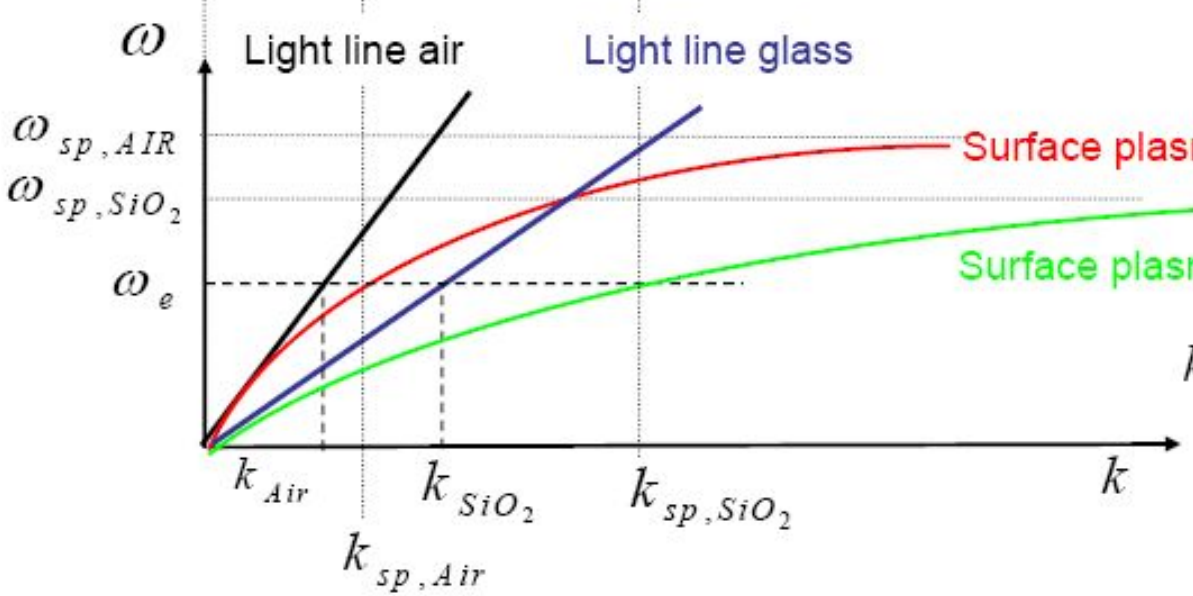




Kretchman Geometry

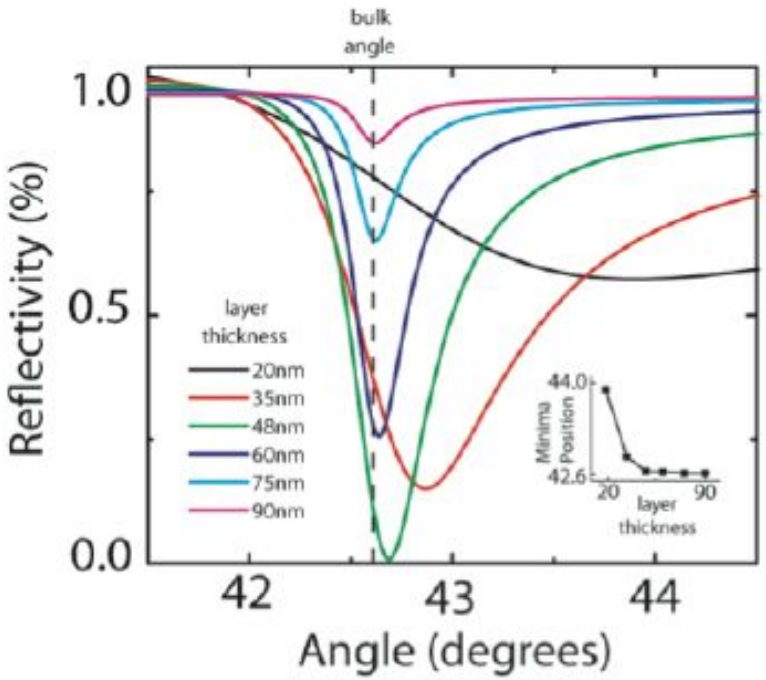


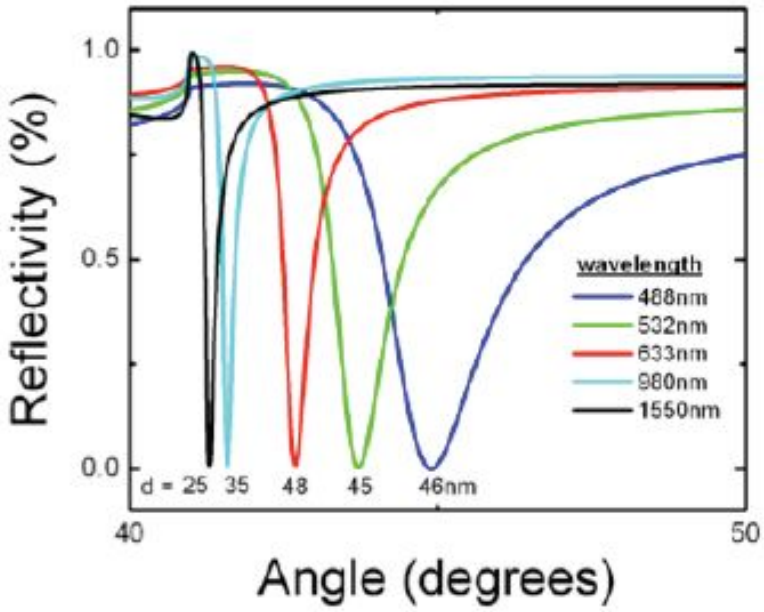
- Makes use of SiO_2 prism
- Enables excitation surface plasmons at the Air/Metal interface
- Surface plasmons at the metal/glass interface can not be excited!



$$k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$$

Metal thickness

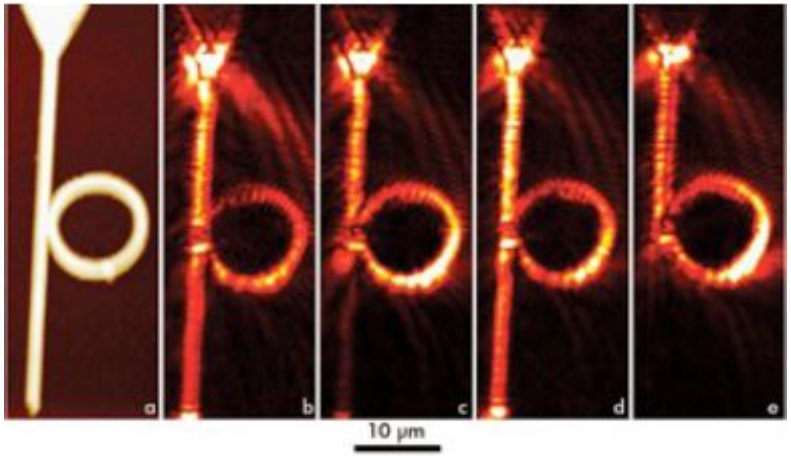




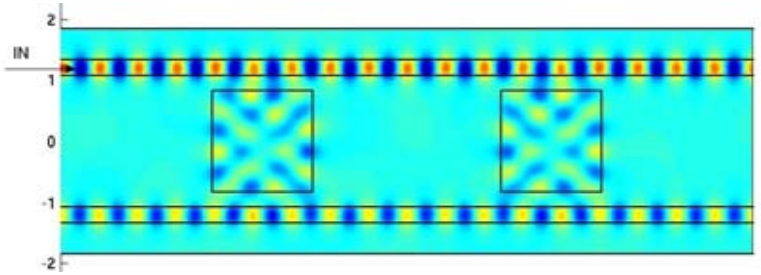
- What should the angle of incidence be?
- What should the thickness of the metal be?
- What should the wavelength of excitation be?

Resonators

Plasmon resonantor



Dielectric resonator



- Dielectric resonators for telecommunications
- Plasmonic resonators make good sensors

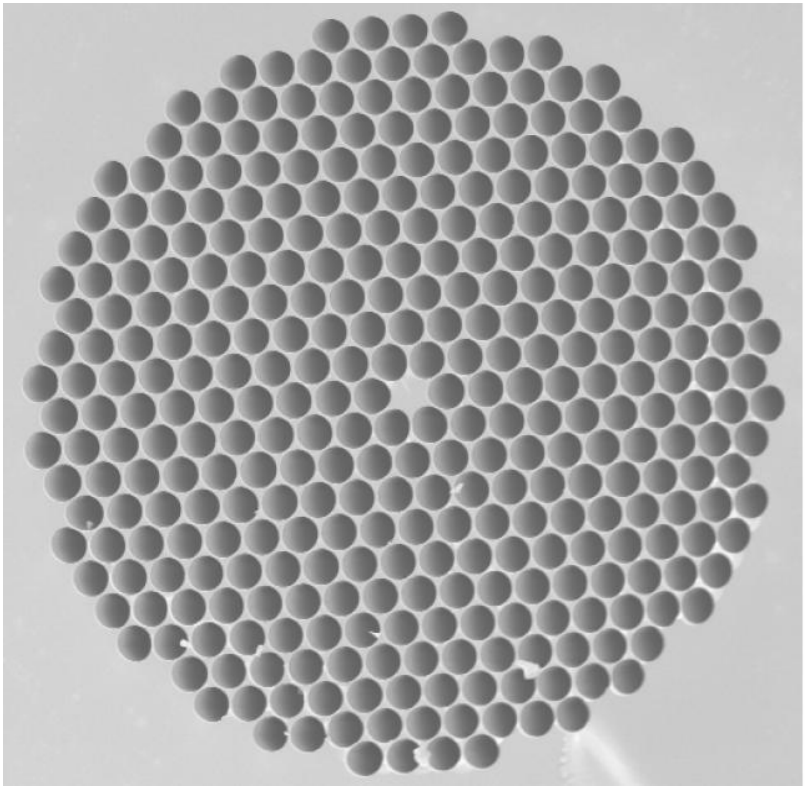
Photonic Crystals

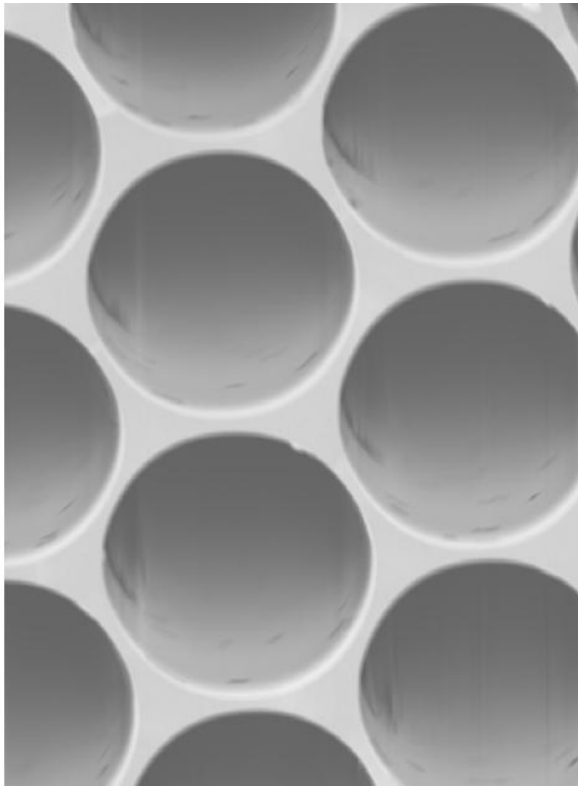
Opal is a naturally occuring crystal with a periodic microstructure

Image: wikipedia

- New generation of synthetic materials
- Lossless bending of light
- Possibility of new devices

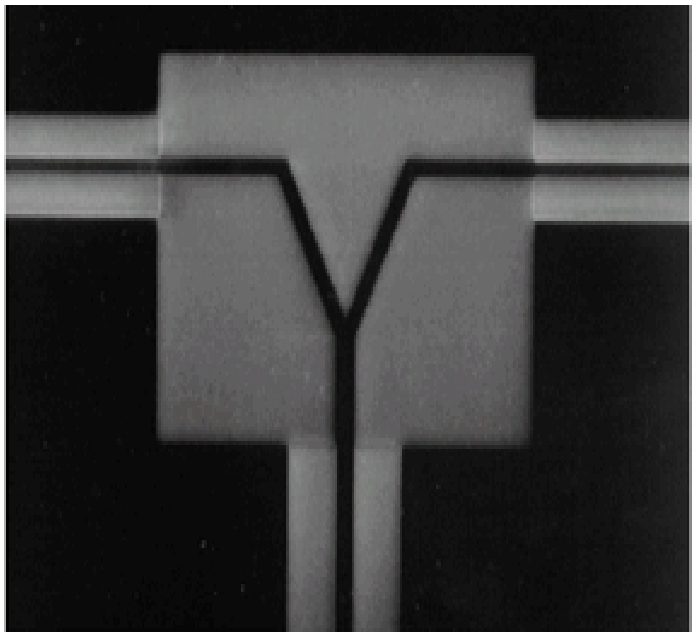
Photonic Crystal Fibre

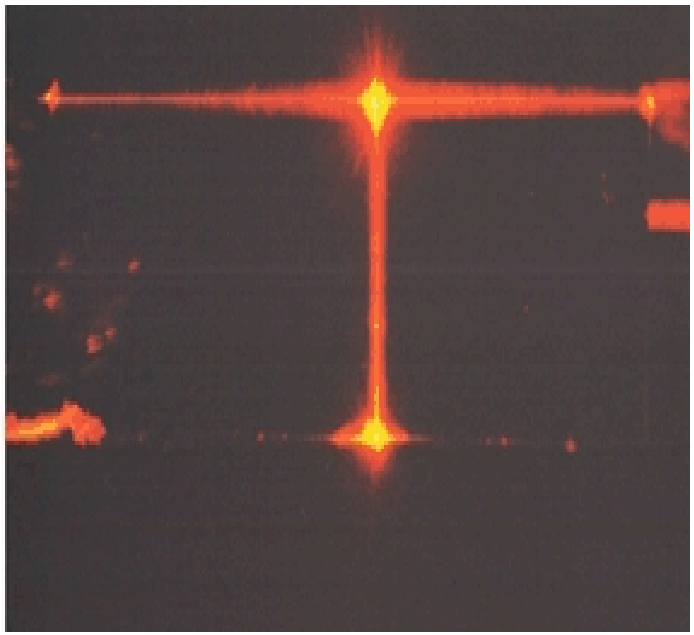


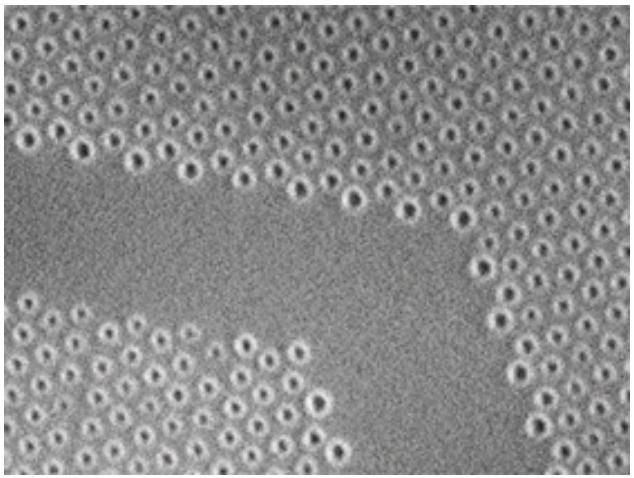


- Produced at Naval Research Labs, USA.
- Diameter of core is 5 μm, holes is 4 μm.
- Fibre drawing facility at CGCRI, Kolkata.

Photonic Splitter







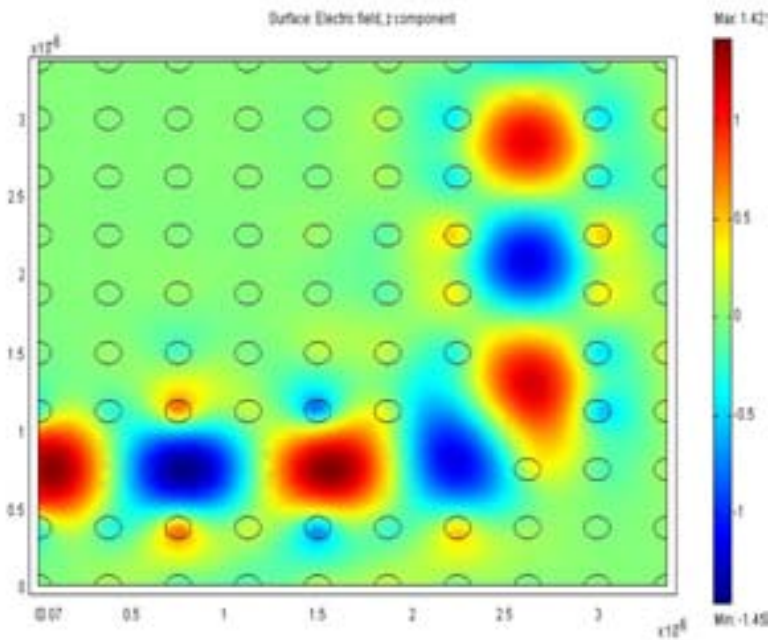
Advantages

- Lossless bends
- Low insertion loss

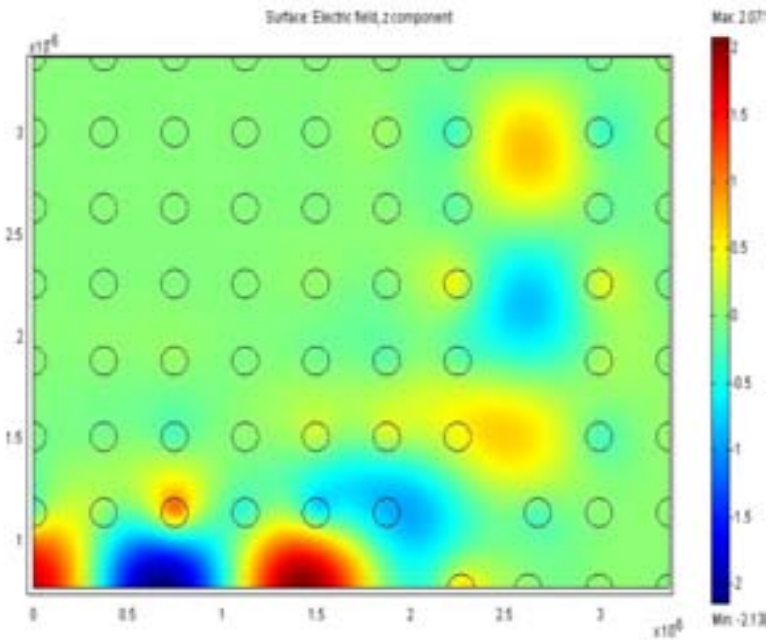
Modeling can be a challenge (fill-ratio)

Photonics with Comsol

Model Library

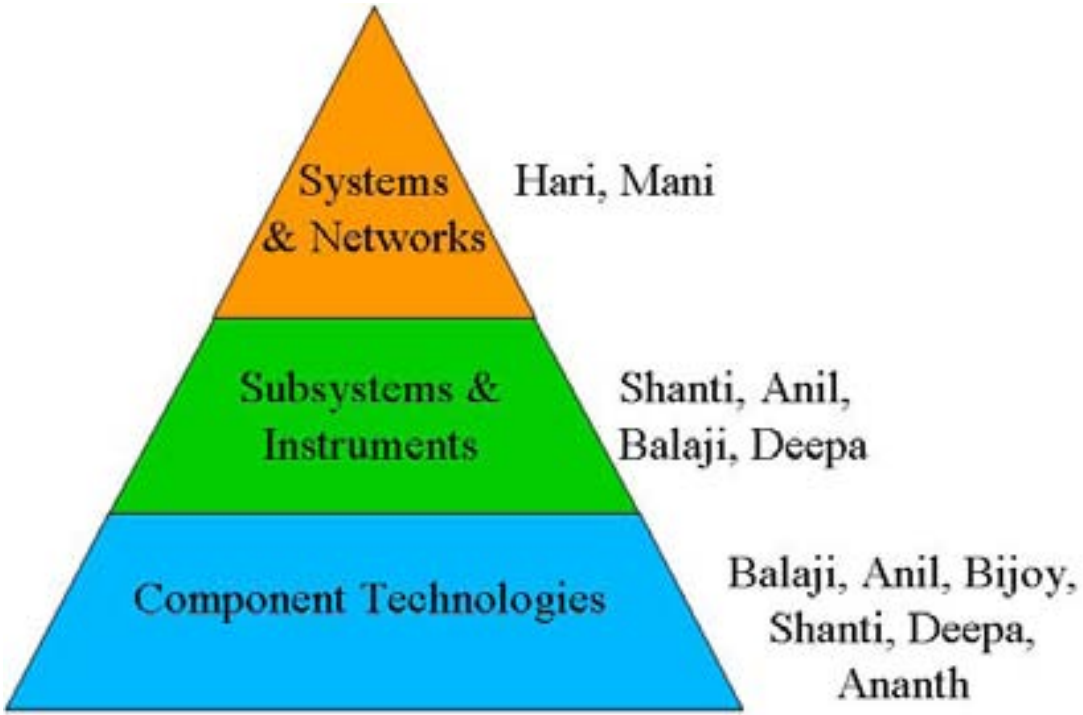


3dB Splitter



- Move a few pillars
- Use symmetric boundary conditions at the bottom

Optics@IITM



Foundations:

- Continuous stream of students and staff.
- M.Tech in Photonics starting July 2011.