Biophotonics and Photonic Crystal Fibers (PCF)

What is Photonics?

- Photonics is the technology that deals with the transmission, control, and detection of light (photons)

  - It is also called fiber optics, lightwave technology and optoelectronics
- Photons serve as the basic unit in photonics, just as electrons are the basic unit in electronics

Motivation of Biophotonics

- There is a rapidly growing use of photonic devices for biomedical diagnosis, therapy, and imaging, and for life sciences research
- Light delivery and collection procedures present challenges in biophotonic systems
- The unique physical and light transmission properties of optical fiber-based photonic components help solve these challenges
- Passive and active optical components used in telecom lightwave equipments are of special interest for biophotonics

Goals of Biophotonics

- How to use photonics in biological systems
  - Optical fibers, light sources, photodetectors
  - The principles describing the interaction of light with biological matter (cells, tissues, fluids)
- How to apply photonic devices to healthcare

This knowledge will serve as an introduction to engineering opportunities in biophotonics

Optical fibers in biophotonic systems

Optical fibers have an important role in biophotonic systems

- Deliver light to a small precise area
  - Therapeutic healthcare sessions
  - Diagnosis of a treatment area
  - A wide range of power levels are needed
- Gather a low level of light from a molecule or a tissue specimen
- Transport the light to a photodetector
- Used in optical fiber sensor systems
  - Monitoring human health conditions
  - Monitoring environmental conditions

Examples of Biophotonic applications

- Endoscopy: Involves simultaneous light-delivery and image-collection processes via fibers
- Spectroscopic analysis: Collect and analyze both scattered light and naturally occurring fluorescence being emitted from the tissue
- Biosensing: Analyze the presence, concentration, and characteristics of biological material
- Light therapy: Eg., photodynamic therapy
- Laser microsurgery: Eg., use within a blood vessel for interventional surgery of life-threatening blood clots

Light sources for Biophotonics

- Reasons for using specific sources
  - The wavelength must match the material's light absorption or scattering properties
  - Lasers and LEDs can emit in the UV, visible or IR spectral regions
  - Diagnostics, therapy, surgery, cosmetics and basic science research each require a variety of different light properties
  - An important issue in biophotonics is the intensity and duration of the light exposure for a particular application

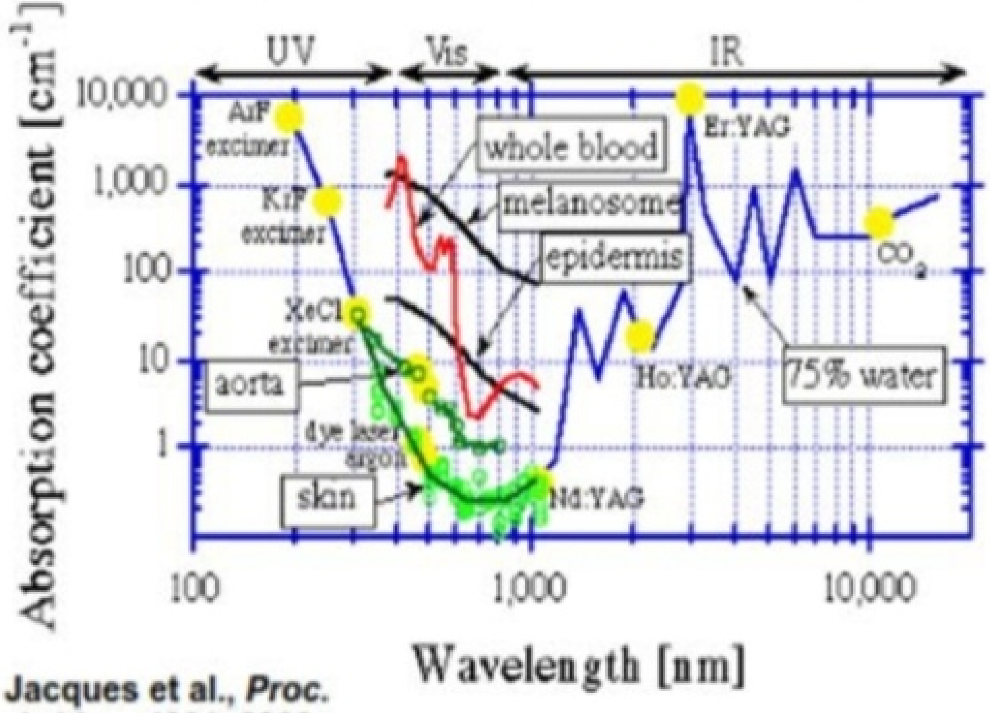
Spectral regions for biomedical imaging

- Strong absorption in the UV (< 600 nm) and IR (> 2 μm) regions

  - Absorbed light is converted to heat or radiated as fluorescent light

- Scattering with little absorption in the 600-1600 nm window

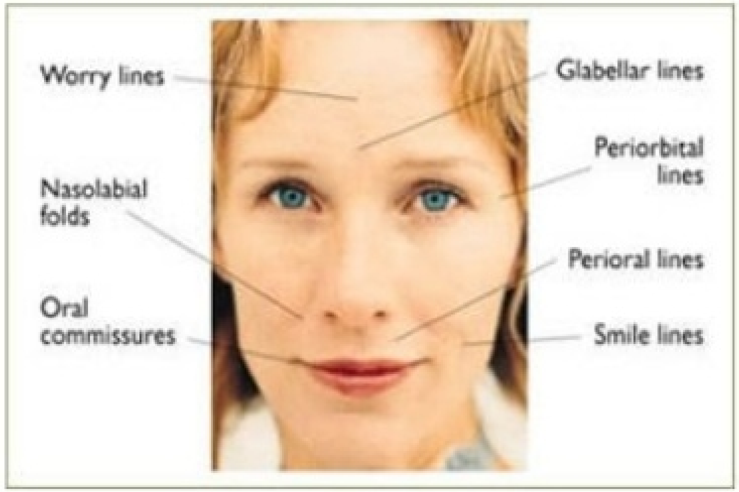
  - 35 to 70 % of light incident on a tissue sample is scattered



From: S.L. Jacques et al., *Proc.*

LED Anti-Aging Light Therapy

- Uses panels or arrays of red and/or infrared light that delivers low-level pulses of light up to three times brighter than the sun to activate skin cells
- Some cosmetic benefits
  - Minimizes fine lines, wrinkles, crow's feet
  - Restores skin's natural collagen production
  - Reduces melanin that causes brown spots
  - Reduces the effects of sun-damaged skin
  - Increases circulation and moisture
  - Reduces skin degradation and redness



Optical Detectors

Optical detectors have an important role in the design of biophotonic systems

Many types of photodetectors with different sizes, device configuartions, light sensitivities and response times are used in biophotonic applications

- Applications: healthcare, cosmetics, basic research
- Photodiodes (semiconductor devices)
  - Small, widely available, reliable, inexpensive
- Photomultiplier tubes
  - Large, widely available, reliable, expensive, sensitive
- CCDs (charge-coupled devices)
  - Consist of arrays of photodetectors
  - Widely used in cameras and other optical instruments

Photodetector Requirements

- Performance requirements

  - High sensitivity to signal wavelength range

  - Minimum addition of noise to the system

  - fast response speed to detect short pulses

- Basic characteristics

  - Insensitive to variations in temperature

  - Reasonable cost compared to other components

  - Long operating lifetime

  - Compatible with dimensions of an optical fiber

Spectroscopy

- Spectroscopy is the science of acquiring and explaining the spectral characteristics of matter

Two types of Spectroscopy methods

(i) Fluorescent spectroscopy

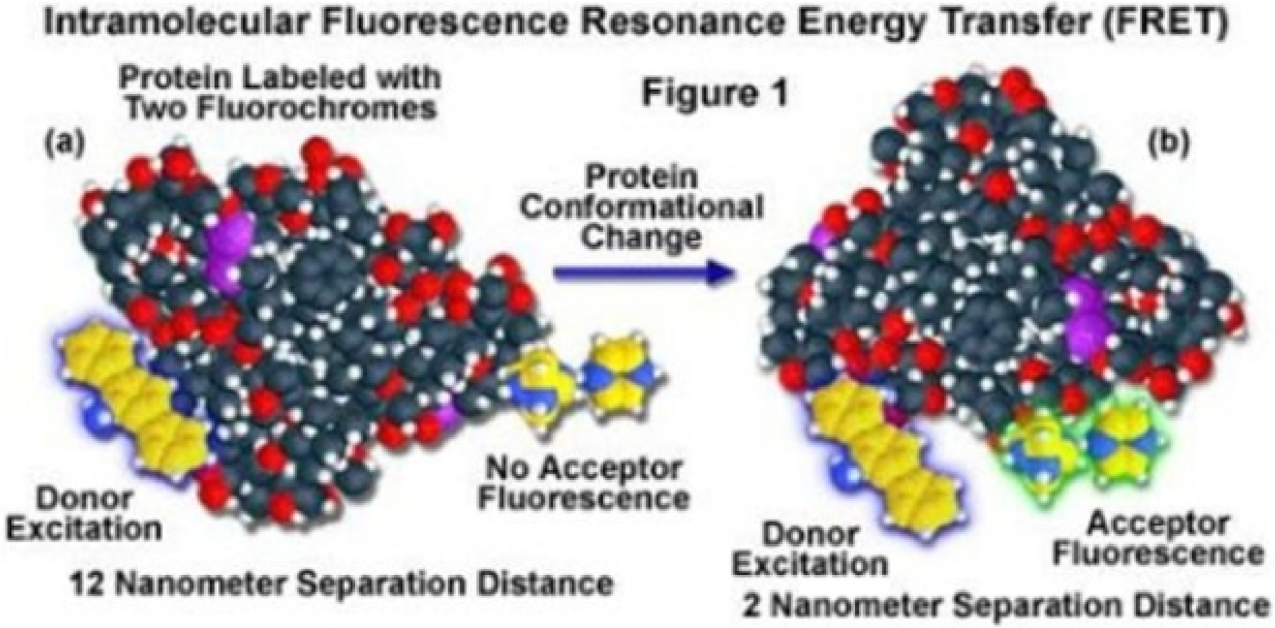
- Fluorescent molecules are attracted to objects
- Or the object itself can be a source of light
- A strong light is used to excite the molecules

(ii) Microscopy (Bright-field/Reflection/Scattering)

- A sample is illuminated with an external light
- The detector measures the same light after it has interacted (reflected, scattered) with the sample.

Fluorescence Resonance Energy Transfer (FRET)

- Using confocal microscopy, FRET permits the determination of the approach between two molecules to within several nanometers
- At this distance, molecular interactions can take place



Example: Protein-Protein Interaction

If two proteins, one labeled with BFP (the donor) and the other with GFP (the acceptor), physically interact, then increased intensity at the acceptor emission maximum (510 nm) will be observed when the complex is excited at the maximum absorbance wavelength (380 nm) of the donor.

FRET Detection of *in vivo* Protein-Protein Interactions

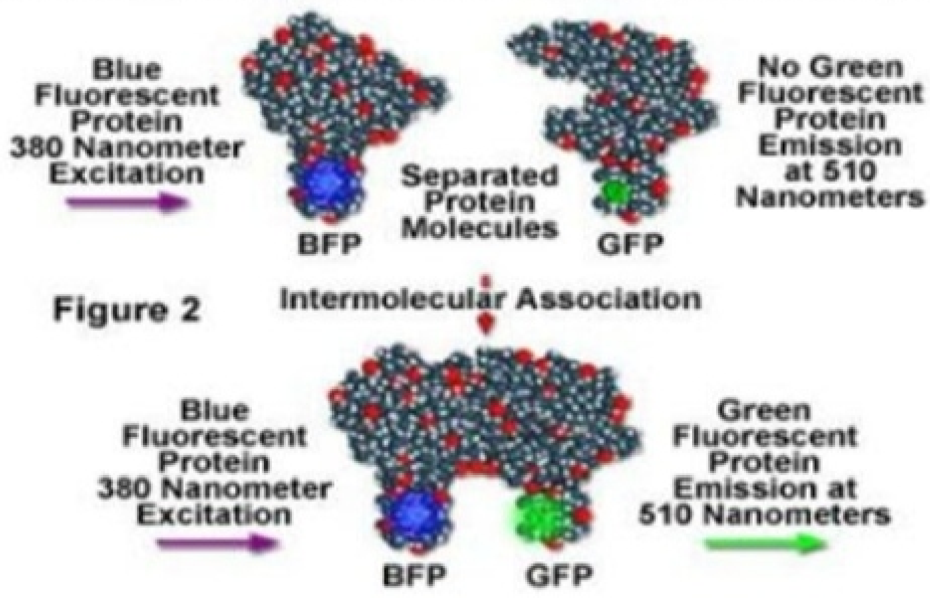
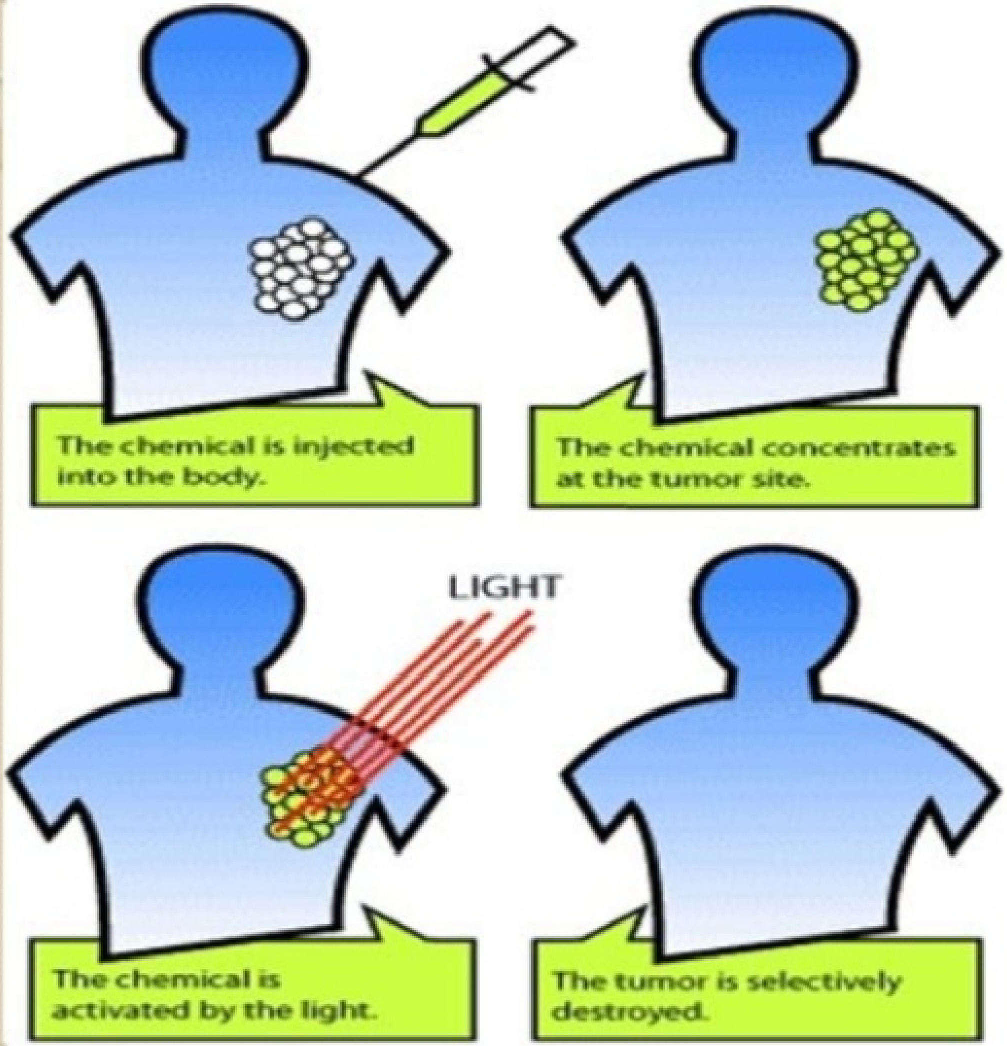


Figure 2

Photodynamic Therapy (PDT)



Cancer cells before PDT

Bronchus during PDT

Bronchus 24 months after

Tissue Diagnosis

- Successful treatment of diseases often depends on analyzing tissue *samples*
  - The samples indicate the presence and progression of tissue degradation
  - Biopsy: a sample is physically removed and test in a laboratory
  - Imaging technique:
    - Does not require tissue removal
    - Can be invasive or noninvasive
    - Does not involve time delays as in biopsy

Alternatives for Tissue Imaging

Available imaging techniques can provide near real-time and 3D biological images

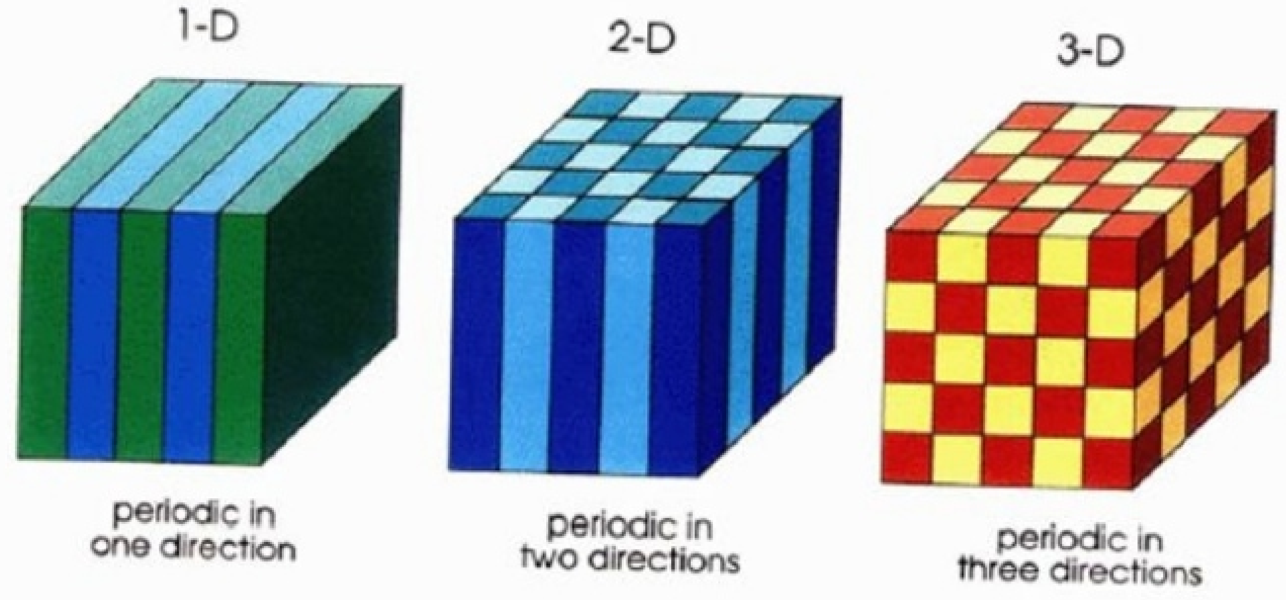
- Magnetic resonance imaging (MRI)
  - Useful for making large images: brain, lungs
  - It is a costly technique
- X-ray computed tomography
  - This method can resolve images to 10s of microns for *cm-size or mm-size objects*
- High-frequency ultrasound
  - Image resolution is under 300 microns; used to evaluate superficial organs (on the outer part of the body) - muscles, tendons, thyroids
- Optical coherence tomography (OCT)

Photonic Crystals & fibers

What are photonic crystals?

Features of a photonic crystal:

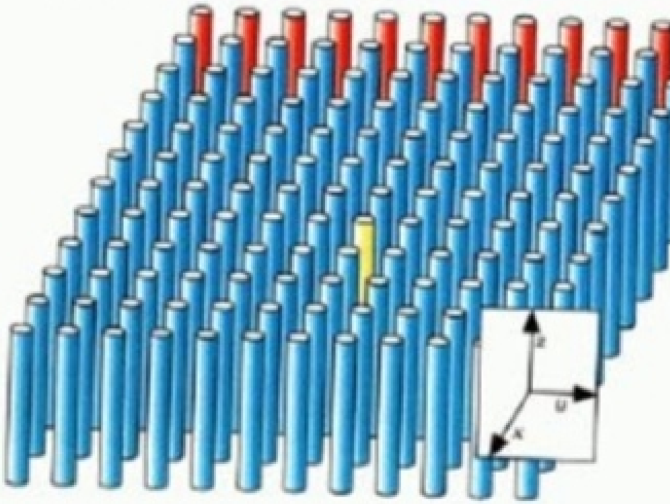
- Made of low-loss periodic dielectric medium
- Optical analog to the electrical semiconductors
- Able to localize light in specified areas by preventing light from propagating in certain directions – optical bandgap.

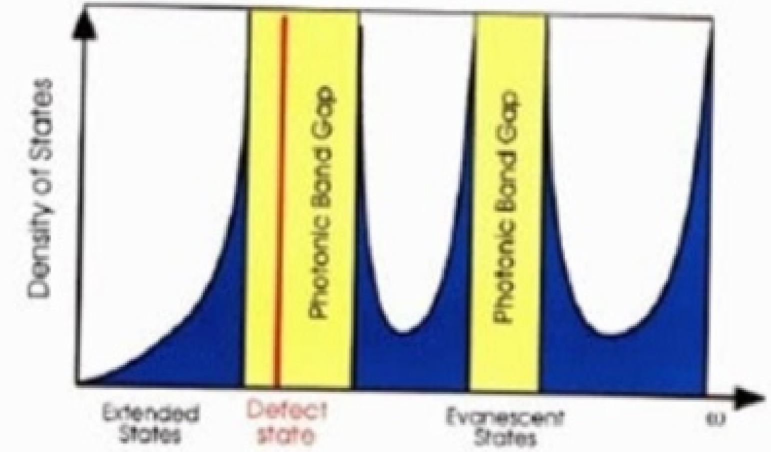


In 2D photonic crystal structures it is possible to confine light within a cavity.

Photonic band gaps appear in the plane of periodicity and in

2D we can achieve linear localization.



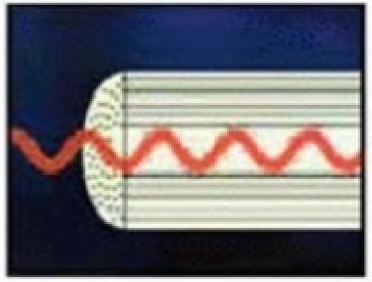


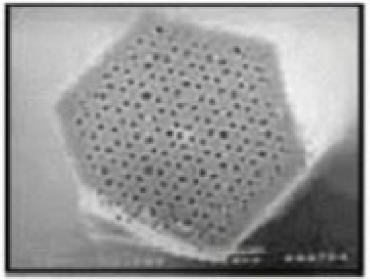
By introducing a defect, i.e. removing one column, we may obtain a peak in the density of states localized in the photonic band gap – similar to semiconductors.

The defect mode cannot penetrate the crystal in the xy-plane because of the band gap but extends in the z-direction

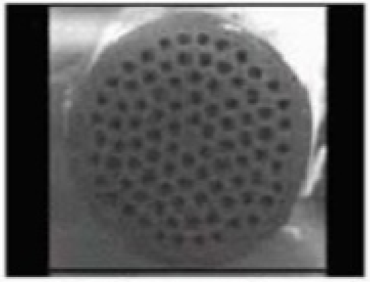
Photonic crystal fibers

By making a suitable geometry of the periodic dielectric medium, a phonic crystal can be used as an optical fiber.





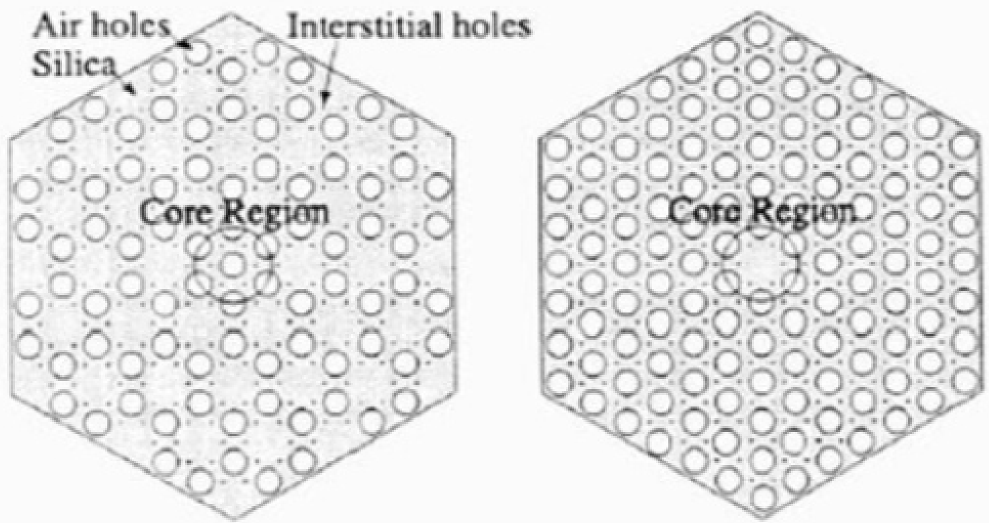
Honeycomb



Triangular

a) The Honeycomb lattice has an air defect in the centre.

b) The triangular lattice lacks a hole in the core region. The high-index core guides the light.



a) b)