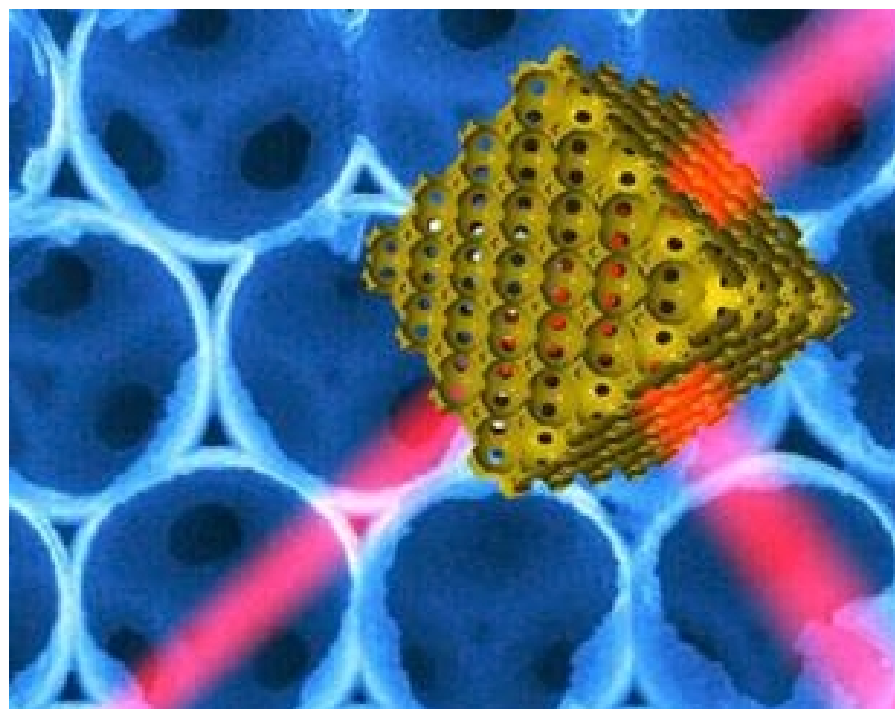


Photonic Band Gap Crystals



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Rensselaer

Summary

- **Physics of photonic bandgap crystals.**
- **Photonic Crystals Classification.**
- **Fabrication.**
- **Applications.**
- **Prototype photonic band gap devices.**
- **Current Research.**
- **Future Directions.**
- **Conclusion.**



What is a PBG ?

- A photonic band gap (PBG) crystal is a structure that could manipulate beams of light in the same way semiconductors control electric currents.
- A semiconductor cannot support electrons of energy lying in the electronic band gap. Similarly, a photonic crystal cannot support photons lying in the photonic band gap. By preventing or allowing light to propagate through a crystal, light processing can be done .

This will revolutionize photonics the way transistors revolutionized electronics.



How is a PBG fabricated ?

- **Photonic crystals usually consist of dielectric materials, that is, materials that serve as electrical insulators or in which an electromagnetic field can be propagated with low loss.**
- **Holes (of the order of the relevant wavelength) are drilled into the dielectric in a lattice-like structure and repeated identically and at regular intervals.**
- **If built precisely enough, the resulting holey crystal will have what is known as a photonic band gap, a range of frequencies within which a specific wavelength of light is blocked .**

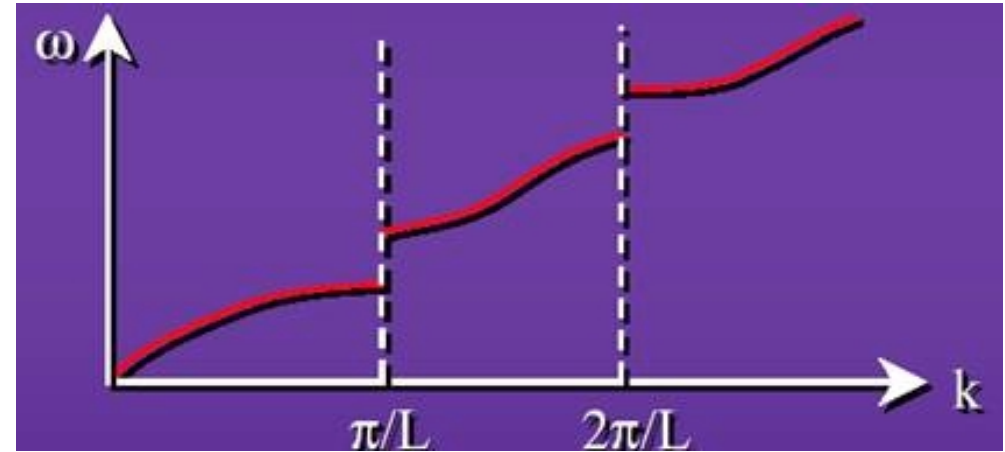


How does a PBG work ?

- In semiconductors, electrons get scattered by the row of atoms in the lattice separated by a few nanometers and consequently an electronic band gap is formed. The resulting band structure can be modified by doping.
- In a photonic crystal, perforations are analogous to atoms in the semiconductor. Light entering the perforated material will reflect and refract off interfaces between glass and air. The complex pattern of overlapping beams will lead to cancellation of a band of wavelengths in all directions leading to prevention of propagation of this band into the crystal. The resulting photonic band structure can be modified by filling in some holes or creating defects in the otherwise perfectly periodic system.



Physics of PBG



PBG formation can be regarded as the synergetic interplay between two distinct resonance scattering mechanisms. The first is the “macroscopic” Bragg resonance from a periodic array of scatterers. This leads to electromagnetic stop gaps when the wave propagates in the direction of periodic modulation when an integer number, $m=1,2,3\dots$, of half wavelengths coincides with the lattice spacing, L , of the dielectric microstructure. The second is a “microscopic” scattering resonance from a single unit cell of the material. In the illustration, this (maximum backscattering) occurs when precisely one quarter of the wavelength coincides with the diameter, $2a$, of a single dielectric well of refractive index n . PBG formation is enhanced by choosing the materials parameters a , L , and n such that both the macroscopic and microscopic resonances occur at the same frequency.



Why is making a PBG hard ?

- Photonic band gap formation is facilitated if the geometrical parameters of the photonic crystal are chosen so that both the microscopic and macroscopic resonances occur at precisely the same wavelength.
- Both of these scattering mechanisms must individually be quite strong. In practice, this means that the underlying solid material must have a very high refractive index contrast (typically about 3.0 or higher and it is to precisely achieve this contrast, holes are drilled into the medium.)
- The material should exhibit negligible absorption or extinction of light (less than 1 dB/cm of attenuation.)

These conditions on the geometry, scattering strength, and the purity of the dielectric material severely restrict the set of engineered dielectrics that exhibit a PBG.



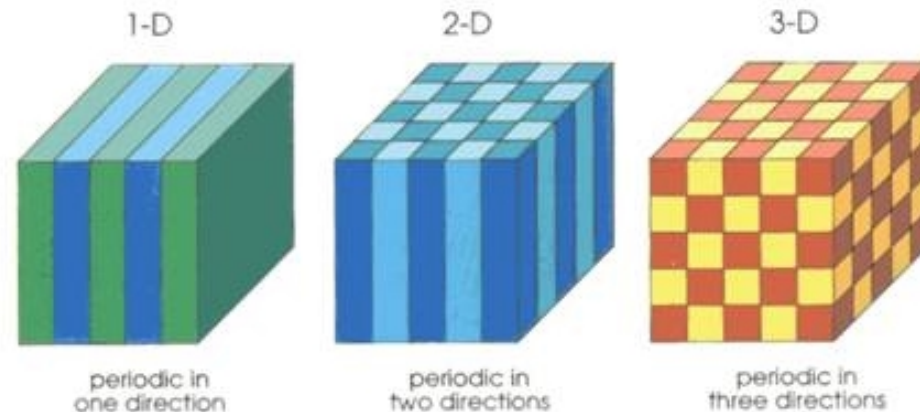
PBG materials

Materials used for making a PBG:

- **Silicon**
- **Germanium**
- **Gallium Arsenide**
- **Indium Phosphide**



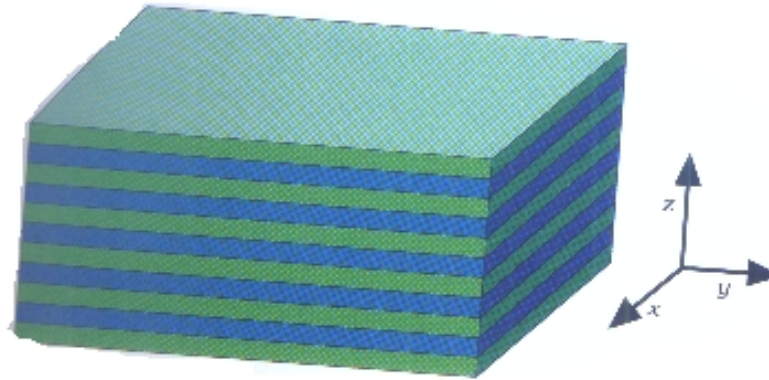
PBG Classifications



Simple examples of one-, two-, and three-dimensional photonic crystals. The different colors represent materials with different dielectric constants. The defining feature of a photonic crystal is the periodicity of dielectric material along one or more axes. Each of these classifications will be discussed in turn in the following slides.



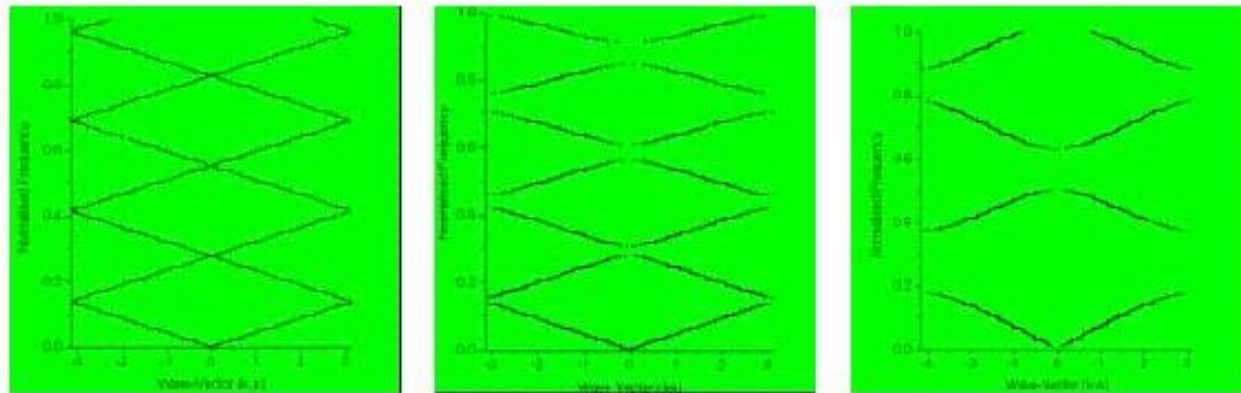
1D PBG Crystal



The multilayer thin film shown above is a one-dimensional photonic crystal. The term “one-dimensional” refers to the fact that the dielectric is only periodic in one direction. It consists of alternating layers of materials (blue and green) with different dielectric constants, spaced by a distance a . The photonic band gap exhibited by this material increases as the dielectric contrast increases.



1D Band Structures



The photonic band structures for on-axis propagation shown for three different multilayer films, all of which have layers of width $0.5a$.

Left: Each layer has the same dielectric constant. $\epsilon = 13$.

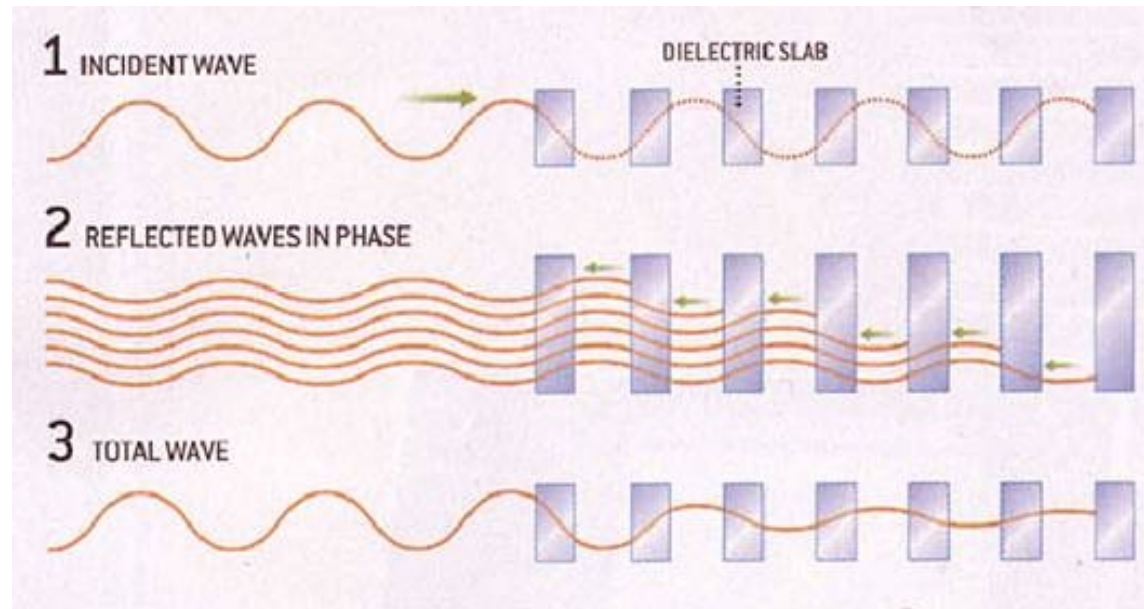
Center: Layers alternate between $\epsilon = 13$ and $\epsilon = 12$.

Right: Layers alternate between $\epsilon = 13$ and $\epsilon = 1$.

It is observed that the photonic gap becomes larger as the dielectric contrast increases.



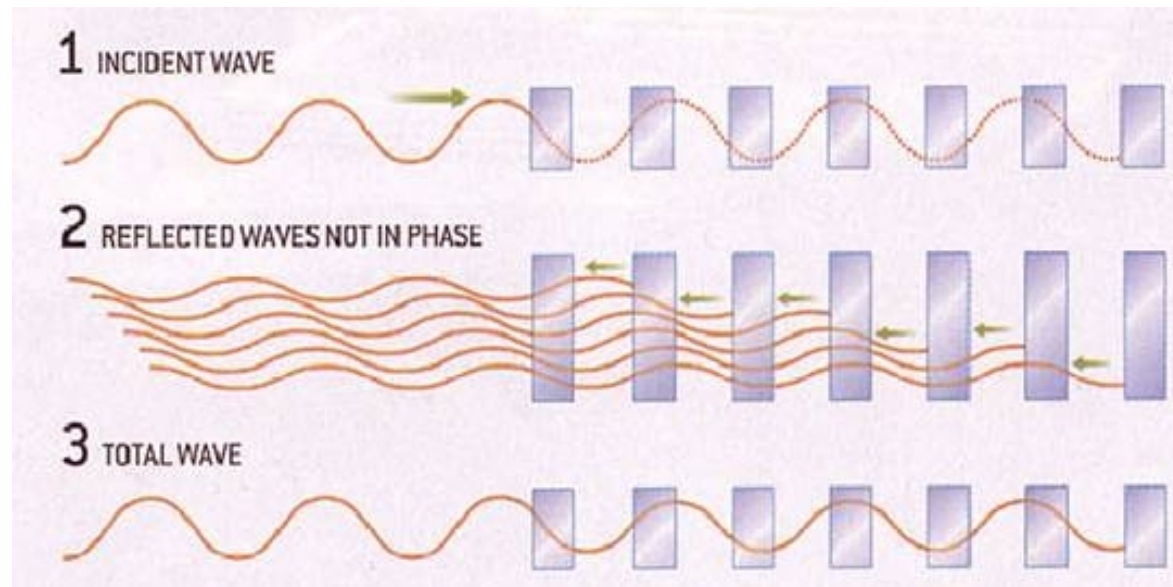
Wavelength in a 1D PBG



- A wave incident on a 1D band-gap material partially reflects off each layer of the structure.
- (2) The reflected waves are in phase and reinforce one another.
- (3) They combine with the incident wave to produce a standing wave that does not travel through the material.



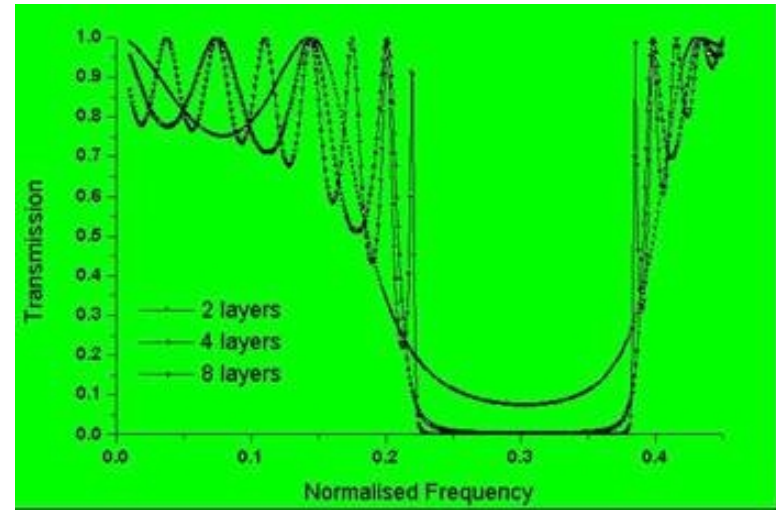
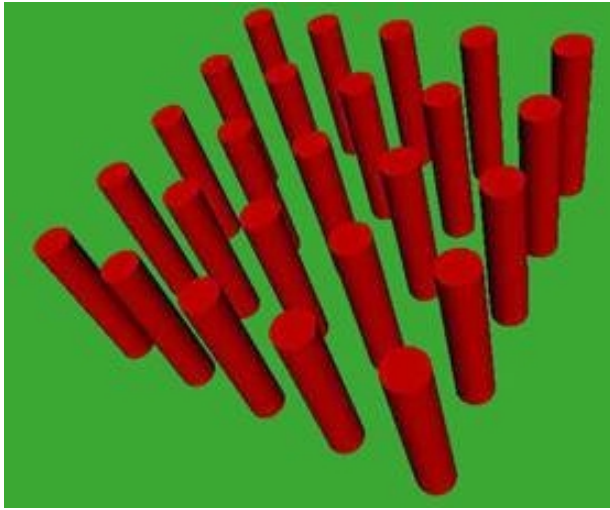
Wavelength not in a 1D PBG



- (1) A wavelength outside the band gap enters the 1D material.
- (2) The reflected waves are out of phase and cancel out one another.
- (3) The light propagates through the material only slightly attenuated.



2D PBG Crystals

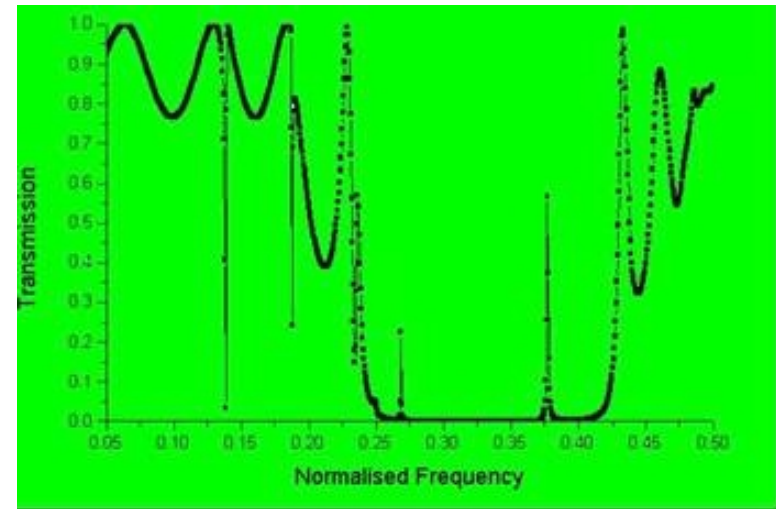
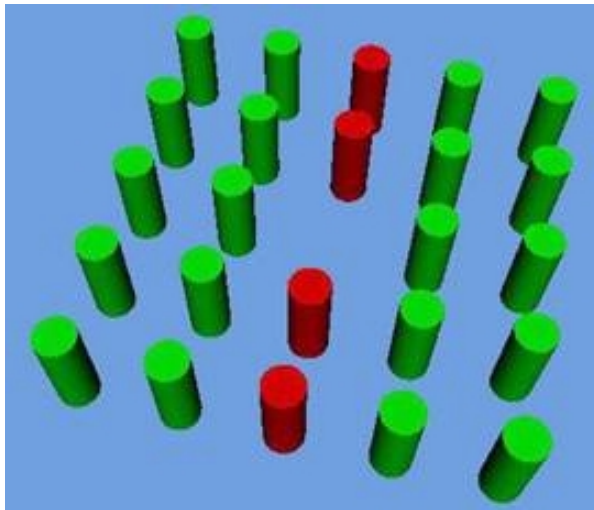


Left: A periodic array of dielectric cylinders in air forming a two-dimensional band gap.

Right: Transmission spectrum of this periodic lattice. A full 2D band gap is observed in the wavelength range 0.22 microns to 0.38 microns.



Defect in a 2D PBG Crystal

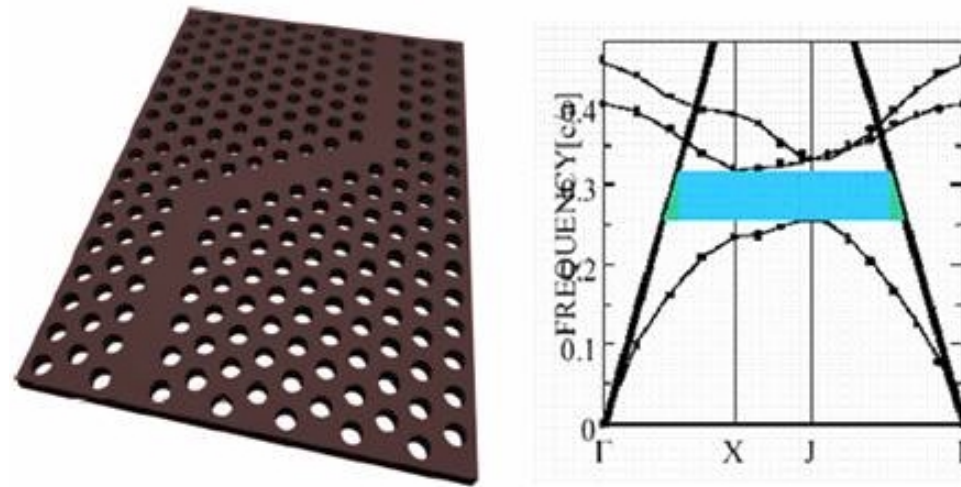


Left: A defect is introduced into the system by removing one of the cylinders. This will lead to localization of a mode in the gap at the defect site

Right: It is seen that some transmission peak is observed in the forbidden band. This corresponds to the defect state which leads to spatial localization of light and has useful applications in making a resonant cavity.



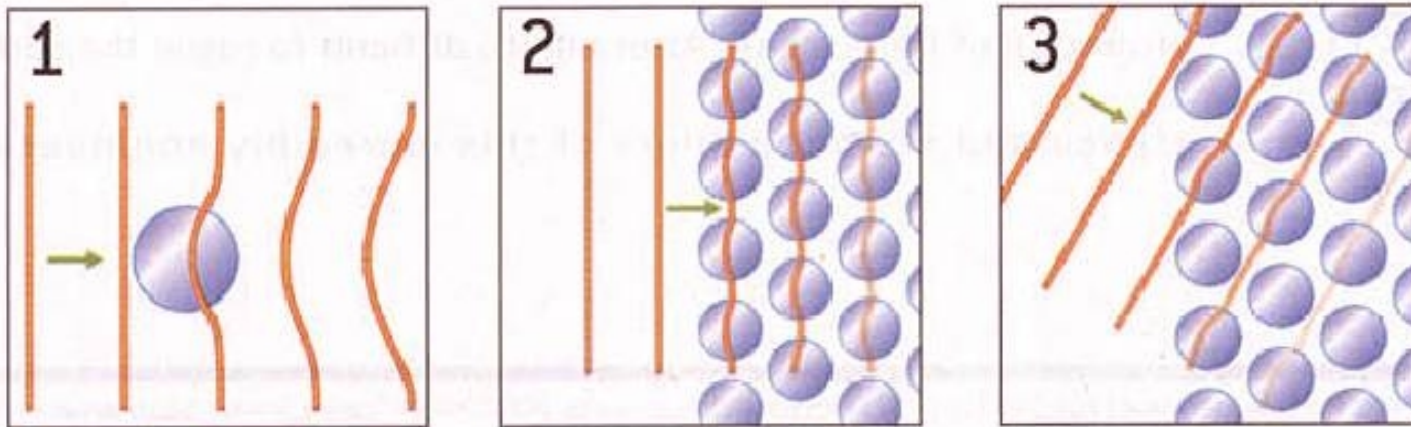
2D Band Structures



A two dimensional photonic crystal with two 60° bends, proposed by Susumu Noda's group. These structures are easy to fabricate but they have the problem of the photons not being confined on the top and bottom. By introducing point defects like making a hole larger or smaller than the normal size, the slab can be made to act like a microcavity and can be used for making optical add-drop filters.



Wavelength in a 2D PBG



- (1) For a two-dimensional band gap, each unit cell of the structure produces reflected waves.**
- (2) Reflected and refracted waves combine to cancel out the incoming wave.**
- (3) This should happen in all possible directions for a full 2D bandgap.**



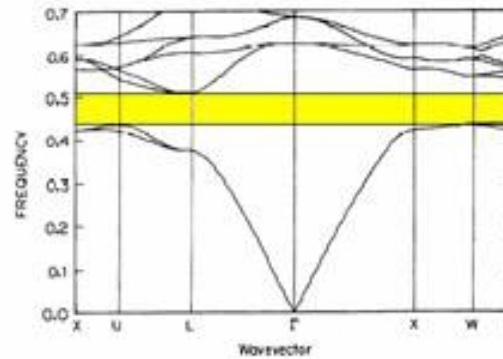
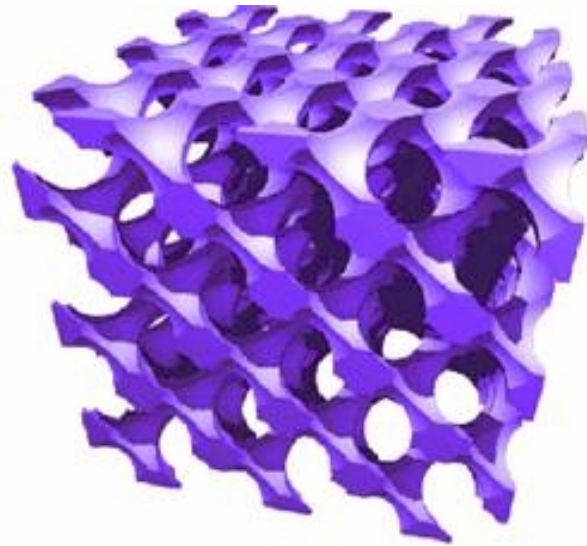
3D PBG crystals

3D photonic bandgaps are observed in

- **Diamond structure.**
- **Yablonovite structure.**
- **Woodpile Structure.**
- **Inverse opal structure.**
- **FCC Structure.**
- **Square Spiral structure.**
- **Scaffold structure.**
- **Tunable Electrooptic inverse opal structure.**



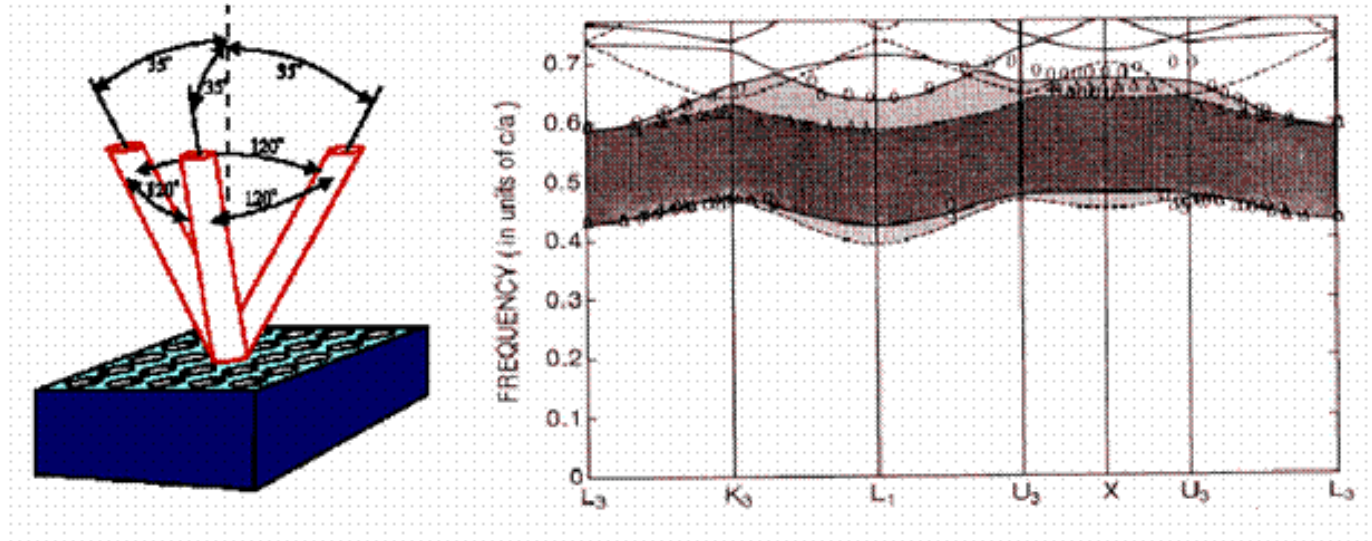
Diamond structure



The inverted diamond structure was one of the first prototype structures predicted by Chan and Soukoulis to exhibit a large and robust 3D PBG. It consists of an overlapping array of air spheres arranged in a diamond lattice. This structure can be mimicked by drilling an array of criss-crossing cylindrical holes in a bulk dielectric. The solid backbone consists of a high refractive index material such as silicon leading to a 3D PBG as large as 27% of the center frequency. The minimum refractive index of the backbone for the emergence of a PBG is 2.0



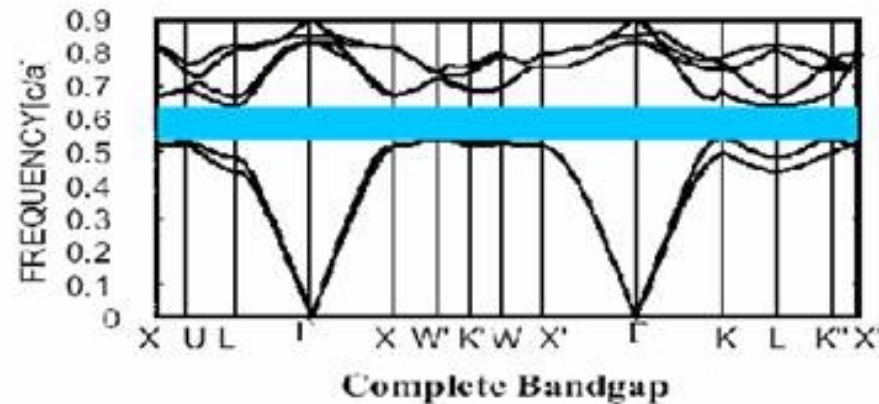
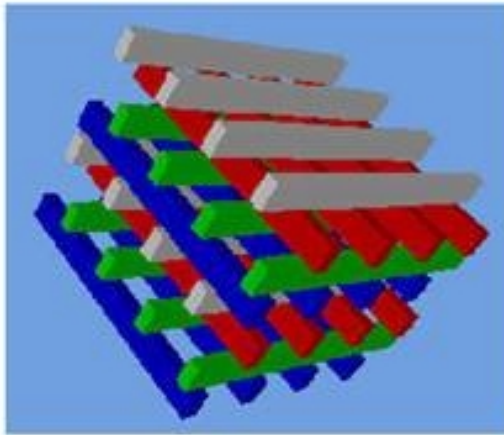
Yablonovite Structure



This is first three dimensional photonic crystal to be made and it was named Yablonovite after Yablonovitch who conceptualized it. A slab of material is covered by a mask consisting of triangular array of holes. Each hole is drilled through three times, at an angle 35.26° away from normal, and spread out 120° on the azimuth. The resulting criss-cross holes below the surface of the slab produces a full three dimensional FCC structure. The drilling can be done by a real drill bit for microwave work, or by reactive ion etching to create a FCC structure at optical wavelengths. The dark shaded band on the right denotes the totally forbidden gap



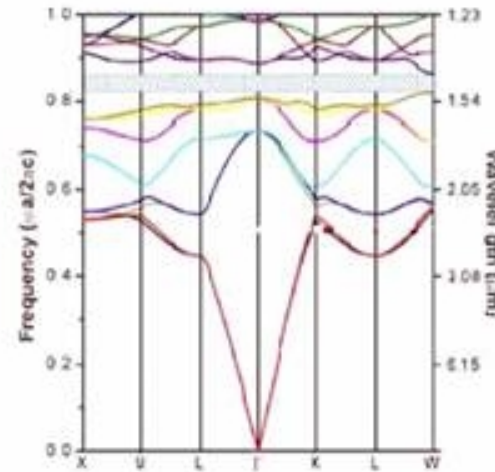
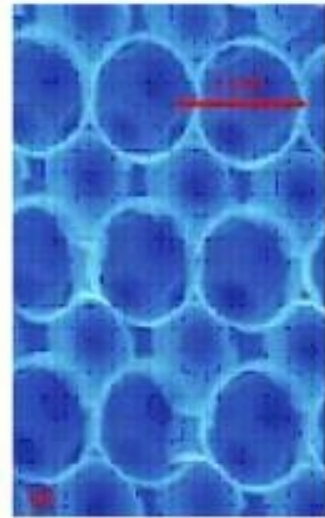
Woodpile Structure



The “woodpile” structure, suggested by Susumu Noda’s group, represents a three-dimensional PBG material that lends itself to layer-by-layer fabrication. It resembles a criss-crossed stack of wooden logs, where in each layer the logs are in parallel orientation to each other. To fabricate one layer of the stack, a SiO₂-layer is grown on a substrate wafer, then patterned and etched. Next, the resulting trenches are filled with a high-index material such as silicon or GaAs and the surface of the wafer is polished in order to allow the next SiO₂ layer to be grown. The logs of second nearest layers are displaced midway between the logs of the original layer. As a consequence, 4 layers are necessary to obtain one unit cell in the stacking direction. In a final step, the SiO₂ is removed through a selective etching process leaving behind the high-index logs.



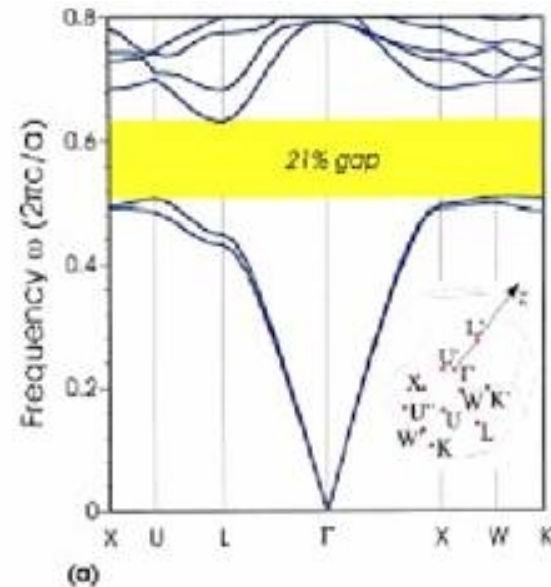
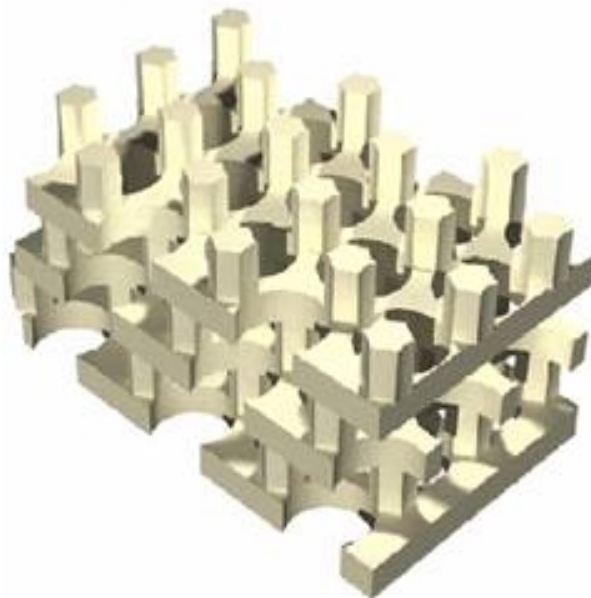
Inverse Opal Structure



SEM picture of a cross-section along the cubic (110) direction of a Si inverse opal with complete 5% PBG around 1.5 μm . The structure has been obtained through infiltration of an artificial opal with silicon (light shaded regions) and subsequent removal of SiO_2 spheres of the opal. The air sphere diameter is 870 nanometers. Clearly visible is the complete infiltration (diamond shaped voids between spheres) and the effect of sintering the artificial opal prior to infiltration (small holes connecting adjacent spheres.)



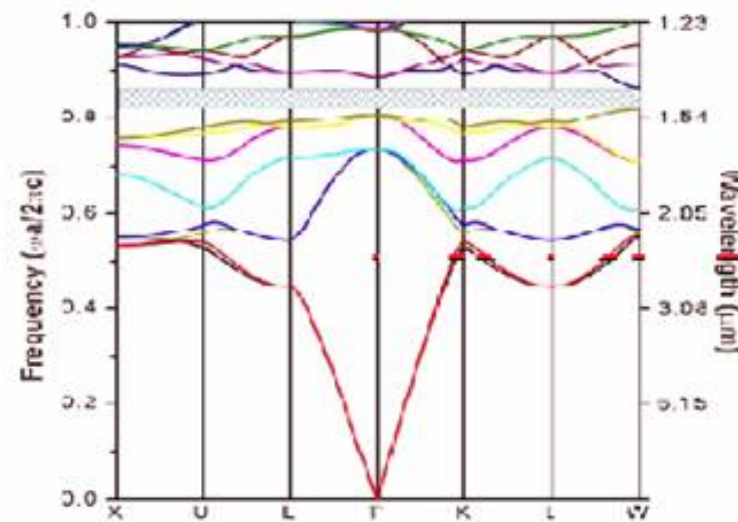
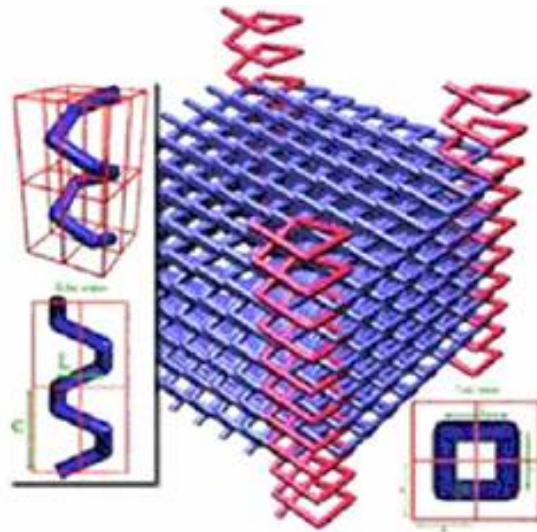
FCC Structure



Computer rendering of a three dimensional photonic crystal, put forth by Joannopoulos and his group, showing several horizontal periods and one vertical period consisting of a FCC lattice of air holes (radius $0.293a$, height $0.93a$) in dielectric. This allows one to leverage the large body of analyses, experiments, and understanding of those simpler structures. This structure has a 21% gap for a dielectric constant of 12.



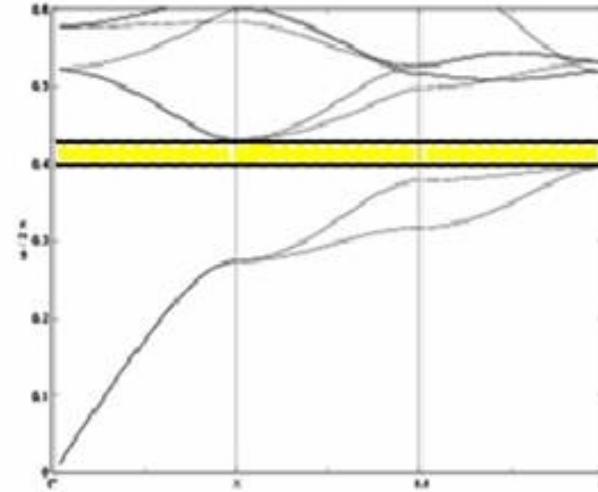
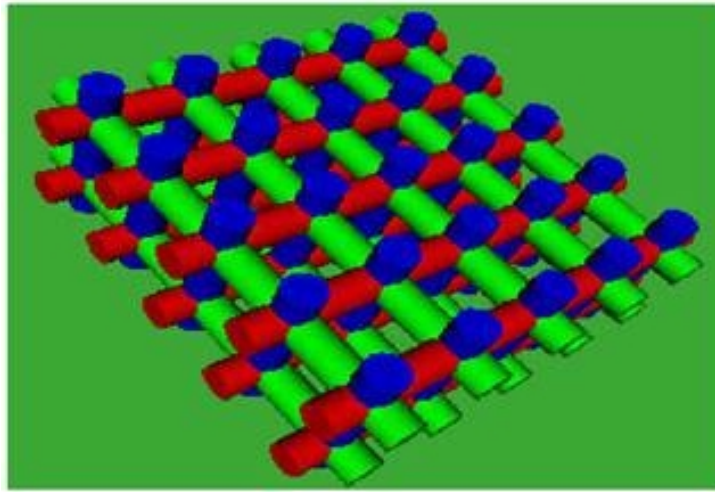
Square Spiral Structure



The tetragonal lattice of square spiral posts exhibits a complete 3D PBG and can be synthesized using glancing angle deposition (GLAD) method. This chiral structure, suggested by John and Toader, consists of slightly overlapping square spiral posts grown on a 2D substrate that is initially seeded with a square lattice of growth centers. Computer controlled motion of the substrate leads to spiraling growth of posts. A large and robust PBG emerges between the 4th and 5th bands of photon dispersion. The inverse structure consisting of air posts in a solid background exhibits a even larger 3D PBG.



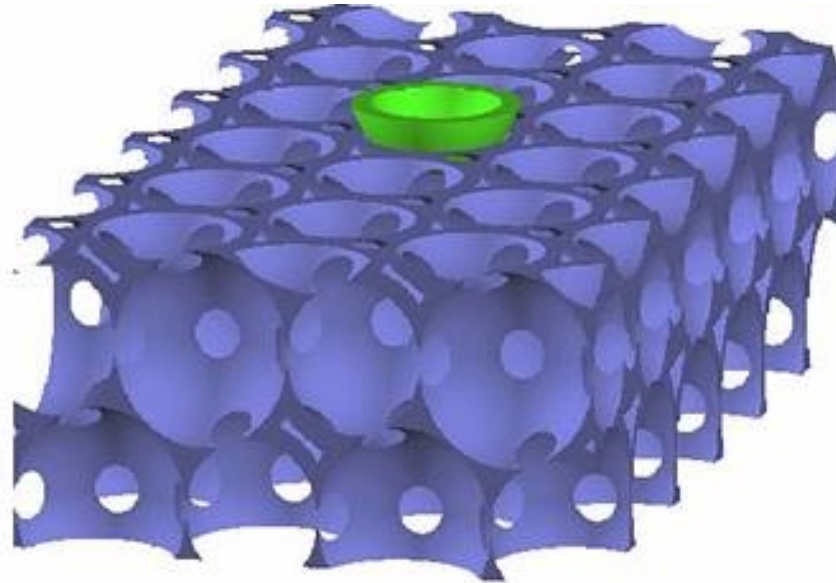
Scaffolding Structure



The scaffolding structure (for its similarity to a scaffolding) is a rare example of a photonic crystal that has a very different underlying symmetry from the diamond structure yet has a photonic band gap. The band gap is small but definitely forbidden and this was suggested by Joseph Haus and his colleagues.



Tunable 3D Inverse Opal Structure



A marriage of liquid and photonic crystals as conceptualized by Busch and John. An inverse opal photonic crystal structure partially infiltrated with liquid crystal molecules. Electro-optic tuning can cause the bandgap to wink in and out of existence. This can have disruptive influence on our present technologies as will be discussed later.

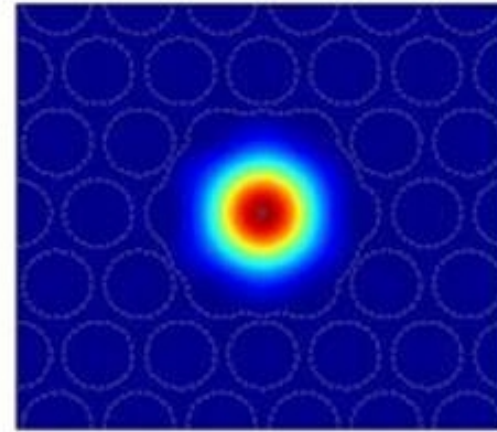
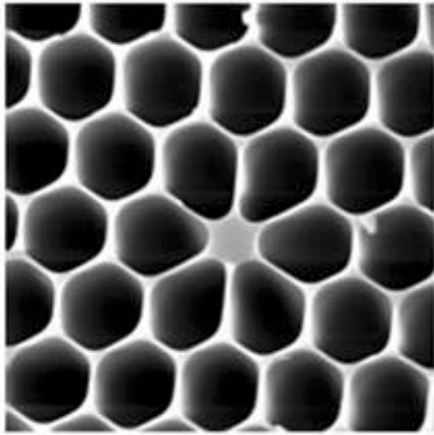


Applications of PBG

DEVICE	DESCRIPTION	STATUS
OPTICAL FIBERS	2-D band-gap material stretched along the third dimension	Early versions already commercialized
NANOSCOPIC LASERS	World's tiniest optical cavities and tiniest lasers; formed in a thin-film 2-D band-gap material	Demonstrated in the lab
ULTRAWHITE PIGMENT	Incomplete 3-D band-gap material, usually patterned as opal structure	Demonstrated; low-cost manufacturing methods under development
RADIO-FREQUENCY ANTENNAS, REFLECTORS	Uses inductors and capacitors in place of ordinary dielectric materials	Demonstrated for magnetic resonance imaging and antennas
LIGHT-EMITTING DIODES	Photonic band-gap structure can extract light very efficiently (better than 50%)	Demonstrated, but must compete with other methods of achieving the same goal
PHOTONIC INTEGRATED CIRCUITS	2-D thin films can be patterned like conventional integrated circuits to make channel filters, modulators, couplers and so on	Under development



1. Photonic Crystal Fibers



- Photonic crystal fibers (PCF) are optical fibers that employ a microstructured arrangement of low-index material in a background material of higher refractive index.
- The background material is undoped silica and the low index region is typically provided by air voids running along the length of the fiber.



Types of PCF

PCFs come in two forms:

- **High index guiding fibers based on the Modified Total Internal Reflection (M-TIR) principle**
- **Low index guiding fibers based on the Photonic Band Gap (PBG) effect.**



M-TIR Fibers



Photonic crystal fiber

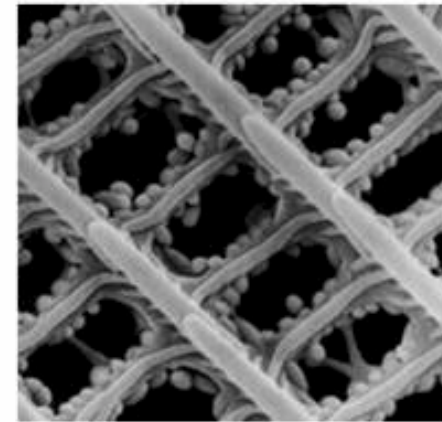


Equivalent step index fiber

- **Tiny cylindrical holes of air separated by gaps are patterned into a fiber. The effective cladding index (of the holes and the gaps) is lower than the core index.**
- **A first glance would suggest that light would escape through the gaps between “bars” of air. But, a trick of geometry prevents this.**
- **The fundamental mode, being the longest wavelength, gets trapped in the core while the higher order modes capable of squeezing in the gaps leak away rapidly, by a process reminiscent of a kitchen sieve.**
- **For small enough holes, PCF remains single moded at all wavelengths and hence given the name “endlessly single moded fiber.”**



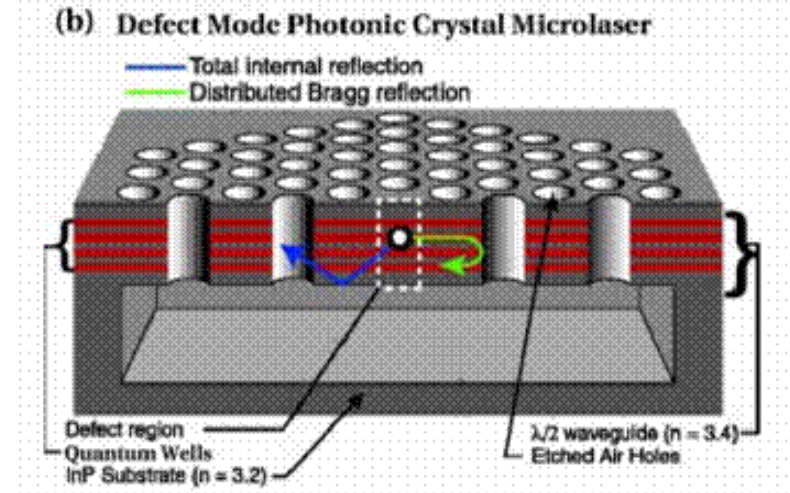
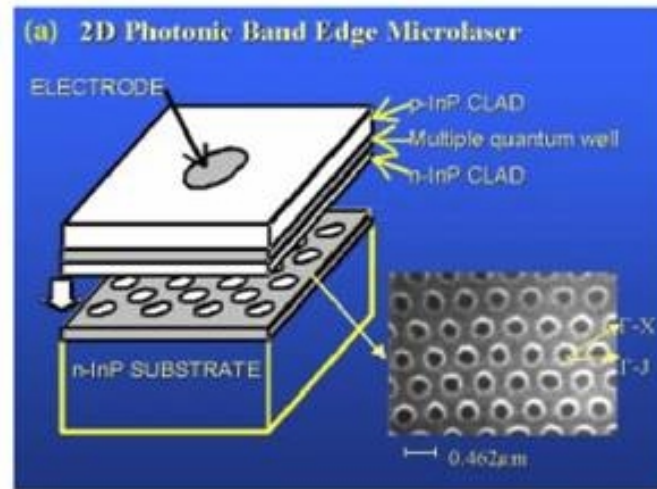
PBG Fibers



- PBG fibers are based on mechanisms fundamentally different from the M-TIR fibers.
- The bandgap effect can be found in nature, where bright colors that are seen in butterfly wings are the result of naturally occurring periodic microstructures. The periodic microstructure in the butterfly wing results in a photonic bandgap, which prevents propagation of certain bands. This light is reflected back and seen as bright colors.
- In a PBG fiber, periodic holes act as core and an introduced defect (an extra air hole) act as cladding. Since light cannot propagate in the cladding due to the photonic bandgap, they get confined to the core, even if it has a lower refractive index.
- In fact, extremely low loss fibers with air or vacuum as the core can be created.



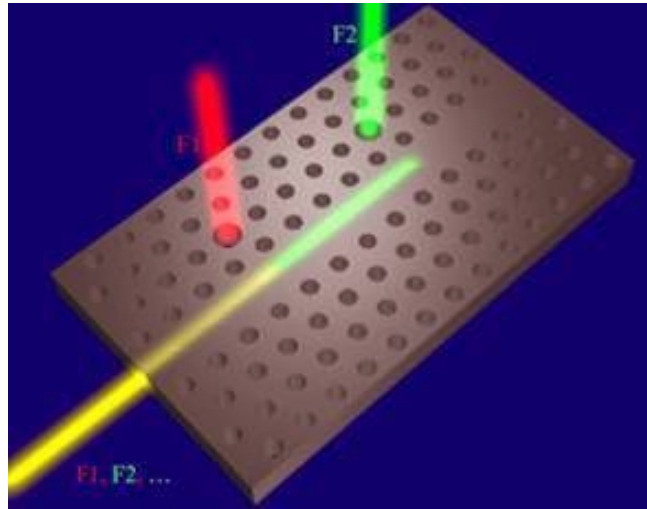
2. Photonic Crystal Lasers



Architectures for 2D photonic crystal micro-lasers are shown above. (a) The Band Edge microlaser utilizes the unique feedback and memory effects associated with a photonic band edge and stimulated emission (arising from electron-hole recombination) from the multiple quantum well active region occurs preferentially at the band edge. There is no defect mode Engineered in the 2D PBG. (courtesy of S. Noda, Kyoto University). (b) Defect Mode micro laser requires the engineering of a localized state of light within the 2D PBG. This is created through a missing pore in the 2D photonic crystal. Stimulated emission from the multiple quantum well active region occurs preferentially into the localized mode. (courtesy of Axel Scherer, California Institute of Technology).



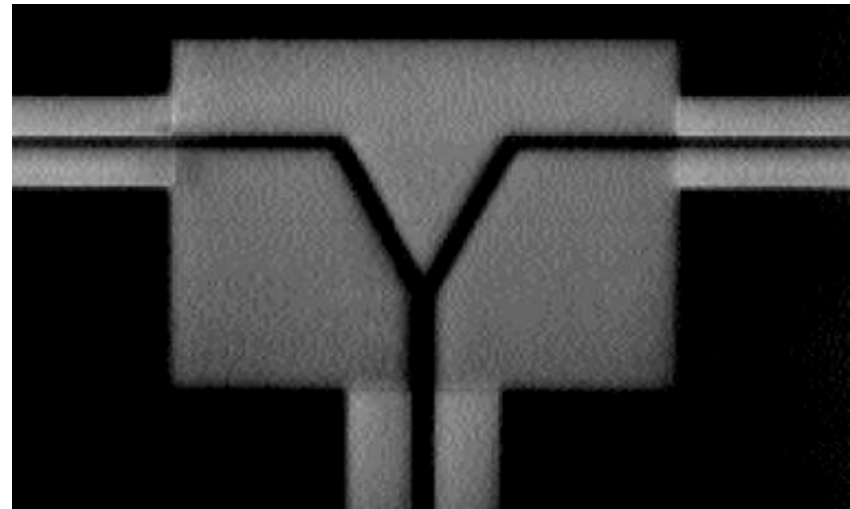
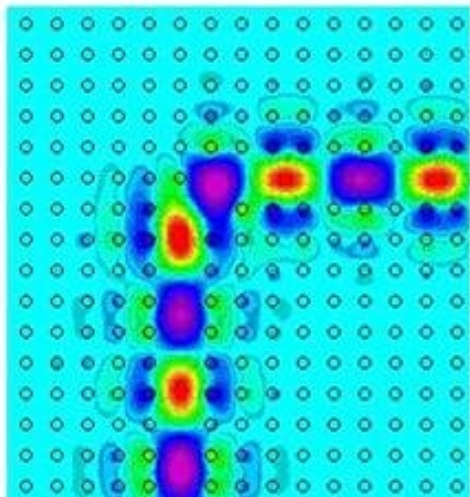
3. Photonic Crystal Filters



Add-drop filter for a dense wavelength division multiplexed optical communication system. Multiple streams of data carried at different frequencies F_1 , F_2 , etc. (yellow) enter the optical micro-chip from an external optical fiber and are carried through a wave guide channel (missing row of pores). Data streams at frequency F_1 (red) and F_2 (green) tunnel into localized defect modes and are routed to different destinations. The frequency of the drop filter is defined by the defect pore diameter which is different from the pore diameter of the background photonic crystal.



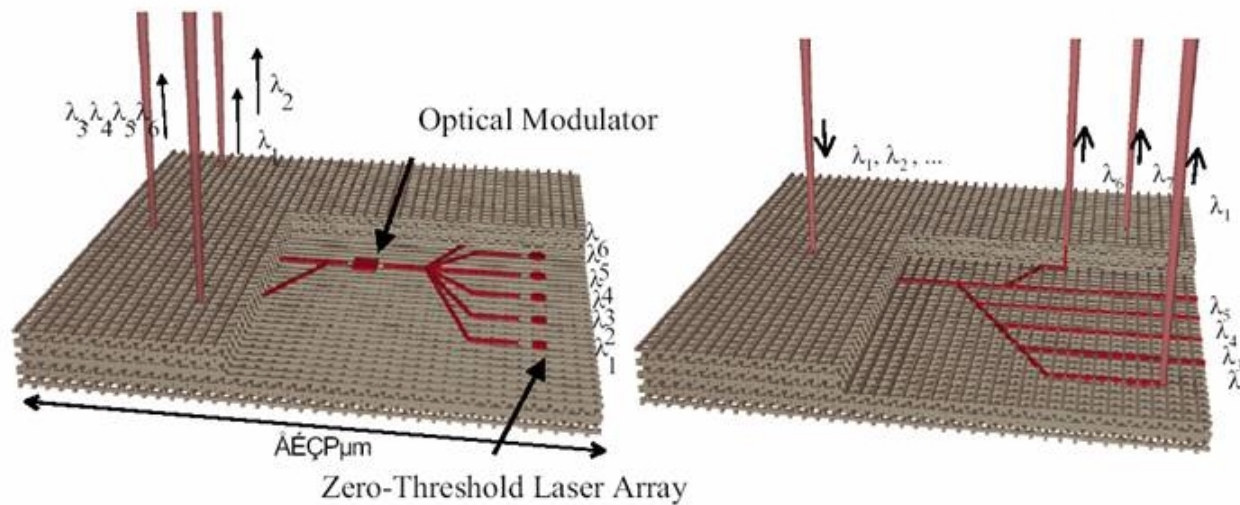
4. Photonic Crystal Planar Waveguides



- Creating a bend radius of more than few millimeters is difficult in conventional fibers because the conditions for TIR fail leading to leaky modes.
- PC waveguides operate using a different principle. A line defect is created in the crystal which supports a mode that is in the band gap. This mode is forbidden from propagating in the crystal because it falls in the band gap.
- When a bend needs to be created in the waveguide, a line defect of the same shape is introduced. It is impossible for light to escape (since it cannot propagate in the bulk crystal). The only possibility is for the mode to propagate through the line defect (which now takes the shape of a sharp bend) leading to lossless propagation.



5. PIC on a 3D PBG Microchip



Example I: Ultra-small Multi-Wavelength Light Source

Example II: Ultra-small Wavelength DEMUX Circuit

An artist's conception of a 3D PBG woodpile structure into which a micro-laser array and de-multiplexing (DEMUX) circuit have been integrated. (courtesy of S. Noda, Kyoto University, Japan). These photonic integrated circuits will be prime movers for deeper penetration of optical networking into telecommunications.

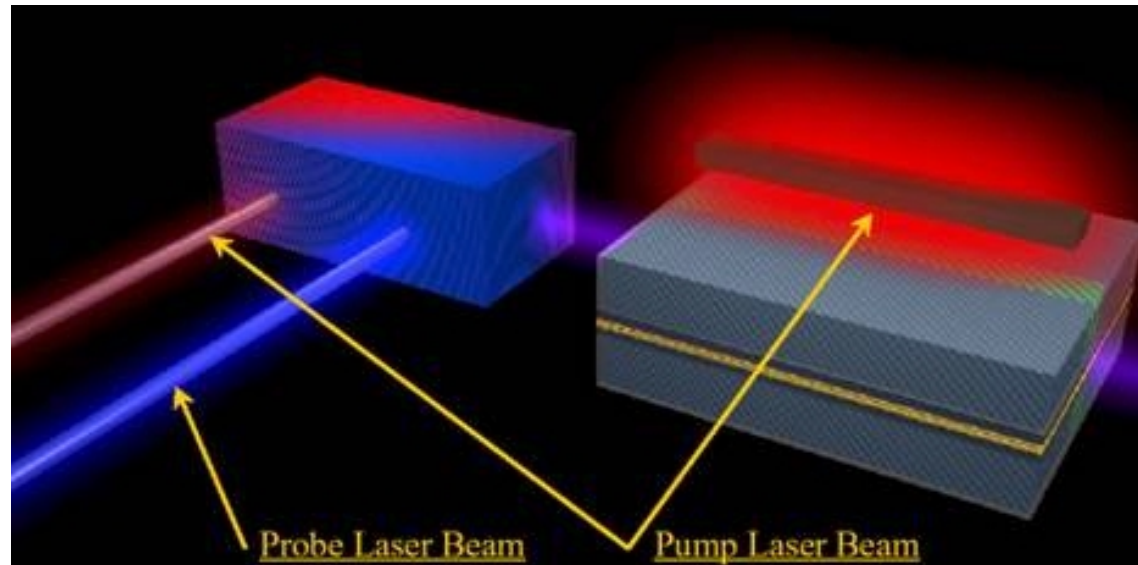


Future Directions

- **Design of ultra compact lasers with almost zero threshold current.**
- **Terahertz all-optical switch for routing data along the internet.**
- **Collective switching of two-level atoms from ground to excited state with low intensity applied laser fields leading to all-optical transistor action.**
- **Ultra-small beamsplitters, Mach-Zehnder interferometers, and functional micro-optical elements such as wavelength add-drop filters leading to compact photonic integrated circuits.**
- **Single atom memory effects for possible quantum computer applications.**



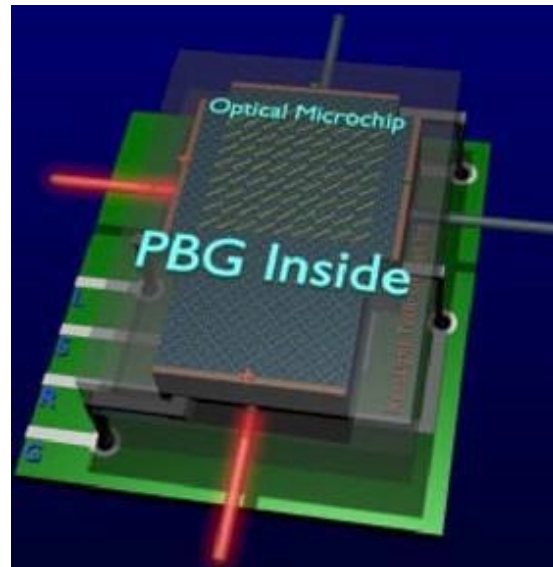
1. All Optical Transistor



Micro-photonic all-optical transistor may consist of an active region buried in the intersection of two wave-guide channels in a 3D PBG material. The two-level systems (“atoms”) in the active region are coherently pumped and controlled by laser beams passing through the wave guides. In addition, the 3D PBG material is chosen to exhibit an abrupt variation in the photon density of states near the transition frequency of the atoms. This leads to atomic “population inversion” through coherent pumping, an effect which is forbidden in ordinary vacuum. The inversion threshold is characterized by a narrow region of large differential optical gain (solid curve in the inset). A second, “control laser” allows the device to pass through this threshold region leading to strong amplification of the output signal. In ordinary vacuum, population inversion is unattainable (dashed curve in the inset).



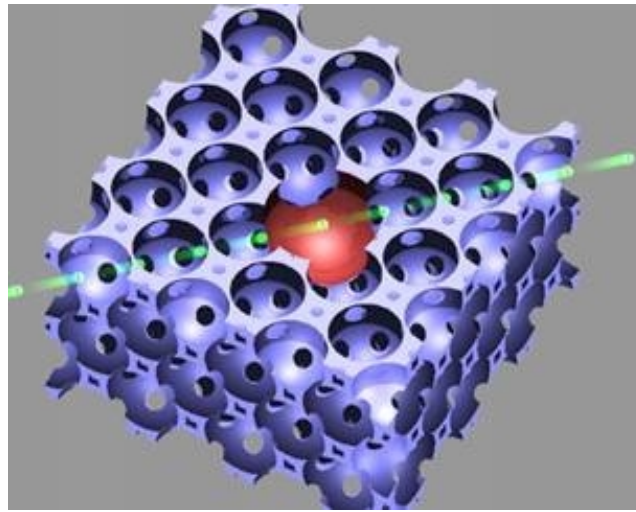
2. All Optical Router



Artist's depiction of an electro-actively tunable PBG routing device. Here the PBG material has been infiltrated with an optically anisotropic material (such as a liquid crystal) exhibiting a large electro-optic response. When a voltage is applied to the electro optically tunable PBG, the polarization state (yellow arrows) can be rotated, leading to corresponding shifts in the photonic band structure. This allows light from an optical fiber to be routed into one of several output fibers.



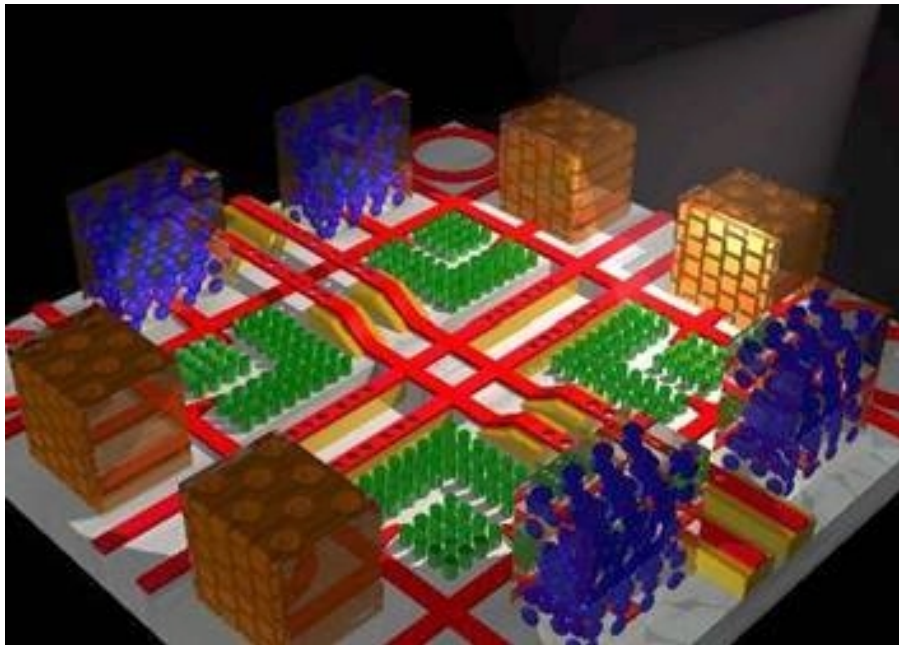
3. Optical Computing



With optical integrated circuits and optical transistor technology being rendered possible by photonic crystals, quantum computing with localized light is a very promising technology for the future. Immense parallelism, unprecedented speeds, superior storage density, minimal crosstalk and interference are some of the advantages that one gets while migrating towards optical computing.



4. Optical Integrated Circuits



An artistic view of a collage of different photonic crystal devices going into an integrated circuit. The buildings are 3-D PBG crystals. The clear buildings with the blue balls depict a metallo-dielectric structure. The green "forests" show two-dimensionally periodic photonic crystals. The red "roads" with holes in them are one-dimensionally periodic crystals.

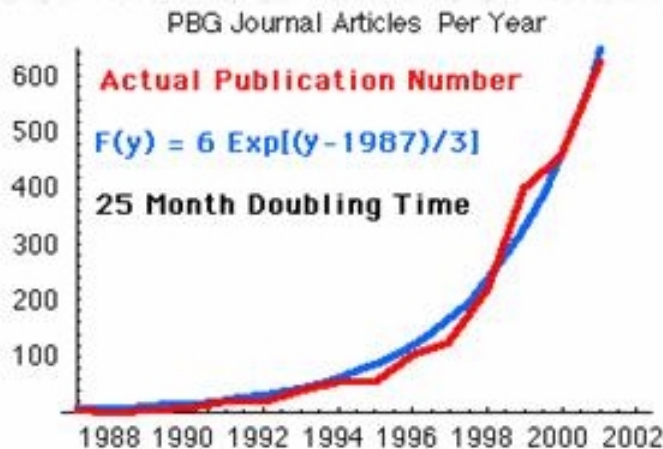


Conclusion

- **Light Localization occurs in carefully engineered dielectrics.**
- **Photonic Band Gap formation is a synergetic interplay between microscopic and macroscopic resonances.**
- **1-D and 2-D photonic crystals are easy to fabricate.**
- **3-D PBG materials: inverse diamond, woodpile, inverse opal, Scaffold and square spiral.**
- **Plane, line or point defects can be introduced into photonic crystals and used for making waveguides, microcavities or perfect dielectric mirrors by localization of light.**
- **Applications – photonic crystal fibers, lasers, waveguides, add drop filters, all-optical transistors, amplifiers, routers photonic integrated circuits, optical computing.**



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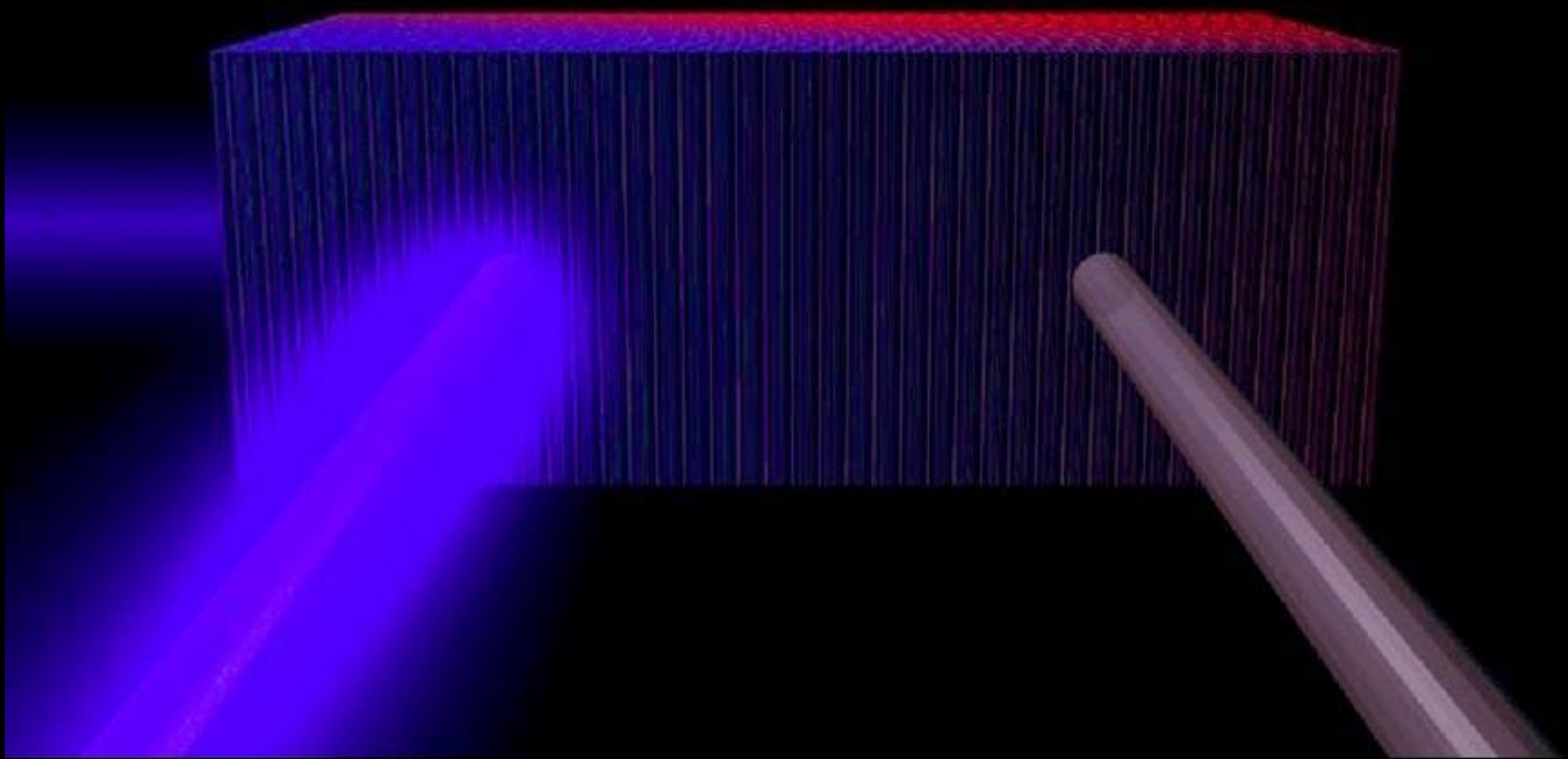
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