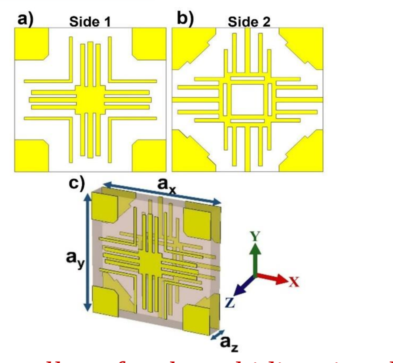
MICROWAVE LABORATORY: MULTIFERROIC MATERIALS AND MICROWAVE DEVICES

Faculty: *Dr. V. Subramanian*

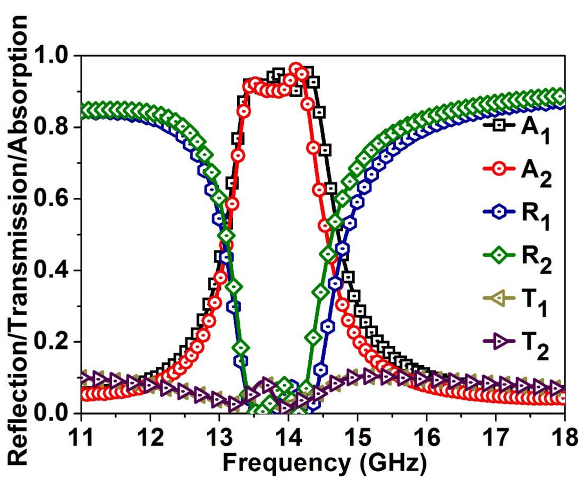
Research Scholars: *Lincy Stephen, Vasantharajan Ganesan, Pranab Biswas, Anjali M, Deepa Xavier, Santosh Dasila, Sarvesh Kumar, Rameez P and Vinaya Kumar*

Realization of Bidirectional, Bandwidth Enhanced Metamaterial Absorber for Microwave Applications

- Perfect absorber is a material which absorbs all the incident radiation at the operating frequency while minimizing the transmission and reflection.
- Metamaterials can be used to make EM absorber by engineering the complex permittivity and permeability.
- Advantageous over the conventional absorbers as metamaterial absorbers can be polarization insensitive, wide angle receptive and can have small size and less thickness.

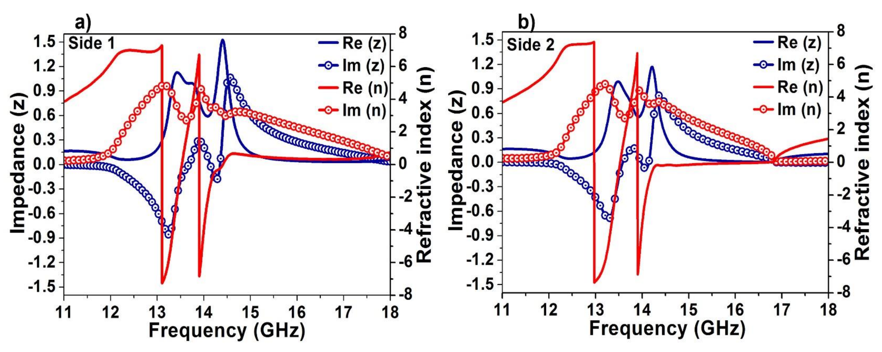


Unit cell of the bidirectional absorber structure a) front layer b) back layer c) perspective view

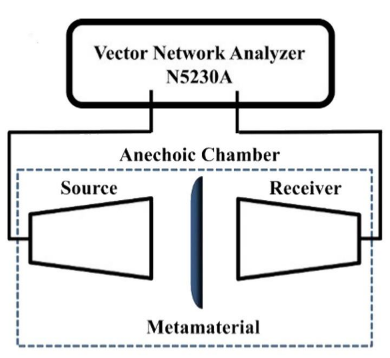


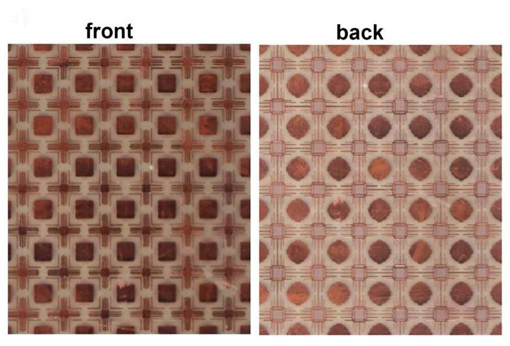
$A_1(A_2)$, $R_1(R_2)$, $T_1(T_2)$ –Absorption, Reflection and Transmission from Side 1(Side 2)

- Design comprises of metal-dielectric-metal configuration with squares and strips.
- Contrary to most of the metamaterial absorbers which uses a complete metallic film on one side of the substrate, the proposed absorber utilizes metallic patterns on both the sides enabling broadband absorption from both incident directions.
- The metallic patterns are made of copper with thickness of 0.034 mm and dielectric layer is FR-4 with a thickness of 1.5 mm and dielectric constant of 4.3.
- Optimized design gives Absorption, A=1-R-T
  - A_1 >90% from 13.38 GHz to 14.4 GHz (bandwidth of 1.02 GHz)
  - A_2 > 90% from 13. 40 GHz to 14.25 GHz (bandwidth of 0.85 GHz)

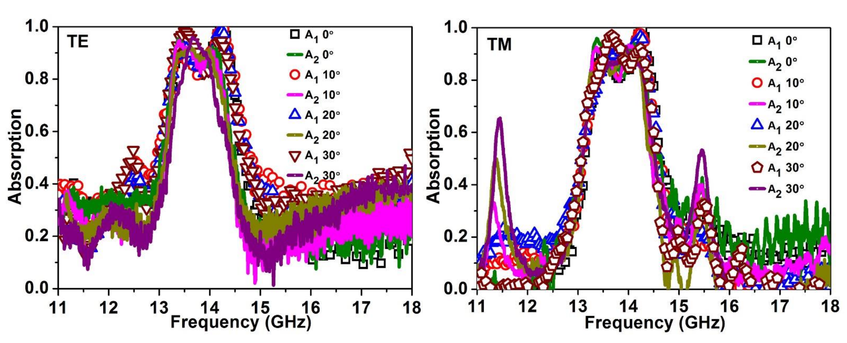


- The two conditions for perfect absorption, are minimum reflection implies impedance matching with the surroundings and minimum transmission suggests a large loss in the structure which is indicated by a positive value of the imaginary part of the refractive index in the effective refractive index spectrum.
- From13. 40 GHz to 14.25 GHz impedance values are in between the range 0.56 and 1.4 imaginary part of refractive index values are in between 2.71 and 4.61.

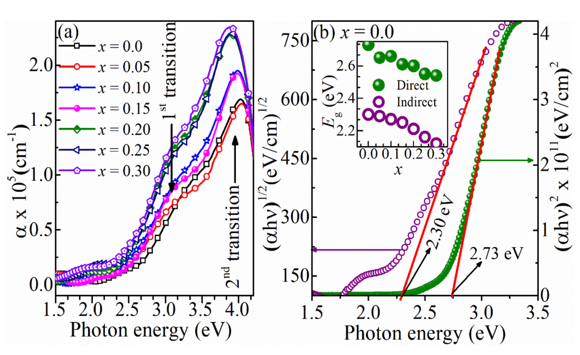


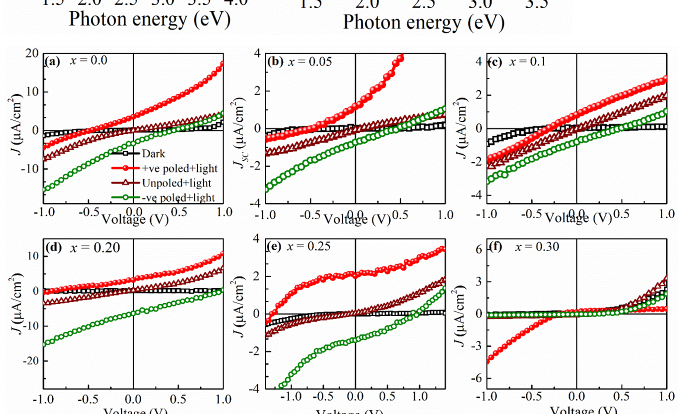


- Microwave experiment is carried out on the fabricated sample using free space method with Ku-band (12 GHz to 18 GHz) horn antennas and a network analyser (N5230A).
- The fabricated metamaterial board is kept between the two horn antennas.
- Reflection measurements are normalized with respect to a reference metal and transmission measurements are normalized with respect to free space .
- Due to the rotational symmetry of the design the proposed absorber exhibits polarization insensitivity.
- For TE polarization, A_1>90% from 13.37 GHz to 14.38 GHz (bandwidth of 1.01 GHz) and A_2>90% from 13.30 GHz to 14.20 GHz (bandwidth of 0.9 GHz).
- For TM polarization, A_1>90% from 13.4 GHz to 14.37 GHz (bandwidth of 0.97 GHz) and A_2>90% from 13.29 GHz to 14.20 GHz (bandwidth of 0.91 GHz)



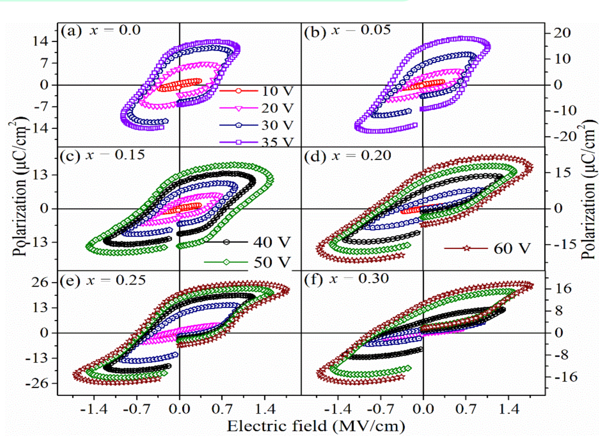
Phovoltaic Effect on La Doped $BiFeO_3$ Films





- Reduced direct E_g increases absorption; reduced indirect E_g decreases radiative recombination rate.

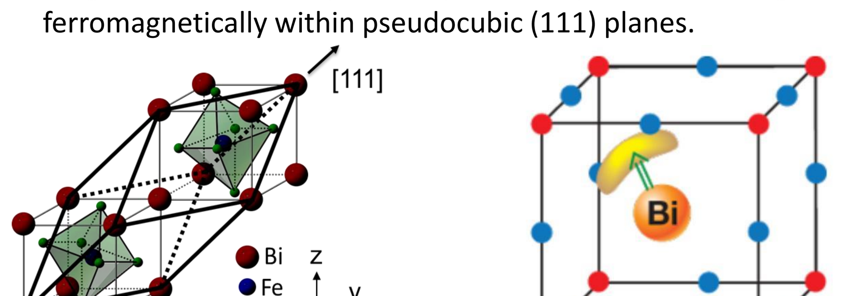
La (%)	V_{OC} (V)	J_{SC} (μA/cm²)
0	-0.47	3.53
5	-0.47	1.17
10	-0.31	0.82
15	-0.52	4.05
20	-0.92	3.24
25	-1.30	2.02
30	-0.189	0.16



- For x = 0.25, P_r = 25 μC/cm²
- For x = 0.30, *P-E* loop shows change in shape with repressed P_r → trademark sign of phase evolution.

$BiFeO_3$ – based perovskite compounds

- Multiferroics exhibit more than one primary ferroic ordering (ferromagnetism, –electricity, –elasticity or –toroidicity) in the same phase. The expression is extended to include non-primary orderings (antiferromagnetism) as well as ferroic composites.
- $BiFeO_3$ (BFO) is a single phase mutliferroic with rhombohedrally distorted perovskite cells (R3c). Ferroelectric (below Tc ~ 830°C) and antiferromagnetic (AFM) G-type (below T_N ~ 370°C with weak ferromagnetism).
- Major drawbacks – relatively high leakage current – induced by Fe^{2+} to Fe^{3+} e-hopping through oxygen vacancies. Difficult to synthesis pure single-phased BFO – therm. stability of Fe^{2+} comparable to Fe^{3+} (unstable perovskite phase). Extremely high coercive field – demands large bipolar switching. Realisation of a large polarisation in bulk BFO still remains a challenge.
- Structural distortions: Large displacement of Bi^{3+} ([111] relative to the FeO_6 octahedra (stereochemical activity of the Bi^{3+} $6s^2$ lone pair es) – Spontaneous ferroelectric polarization (<111>). Each Fe^{3+} spin is surrounded by six antiparallel spins on the nearest Fe (G-type AFM). Magnetic moments/spins couple AFMlly between neighbouring ferromagnetically within pseudocubic (111) planes.

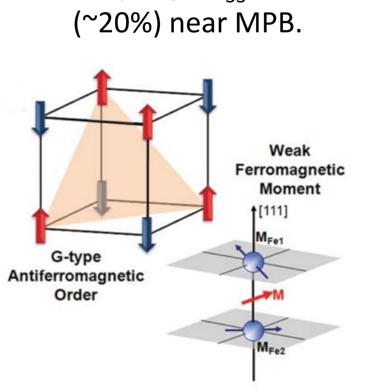


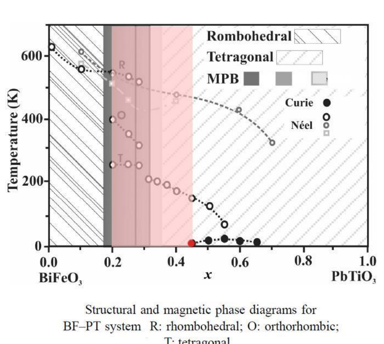
(Spaldin, 2019; Yang, 2015: and McKinstry, 2018) and (Leist, 2010; and Feitas, 2013)

- AFM spin structure is modified by a long-range (~620 Å periodicity) modulation leading to a 'spiral modulated spin structure' – cancellation of macroscopic magnetization.
- AFM moments are perpendicular to the <111> – the symmetry permits a canting of the AFM moments between neighbouring planes - a weak ferromagnetic moment (Dzyaloshinskii–Moriya). AFM plane – always perpendicular to the ferroelectric polarization (intrinsic coupling).
- *Spiral spin modulation of the canted-AFM spin led to the cancellation of the spontaneous, macroscopic magnetisation*

How to suppress the spiral spin modulation?

- Solid state solutions: Alloy $BiFeO_3$ with other perovskite ABO_3 materials (forming pseudo-binary systems) such as $BaTiO_3$, $PbZrO_3$, or $PbTiO_3$.
- $PbTiO_3$ has tetragonal structure (*P4mm*), very good ferroelectric, piezoelectric perovskite (Pb^{2+} classical lone pairs), and induces chemically ordered micro-regions where spiral spin modulation decreases.
- Helps in phase stabilisation, in strong magnetoelectric coupling (α_{33}) and in achieving large tetrogonality (~20%) near MPB.



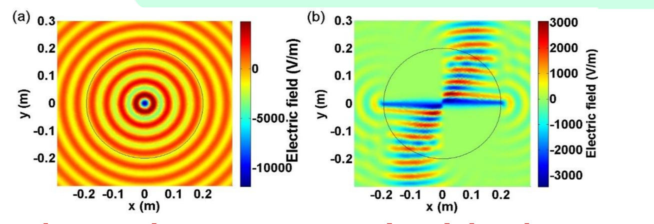


Freitas, 2013; Leist, 2009 and 2010; Martin, 2010; McKinstry, 2018; Narayan, 2018; Spaldin, 2019; and Yang, 2015

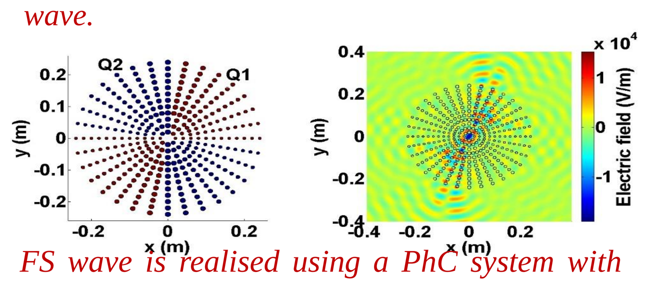
$BiFeO_3$ – $PbTiO_3$ (BF–PT)

- In BF–PT, the rhombohedral $BiFeO_3$ is associated with the magnetic properties whereas the tetragonal $PbTiO_3$ is associated with ferroelectric/piezoelectric properties.
- Phase diagram – coexistence of rhombohedral and tetrogonal in the MPB [MPB ~ x ($PbTiO_3$) = 0.20 to 0.45]. Claims of orthorhombic/monoclinic phase (*Cc*) in MPB.

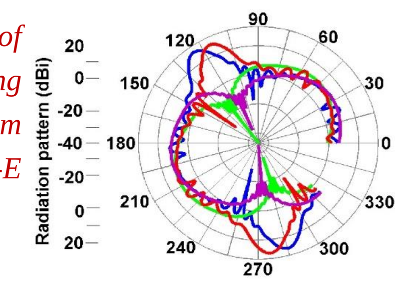
Transformation Optics for Microwave Applications



The circular em wave produced by the point converted charge is into a Fermat spiral (FS) wave.



FS wave is realised using a PhC system with two different dielectric Q1 and Q2 as shown in figure



Radiation pattern of the field emanating from the T-E system as we rotate the T-E disk.

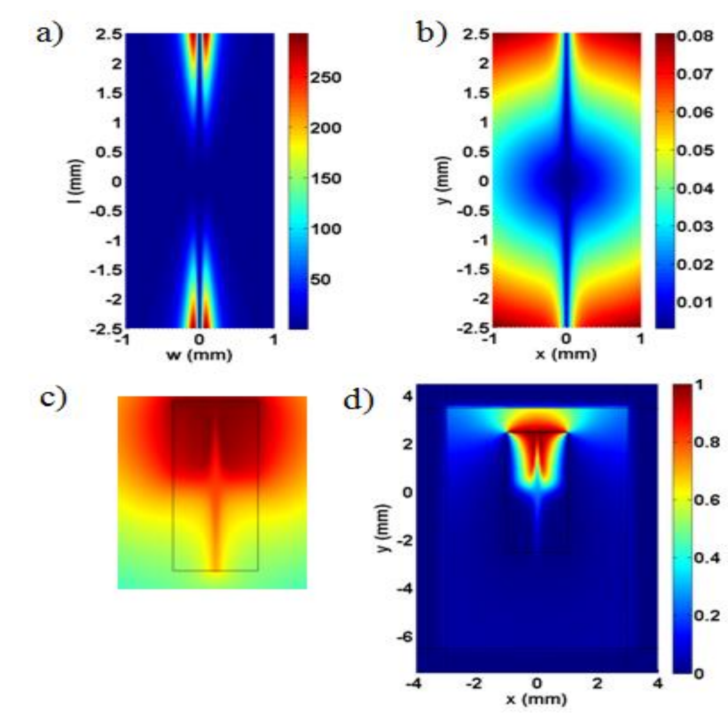
- Maxwell equations are form-invariant under coordinate transformation (CT) and the electromagnetic (em) waves follow the geodesics of the medium are the prime facts based on which transformation electromagnetics (T-E) work.
- Using CT, the geodesics of the spaces are distorted and the em wave flows through the distorted geodesic.
- Electromagnetically speaking, the distorted geodesic can be equated to a new medium with permittivity (ε) and permeability (μ) values different from the undistorted space.
- Devices such as cloak, hyperlenses, beam steerer, wave concentrator, field rotators, lenses like flat lens, Lunberg lens, etc. are realised.
- In electromagnetics, the theoretically proposed devices are achieved using metamaterials (MMs) and photonic crystals (PhCs).
- The major drawback of the T-E is the fabrication of MMs (or the arrangement of PhCs) according the desired application based on ε and μ.
- The application of T-E has been extended to various fields such as acoustics, acousto-optics, heat flow, hydrodynamics, seismology, etc.

Beam Steering using Fermat spiral configuration

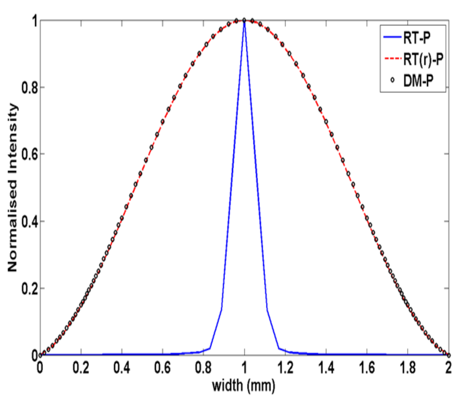
- A point charge placed in a 2-dimensional (2D) isotropic space will produce circular wavefront. By converting the surrounding space with required ε and μ, circular wavefront can be modified as Fermat spiral (FS) wave.
- A point charge in 2D could be interpolated to a line charge in 3D and the T-E medium could be constructed as a disk with positive and negative medium planes connected by a knot.
- By rotating the disc in the desired fashion, beam can be steered at all directions and desired antenna radiation (bi-directional or dipolar) can be obtained (antenna switching).

Near field (NF) producing and magnifying media in sub-diffraction limit

- A flat lens, that could reduce the intensity of the incoming em wave and could emanate a near field wave is constructed using rectangular transformation (RT) and placed inside PEC for focusing (named as RT-P medium)
- This will be an alternate to metalenses and hyperlenses, for magnification of the closely placed em sources
- The NF T-E medium with highly anisotropic ε and μ can be replaced by achieving an em media (like near isotropic bilayer) using reduced parametric T-E approach (named as RT(r)-P medium)
- For practical realisation a discrete medium (DM) is constructed, simulated and verified that it behaves as RT(r)



a) ε_{yy} profile of the TO medium, b) Ez field map at 6 GHz inside TO medium (Zoomed), c) Ez map at 6 GHz inside TO medium placed inside PEC d) effective refractive index of TO medium



Comparison of intensities along exiting line for RT-P, RT(r)-P and DM media

Transformation Optics and Transformation Acoustics

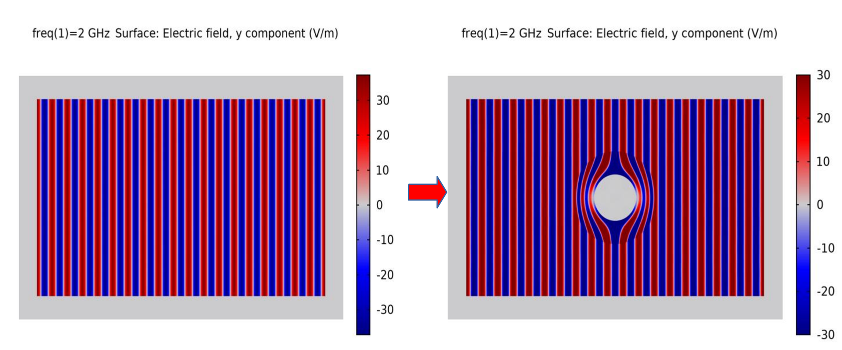
- Transformation optics and transformation acoustics are the mathematical tools that simplify the design and modelling of optical and acoustical devices by alternating the coordinate system.
- These techniques are drawn on a correspondence between coordinate transformation and materials parameters.
- Complex artificial materials known as Metamaterials are used to produce transformation in optical and acoustical space.

Transformation Optics

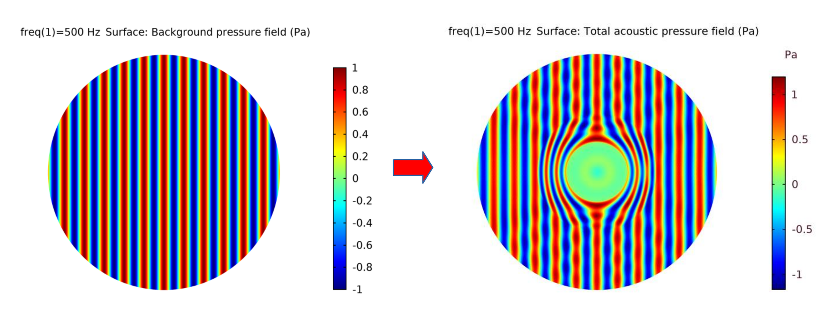
- In EM system, the magnetic field vector (B), the electric displacement vector (D) and Poynting vector (S) transform in a certain way in order to preserve the form of the Maxwell's equations.
- Since the Maxwell's equation retain the same form under coordinate transformation, it is the successive value of permittivity and permeability that change over time.

Transformation Acoustics

- The same idea of transformation can be applied to acoustical waves where mass density tensor and bulk modulus are the associated parameter to coordinate transformation.
- Any manipulation of sound fields that can be described by a coordinate transformation can be realized through complex acoustic materials defined by the transformation itself.



Electric field distribution (a) Without Cloak (b) With Cloak

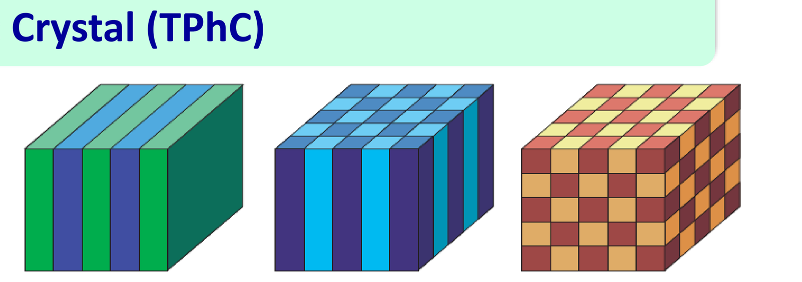


Acoustic pressure field distribution (a) Without Cloak (b) With Cloak

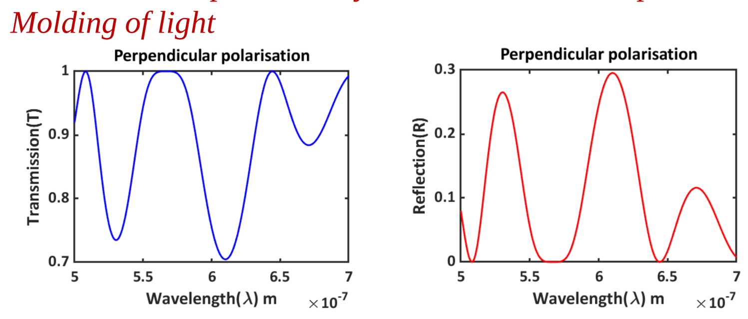
Temporal Photonic Crystal (TPhC)

Photonic Crystal (PhC)

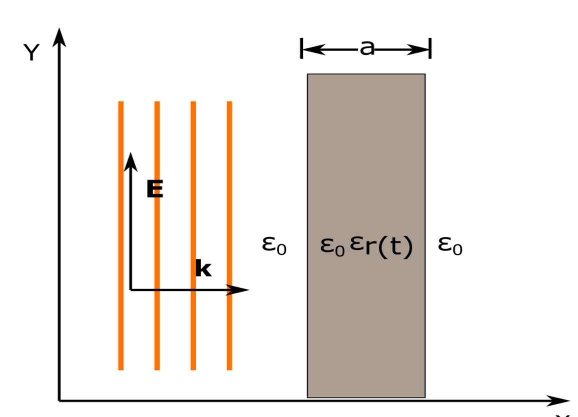
- Photonic Crystals are periodic arrangements of different media with varying electrical permittivities.
- The macroscopic spatial periodicity, like periodic arrangements of atoms or molecule in crystal lattice that results in electronic band gaps, give rise to photonic band gap.
- Depending on the directional periodicity photonic crystals are of three types 1D, 2D and 3D.
- Photonic band gaps (PBG) block electromagnetic waves of certain wavelengths. This gives us leverage to control the propagation of light in certain directions in photonic crystals.



1D, 2D and 3D photonic crystals; John D Joannopolous et. al., Molding of light



Band gap in 1D photonic crystal.



Schematic diagram of plane wave incident on A dynamic medium.

Temporal Photonic Crystal

- Temporal Photonic Crystals (TPhC), unlike photonic crystals (PhC), have time dependent electrical permittivity ε(t). The dynamic interface and bulk of a dielectric medium influence the reflection and transmission of incident electromagnetic wave (EMW).
- Similar to frequency gap or band gap in PC, we expect a k-gap in TPC.
- Reflected and transmitted EMW have upshifted frequency than incident.
- Dynamical electrical permittivity system can produce pair of photons from vacuum states (analogous to Casimir Effect).
- Self phase modulation of a plane EMW due to decreasing refractive index w.r.t. time exhibit Unruh effect like phenomenon.