Electromagnetic Interactions in Non-Magnetized and Magnetized Plasma Metamaterials and Photonics Crystals

Mark A. Cappelli
Stanford University

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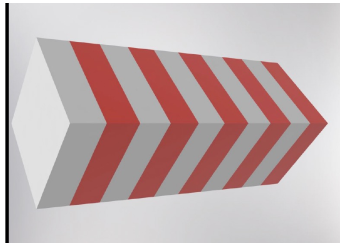
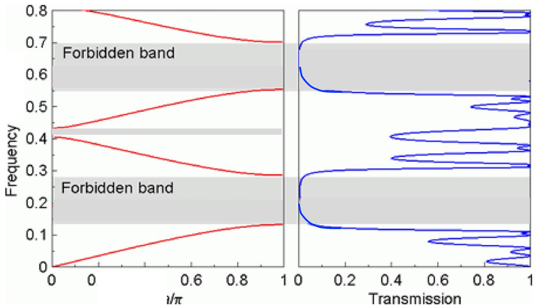
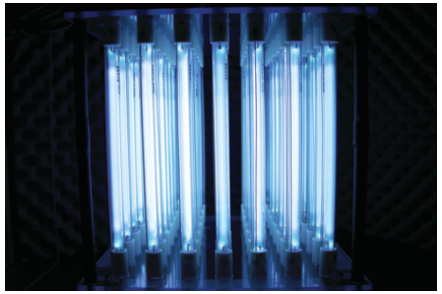
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

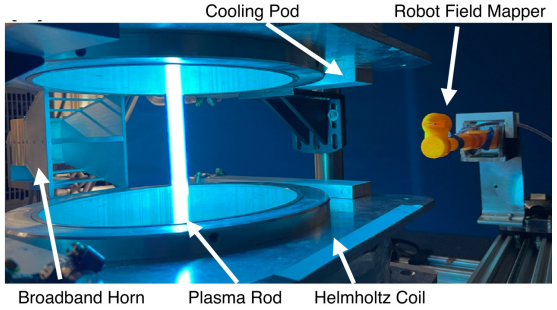
Outline

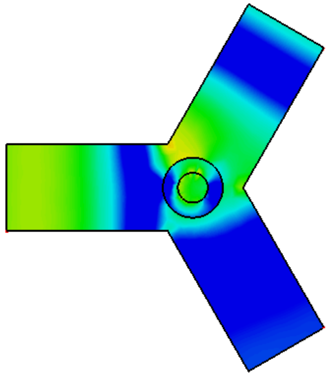
- Introduction
- Non-magnetized plasmas as elements in electromagnetically active systems
- Magnetized plasmas
- Some applications

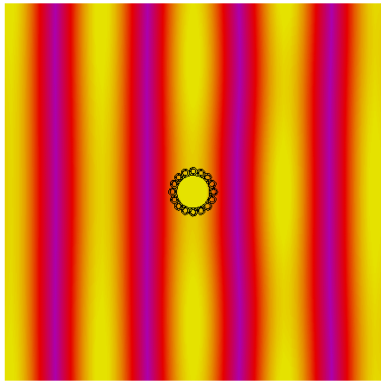






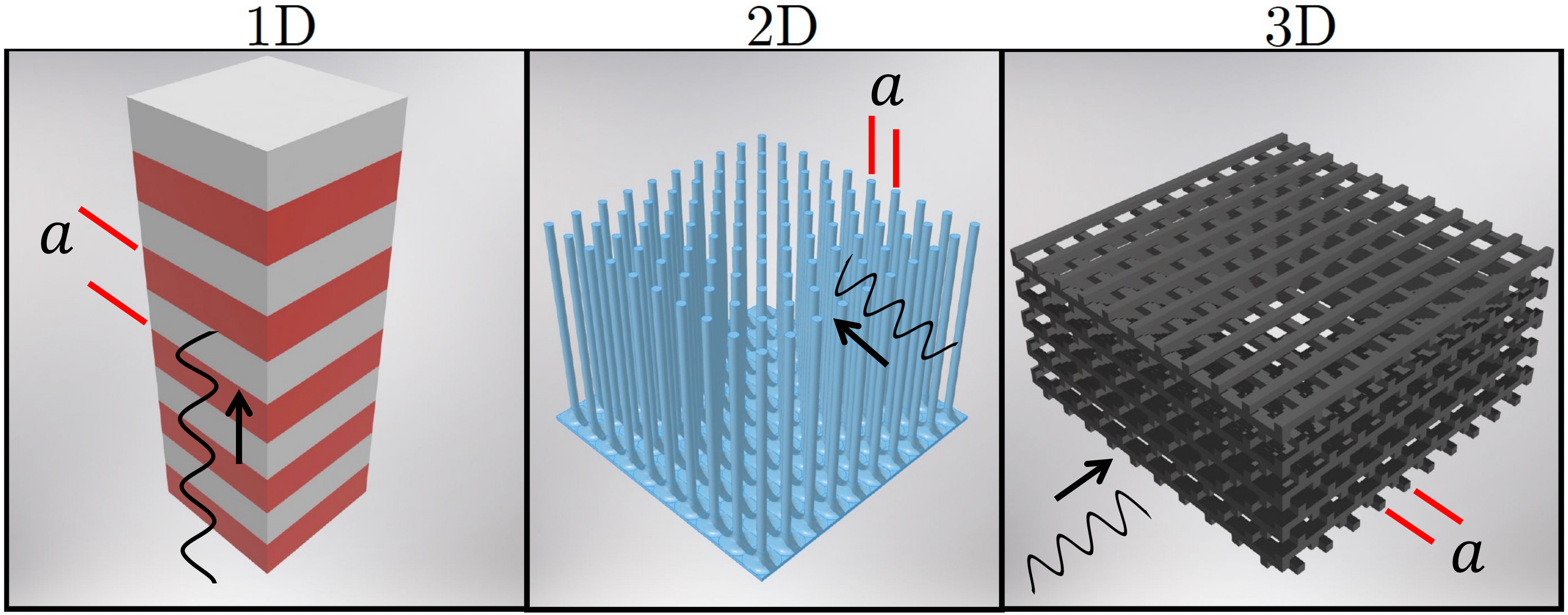






Introduction

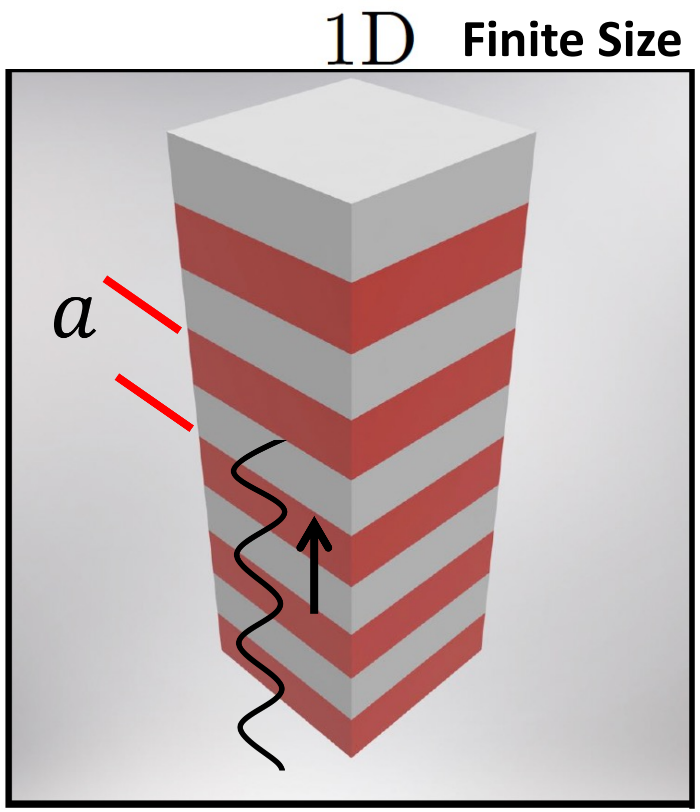
Photonic Crystals

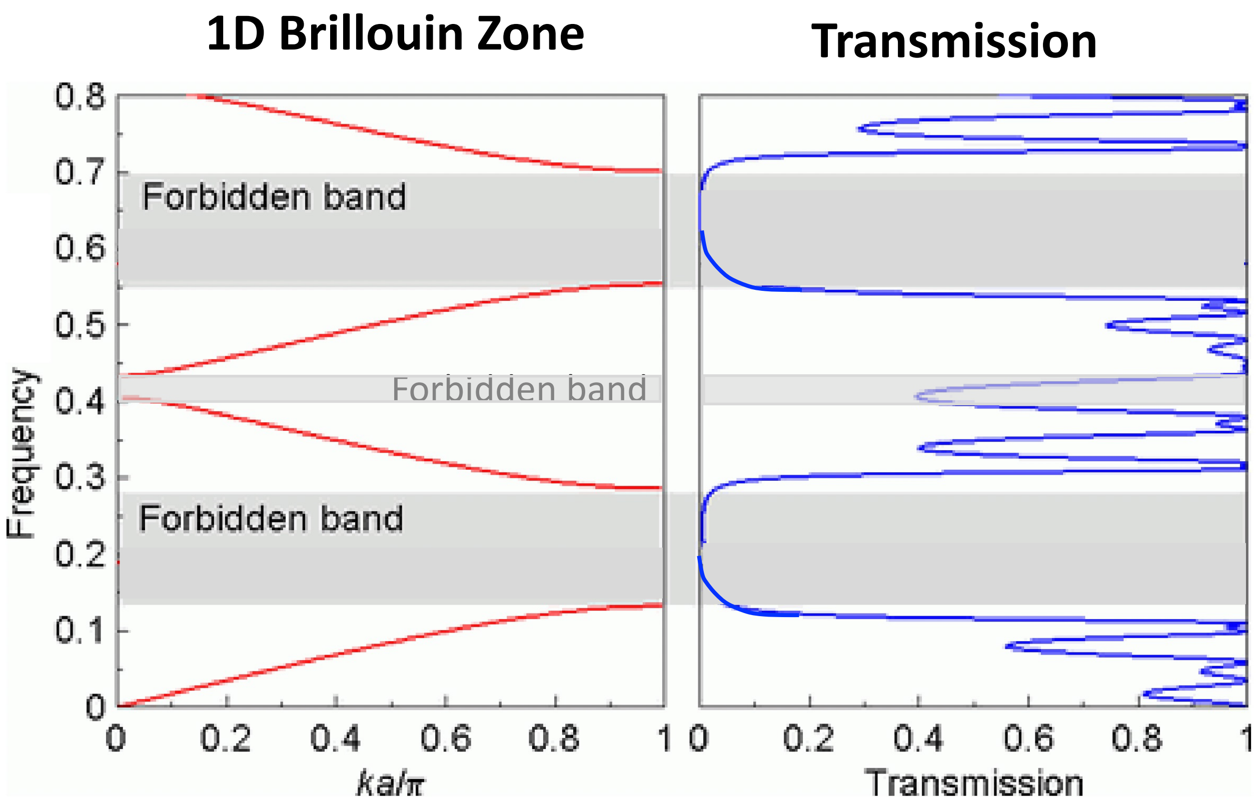


Successive (Bragg) scattering of EM waves results in the formation of bandgaps

Introduction

Photonic Crystals



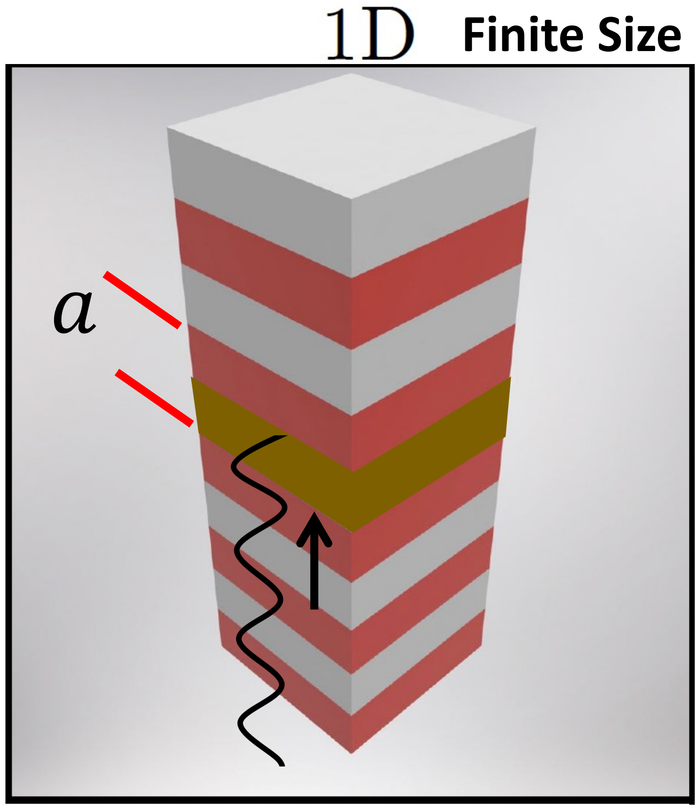


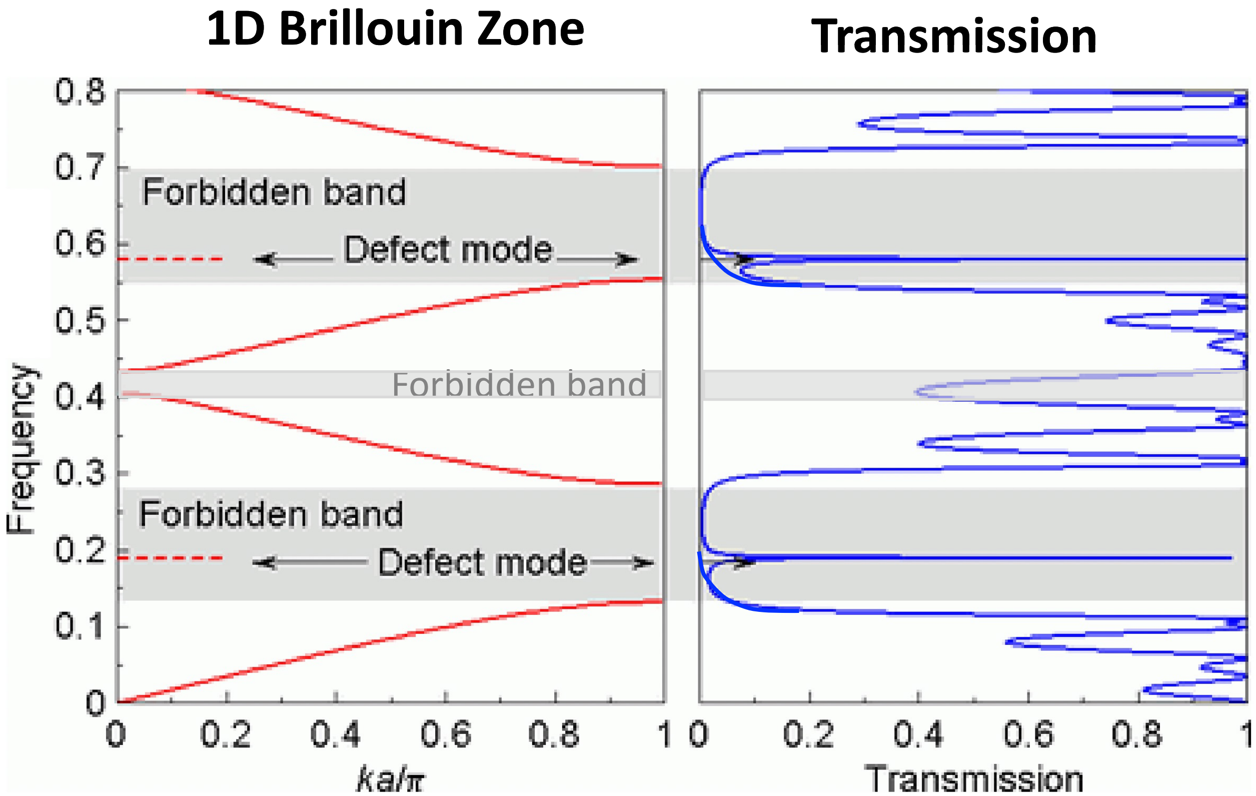
Successive (Bragg) scattering of EM waves results in the formation of bandgaps

Image Creidt: F. Koenderink

Introduction

Photonic Crystals





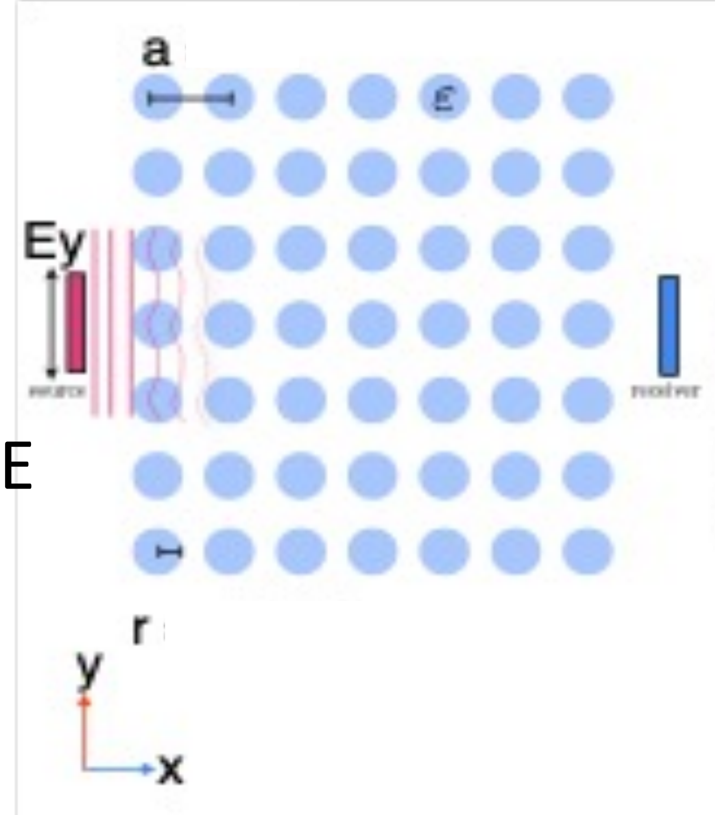
Successive (Bragg) scattering of EM waves results in the formation of bandgaps

Image Creidt: F. Koenderink

Two-Dimensional Photonic Crystals

Array of Dielectric Columns

Square Lattice Array of Dielectric Rods



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2D calculation (infinite size/square)

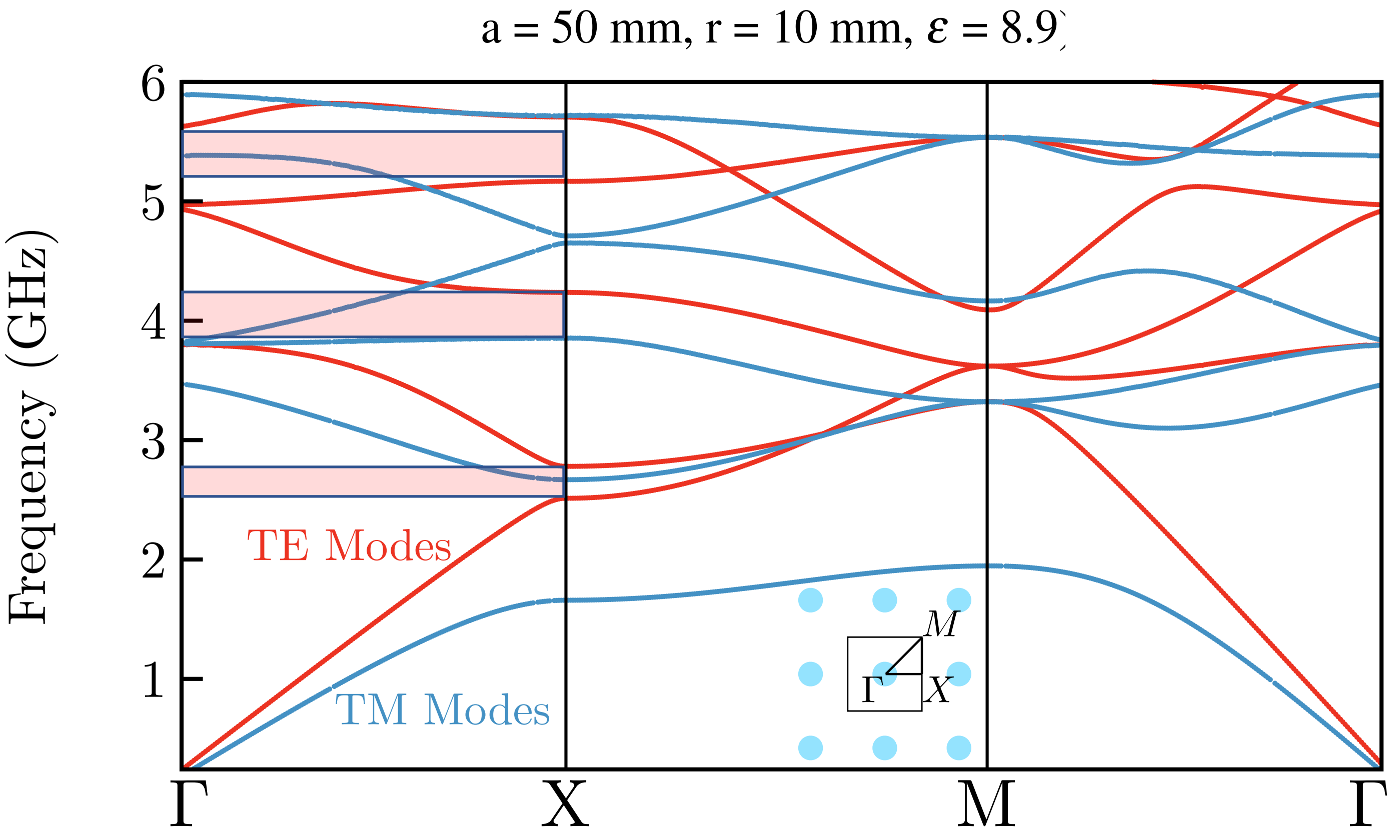
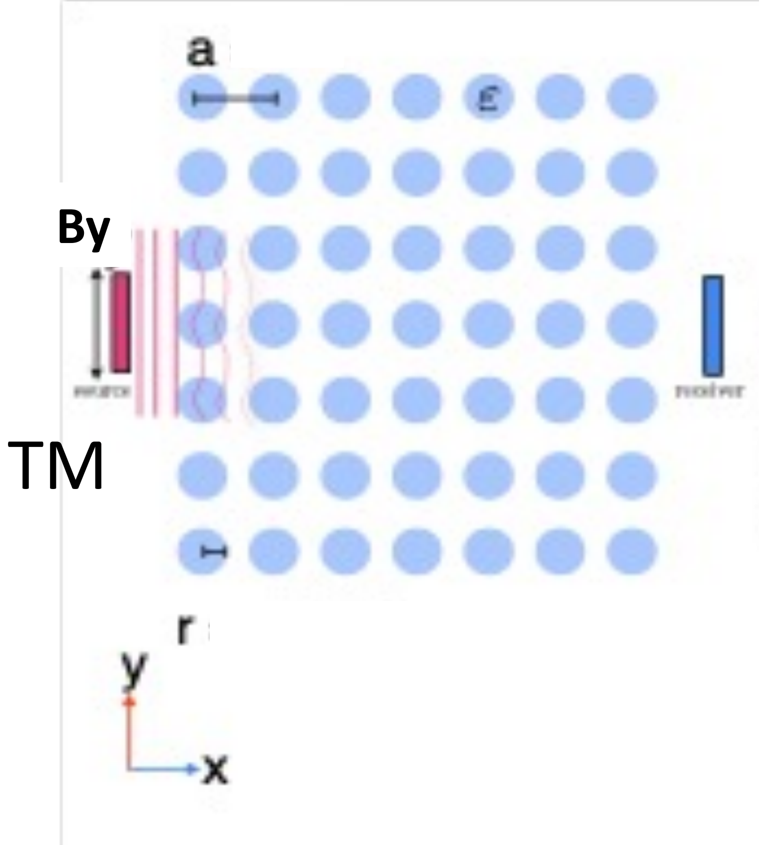


Figure credit - B. Wang

Two-Dimensional Photonic Crystals

Array of Dielectric Columns

Square Lattice Array of Dielectric Rods



2D calculation (infinite size/square)

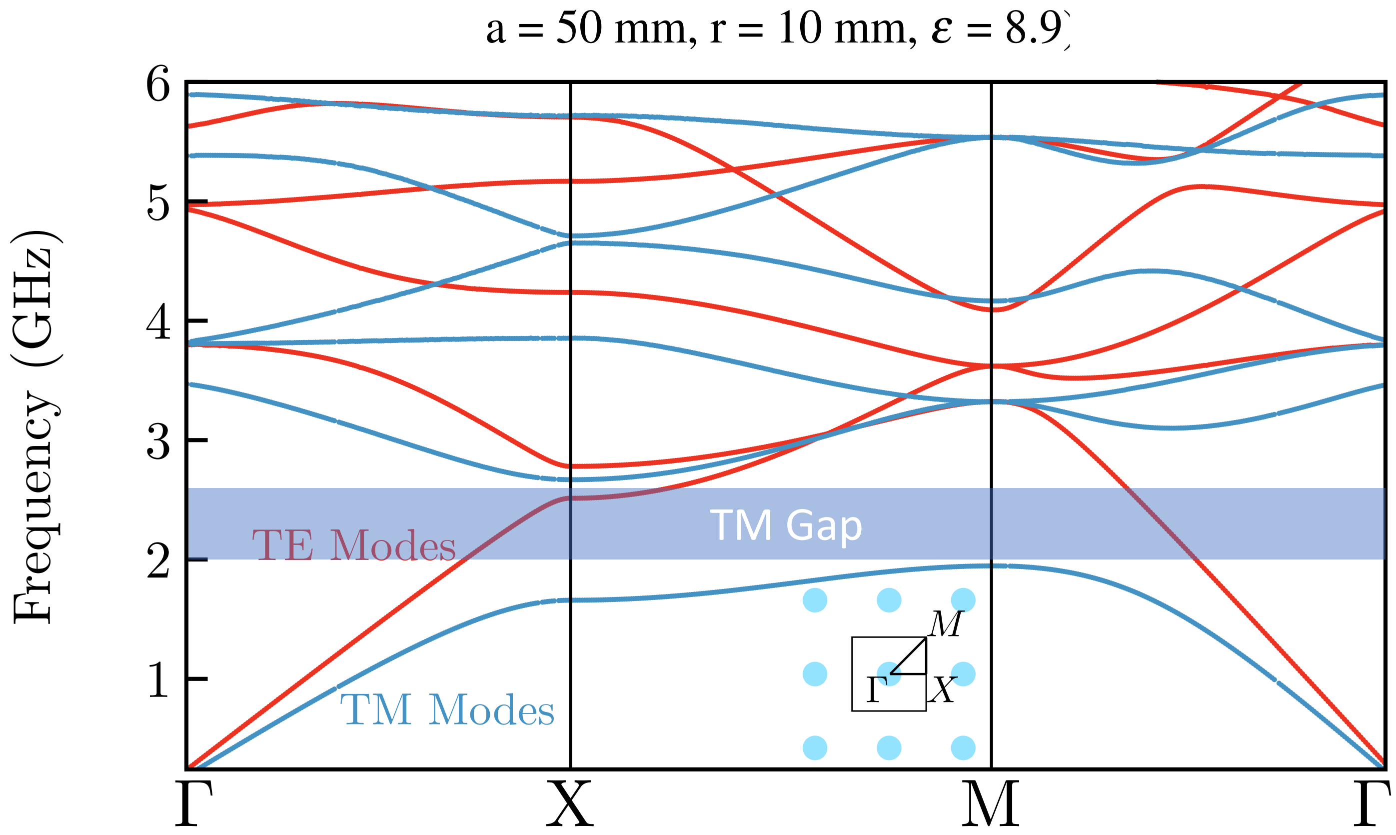
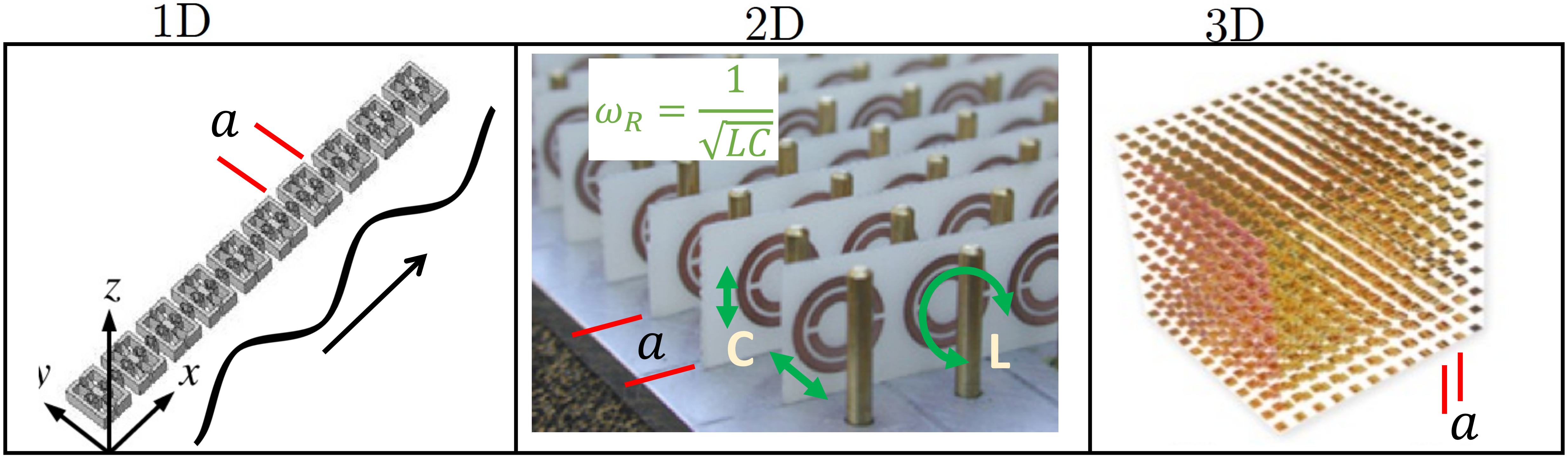


Figure credit - B. Wang

Introduction

Metamaterials $(\lambda \gg a)$ (Sub-Wavelength)



C. Cai et al., 2020

D.R. Smith et al., 2000

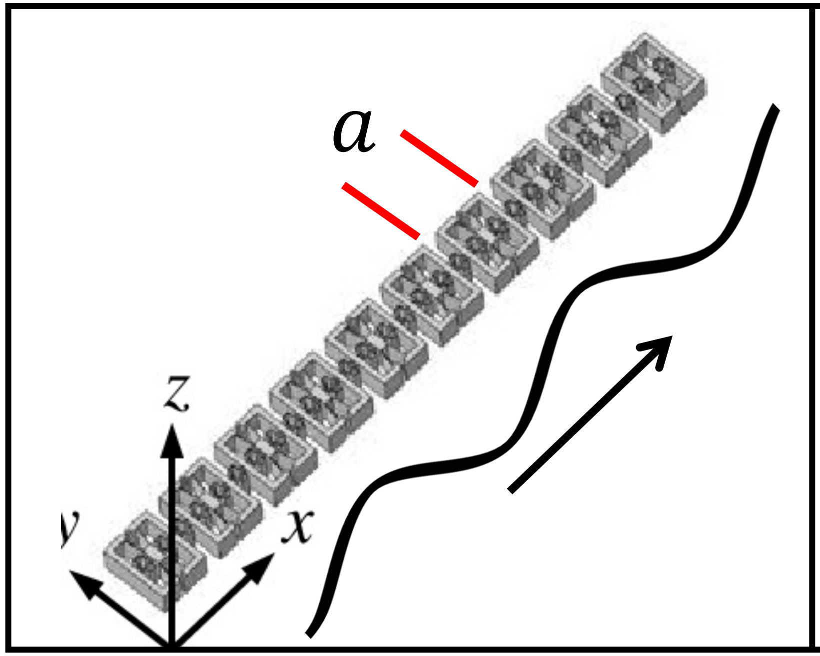
Meng et al., 2021

Wave fields drive structure inductive and capacitive resonances to produce local effective properties ε, μ

Introduction

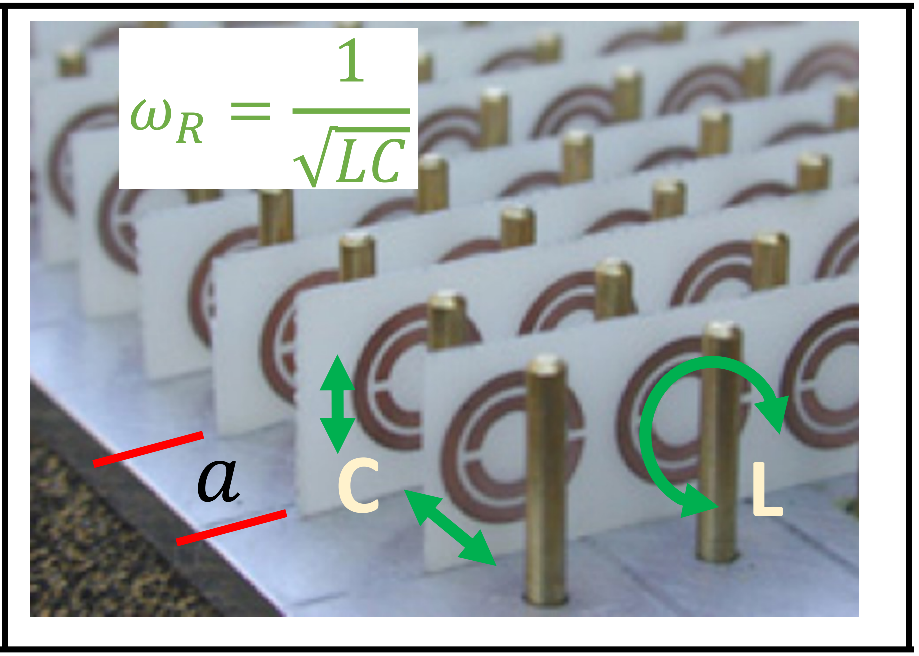
Metamaterials $(\lambda \gg a)$

1D



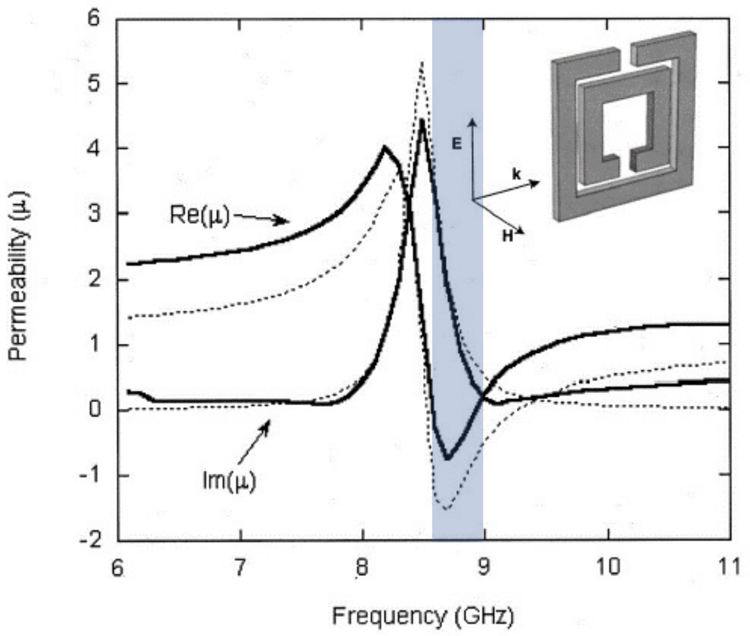
C. Cai et al., 2020

2D



D.R. Smith et al., 2000

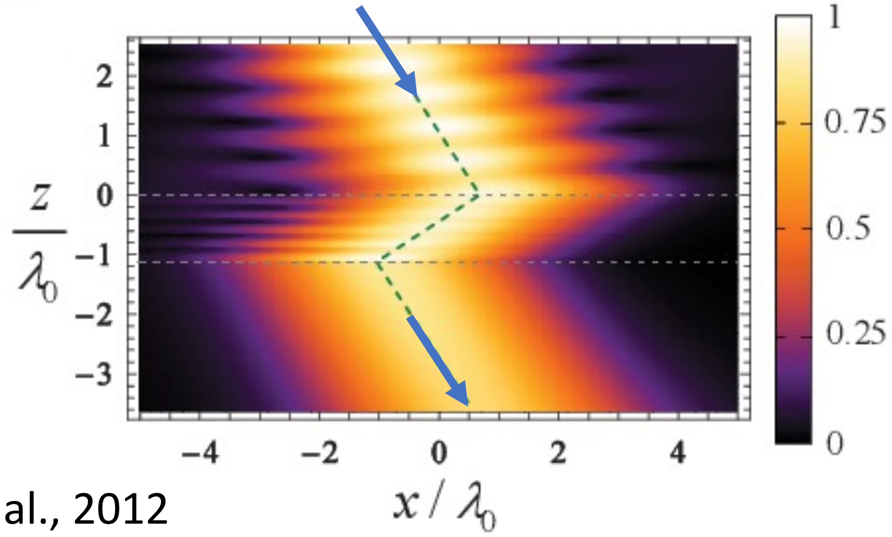
Smith et al, 2002 (EM Simulations/Experiments)



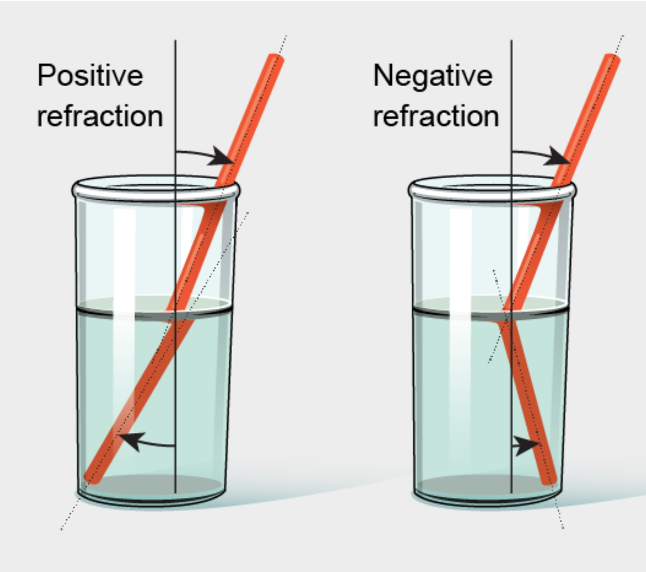
Wave fields drive structure inductive and capacitive resonances to produce local effective properties ε, μ

Introduction

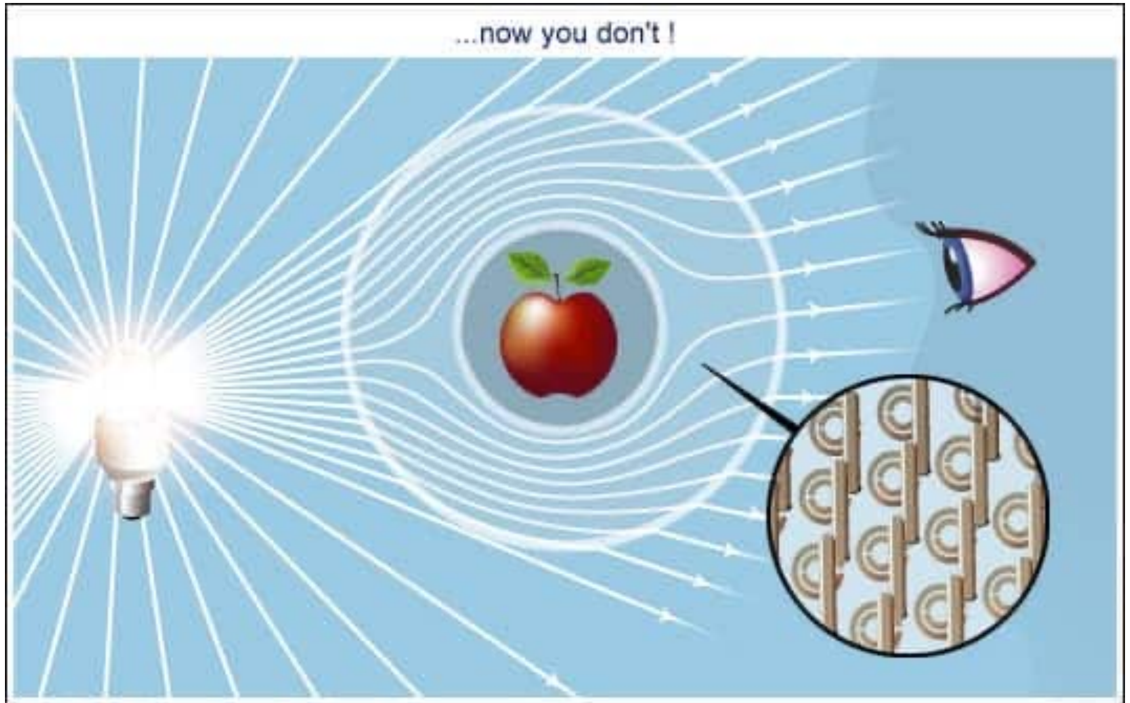
Negative Refraction



Tiago et al., 2012



Invisibility Cloaks

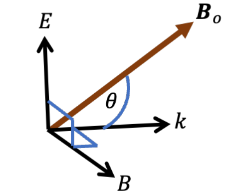


Thanks to tiny, carefully placed metal rods and rings, metamaterials can bend light around an object. If light can't reach it, we can't see it. To date scientists have only been able to make things disappear in the microwave range of frequencies, but it wouldn't be a physics illustration without an observer or an apple.

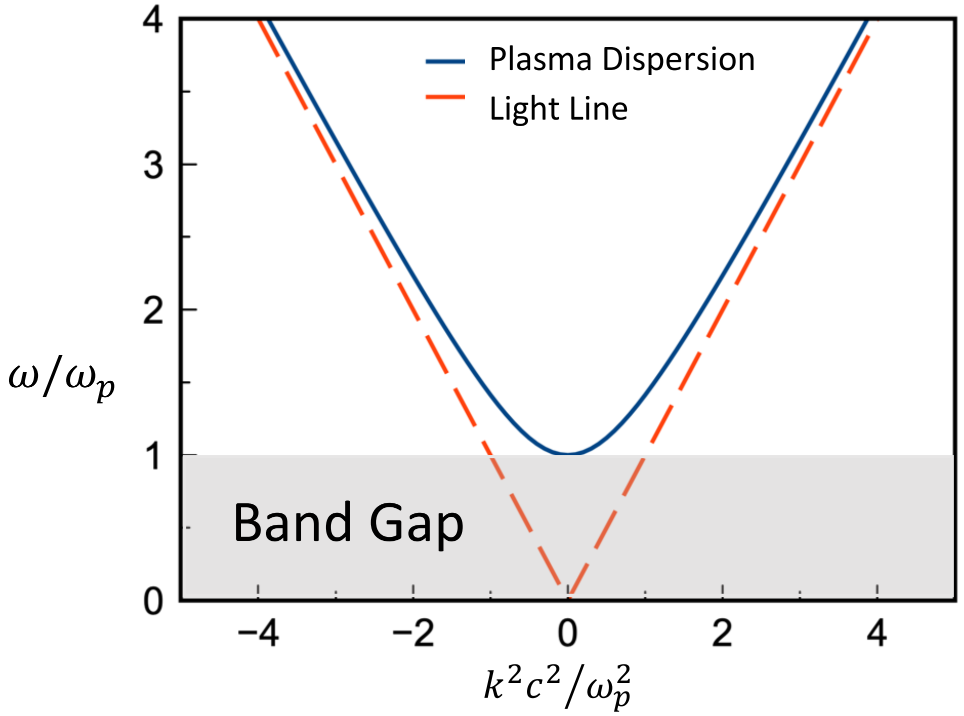
ZME Science

Plasma Electromagnetics

Bulk Plasma Dispersion

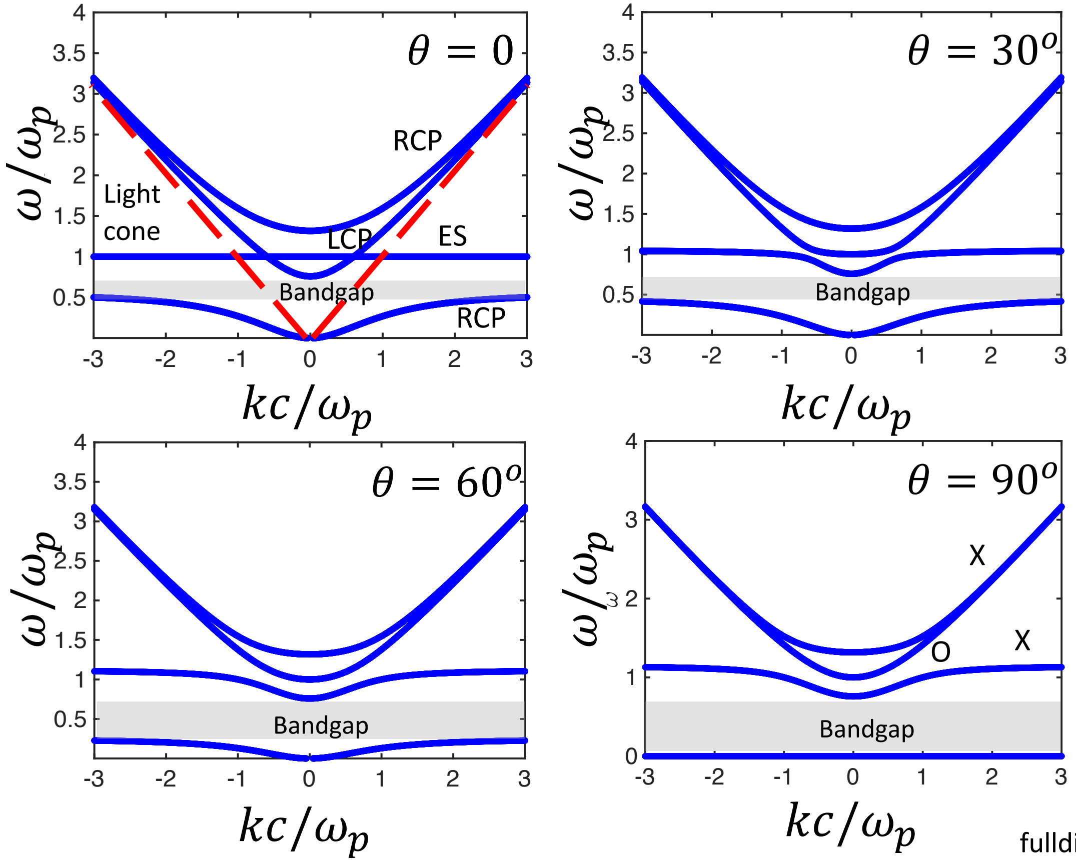


Non-Magnetized



- Stop band below the plasma frequency
- “Fast waves” above the plasma frequency

Magnetized



fulldisp.m

- Multiple bandgaps emerge
- “Slow waves outside the light cone

Plasma Electromagnetics

Finite Size Plasma Electromagnetics

- Previous result applies for infinite medium
- EM “tunnels” through plasma slabs
  - $n = ck/\omega = \sqrt{\varepsilon_p} = \sqrt{1 - \omega_p^2/\omega^2}$

    imaginary for $\omega/\omega_p < 1$
  - evanescent wave $\boldsymbol{E}_o e^{-i\omega t} \underbrace{e^{-\frac{\omega}{c}\lfloor \boldsymbol{n} \rfloor \cdot \boldsymbol{r}}}_{\text{decays exponentially}}$
  - wave energy transmitted and reflected:*

$$T = \frac{1}{\left|1 + \frac{d}{2}\left(\frac{\sigma_p}{\varepsilon_o c}\right)\cos\theta\right|^2}$$

$R = 1 - T$

θ represents angle of incidence

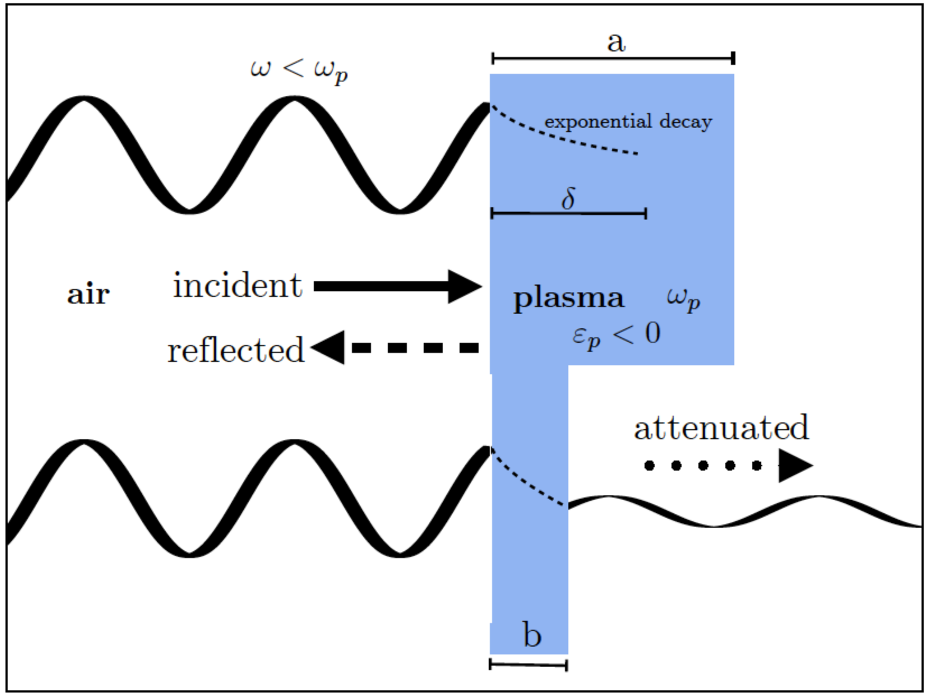
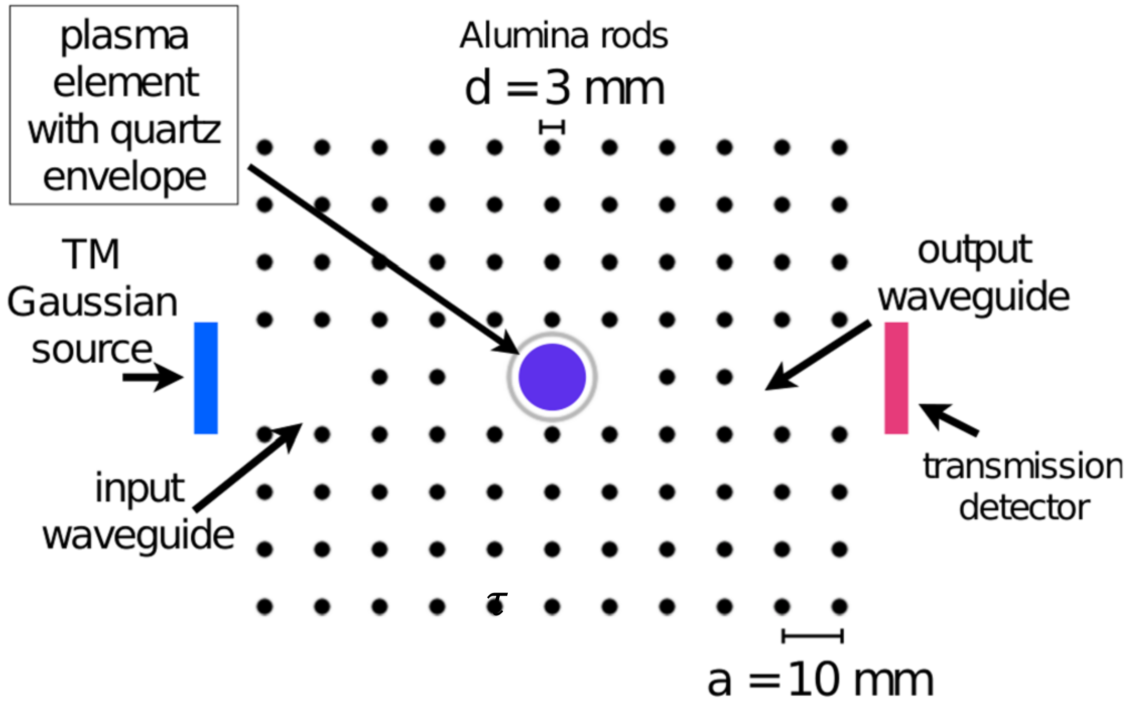


Figure credit - B. Wang

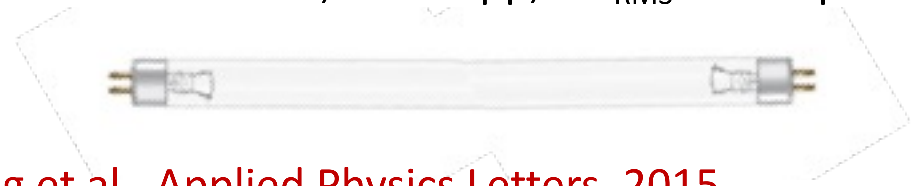
*Latyshev and Yushkanov, Optics and Spectroscopy, 2011, Vol. 110, No. 5, pp. 795–801.

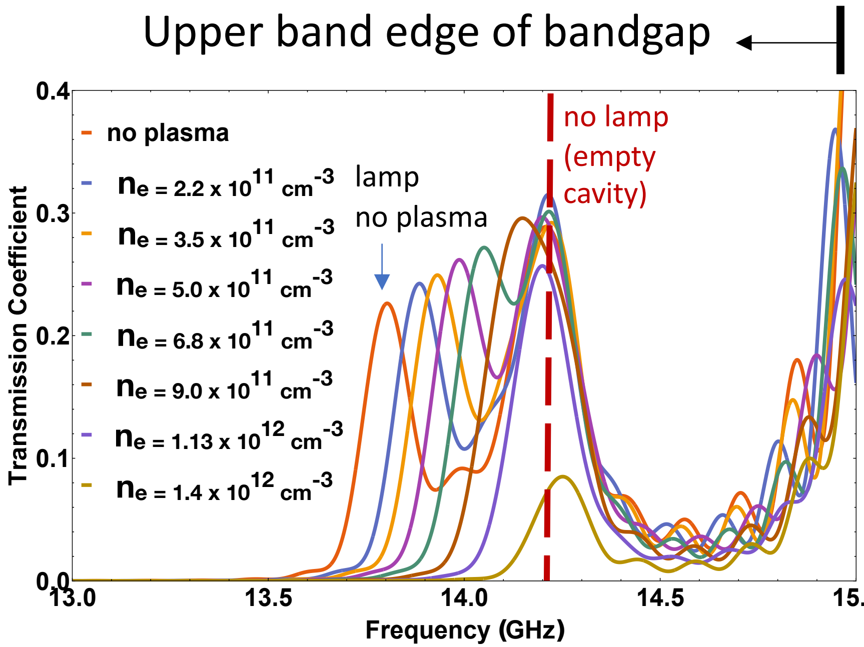
Plasma Loaded Photonic Crystal Vacancies

Plasma-Tuning of Defect State Transmission



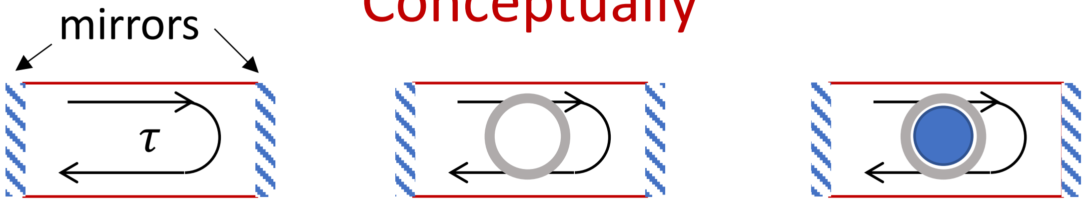
- AC Hot-electrode discharge plasma (Ar-Hg)
  - 250 Pa, ~150V pp, 0.2_{RMS} 1 mm quartz





FDTD Simulations

Conceptually



$\omega_R = \omega_o \approx 1/\tau$ — empty cavity

$\omega_{QF} < \omega_o$ — quartz-filled cavity

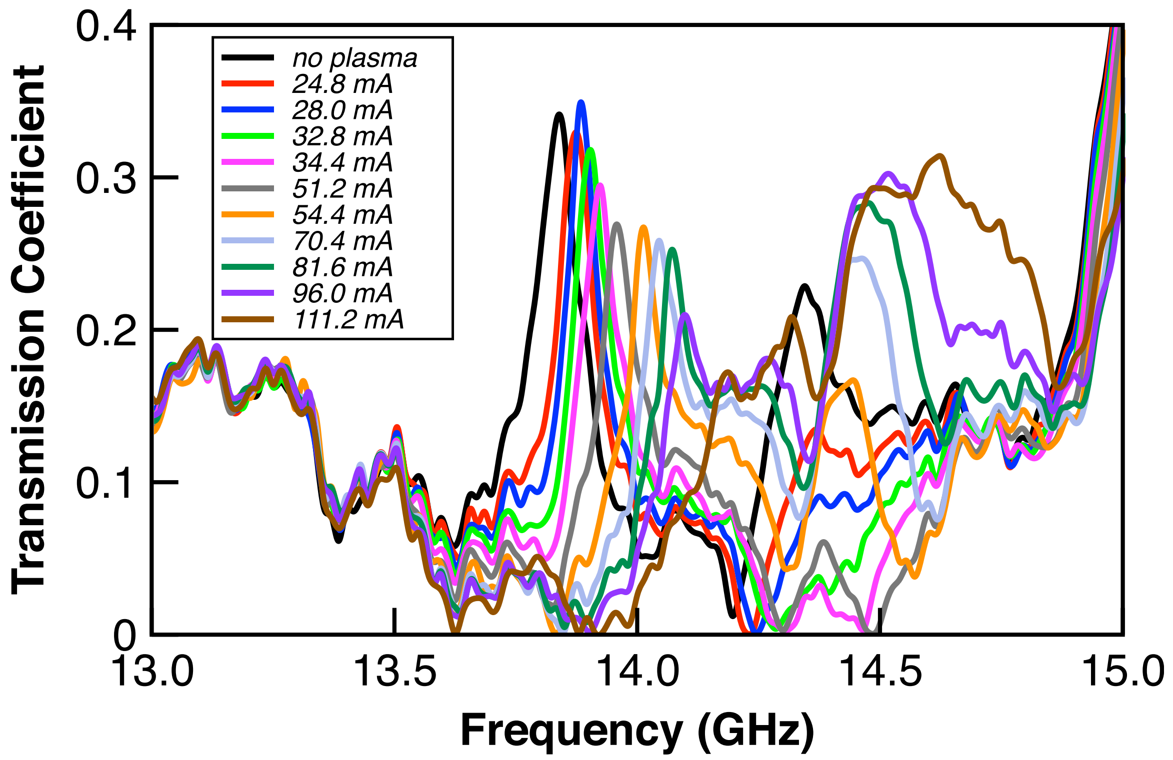
$\omega_{PF} > \omega_{QF}$ — plasma-filled cavity

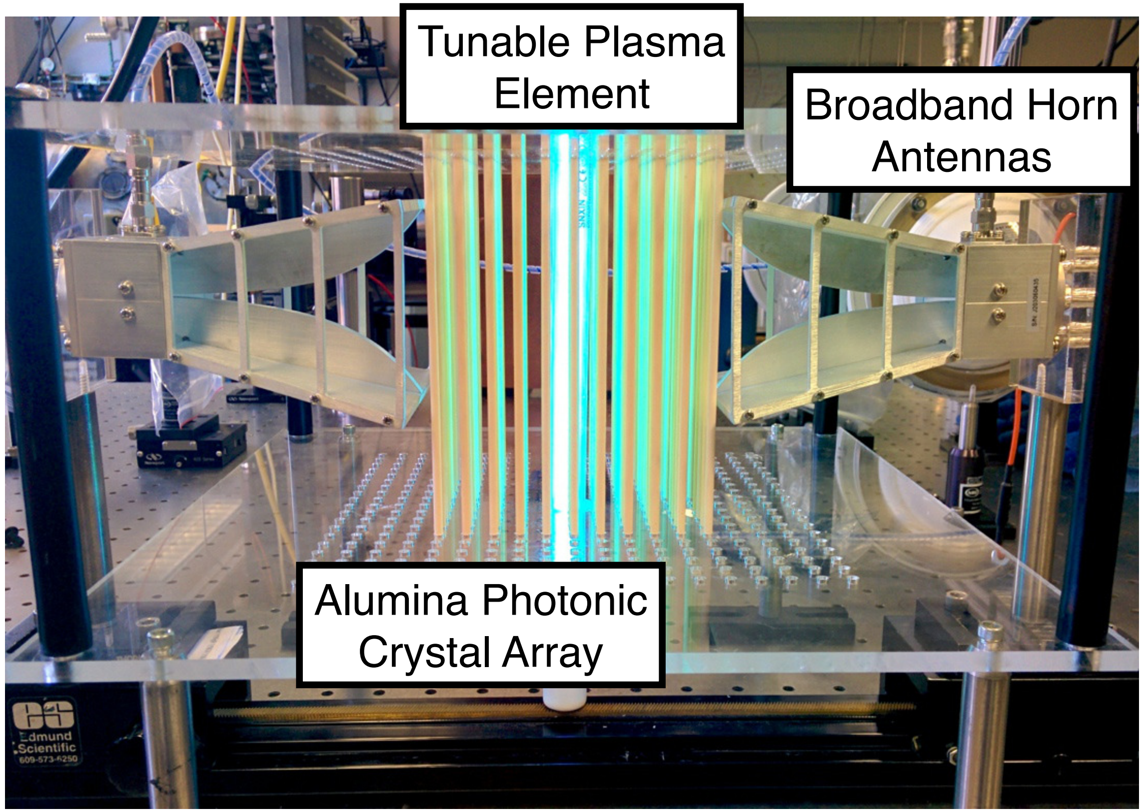
Wang et al., Applied Physics Letters, 2015

Plasma Loaded Photonic Crystal Vacancies

Plasma-Tuning of Defect State Transmission

Experimental Results



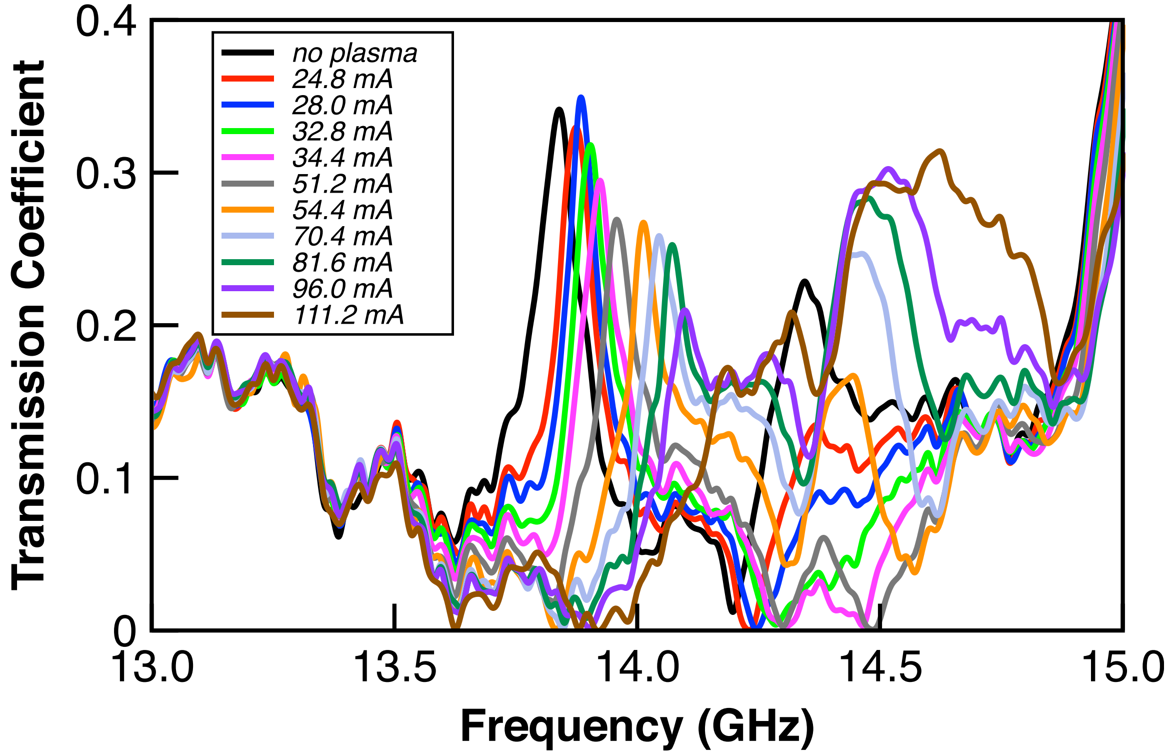


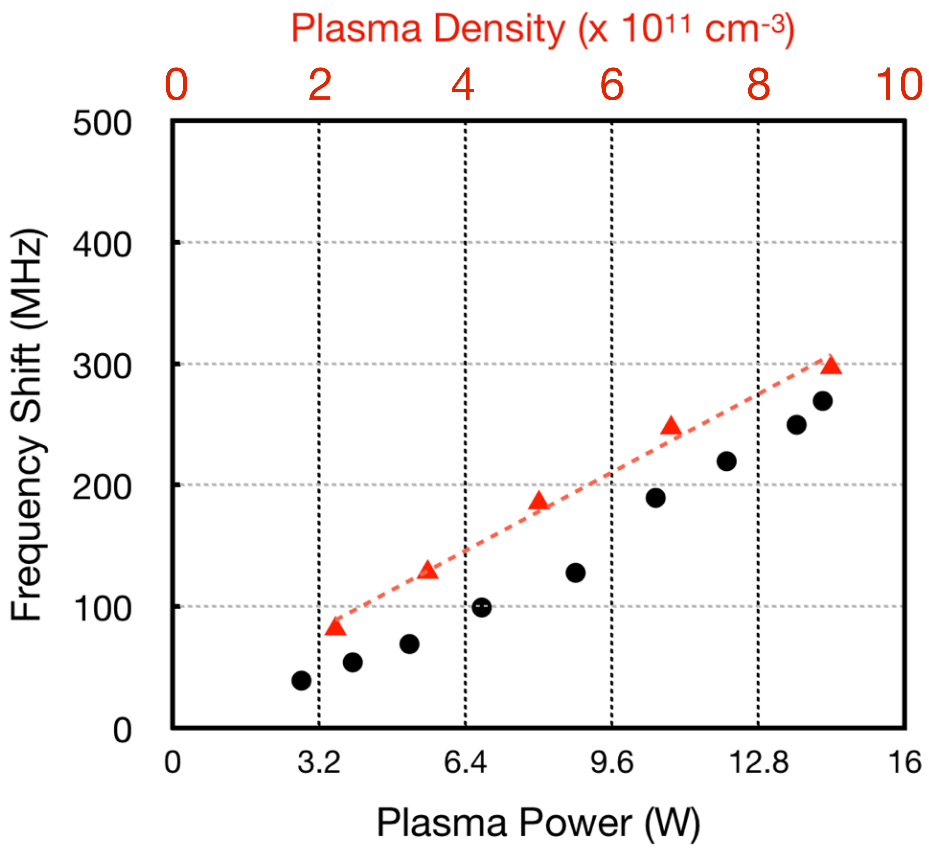
Wang et al., Applied Physics Letters, 2015

Plasma Loaded Photonic Crystal Vacancies

Plasma-Tuning of Defect State Transmission

Experimental Results



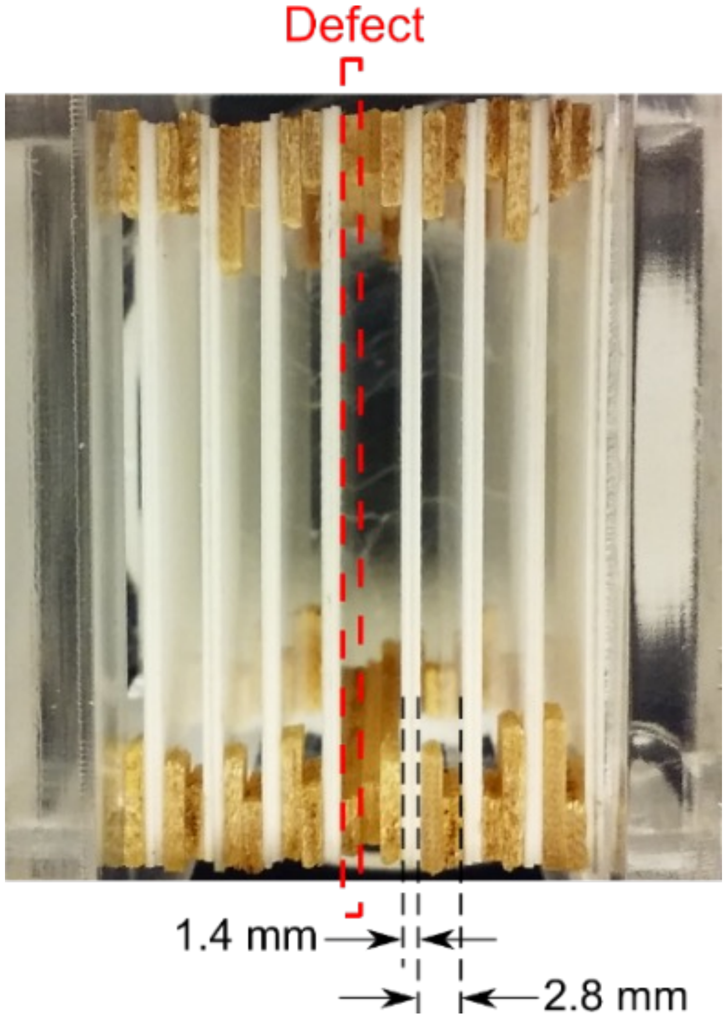


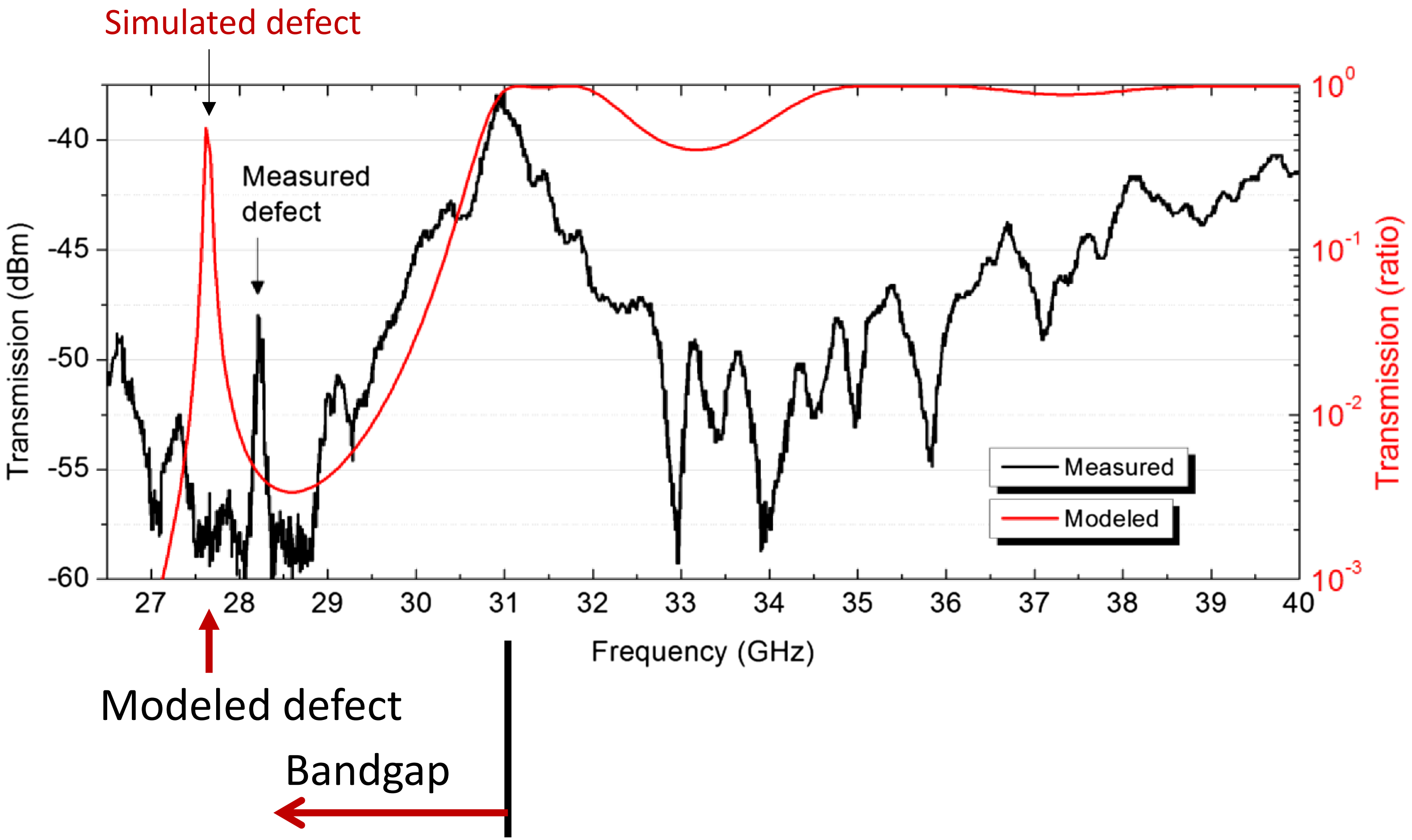
Plasma density from measured shifts

Wang et al., Applied Physics Letters, 2015

Plasma Loaded Photonic Crystal Vacancies

Plasma-Loaded 1D Photonic Crystal Defect

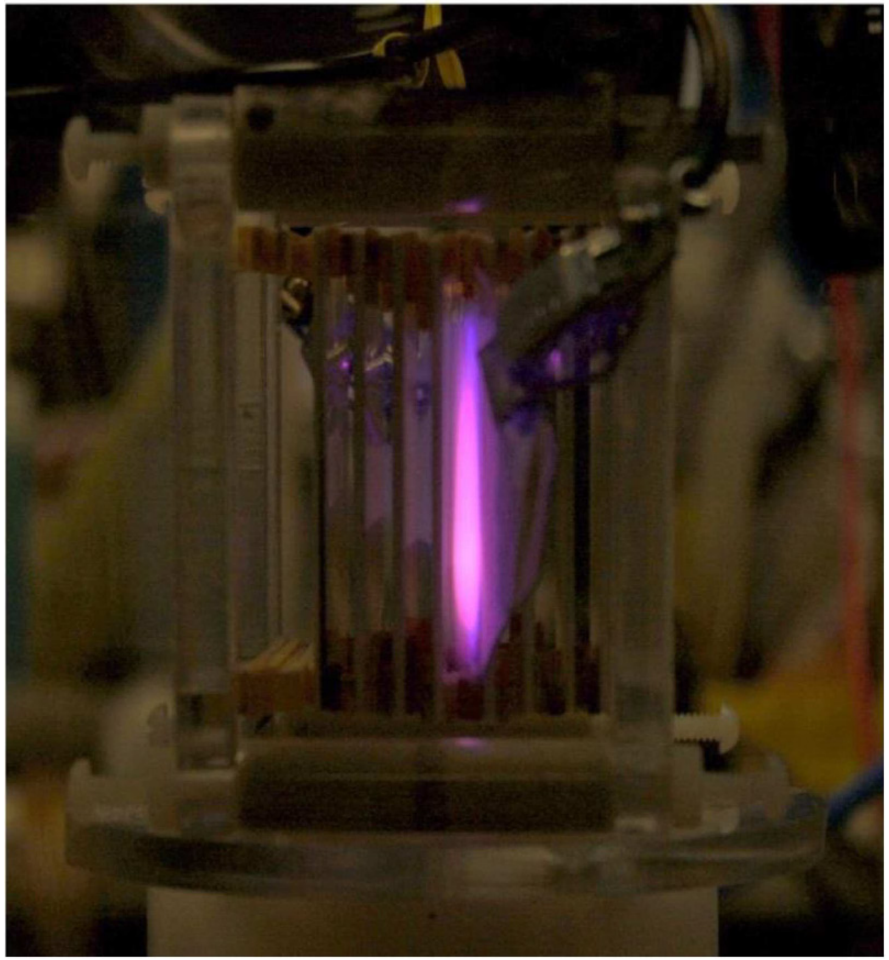


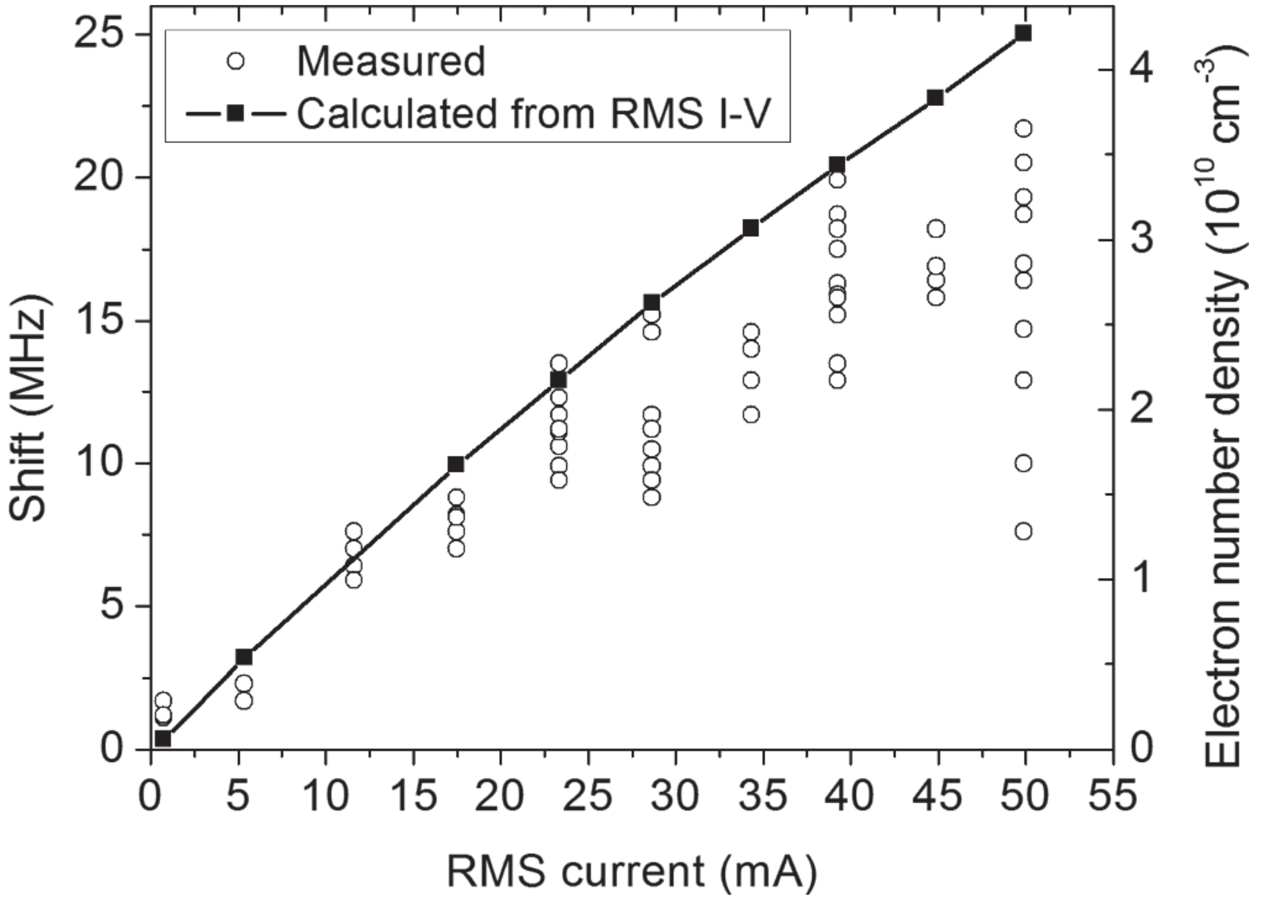


Pai et al, 2019

Plasma Loaded Photonic Crystal Vacancies

Plasma-Loaded 1D Photonic Crystal Defect

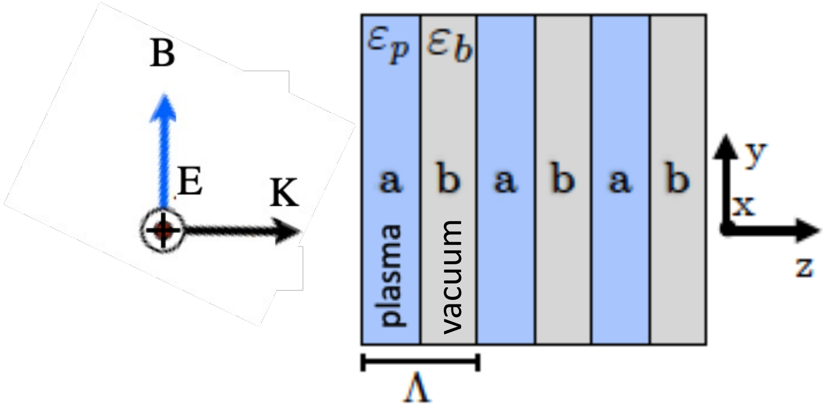


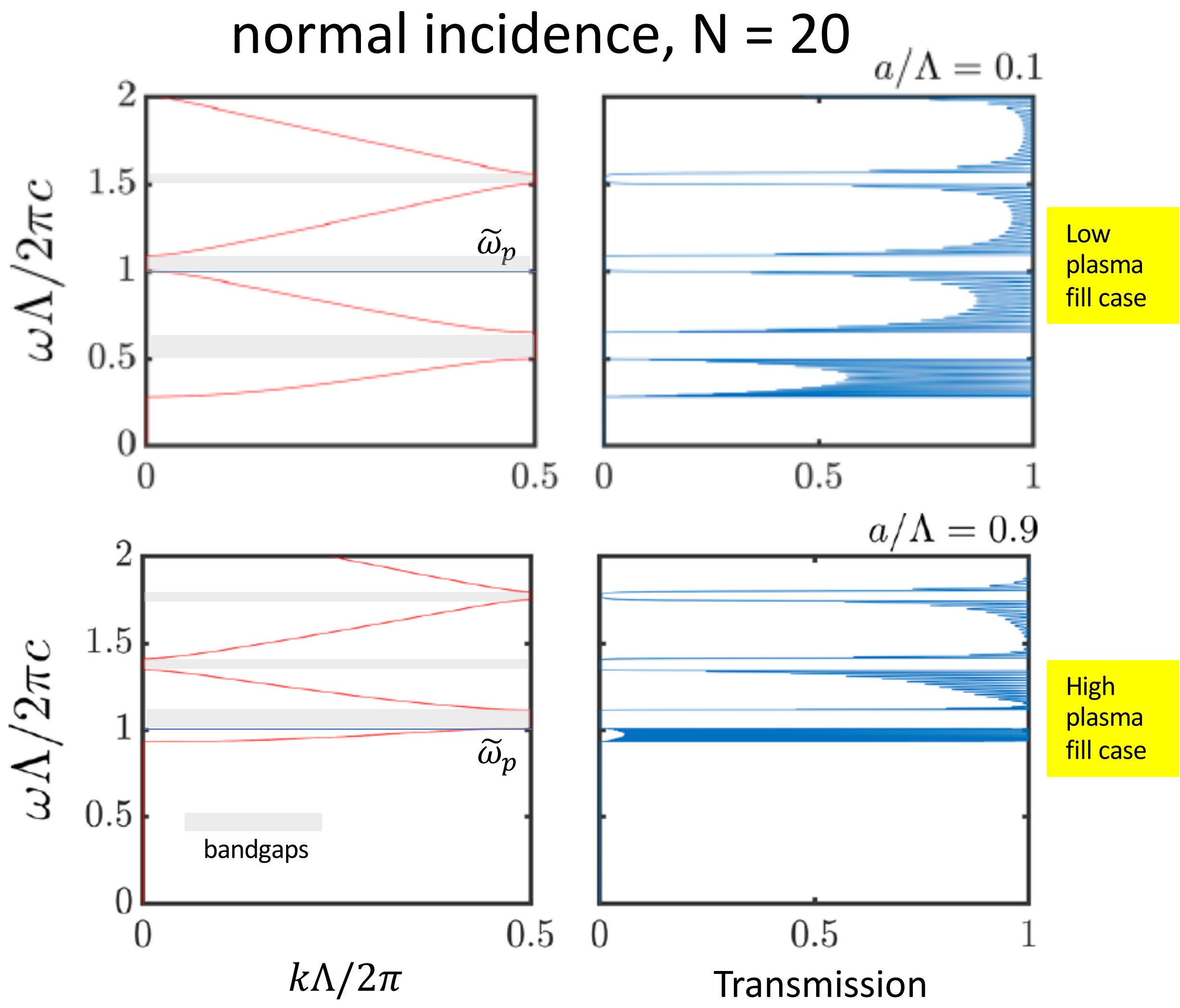


One-Dimensional Gratings (1D Photonic Crystals)

Normal Excitation

- Series of plasma slabs (grating/1D photonic crystal) more complex





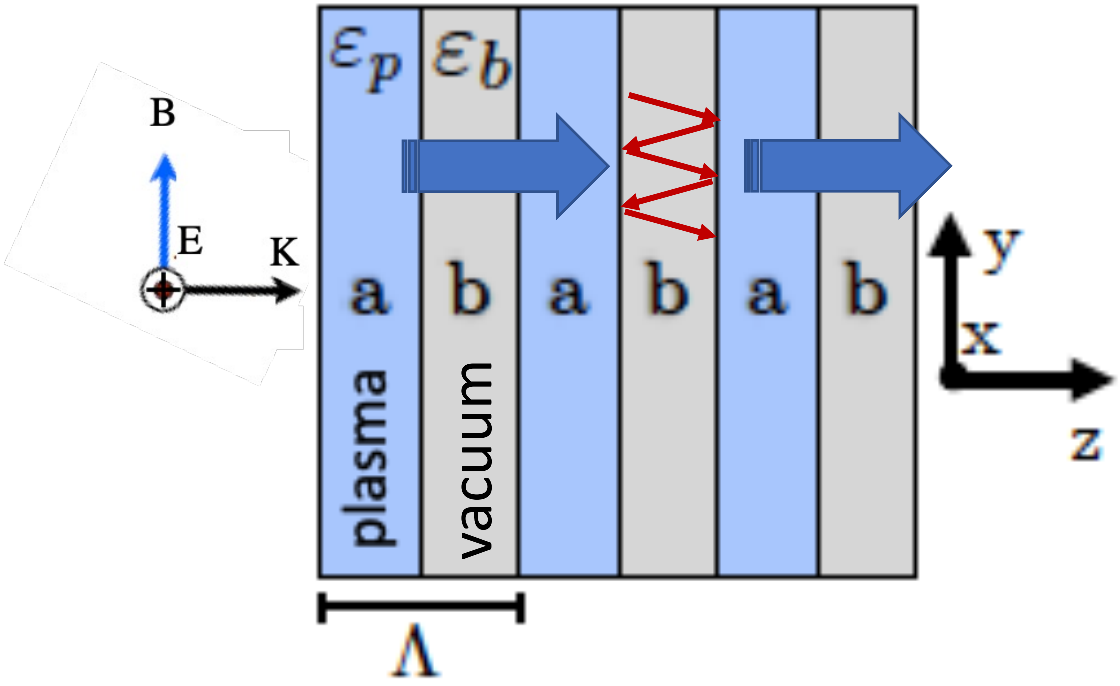
- $N = 20$ slabs result in distinct bands due to successive scattering/interference (Bragg resonances)
- low plasma fill factor a/Λ results in transmission below $\tilde{\omega}_p = \frac{\omega_p \Lambda}{2\pi c}$
- regions of anomalous dispersion ($n_g < 0$) - not unique to plasma photonic crystals

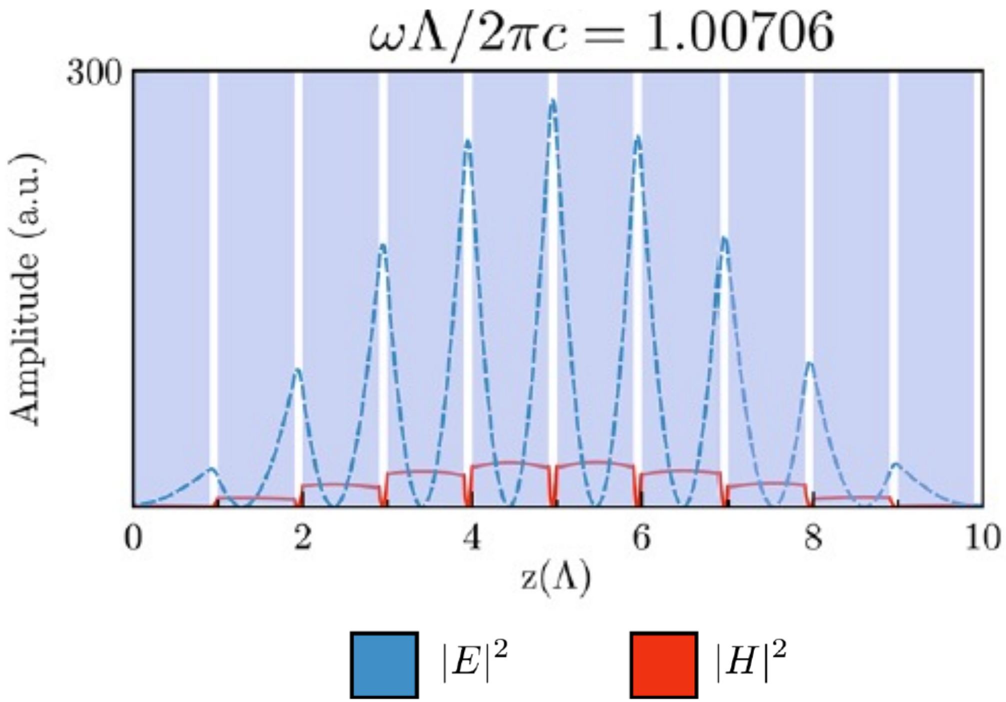
Wang, Righetti, and Cappelli , Phys. Plasmas 25, 031902, 2018.

One-Dimensional Gratings (1D Photonic Crystals)

Normal Excitation

- Plasma slabs serve as EM wave resonators





- Bouncing of electromagnetic waves within the space between plasma slabs builds up EM fields
- Finite number (N = 20) allows leakage (tunneling)

Wang, Righetti, and Cappelli , Phys. Plasmas 25, 031902, 2018.

One-Dimensional Gratings (1D Photonic Crystals)

Mechanical Analogy

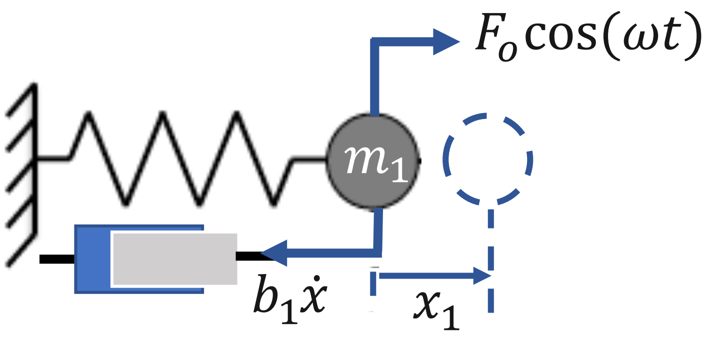
- Incident EM Wave serves as a "forcing function" exciting Bragg modes within the resonator planes
- Tunneling leaks energy out of the resonator array
- Equation of motion for m_1:

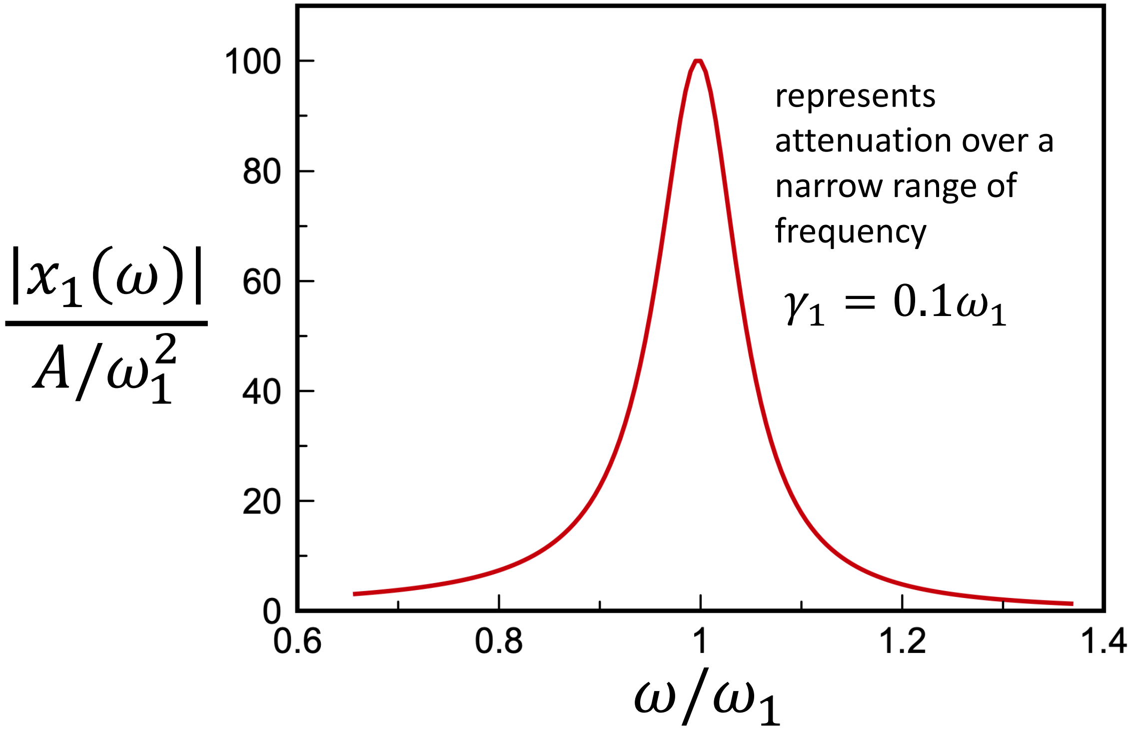
$$\ddot{x}_1 + \frac{b_1}{m}\dot{x}_1 + \frac{k_1}{m}x = A\cos\omega t$$

- Solution:

$$|x_1(\omega)| = \frac{A}{\sqrt{(\omega_1^2 - \omega^2)^2 + \gamma_1^2\omega^2}}$$

$$A = \frac{F_o}{m} \qquad \gamma_1 = \frac{b_1}{m} \qquad \omega_1 = \frac{k_1}{m}$$

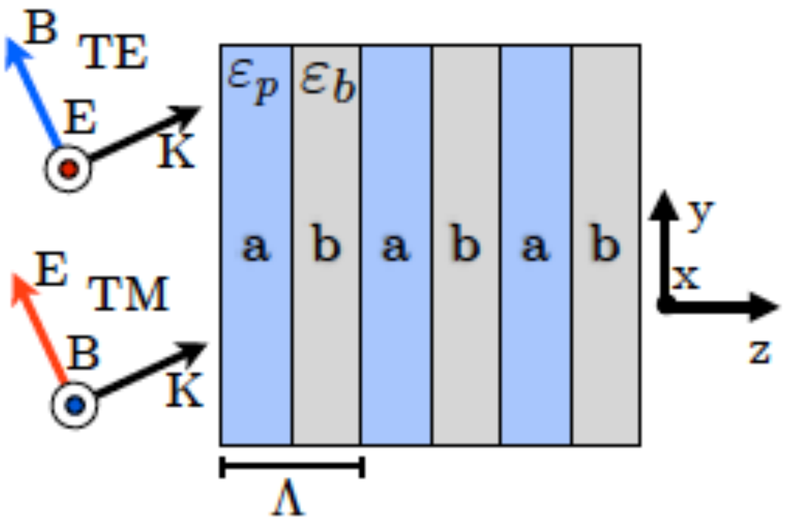


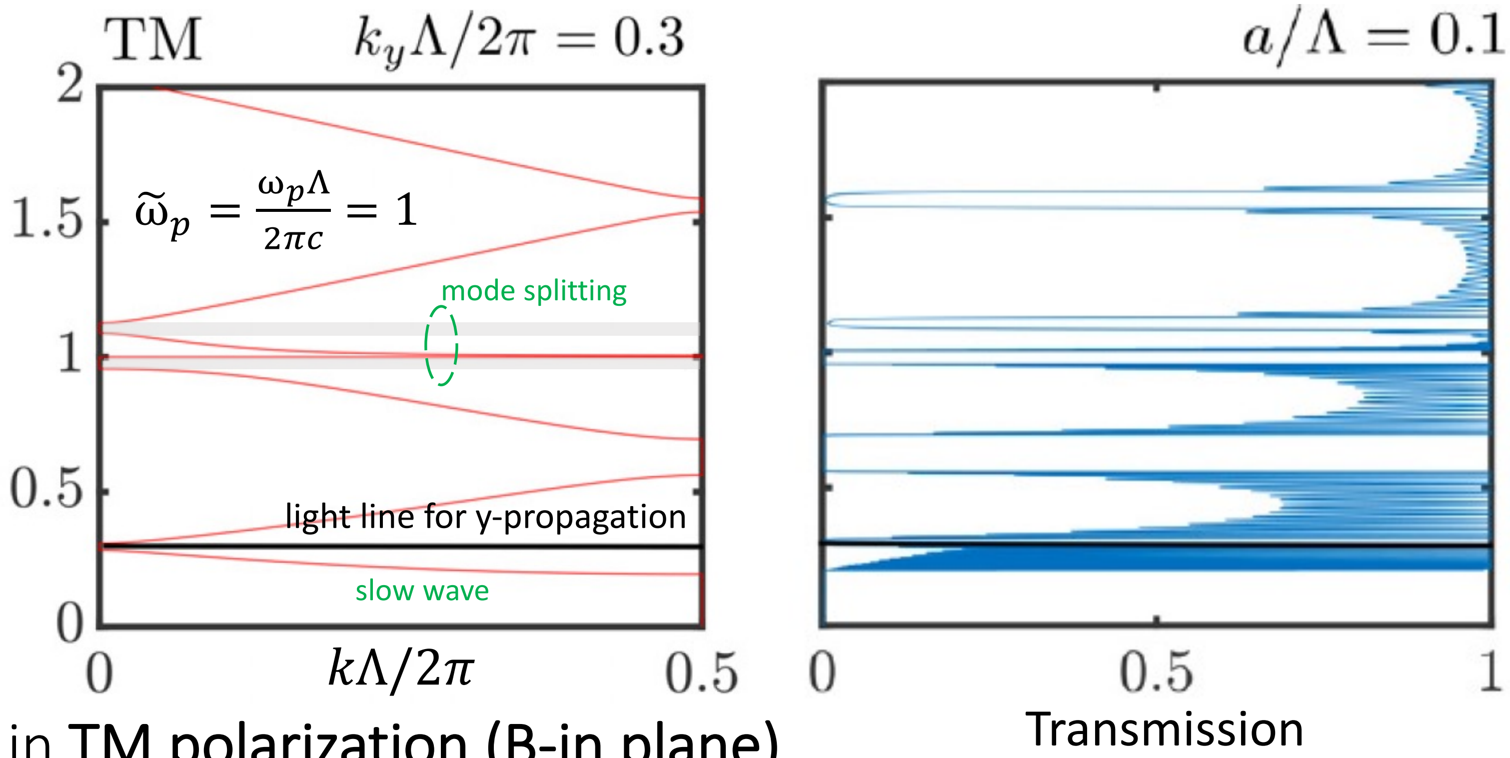


One-Dimensional Gratings (1D Photonic Crystals)

Oblique Excitation

- Interesting features are seen with oblique incidence angles

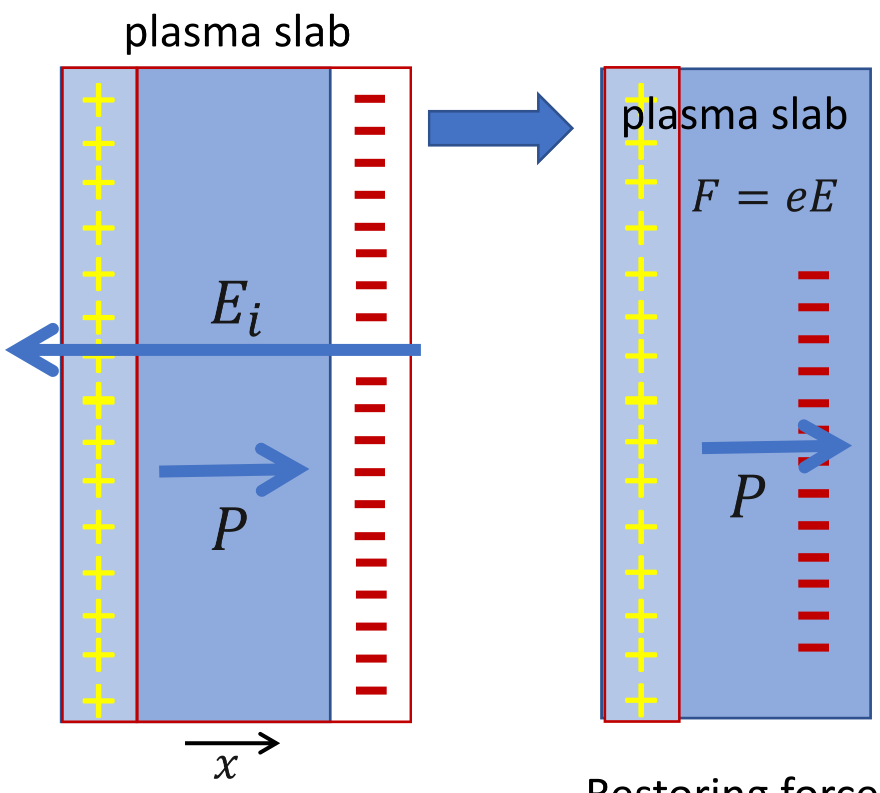




- E-field component across slabs in **TM polarization (B-in plane)**
- Mode splitting occurs when $\omega = \omega_{Bragg} = \omega_p$
- EM activity is seen below the light line for propagation along the y-direction (everything below represents slow-waves) - surface modes propagating along interface?

One-Dimensional Gratings (1D Photonic Crystals)

Resonant Electrostatic Plasmonic Oscillations



$$P = \sigma_C/\varepsilon_o = n_e e x/\varepsilon_o$$

Restoring force drives
Electrostatic oscillations

$$F = eP = m\ddot{x}$$

$$\ddot{x} = n_e e^2 x/m_e \varepsilon_o$$

Electron Equation of Motion

$$\ddot{x} = \omega_p^2 x$$

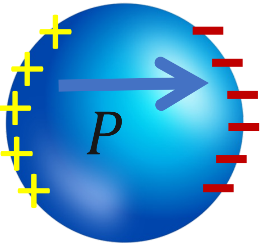
$$\omega_{PR} = \sqrt{n_e e^2/m_e \varepsilon_o}$$

Plasmon Frequency of slab geometry

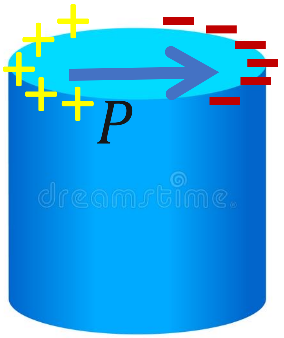
σ_C is geometry dependent

Sphere

$$\omega_{PR} = \omega_p/\sqrt{3}$$



Cylinder

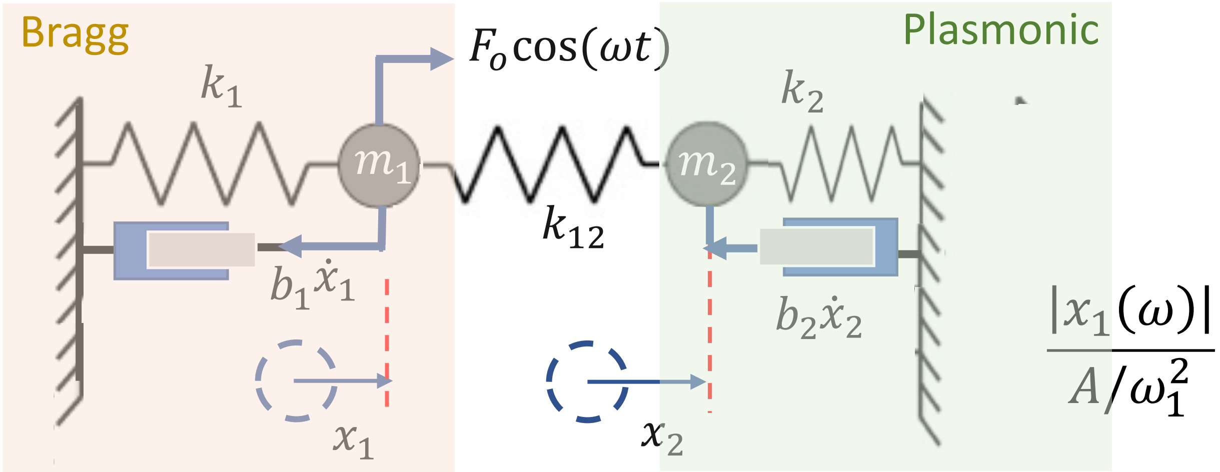


$$\omega_{PR} \approx \omega_p/\sqrt{2}$$

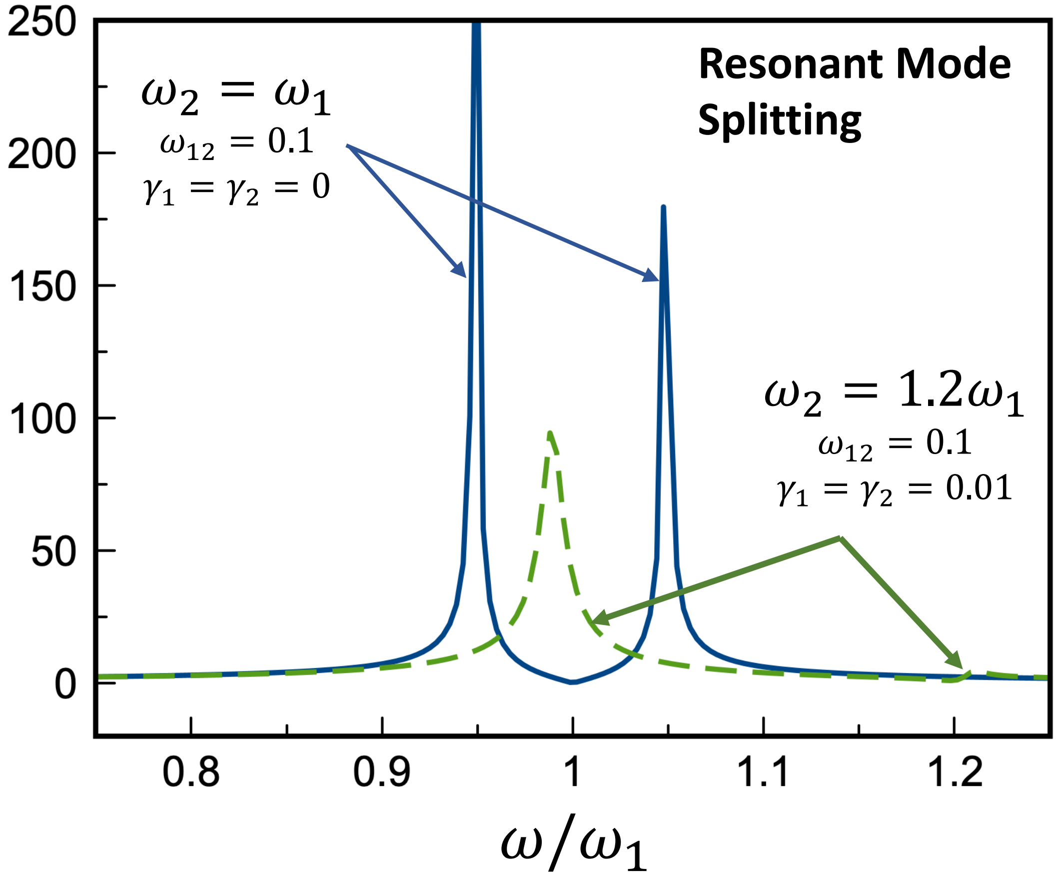
One-Dimensional Gratings (1D Photonic Crystals)

Mechanical Resonator Analogy – Fano Resonance

- Resonant plasmonic oscillations in the slab represented by m_2 and k_2
- EM Field couples the two resonators



Equilibrium positions



$$\frac{x_1(\omega)}{A/\omega_1^2} = \frac{\omega_1^2(\omega_2^2 - \omega^2 + i\gamma_2\omega)}{(\omega_1^2 - \omega^2 + i\gamma_1\omega)(\omega_2^2 - \omega^2 + i\gamma_2\omega) - \omega_{12}^2}$$

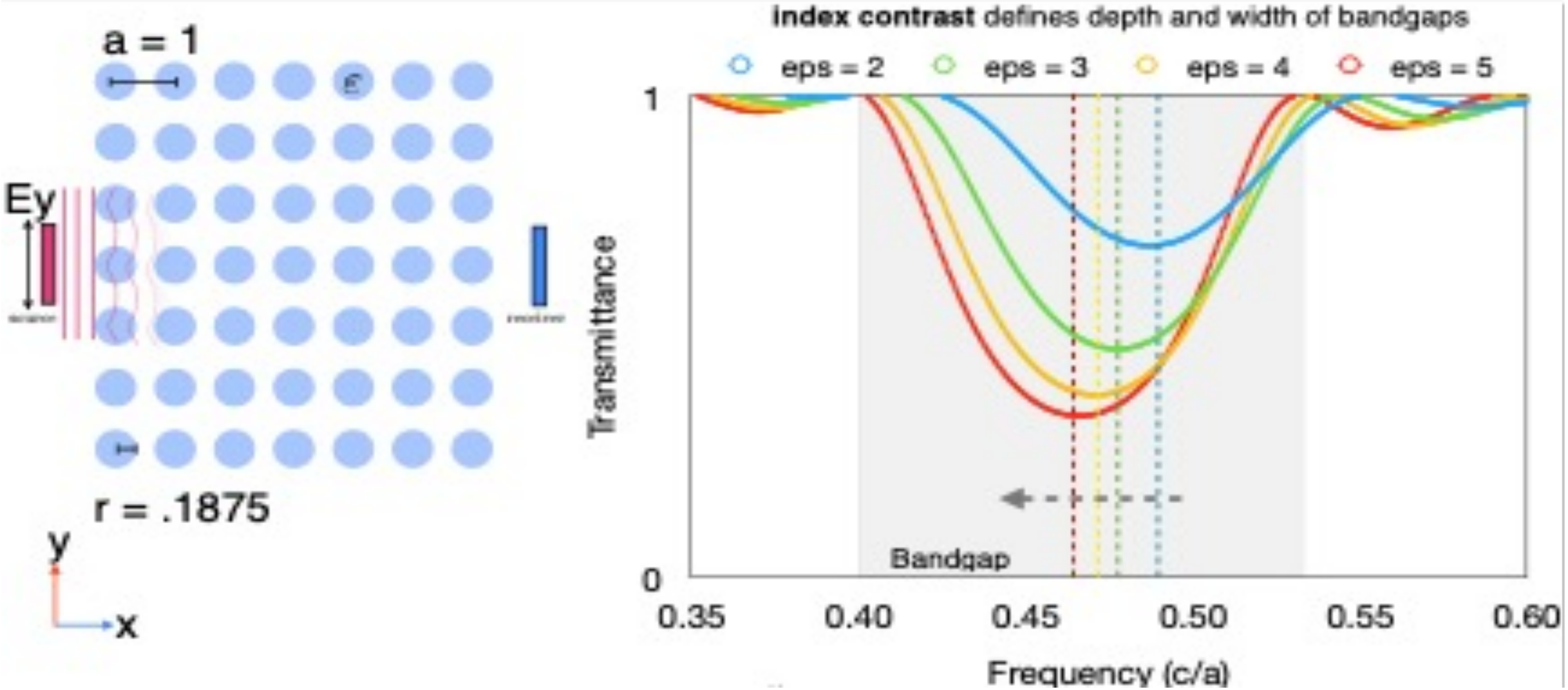
$A = \frac{F_o}{m}$ $\gamma_2 = \gamma_1 = \frac{b_2}{m}$ $\omega_2 = \frac{k_2}{m}$ $\omega_{12} = \frac{k_{12}}{m}$ For $m_1 = m_2 = m$

Y.S. Joe et al., Phys. Scr. 74 (2006) 259–266

Two-Dimensional Gratings (2D Photonic Crystals)

Finite Array of Plasma Columns

- 2D photonic crystals of finite array size result in relatively shallow bandgaps
- Exacerbated by a lower refractive index (index contrast)



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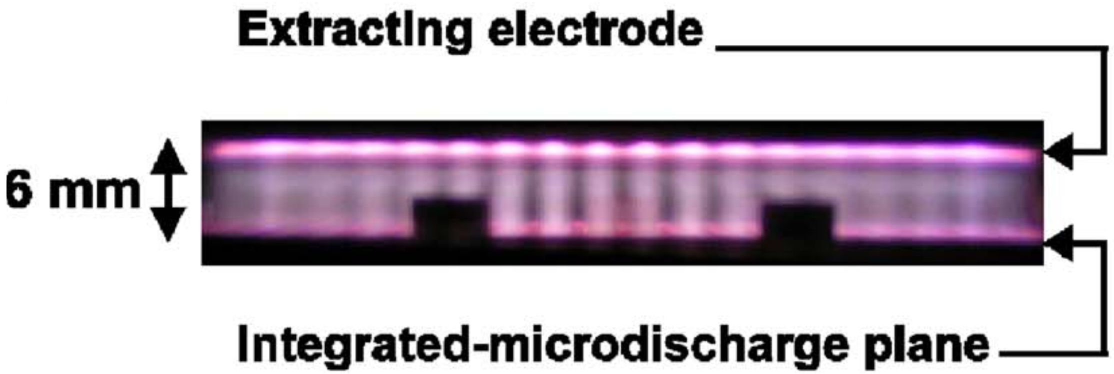
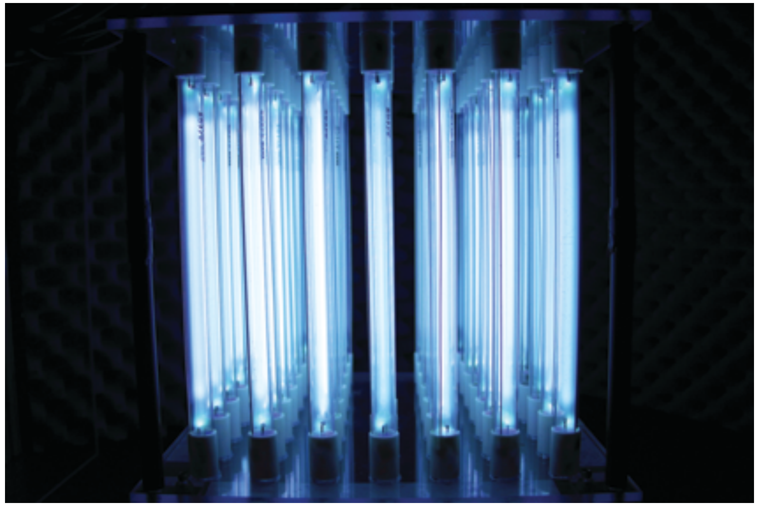
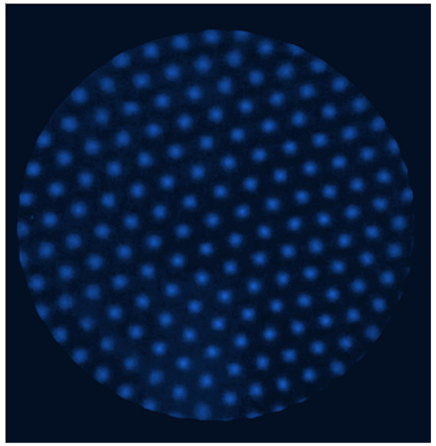


Sakai et al, 2005, 2007 (T ~80% @74GHz)



Wang and Cappelli 2016 (T ~15% @ 4GHz)

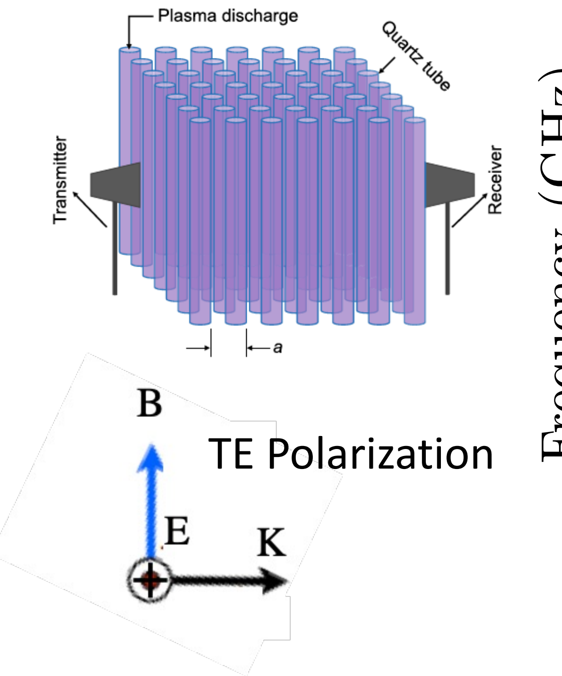


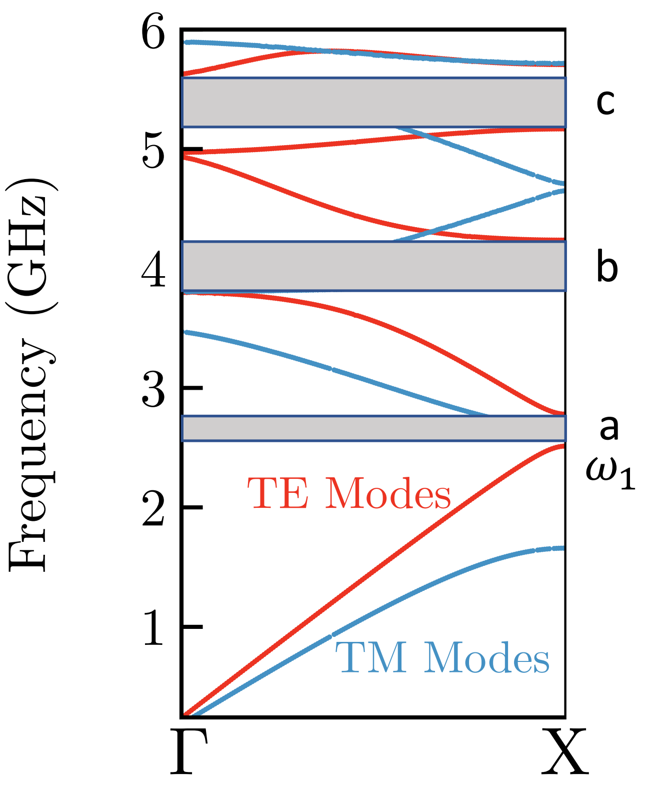
Matlis and Corke, 2018 (T ~70% @ 16GHz)

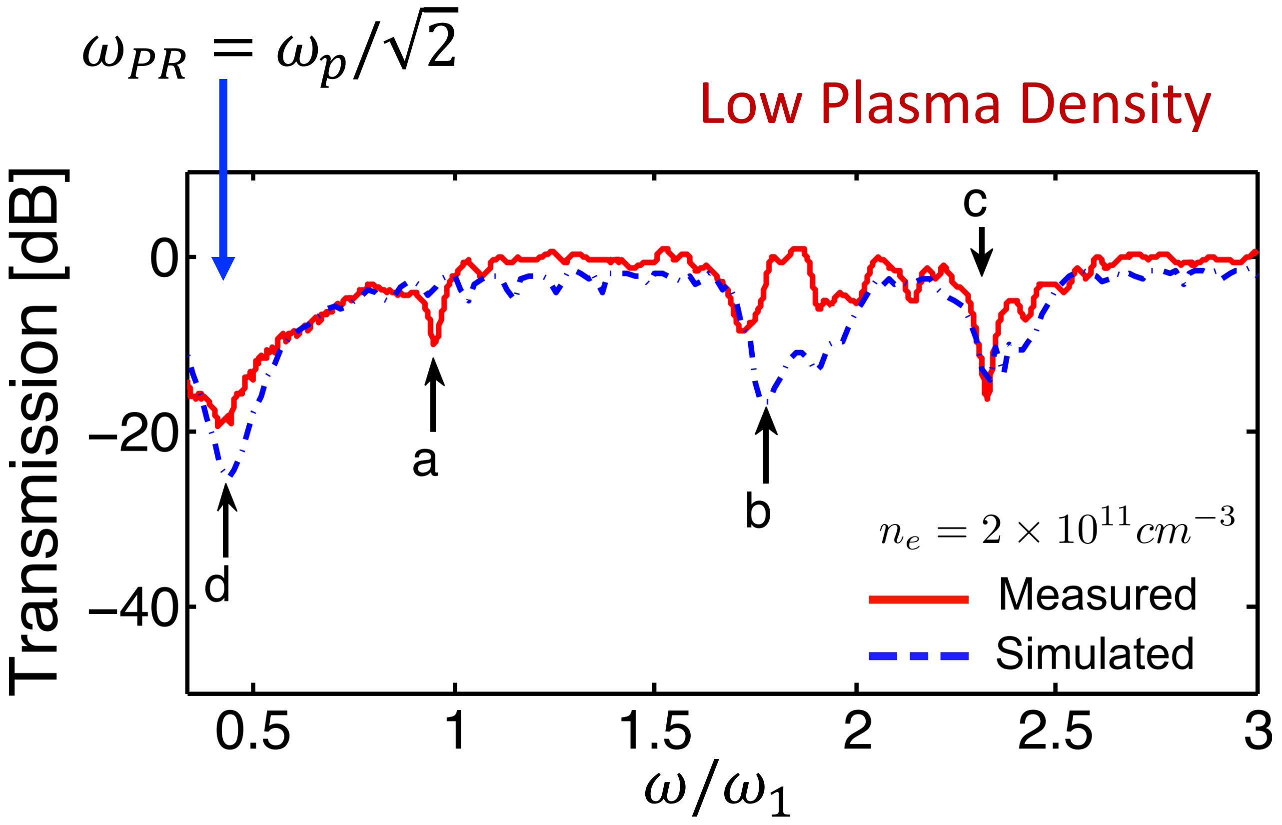
This relatively low attenuation is due to either low plasma density, finite size, or poor crystal order

Two-Dimensional Gratings (2D Photonic Crystals)

Experiments – Variation in Plasma Density





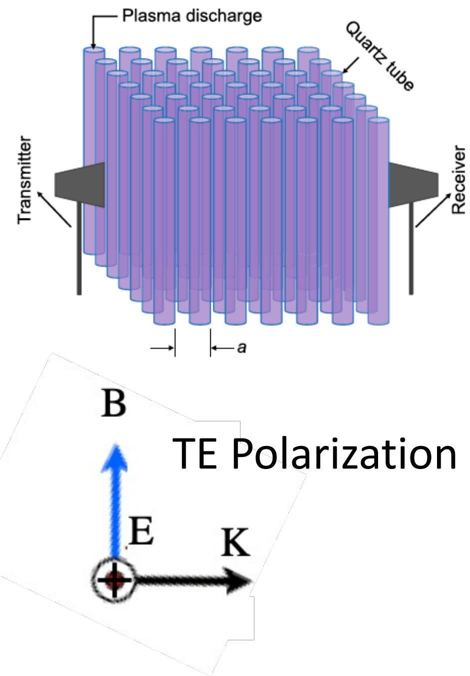


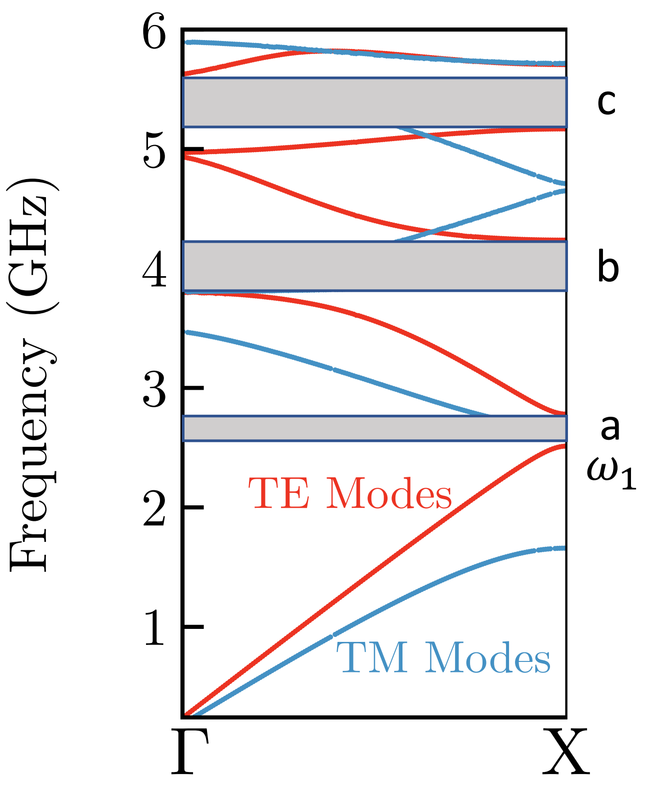
- Photonic bands are relatively shallow (~10-15 dB attenuation)
- Plasmonic attenuation seen at low frequency for relatively low n_e

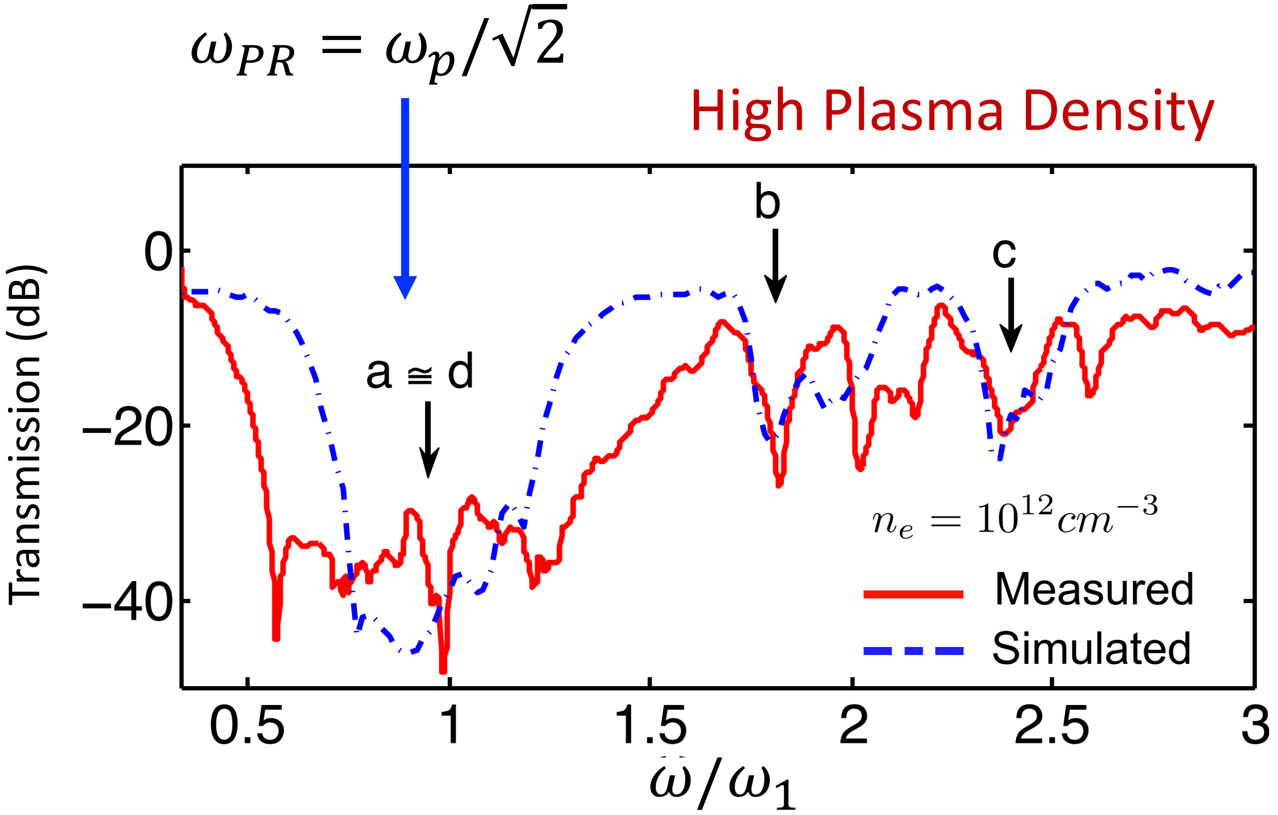
Righetti, Wang, and Cappelli., Phys. Plasmas 25, 124502 (2018)

Two-Dimensional Gratings (2D Photonic Crystals)

Experiments – Variation in Plasma Density







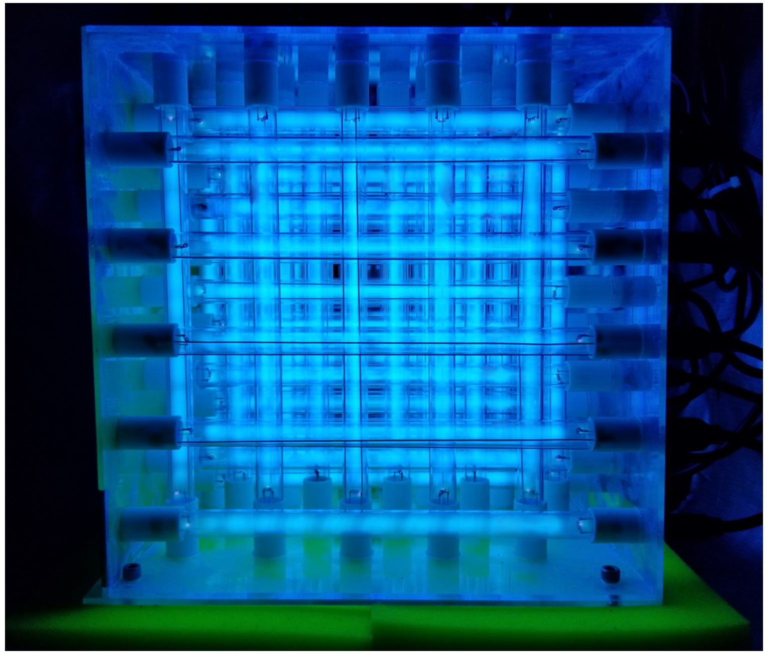
- Photonic bands increase in depth due to higher contrast ratio (lower ε_p)
- Plasmonic mode (d) shifts into resonance with (a); Fano splitting

Righetti, Wang, and Cappelli., Phys. Plasmas 25, 124502 (2018)

Three-Dimensional Photonic Crystals

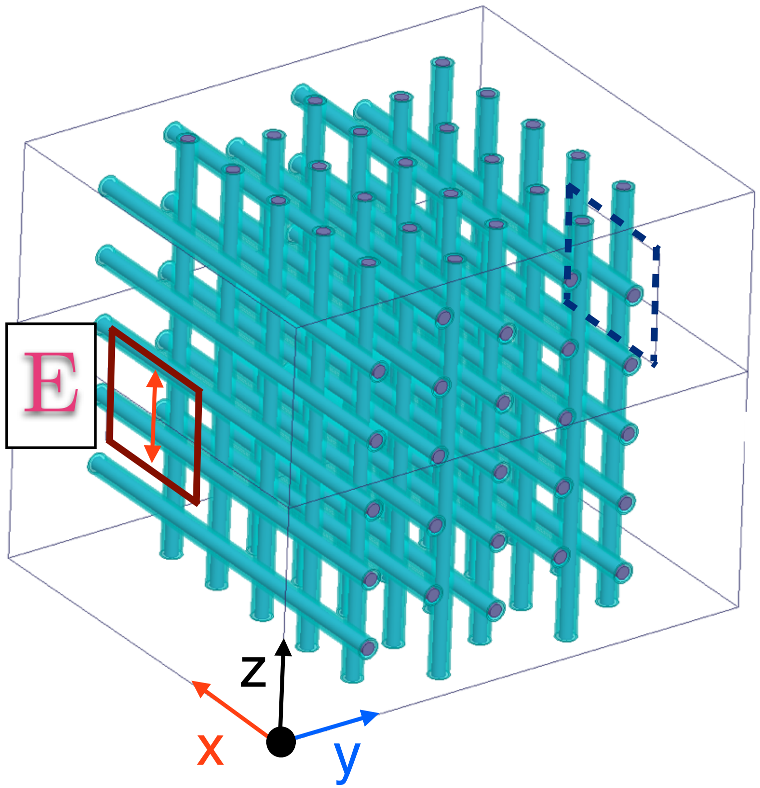
Woodpile Configuration

Alternating orthogonal layers of 5 plasma columns

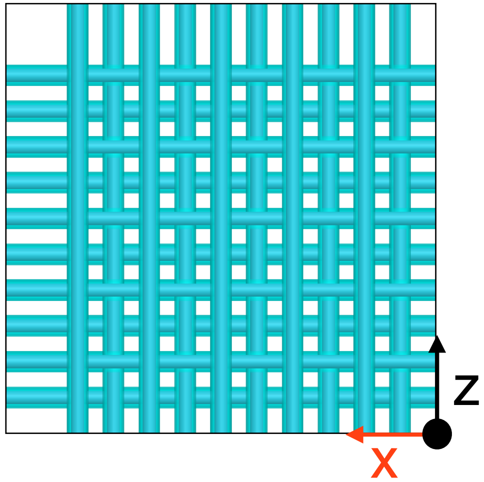


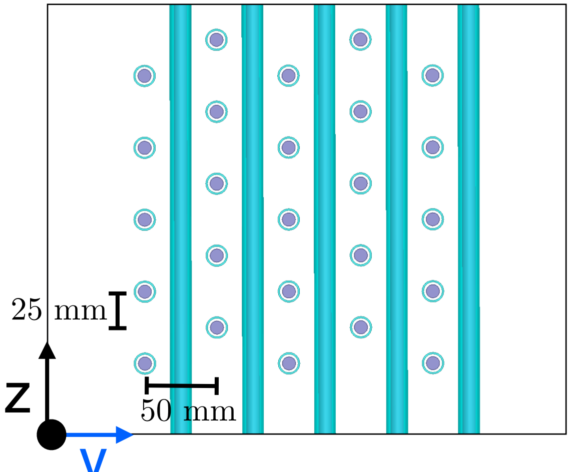
$$n_e(cm^{-3}) \approx 5 \times 10^9 I_p(mA).$$

3D rendering



Front View





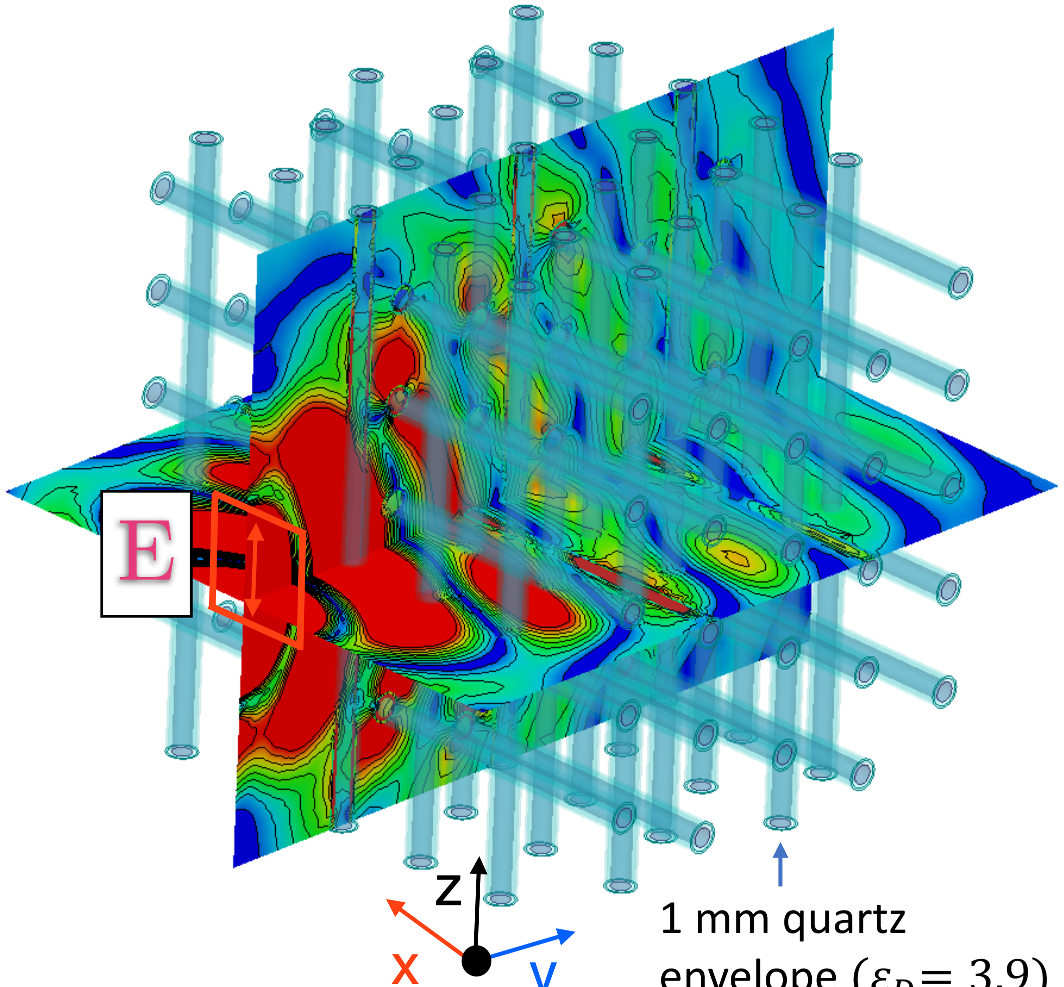
Side View

B Wang, JA Rodríguez, MA Cappelli - Plasma Sources Science and Technology, 2019

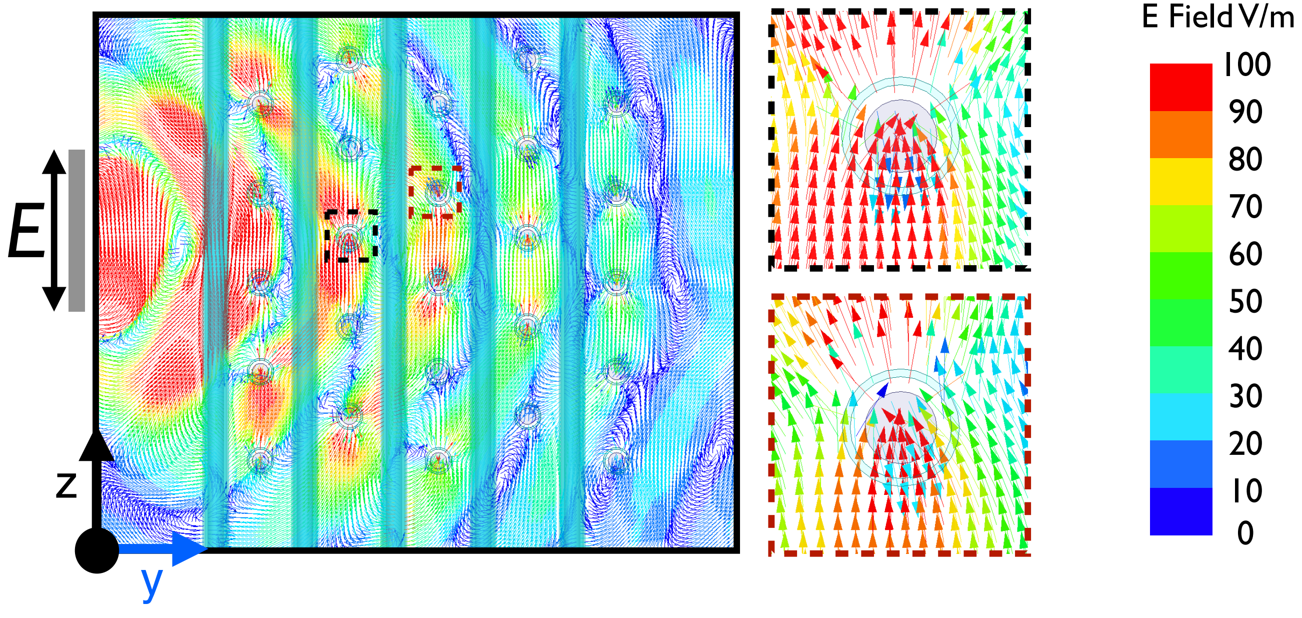
Three-Dimensional Photonic Crystals

Woodpile Configuration

Simulations: ANSYS HFSS 16



$f = 2.775$ GHz



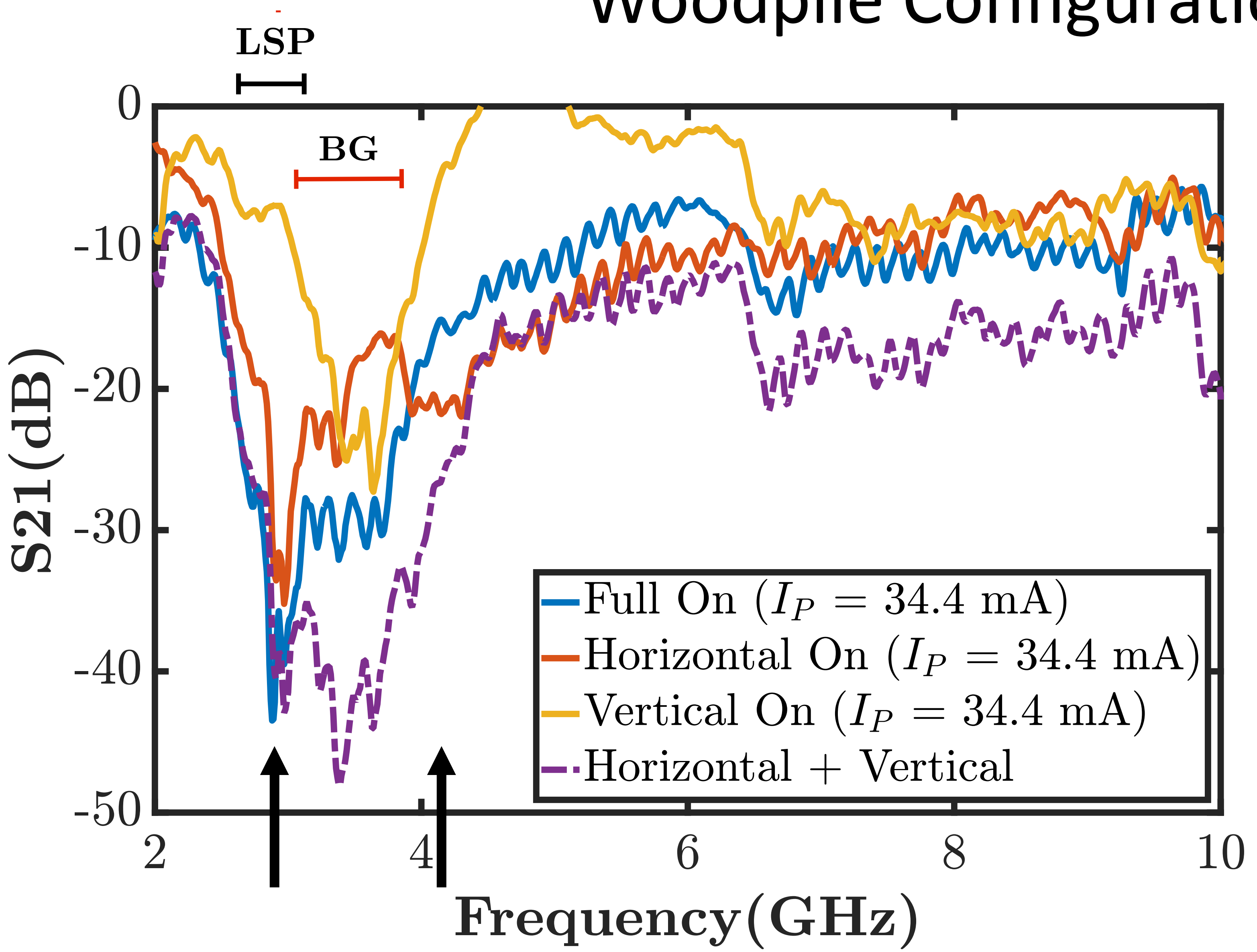
$\omega_p = 7$ GHz, $\gamma_p = 1$ GHz at $f = 2.775$ GHz

($n_e = 6.1 \times 10^{17} m^{-3}$)

B Wang, JA Rodríguez, MA Cappelli - Plasma Sources Science and Technology, 2019

Three-Dimensional Photonic Crystals

Woodpile Configuration



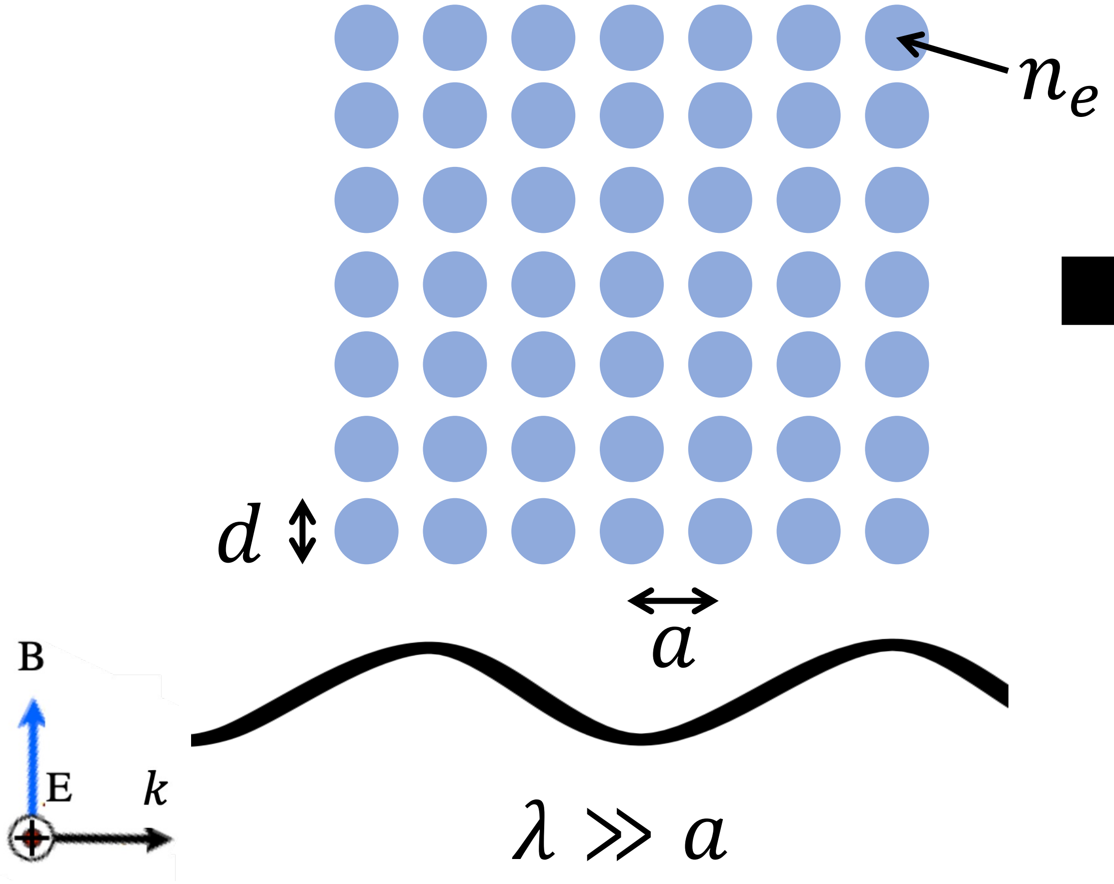
Bragg Mode Only (Vertical)

Plasmonic Enhanced Bragg (Horizontal)

Combined Layers

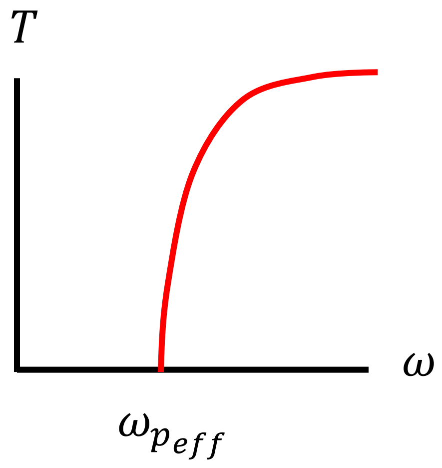
Plasma Array as an Effective Medium

Plasma Metamaterial



$$f < \sqrt{\frac{n_{eff} e^2}{m_e \varepsilon_o}}$$

$$\varepsilon_p < 0$$

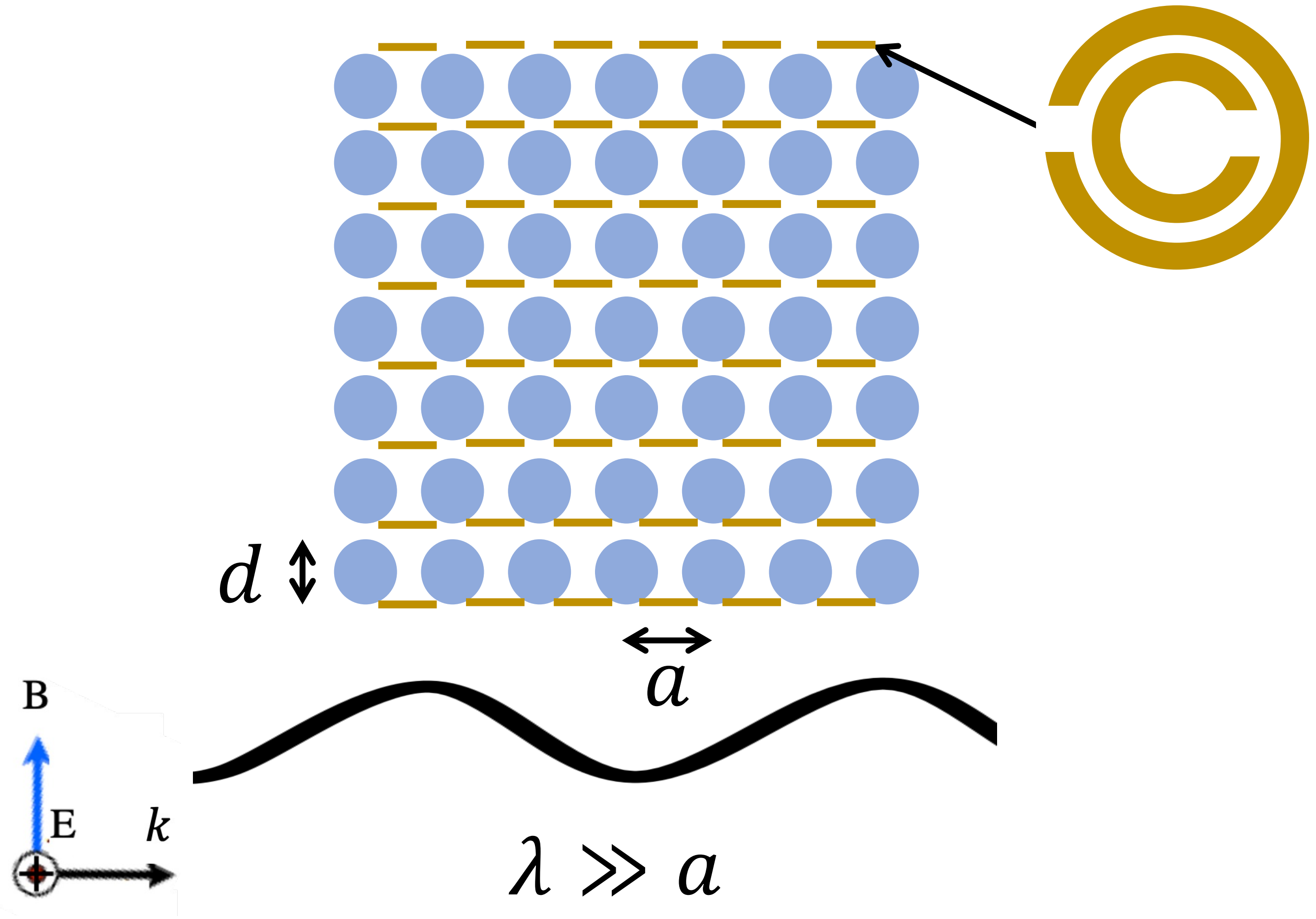


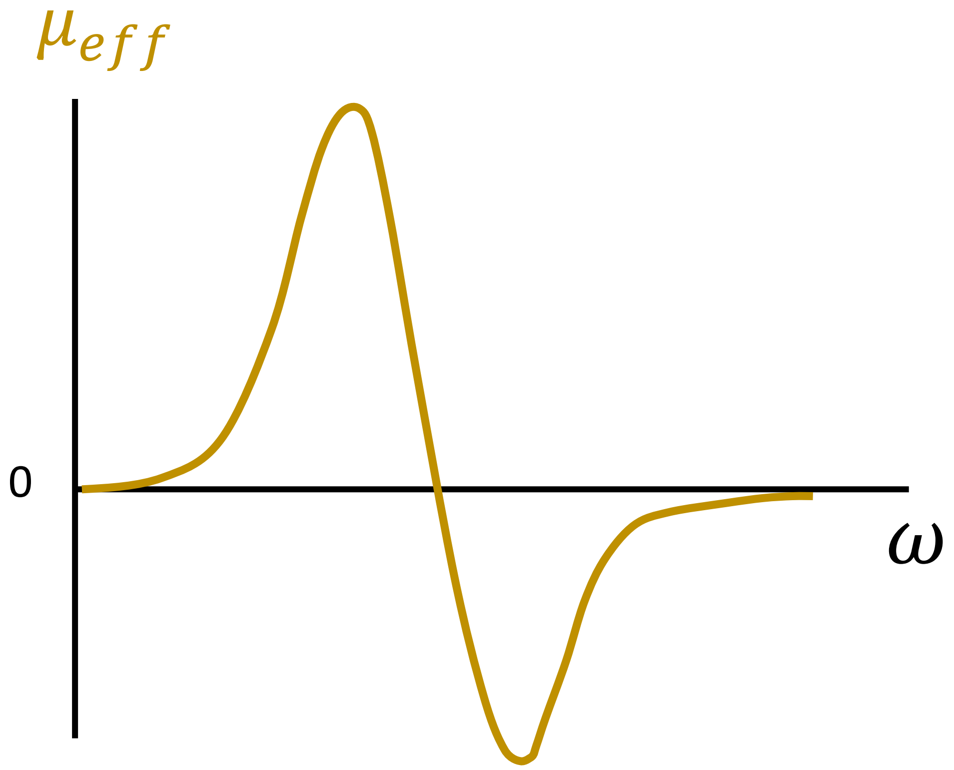
Effective bulk medium of lower volume-averaged plasma density

$$n_{eff} \approx \frac{\pi d^2}{4a^2} n_e$$

Plasma Array as an Effective Medium

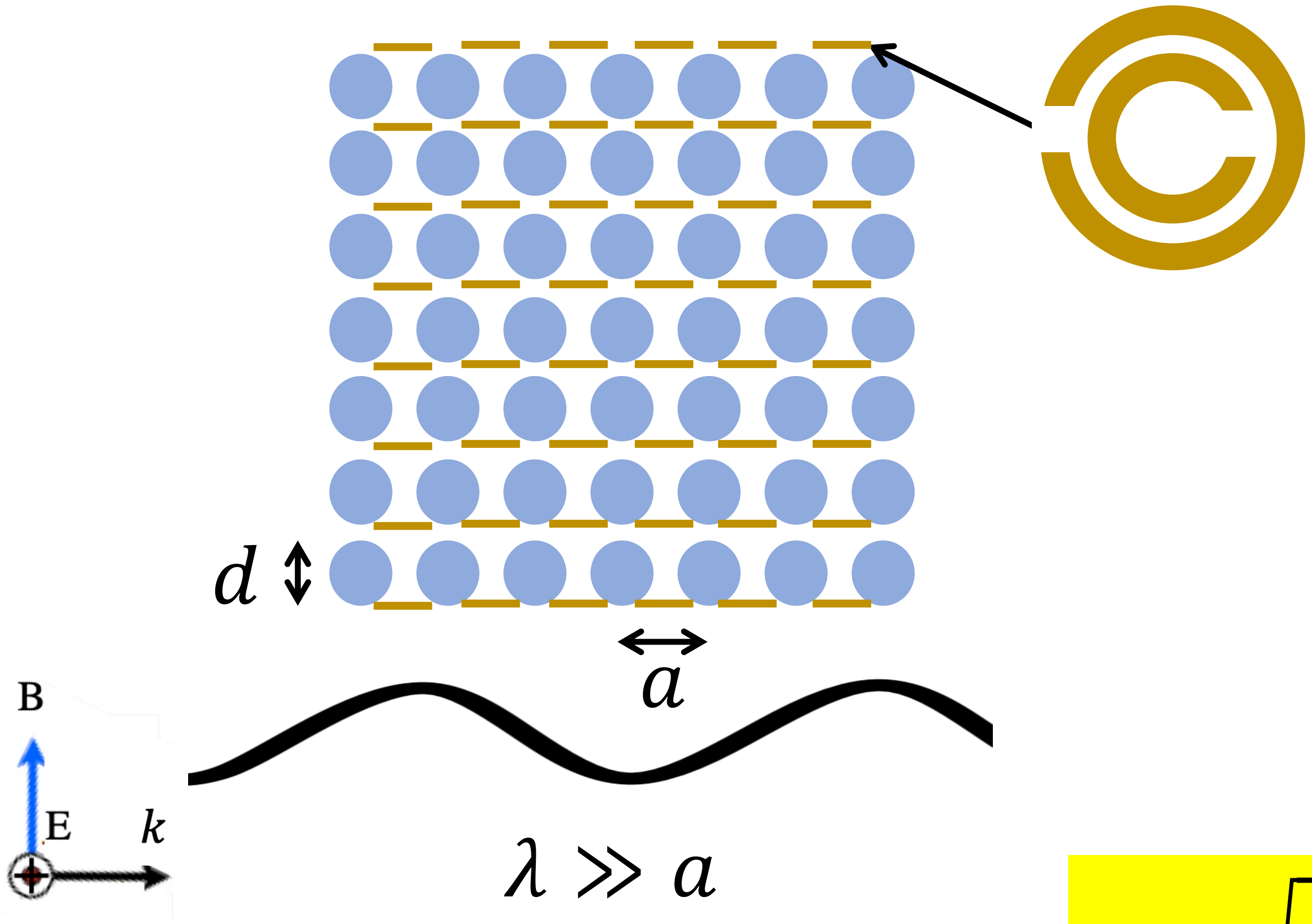
Plasma Metamaterial

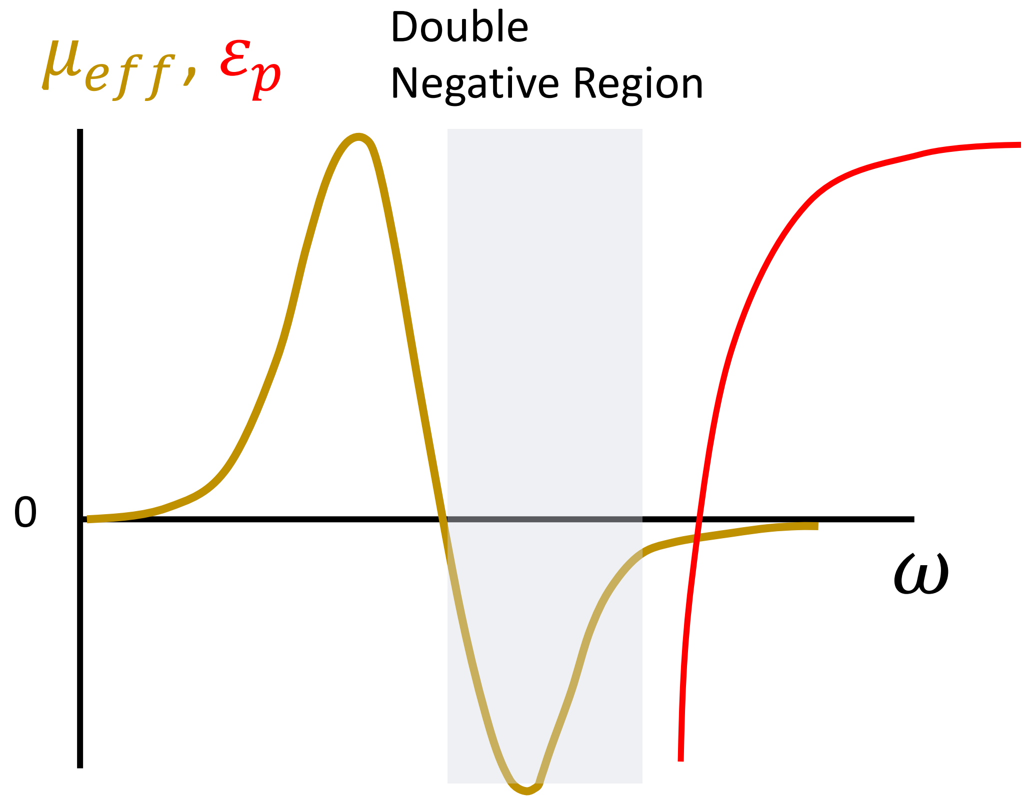




Plasma Array as an Effective Medium

Plasma Metamaterial





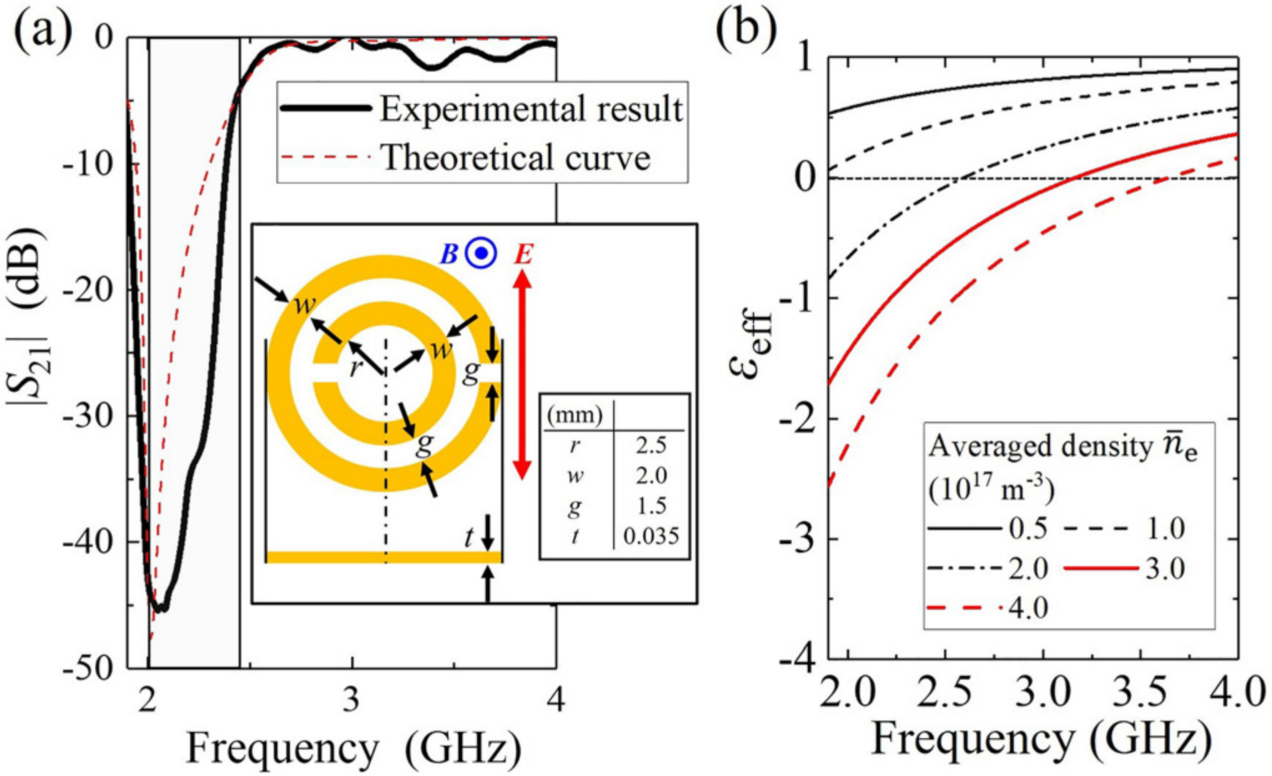
$$n = \sqrt{-|\mu_{eff}|} \cdot \sqrt{-|\varepsilon_P|} = -\,|\mu_{eff}| \cdot |\varepsilon_P|$$

Plasma Array as an Effective Medium

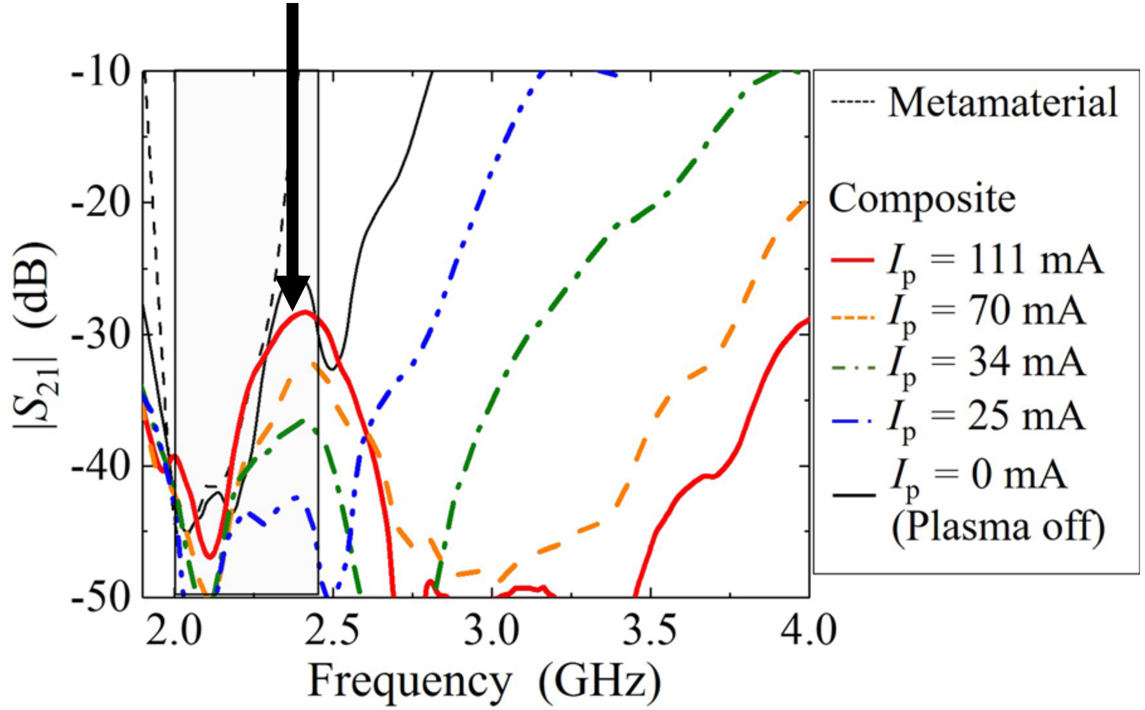
Double-Negative Medium: Experimental Verification

Split Ring Array Alone

Plasma



Peak in Transmission due to Double Negative Region



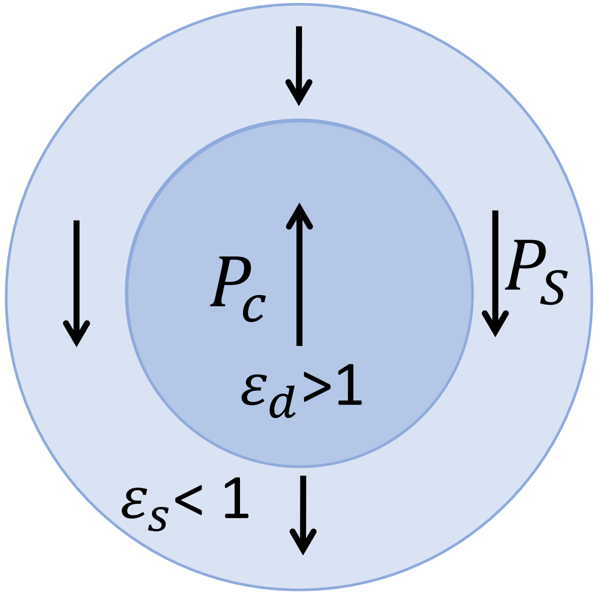
Plasma and Split Ring Array

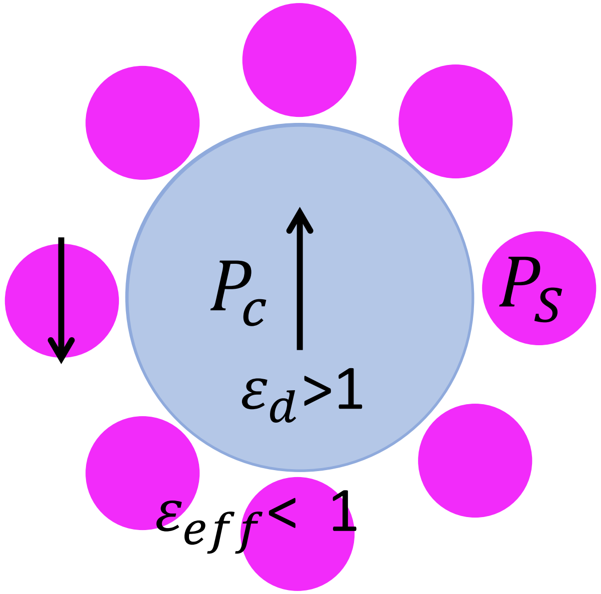
Iwai et al, Phys. Plasmas 27, 023511 (2020)

Invisibility Cloaks

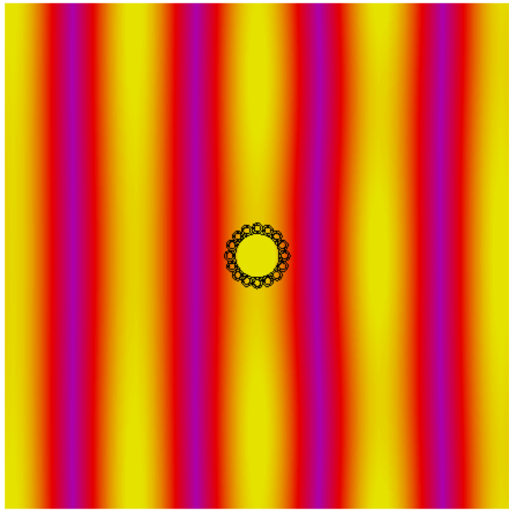
Switchable Invisibility Cloaks using Plasma Mantles

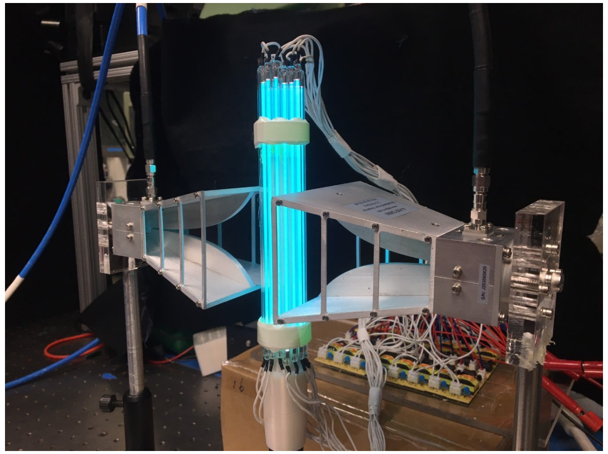
$$P = (\varepsilon - \varepsilon_o)E$$





CST Simulations





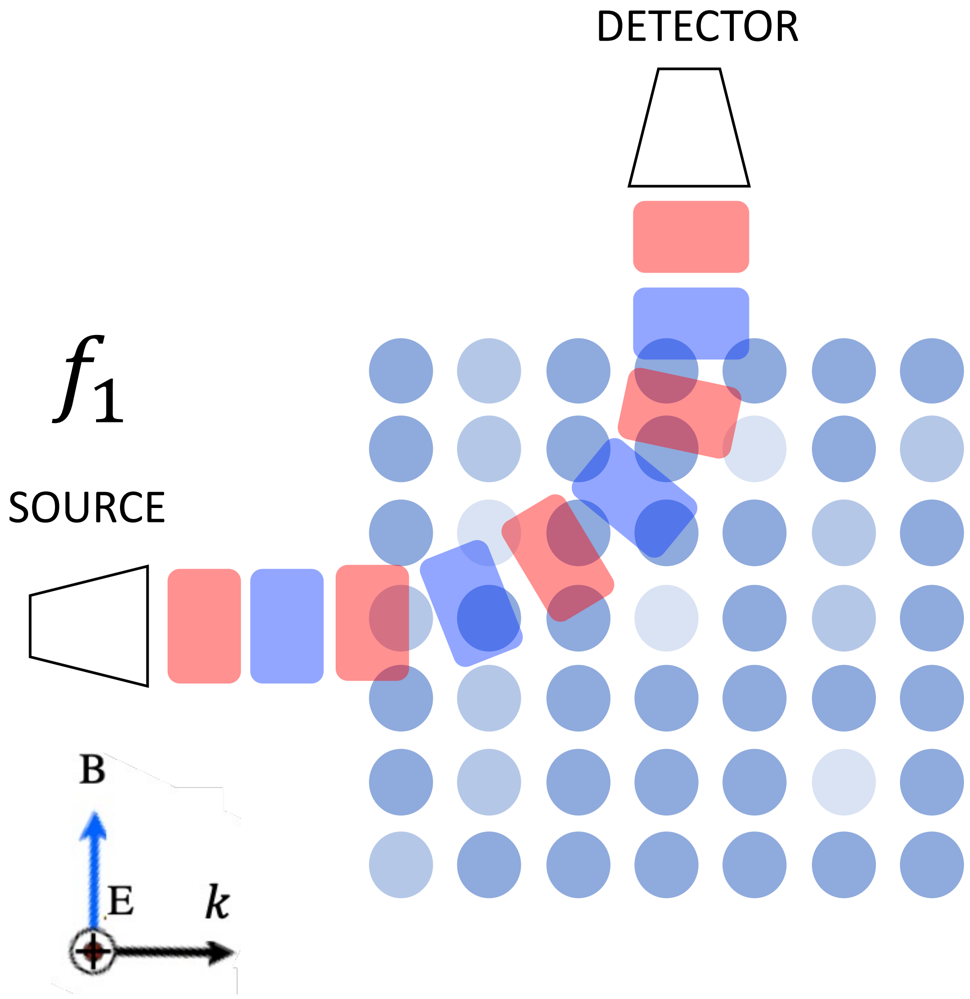
- incident field induced radiating dipole in core and shell medium
- $\lambda \gg D$ first (dipole) term dominates
- Surrounding negative epsilon medium cancels dipole of dielectric core

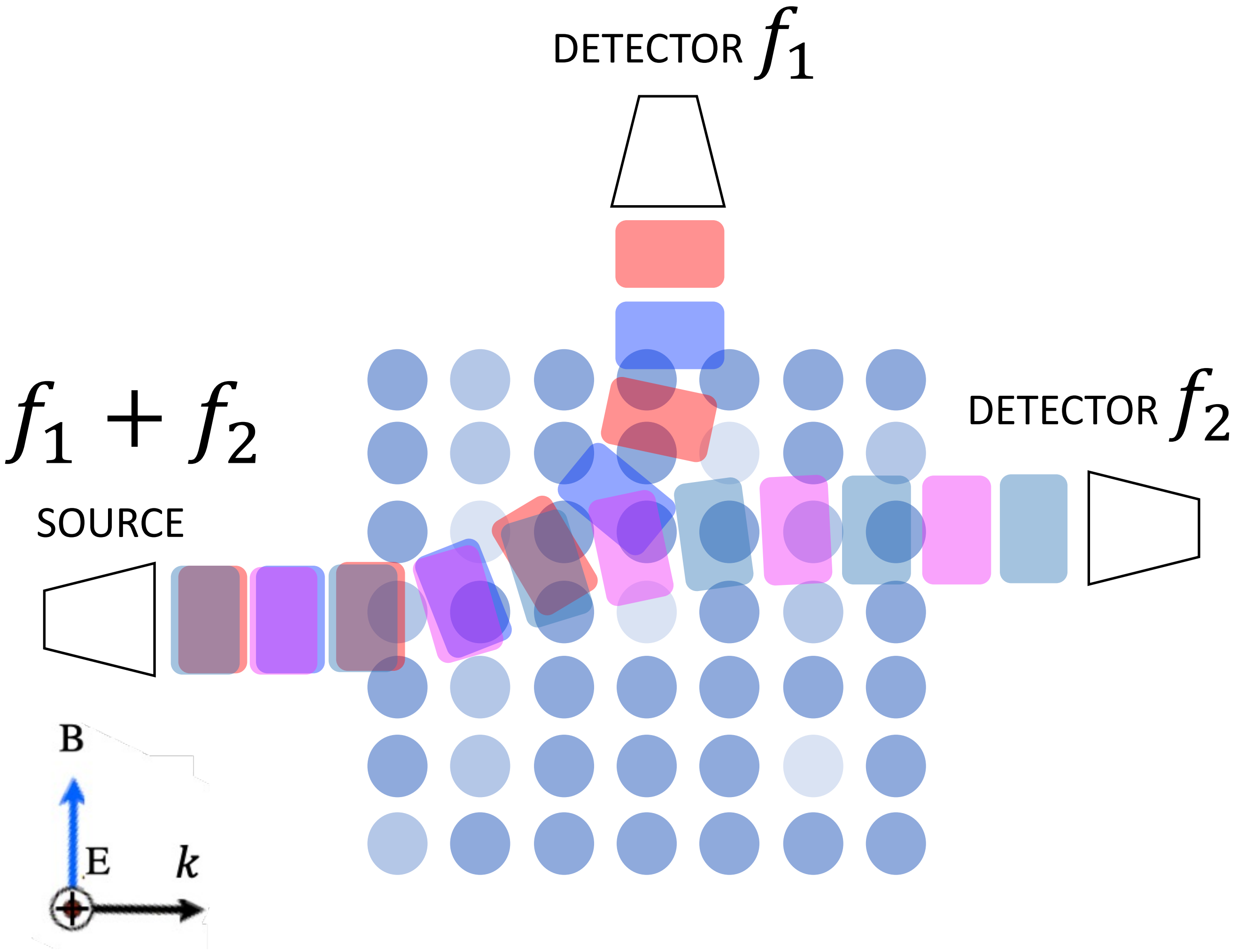
- Design shell of plasma columns that provides the necessary ε_{eff}

A. Alu and N. Engheta (2005), PHYSICAL REVIEW E **72**, 016623

Plasma Array as an Effective Medium

Plasma Functional Metamaterial



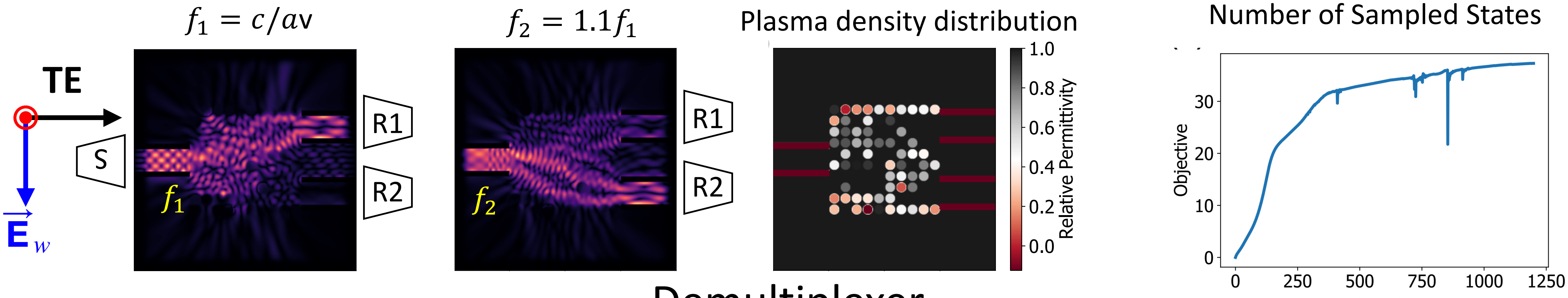


Objective: Redirect Waves

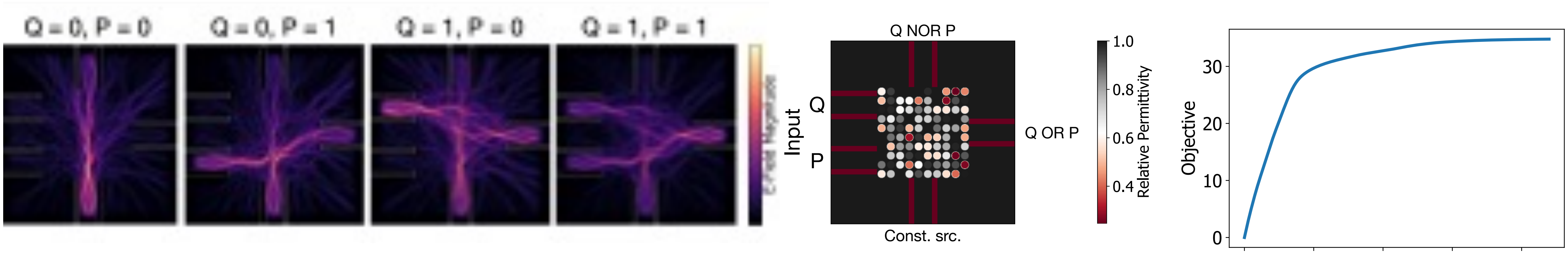
Objective: Demultiplex

Plasma Array as an Effective Medium

Plasma Computer



Demultiplexer



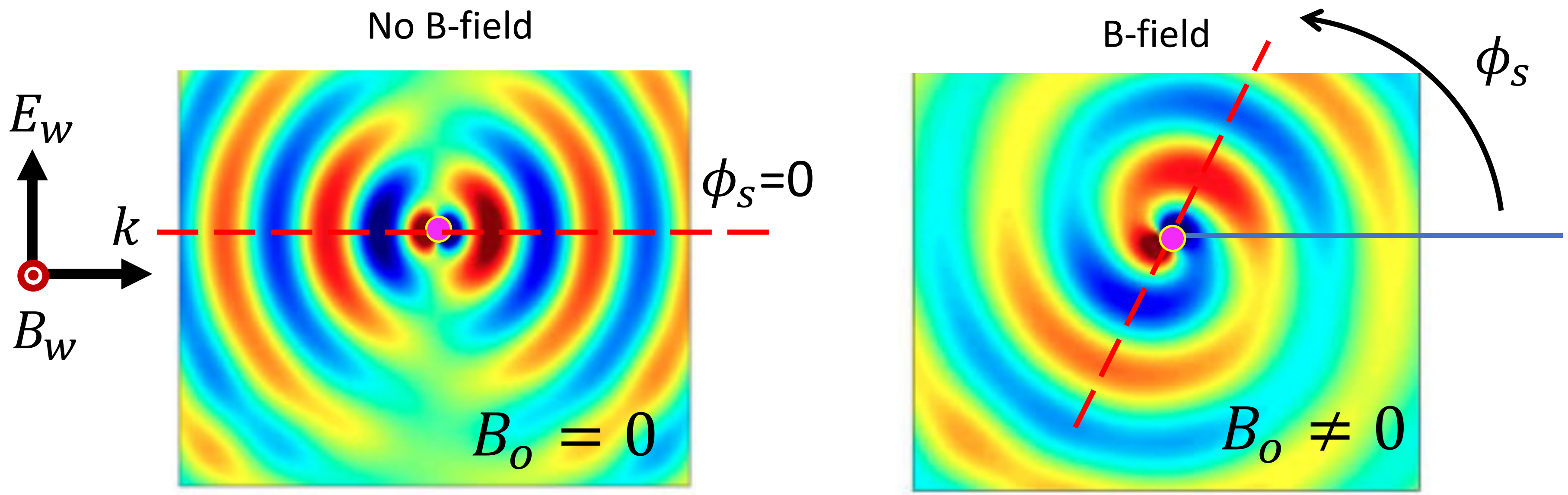
Logic Gate (NOR Gate)

J. Rodríguez, et al., Physical Review Applied 16 (1), 014023, 2021

Magnetized Plasma Electromagnetics

Gyrotropic Plasma Rods

Scattering from Magnetized Plasma Discharges

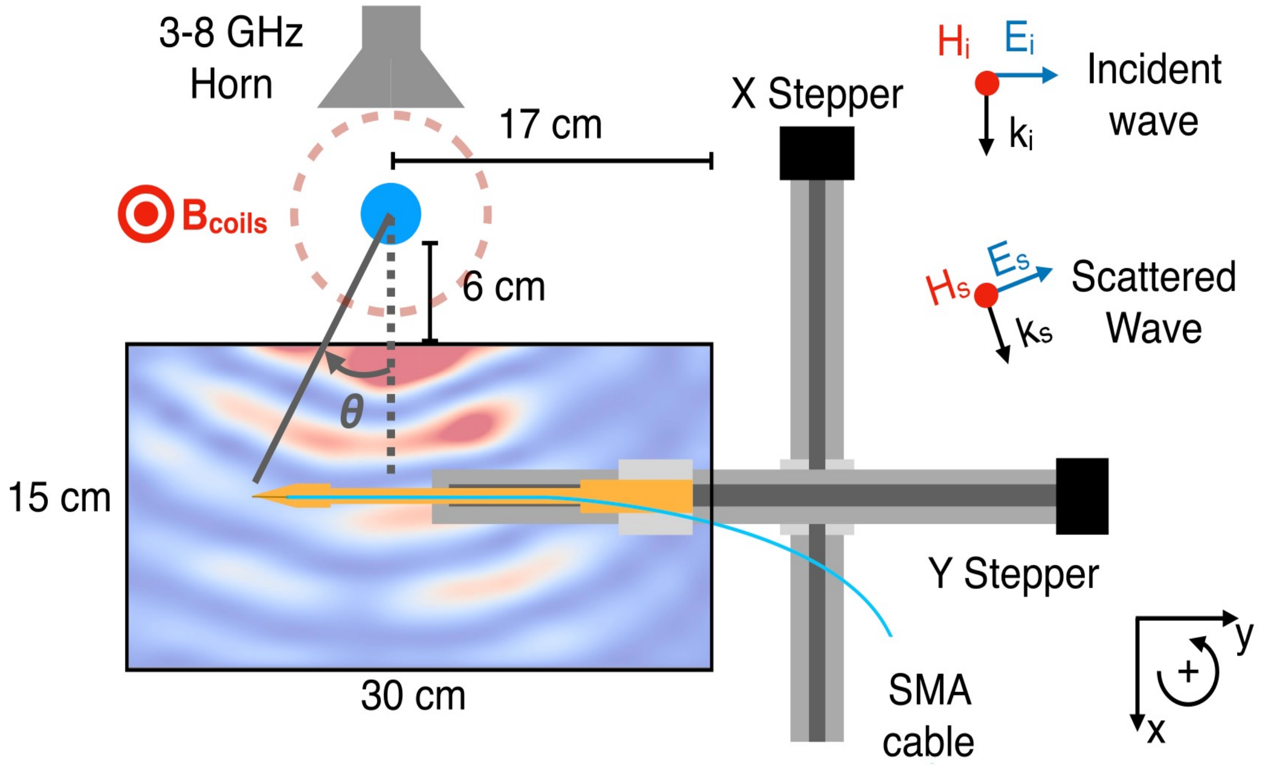


- Magnetized plasma columns exhibit asymmetric scattering*
- Scattering depends on plasma and field properties $\phi_s(f_p, f_c, \nu)$
- Experiments needed to confirm scattering behavior

*Valagiannopoulos et al., Nanomaterials and Nanotechnology 8: 1–10 (2018)

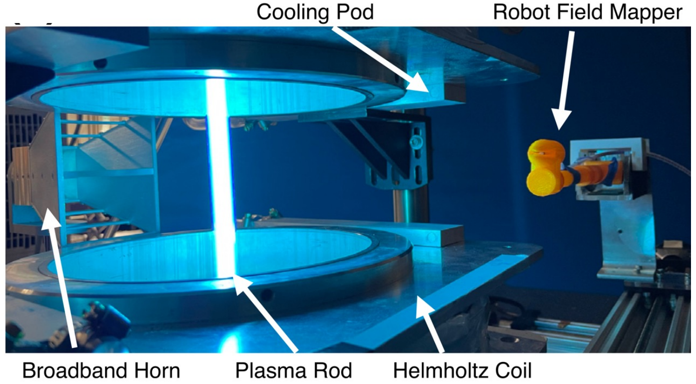
Gyrotropic Plasma Rods

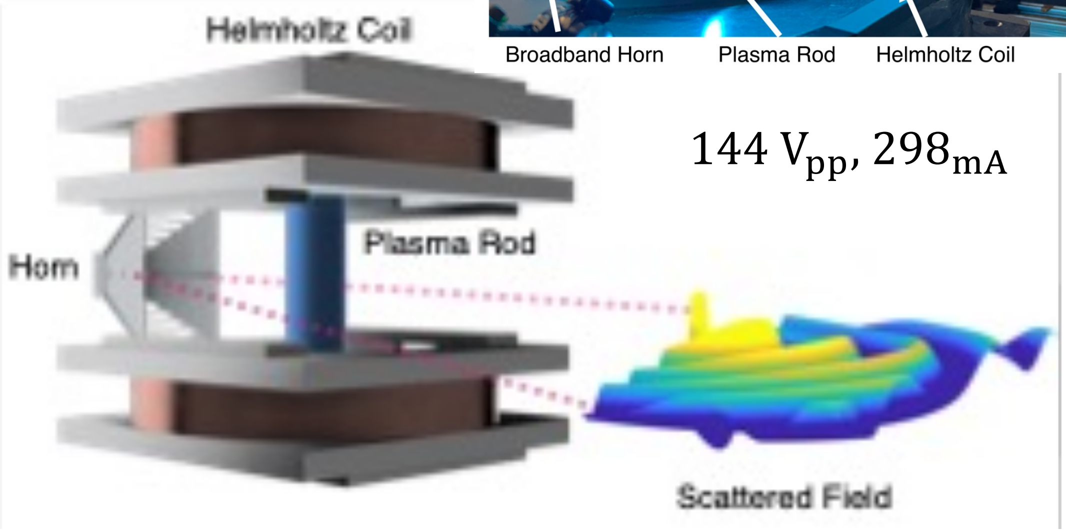
Experimental Measurements



Setup

(15 mm diameter discharge tube)





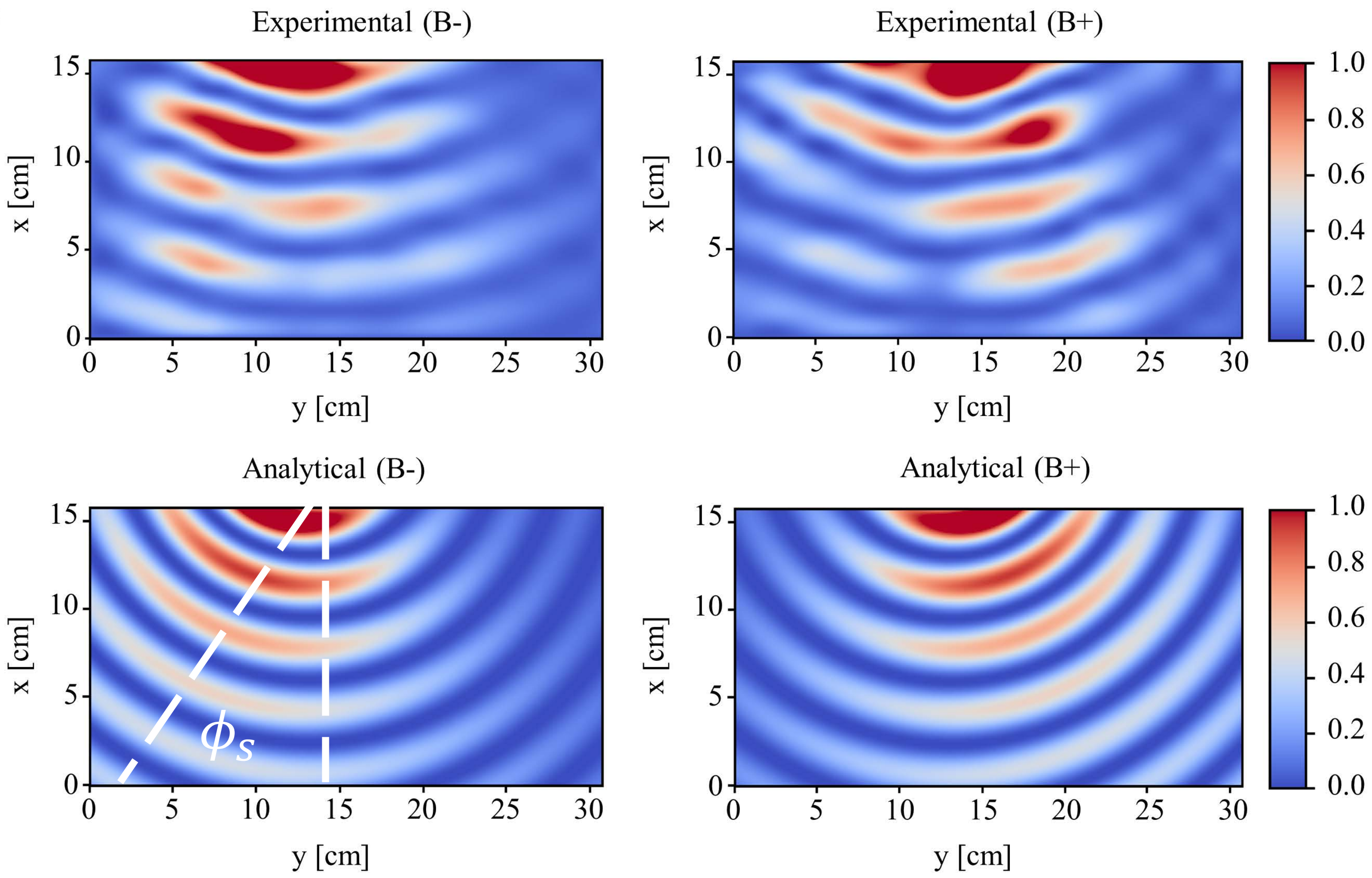
$144\ V_{pp}, 298_{mA}$

3D Rendering of Measured Fields

Houriez et al., Appl. Phys. Lett. **120**, 223101 (2022)

Gyrotropic Plasma Rods

Results



$B_o = 58\ mT$

$\omega/2\pi = 4.43$ GHz

$\omega_c/2\pi = 1.34$ GHz

$\omega_p/2\pi = 8.14$ GHz

$\upsilon_c = 1.34$ GHz

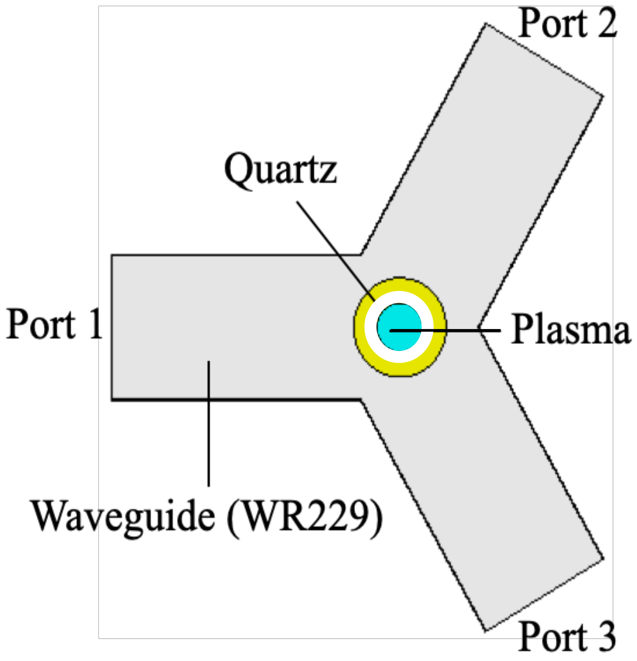
$(n_e = 8.2 \times 10^{17}\ \mathrm{m}^{-3})$

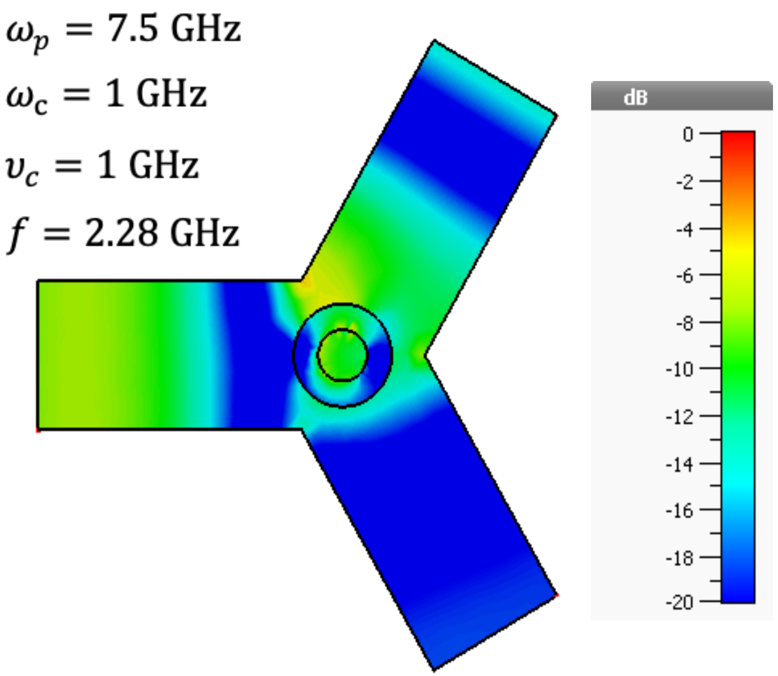
Mehrpour Bernety et al., AIP Advances, in press

Houriez et al., Appl. Phys. Lett. **120**, 223101 (2022)

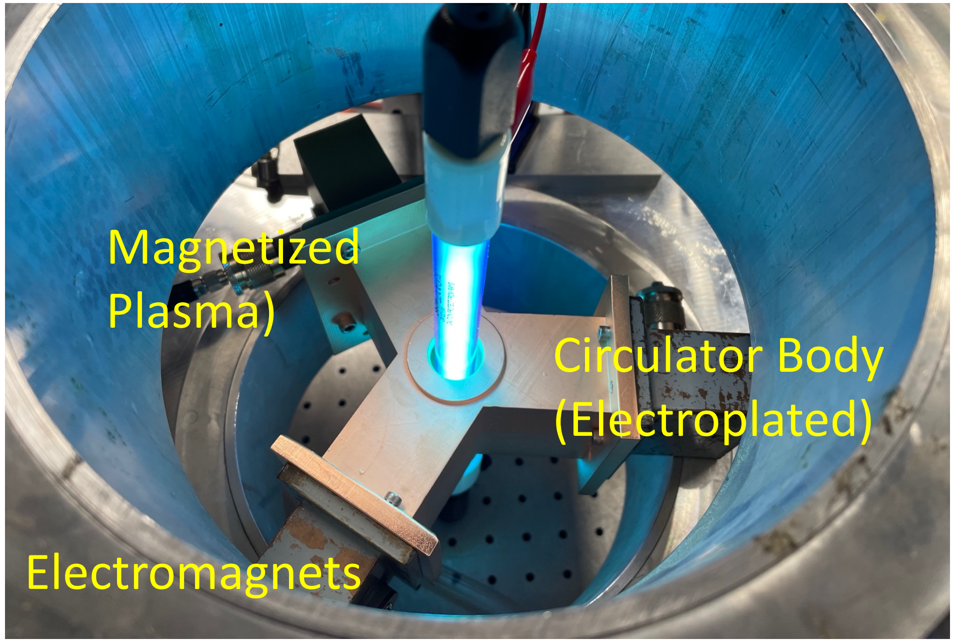
Non-Reciprocal Devices

Tunable Plasma Circulator





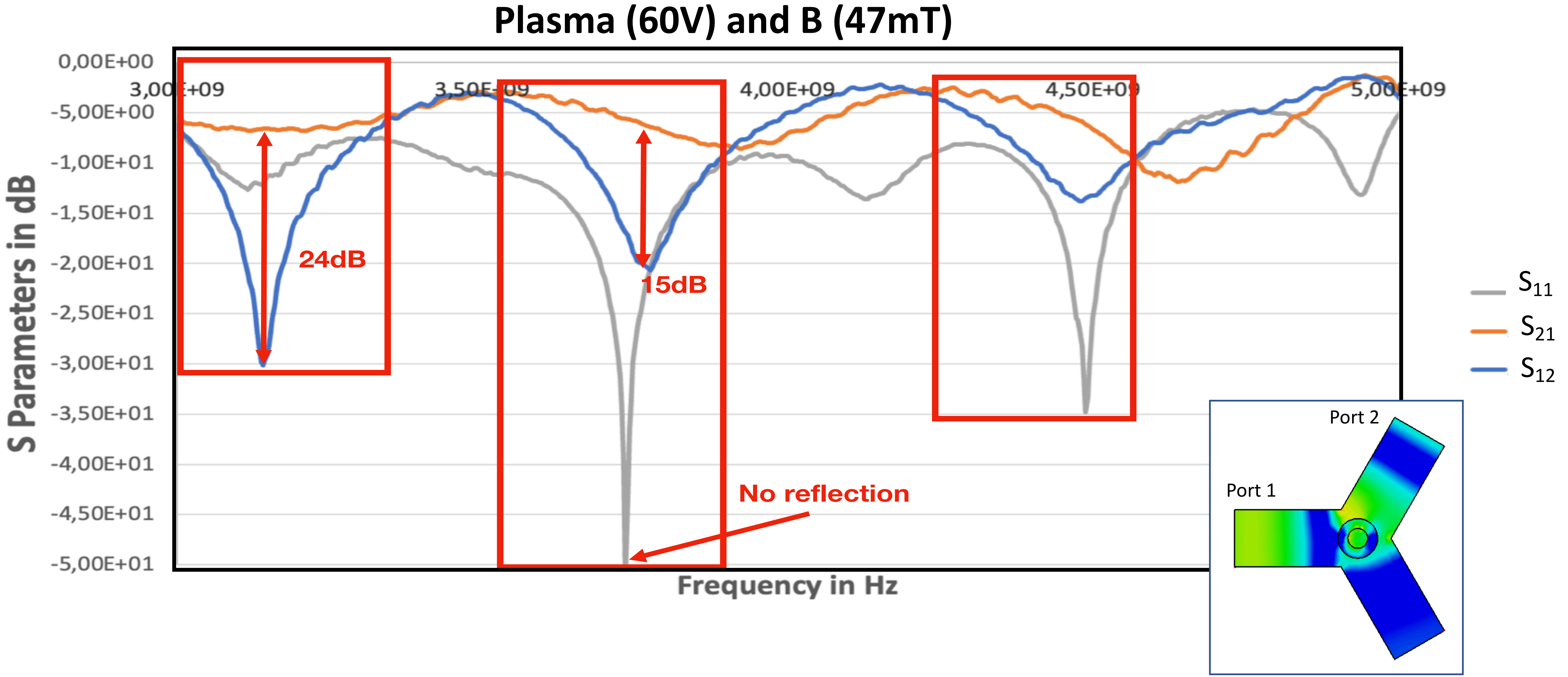
Experimental Facility



Mehrpour Bernety, et al, Physics of Plasmas (2022)

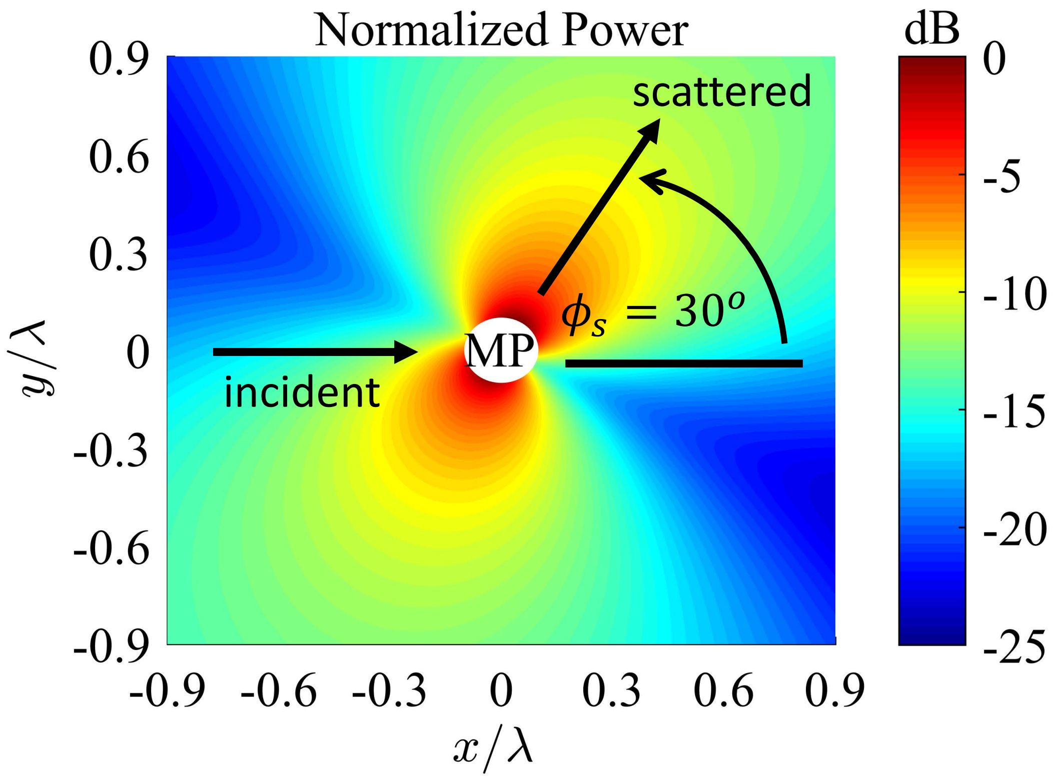
Non-Reciprocal Devices

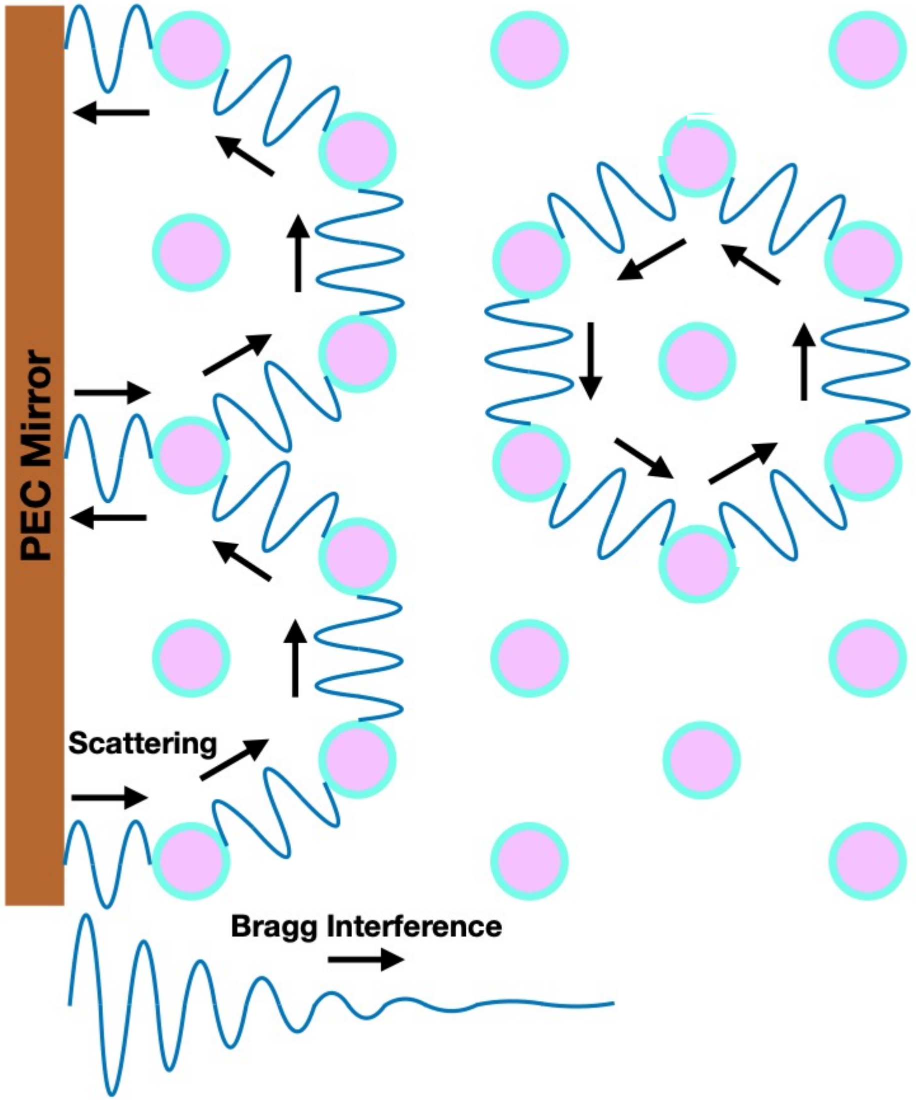
Tunable Plasma Circulator Performance



Magnetized Plasma Photonic Crystals

Edge State Propagation



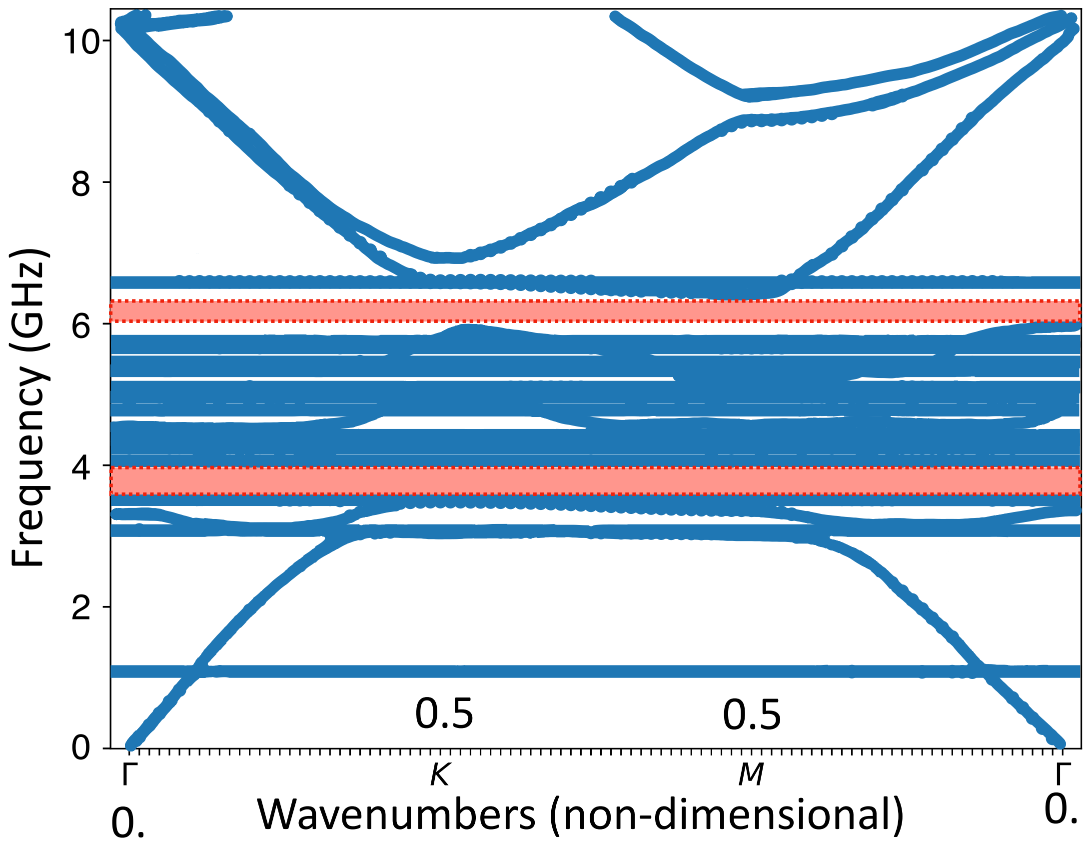


Magnetized Plasma Photonic Crystals

Photonic Crystal Design and Edge State Confirmation

FDTD Eigenmode Simulations

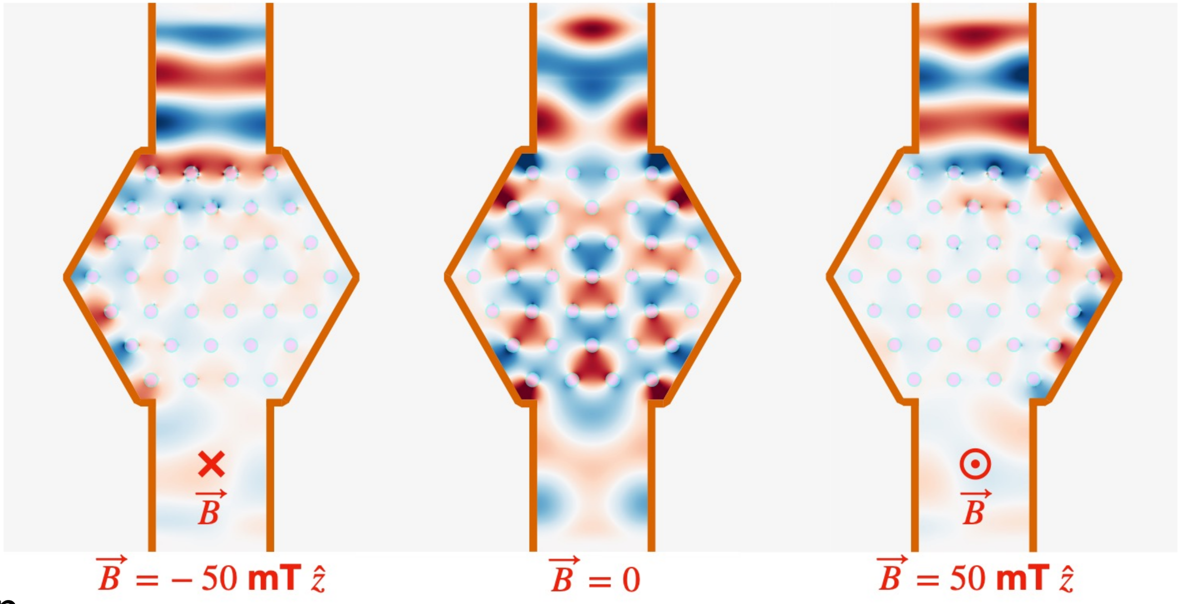
B_{ext} on



Opens up only with B

Bandgap @ ≈ 3.7- 4 GHz forms when B $\neq 0$

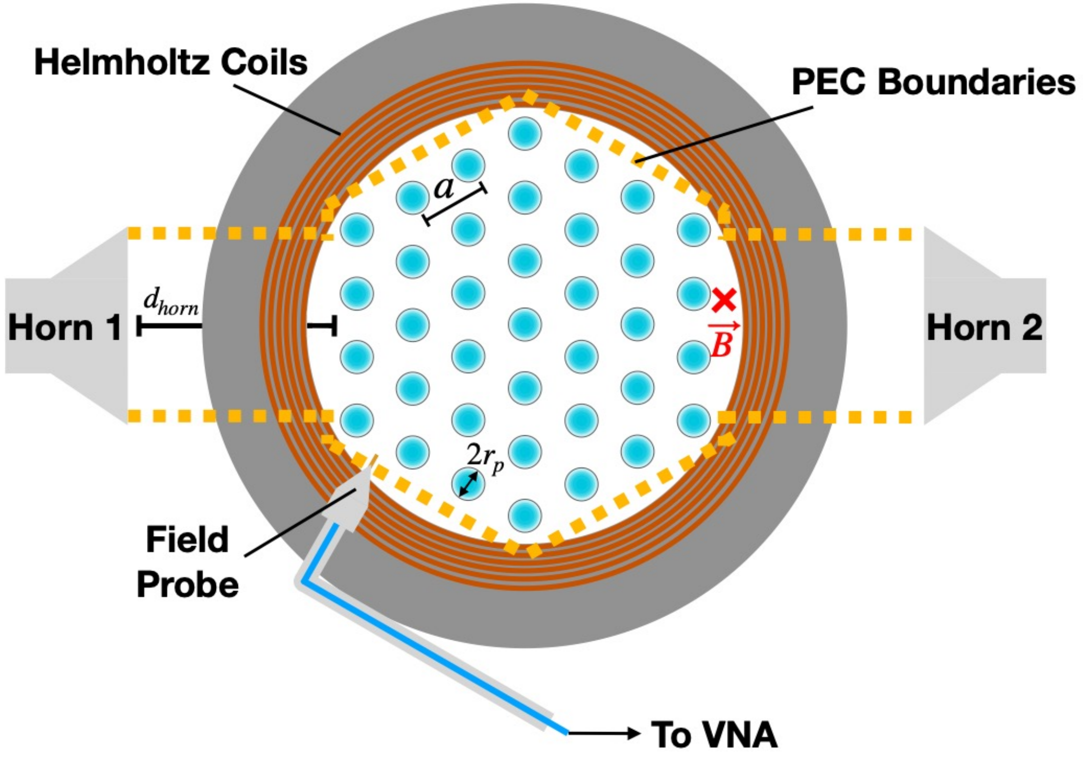
FDTD Field Simulations

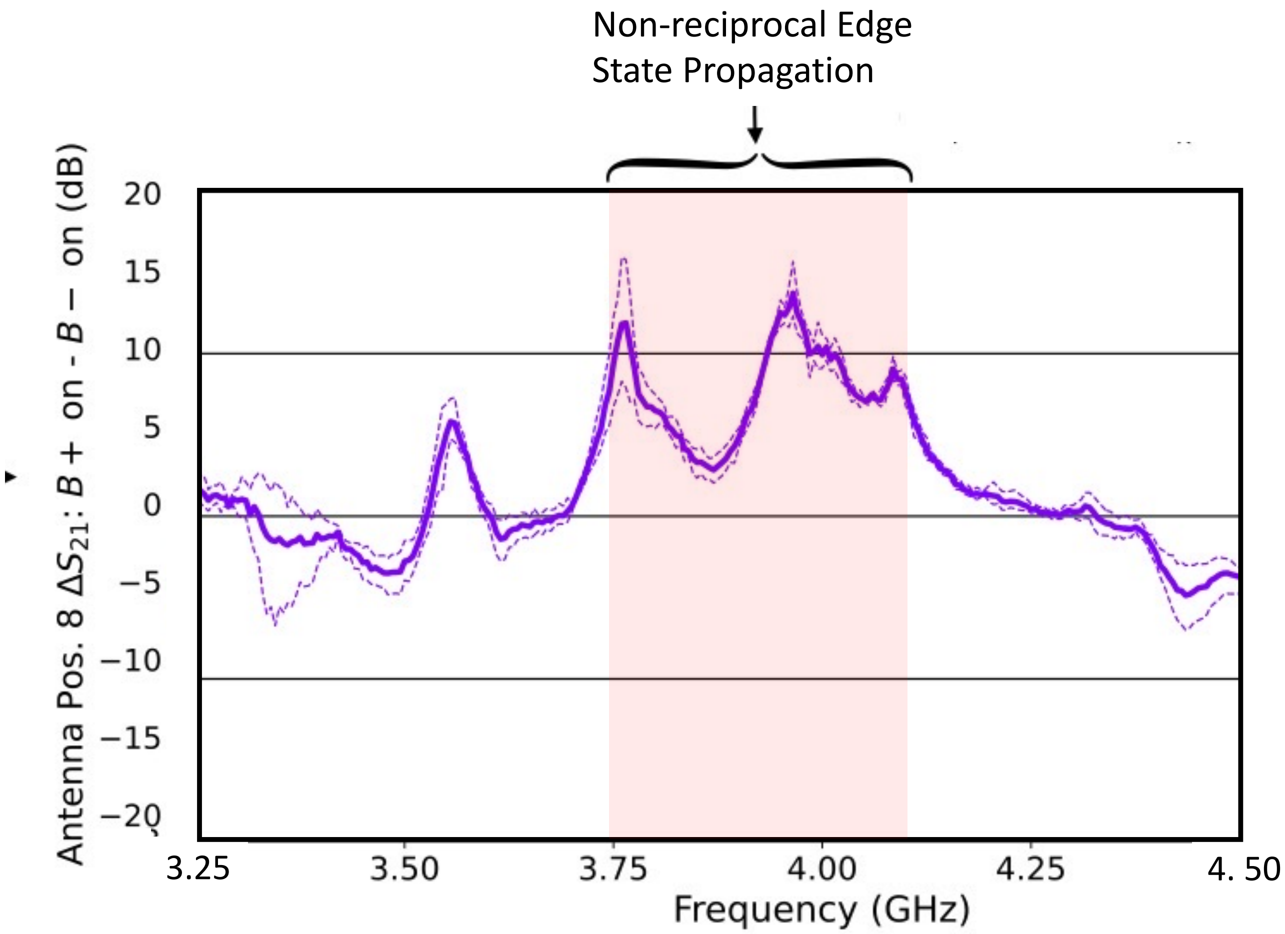


B^- B=0 B^+

Magnetized Plasma Photonic Crystals

Experimental Validation of Non-Reciprocal Propagation





Thank You for your patience
and for your questions!

This work is supported by the Air Force Office of Scientific Research, with Dr. Mitat Birkan as Program Manager

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