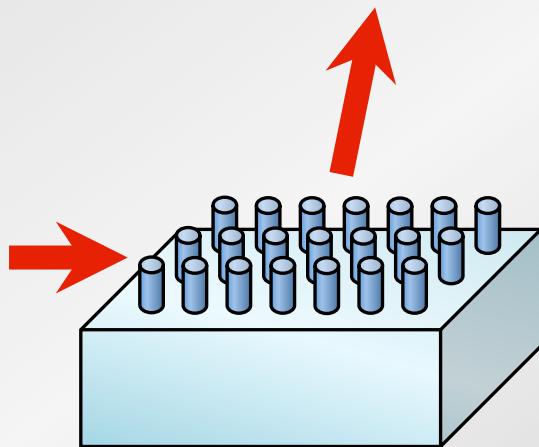


# **Zero-index waveguides for metasurface applications**

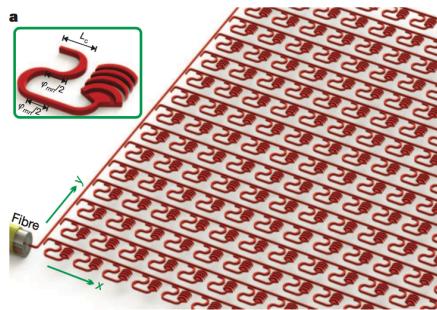
**Philip Muñoz**



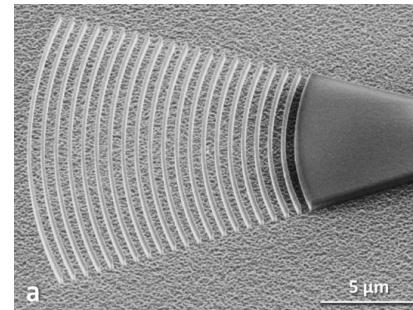
**HARVARD**  
John A. Paulson  
School of Engineering  
and Applied Sciences

# Beam Steering Technologies

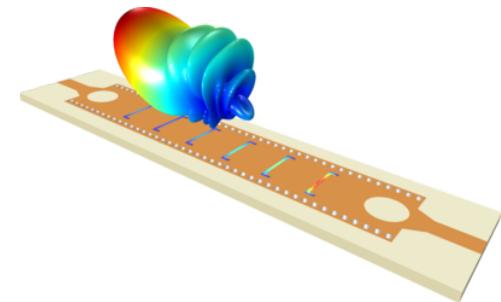
optical phased array



grating coupler



leaky wave antenna



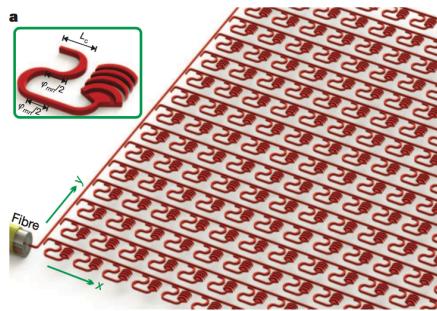
1

beam steering

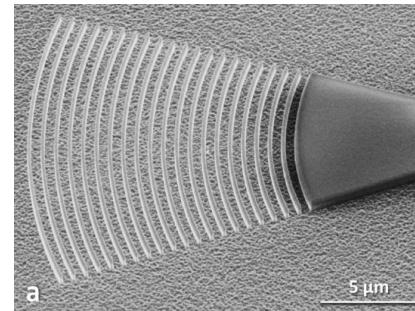
Sun, J., et al., Nature 2013  
Rath, P., et al., Beilstein J. Nanotech. 2013  
COMSOL Multiphysics

# Beam Steering Technologies

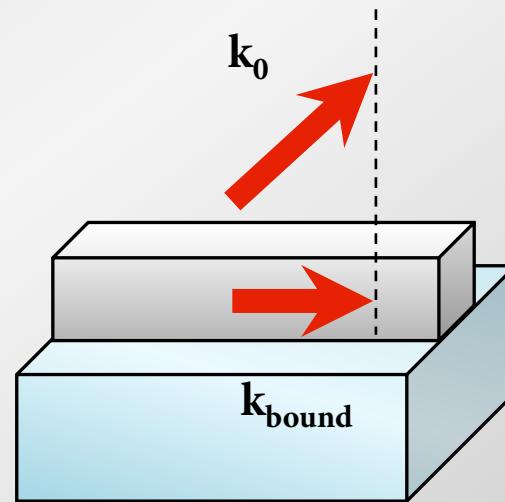
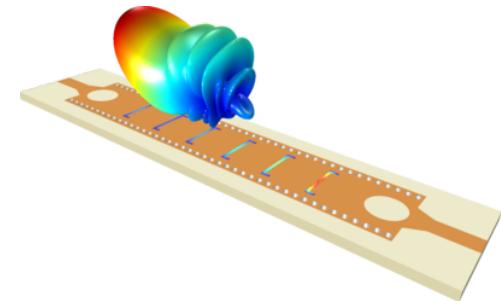
optical phased array



grating coupler



leaky wave antenna



1

beam steering

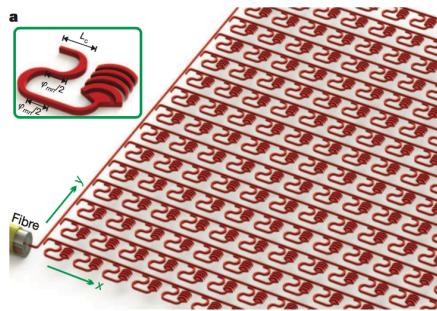
Sun, J., et al., Nature 2013

Rath, P., et al., Beilstein J. Nanotech. 2013

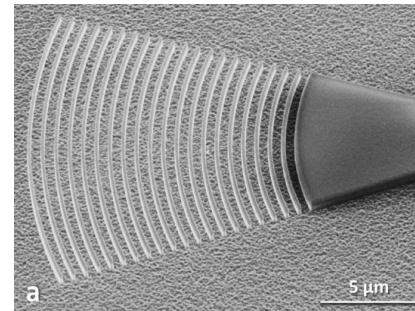
COMSOL Multiphysics

# Beam Steering Technologies

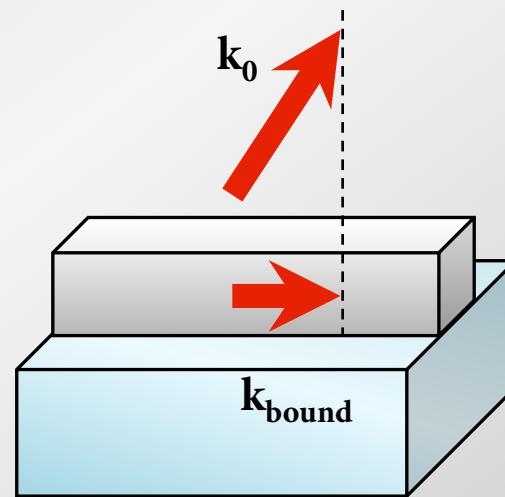
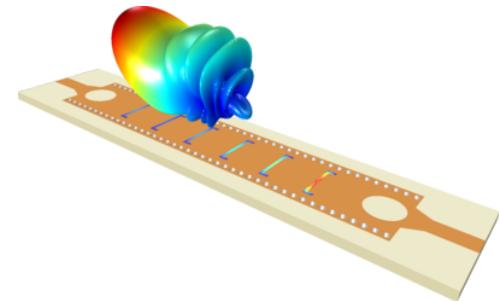
optical phased array



grating coupler



leaky wave antenna



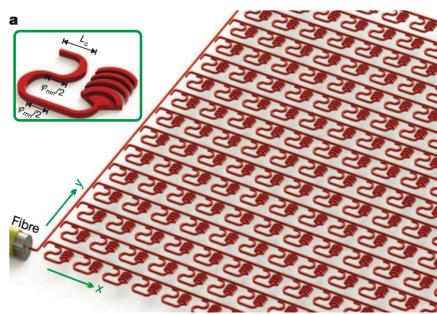
1

beam steering

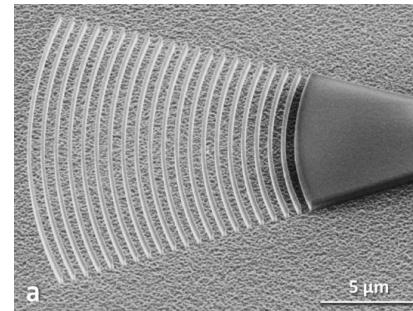
Sun, J., et al., Nature 2013  
Rath, P., et al., Beilstein J. Nanotech. 2013  
COMSOL Multiphysics

# Beam Steering Technologies

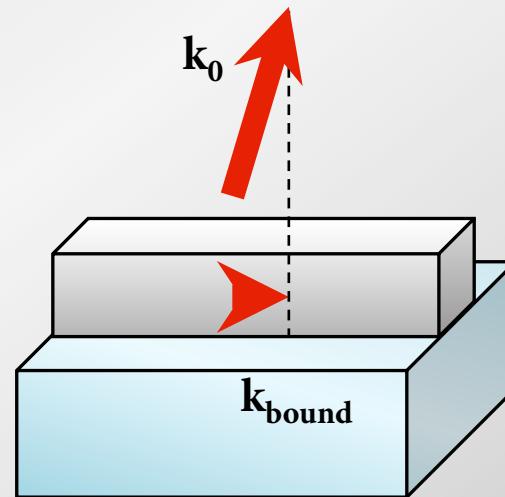
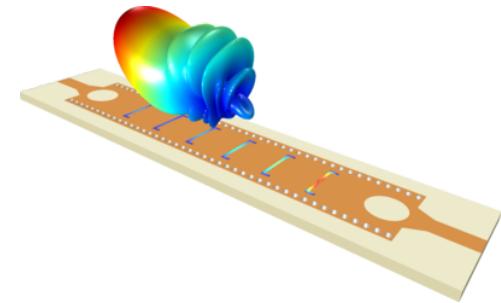
optical phased array



grating coupler



leaky wave antenna



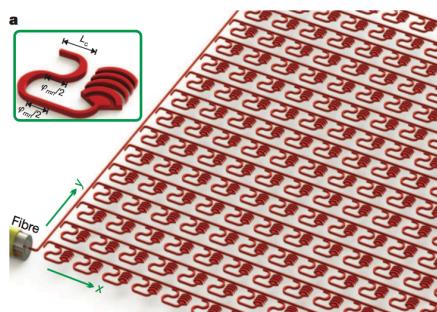
1

beam steering

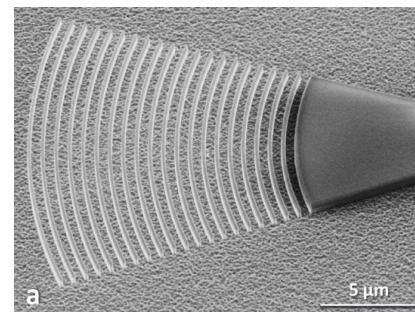
Sun, J., et al., Nature 2013  
Rath, P., et al., Beilstein J. Nanotech. 2013  
COMSOL Multiphysics

# Beam Steering Technologies

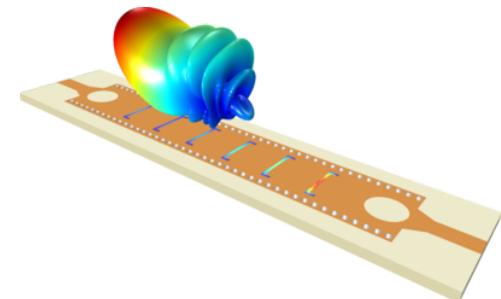
optical phased array



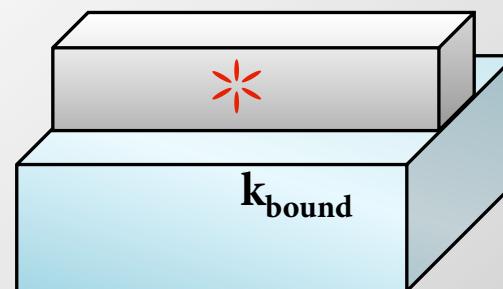
grating coupler



leaky wave antenna



$k_0$



Scattering is inefficient  
at  $90^\circ$  (broadside)

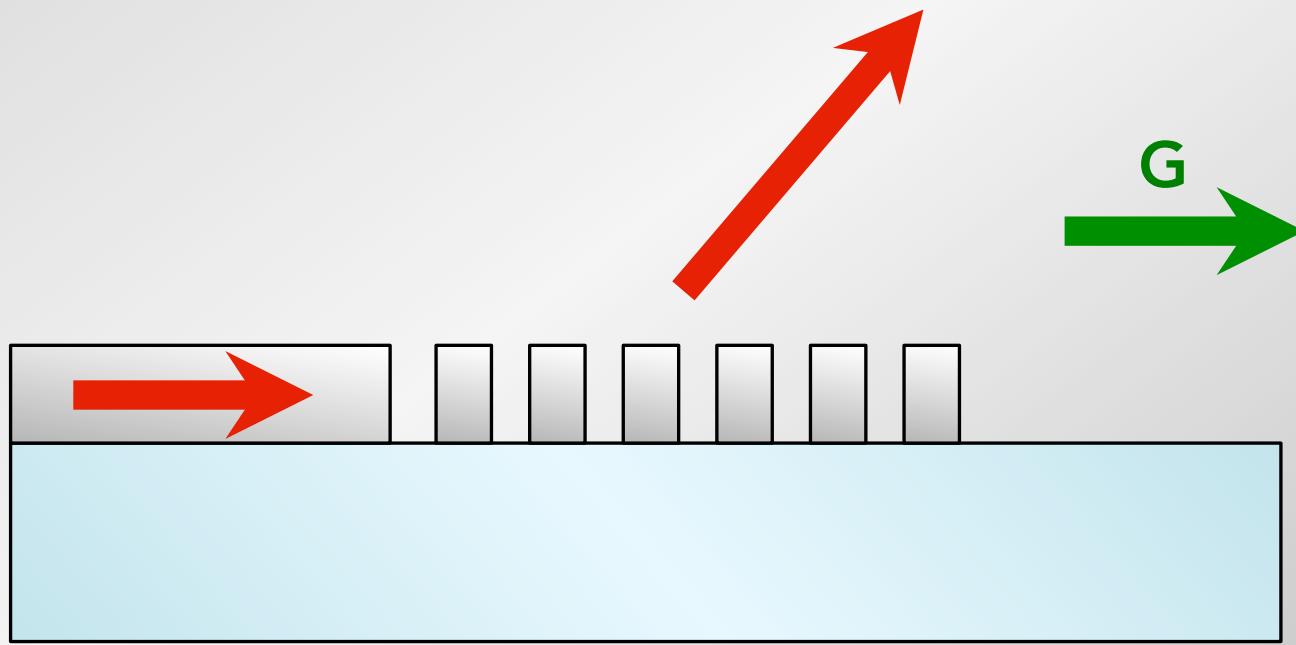
1

beam steering

Sun, J., et al., Nature 2013

Rath, P., et al., Beilstein J. Nanotech. 2013  
COMSOL Multiphysics

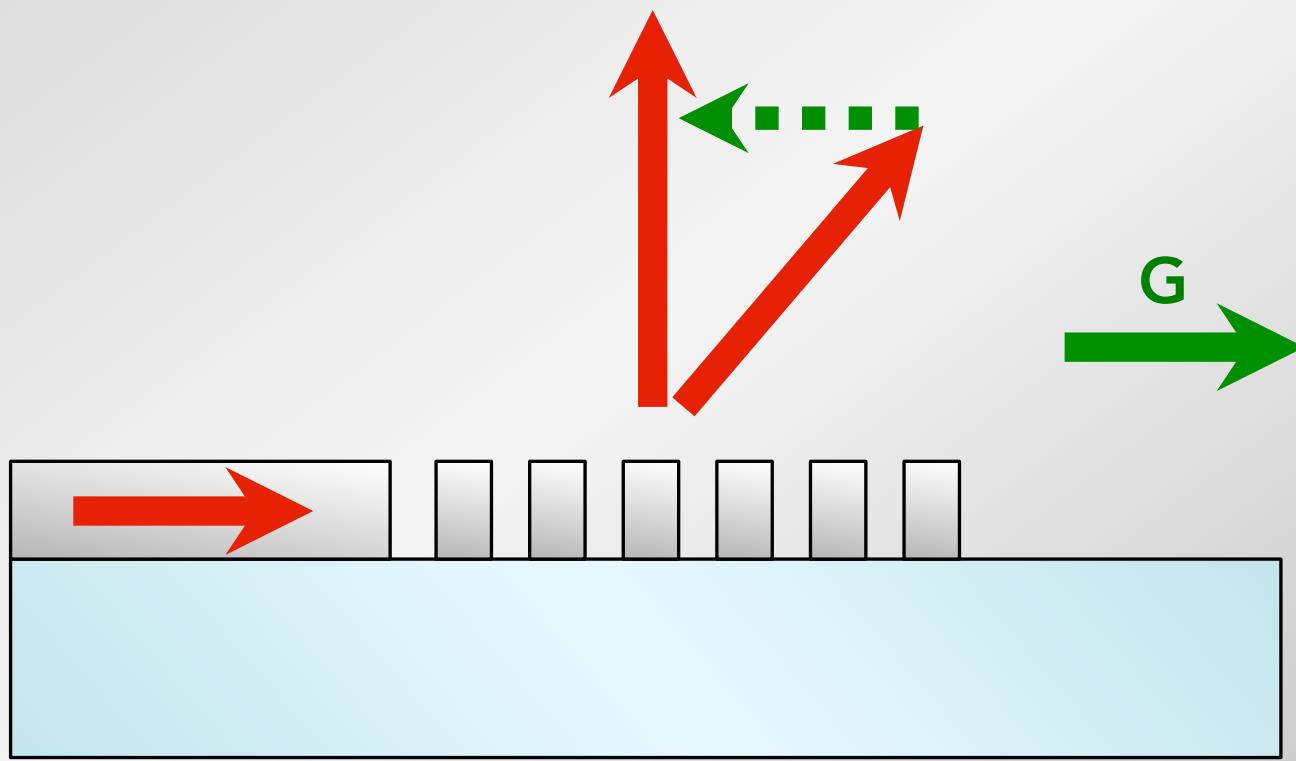
# Broadside Radiation



1

beam steering

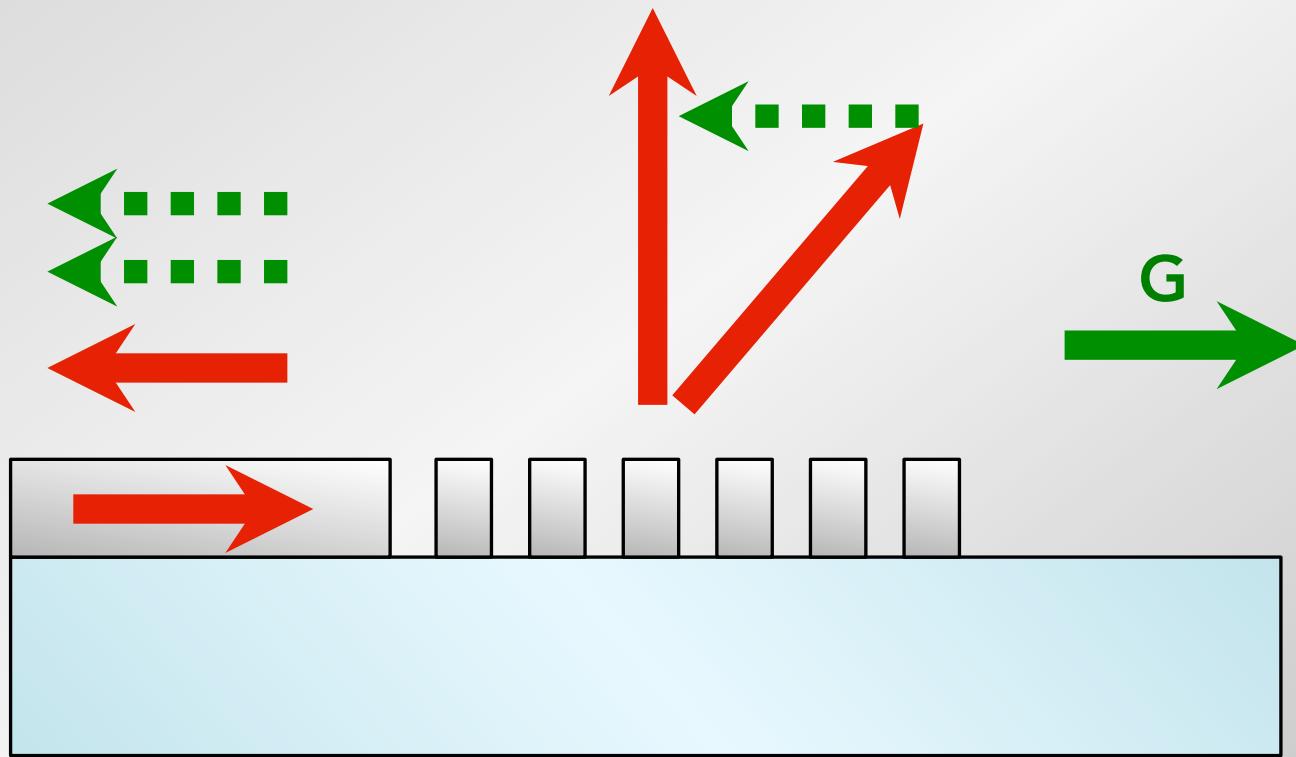
# Broadside Radiation



1

beam steering

# Broadside Radiation

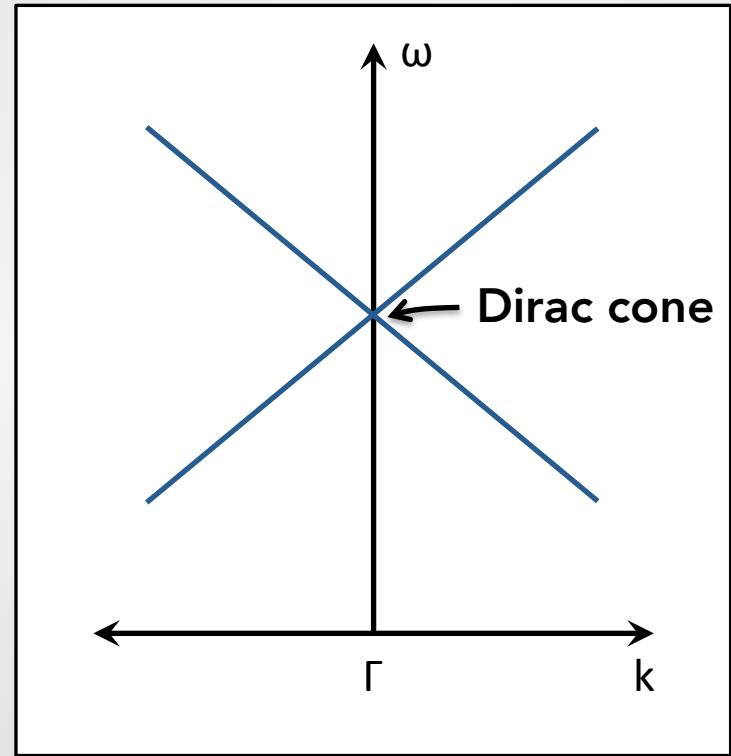
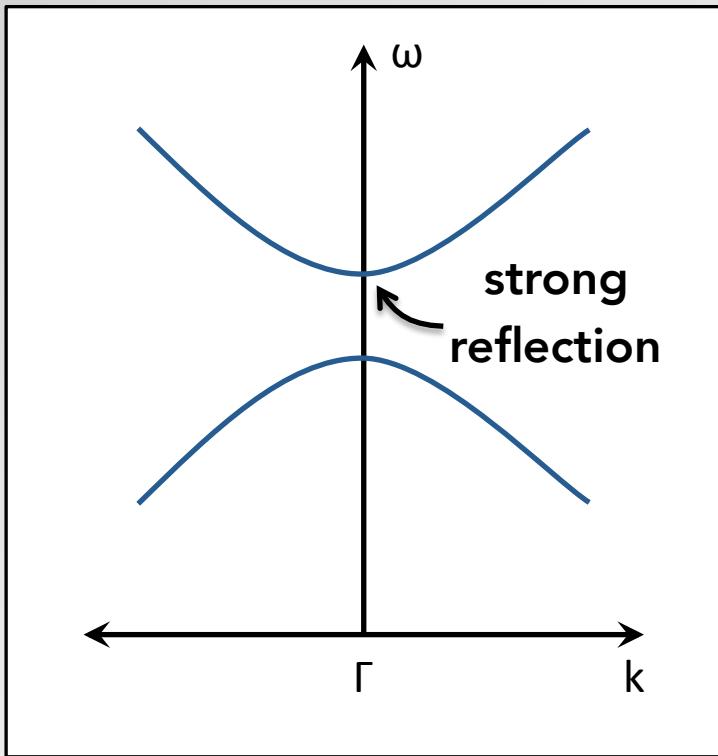


broadside radiation is associated with strong reflection

1

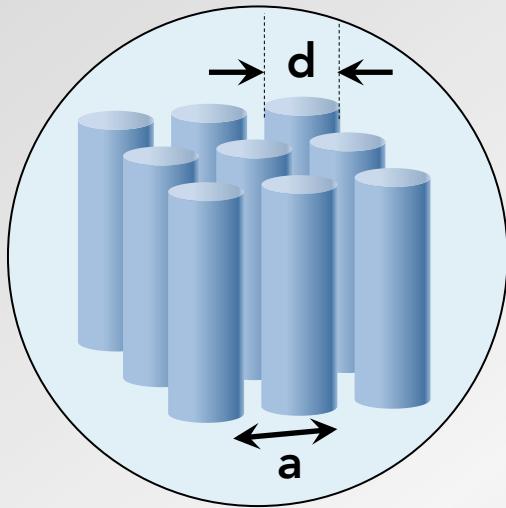
beam steering

# Bandstructure



Poor coupling will always arise at a band edge.  
So... eliminate the bandgap

# Dirac Cone Metamaterials



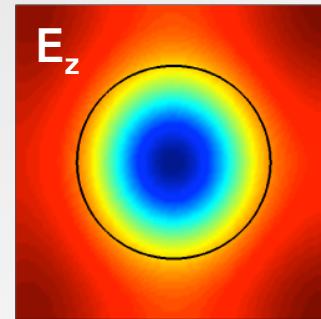
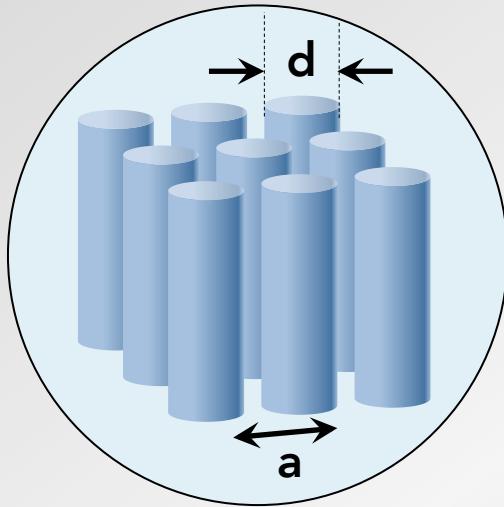
1

beam steering

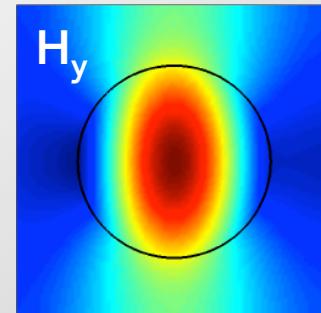
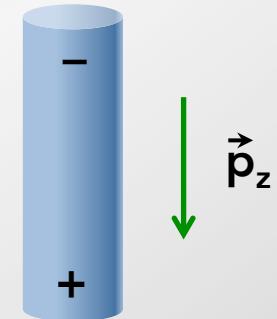
2

zero index

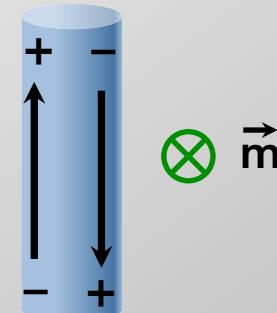
# Dirac Cone Metamaterials



electric monopole



magnetic dipole



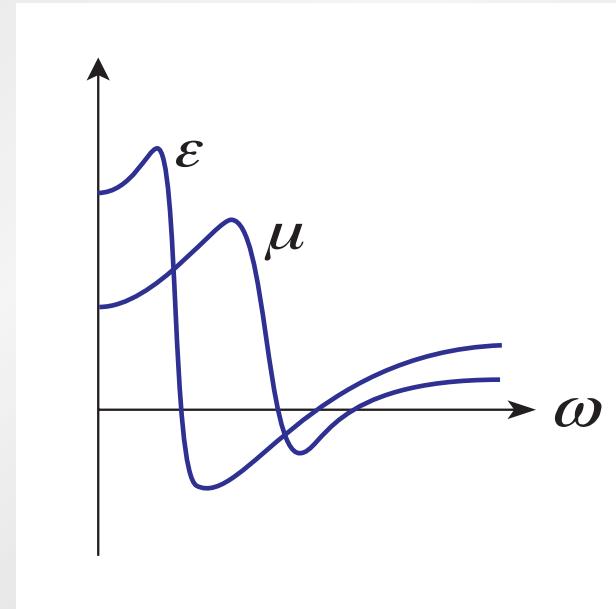
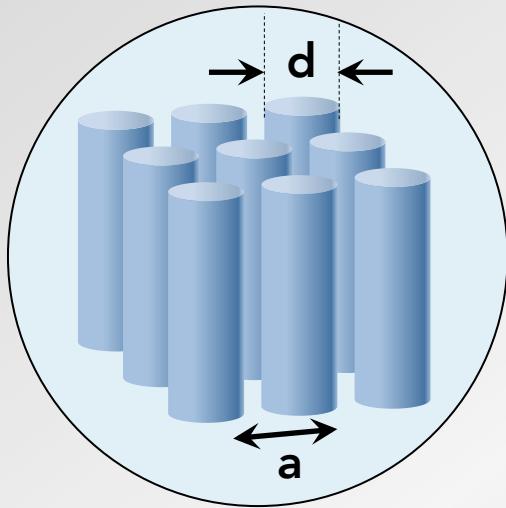
1

beam steering

2

zero index

# Dirac Cone Metamaterials



Monopole and dipole modes give rise to effective permittivity and permeability

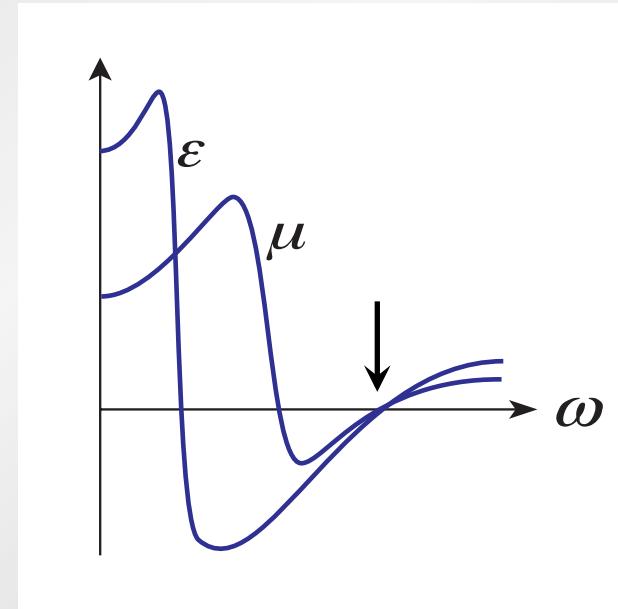
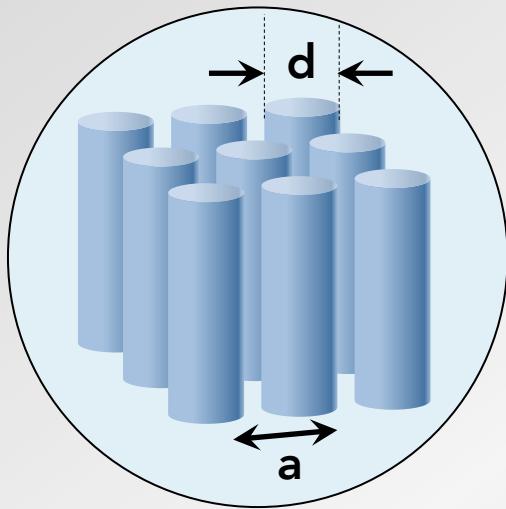
1

beam steering

2

zero index

# Dirac Cone Metamaterials



Monopole and dipole modes give rise to effective permittivity and permeability  
By tuning the pillar radius and pitch, we can drive both  $\epsilon_{\text{eff}}$  and  $\mu_{\text{eff}}$  to zero

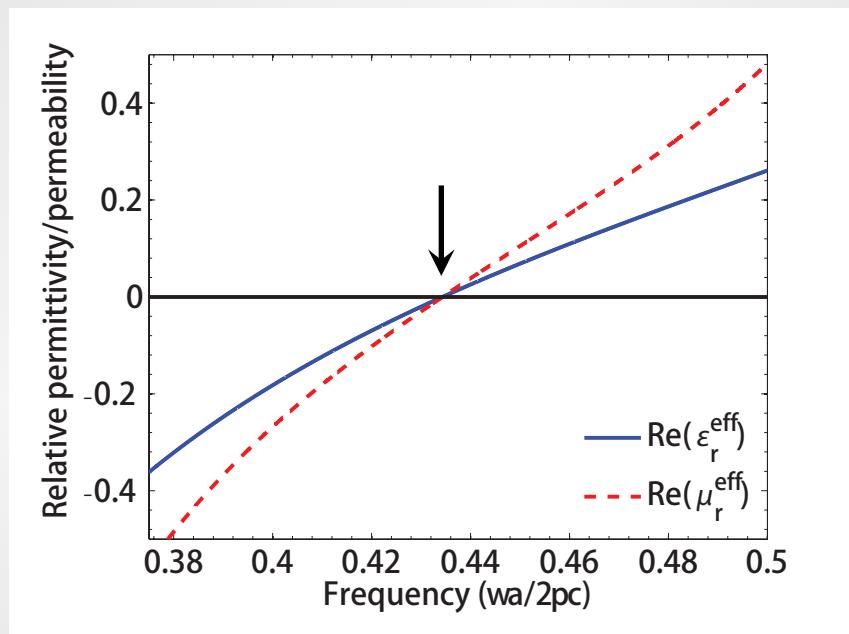
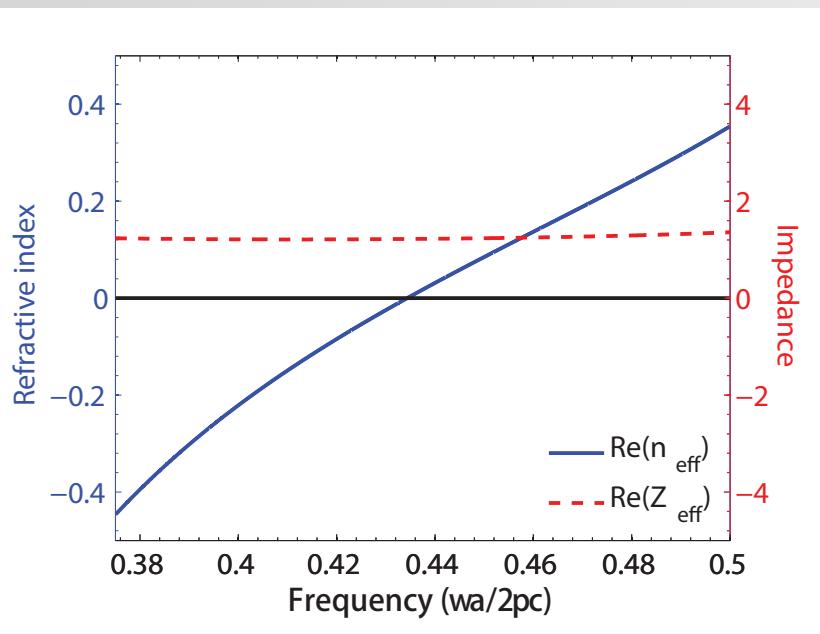
1

beam steering

2

zero index

# Dirac Cone Metamaterials



index

$$n = \sqrt{\epsilon\mu} = 0$$

impedance

$$Z = \sqrt{\mu/\epsilon} \approx 1.7$$

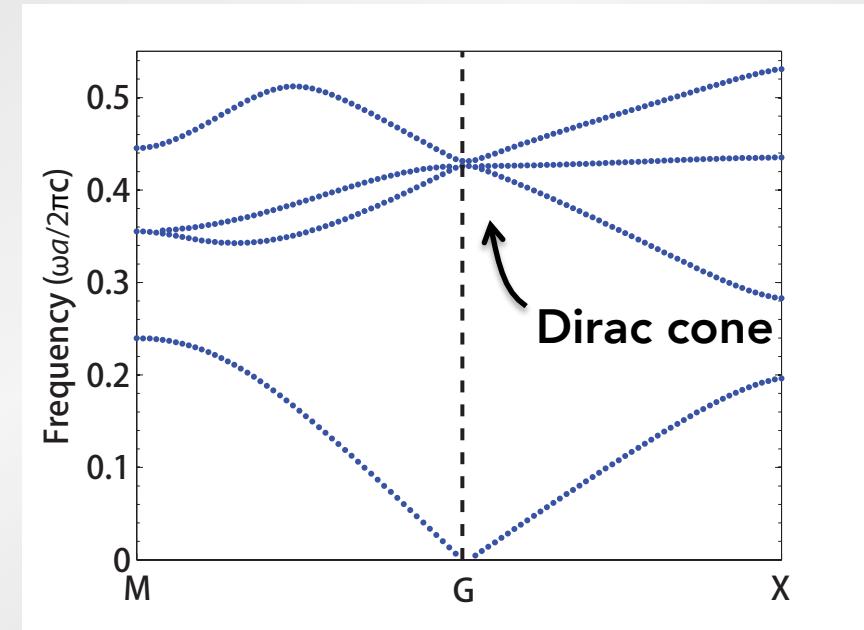
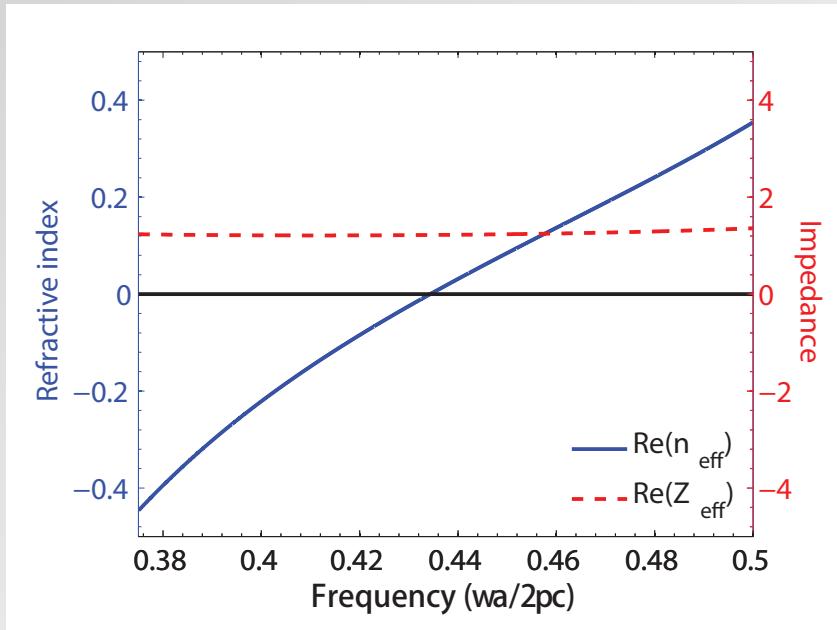
1

beam steering

2

zero index

# Dirac Cone Metamaterials



index

$$n = \sqrt{\epsilon \mu} = 0$$

impedance

$$Z = \sqrt{\frac{\mu}{\epsilon}} \approx 1.7$$

impedance matching  
at the  $\Gamma$ -point

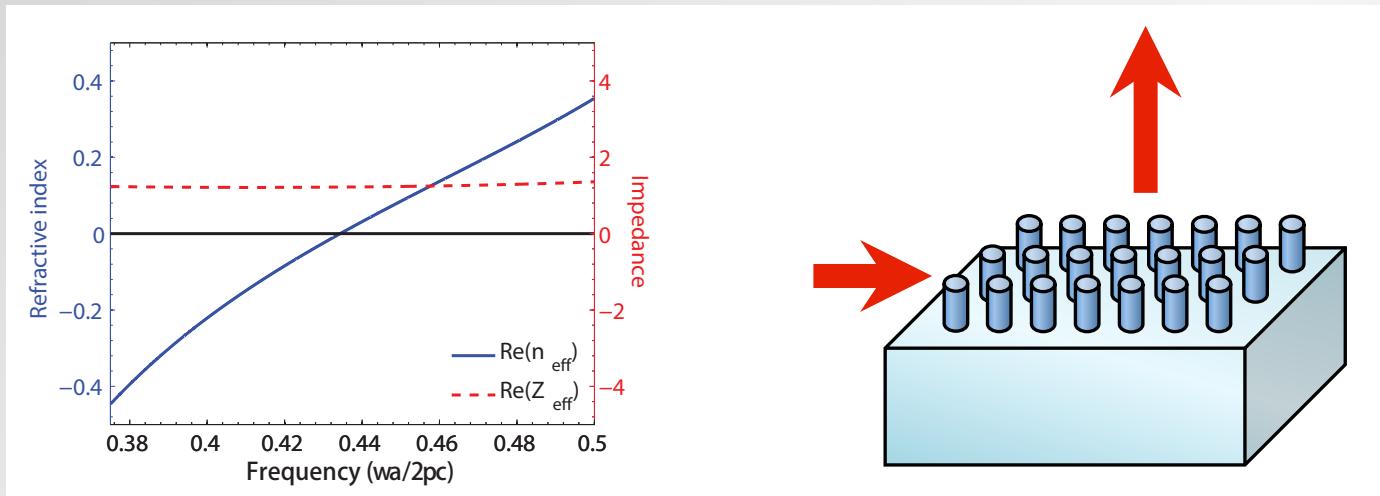
1

beam steering

2

zero index

# Radiation from Finite Pillars



finite pillars can couple to plane waves in free space

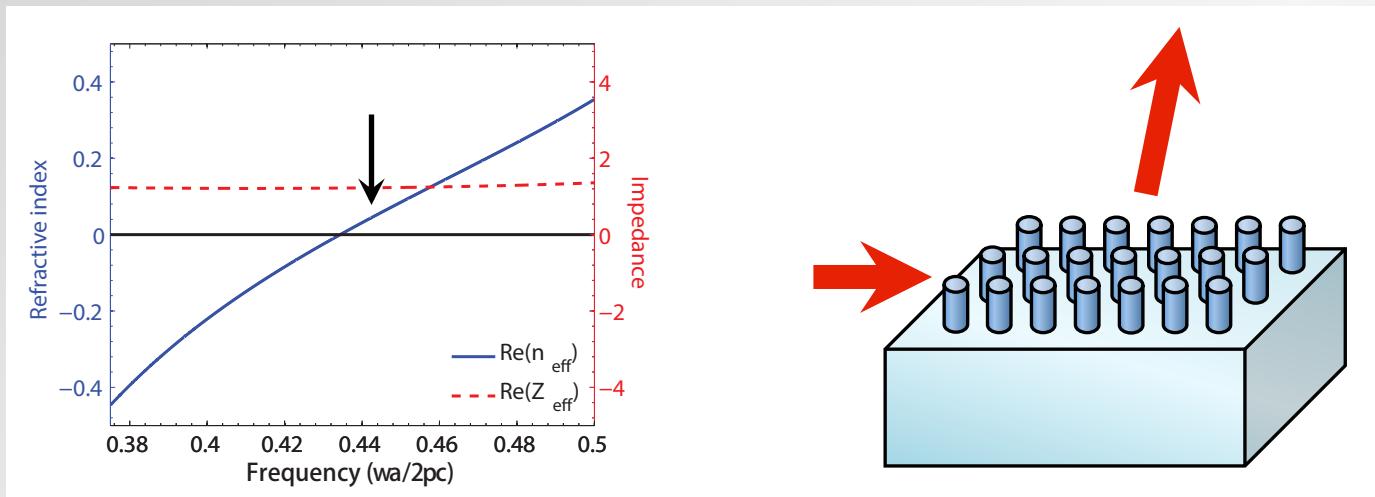
1

beam steering

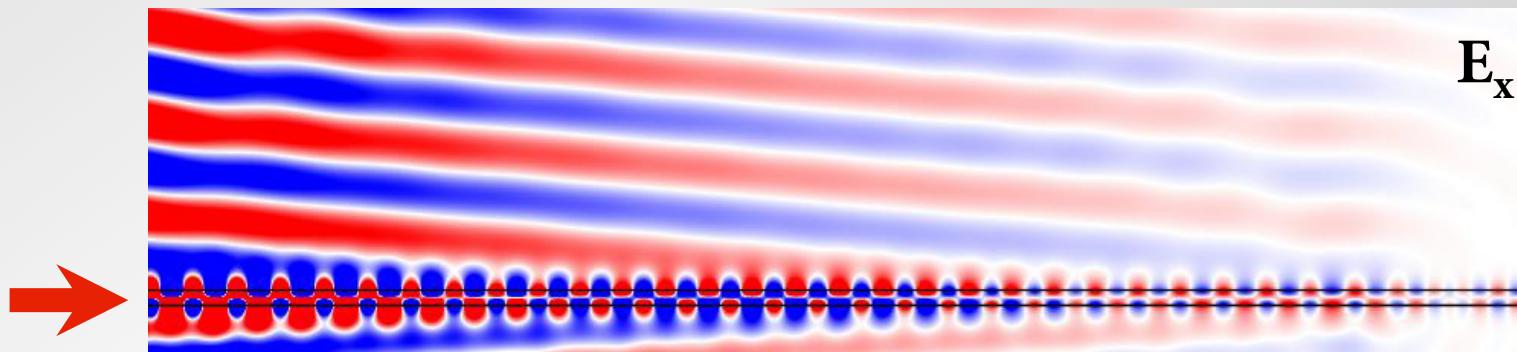
2

zero index

# Radiation from Finite Pillars



positive index



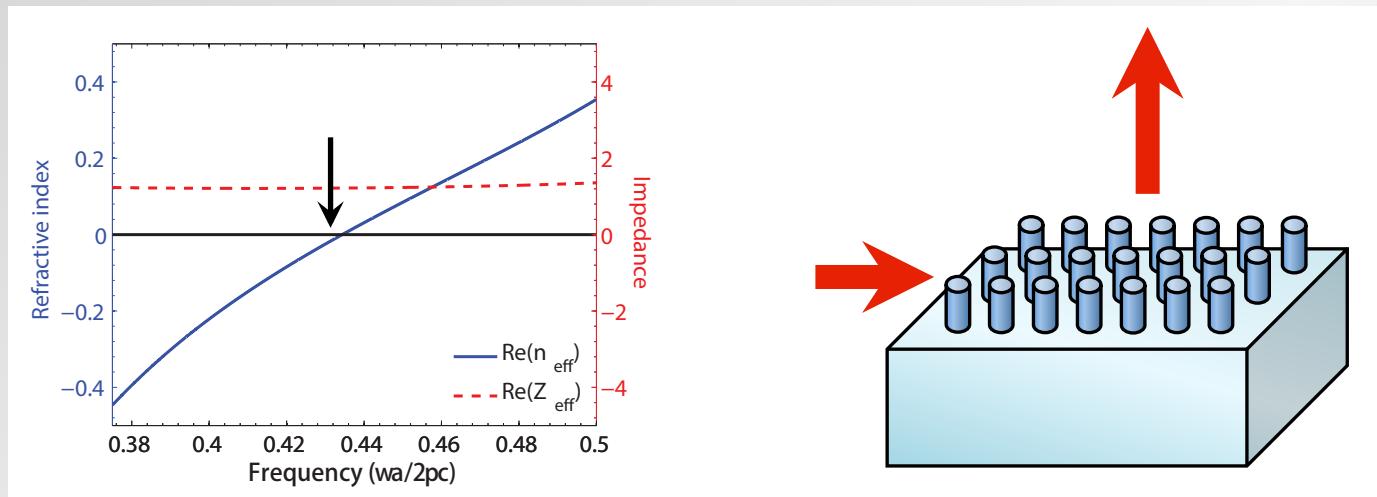
1

beam steering

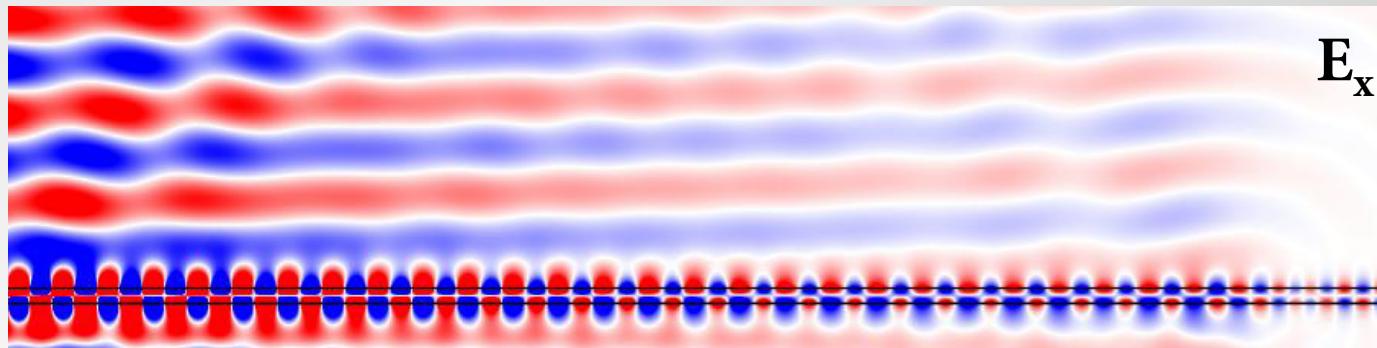
2

zero index

# Radiation from Finite Pillars



zero index



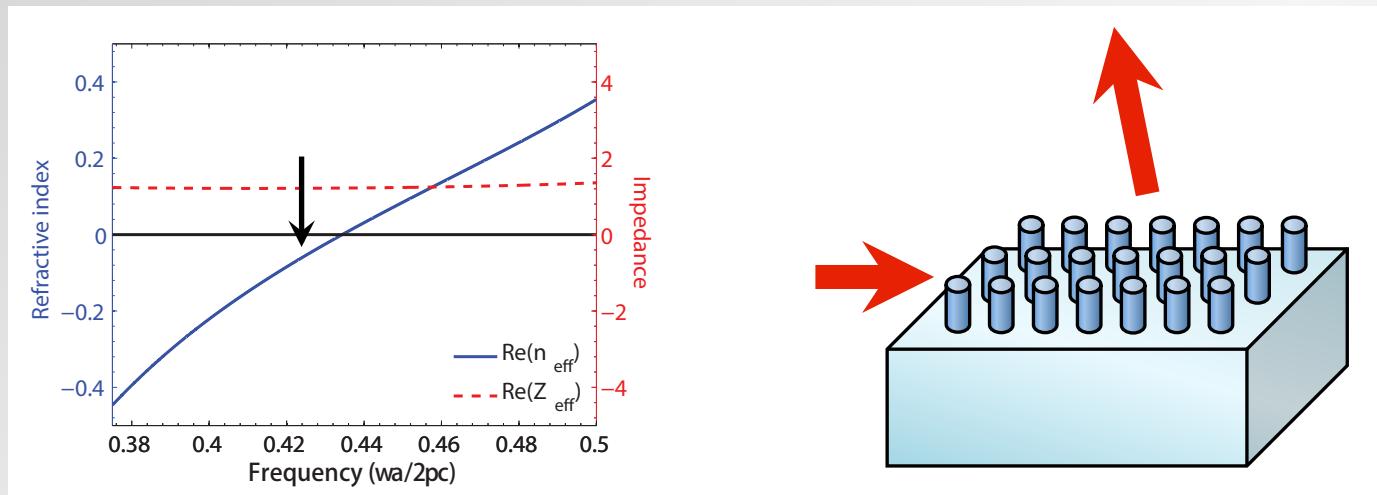
1

beam steering

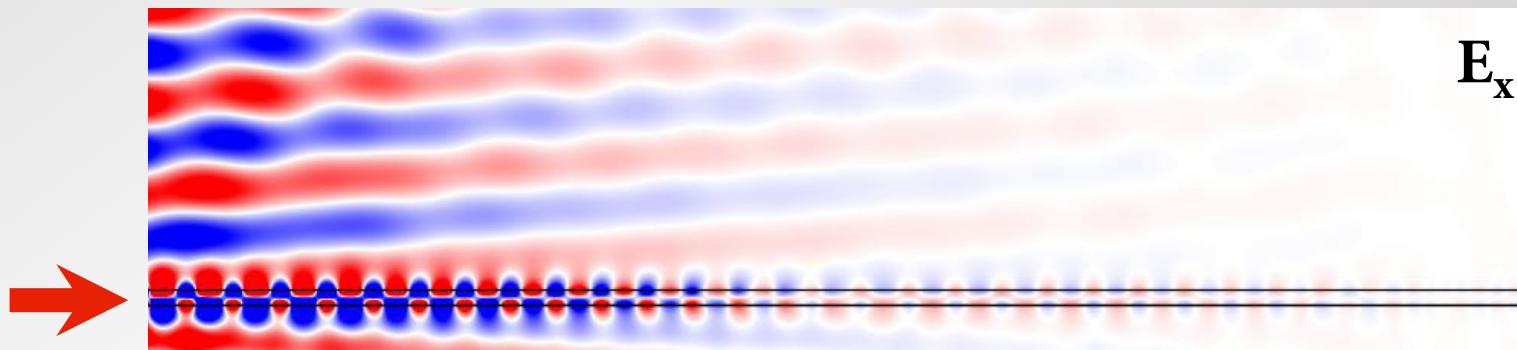
2

zero index

# Radiation from Finite Pillars



negative index



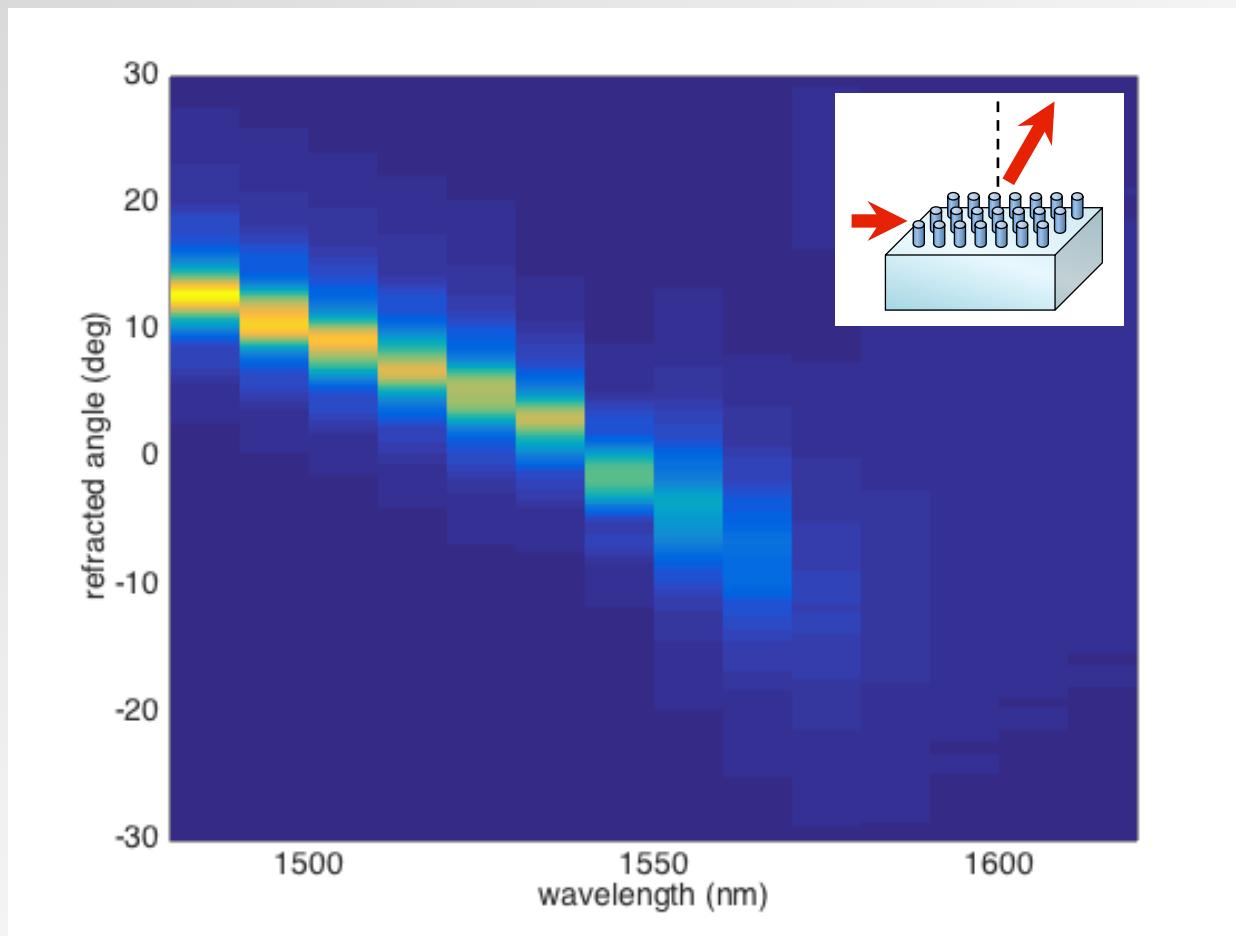
1

beam steering

2

zero index

# Radiation from Finite Pillars



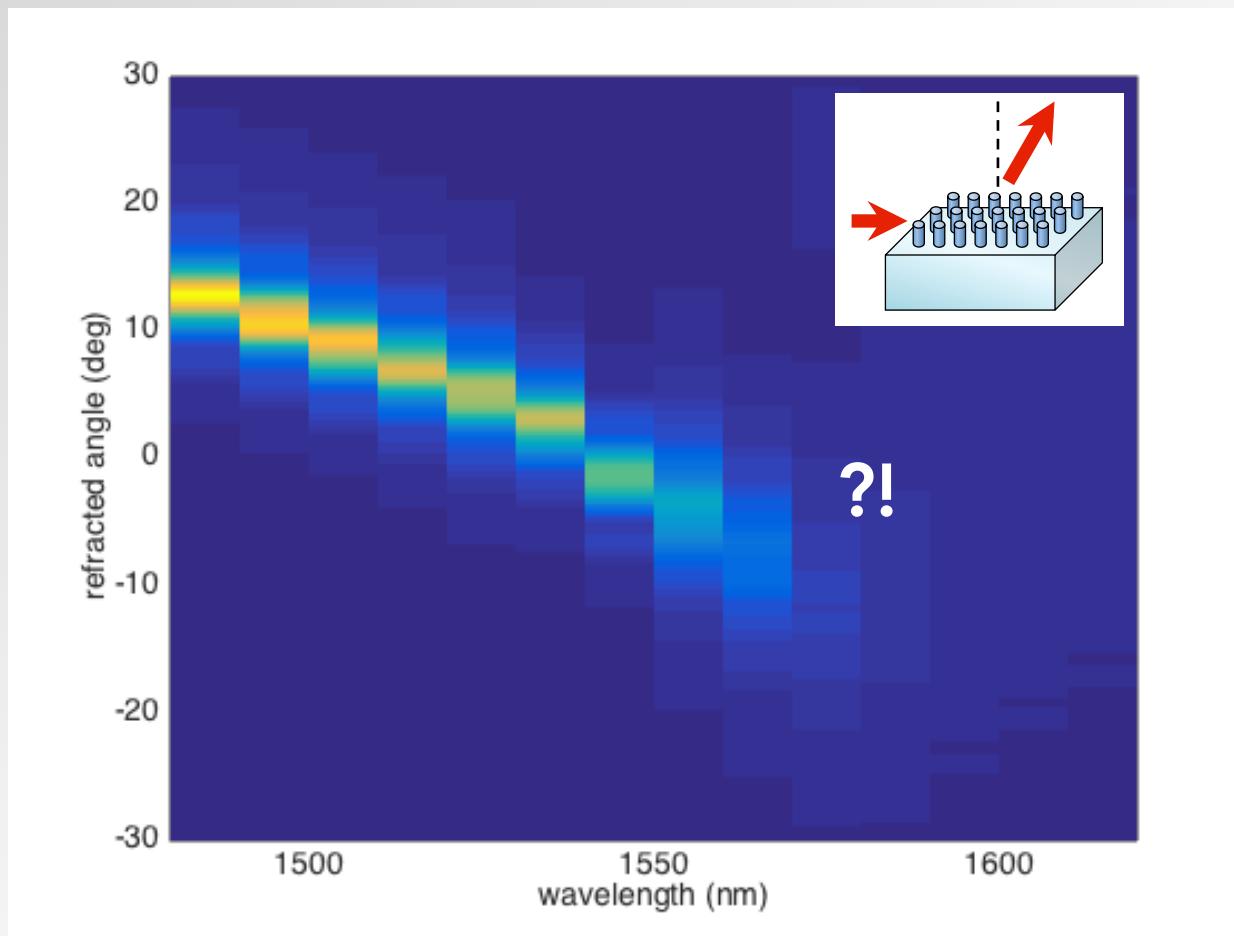
1

beam steering

2

zero index

# Radiation from Finite Pillars



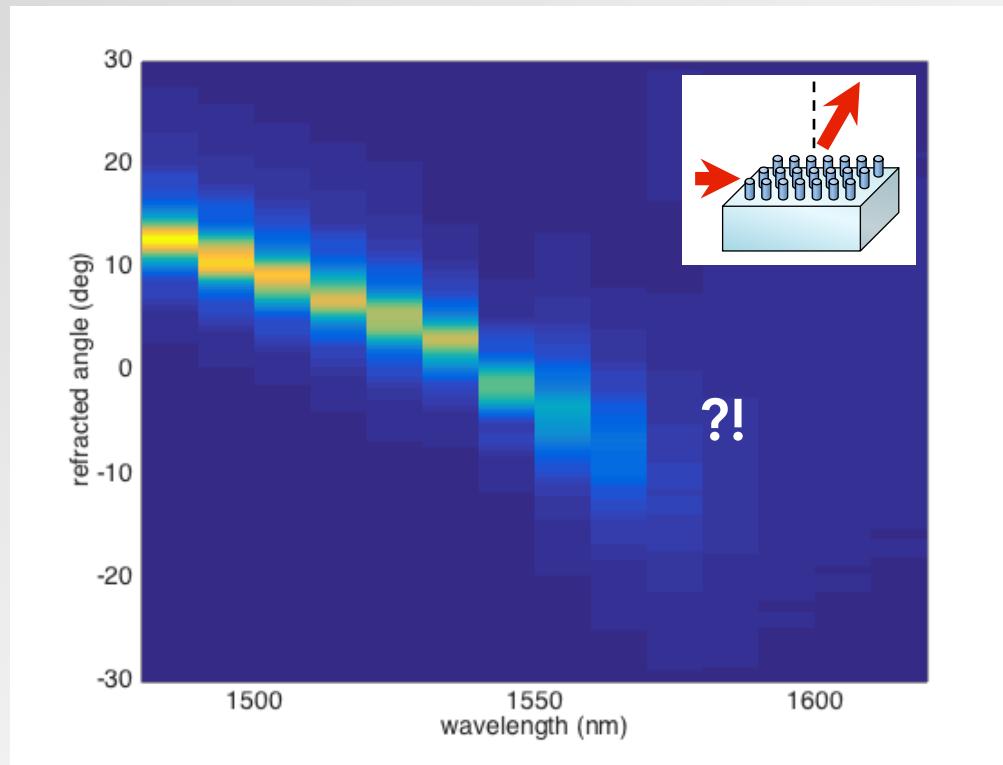
1

beam steering

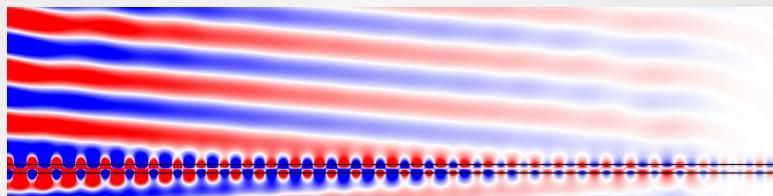
2

zero index

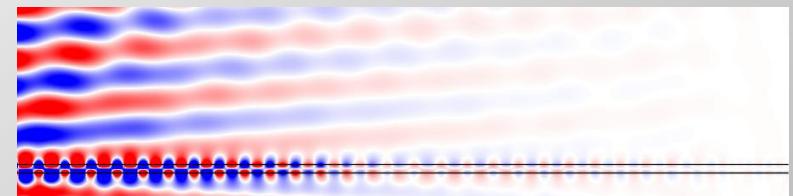
# Radiation from Finite Pillars



positive angle



negative angle



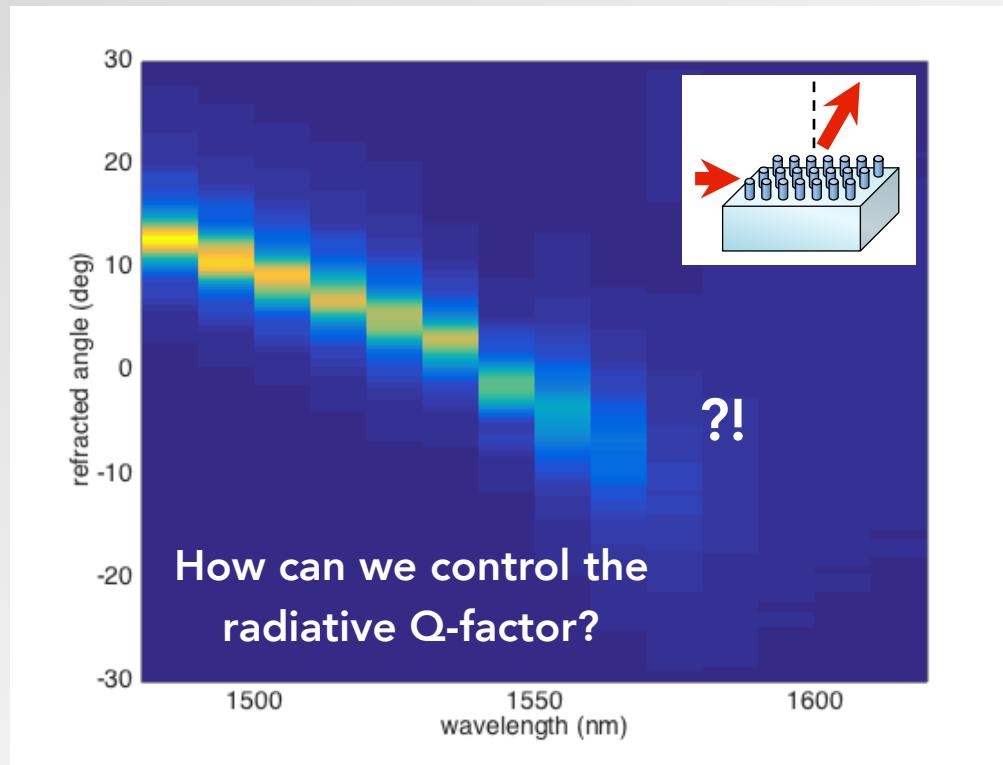
1

beam steering

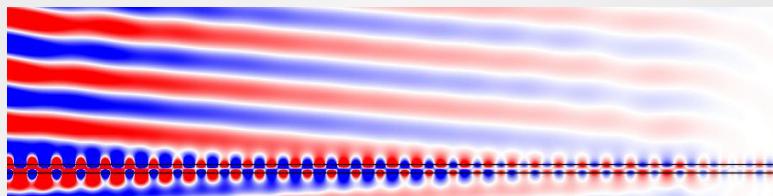
2

zero index

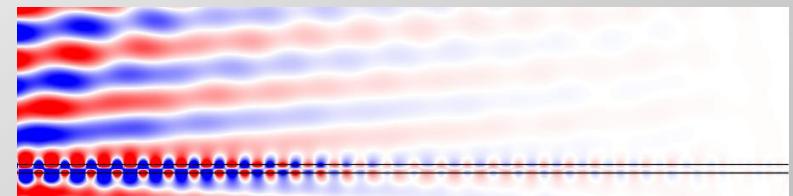
# Radiation from Finite Pillars



positive angle



negative angle



1

beam steering

2

zero index

We need an alternative way to confine the energy:

1

beam steering

2

zero index

3

bound states

We need an alternative way to confine the energy:

Bound states in the continuum (BiCs) can confine light by destructive interference of radiative loss channels

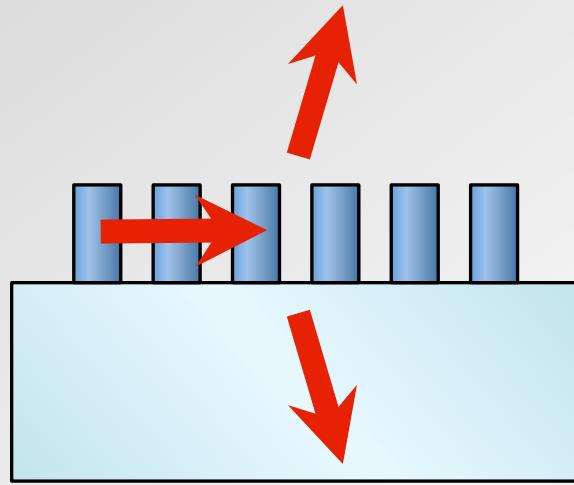
LETTER

doi:10.1038/nature12289

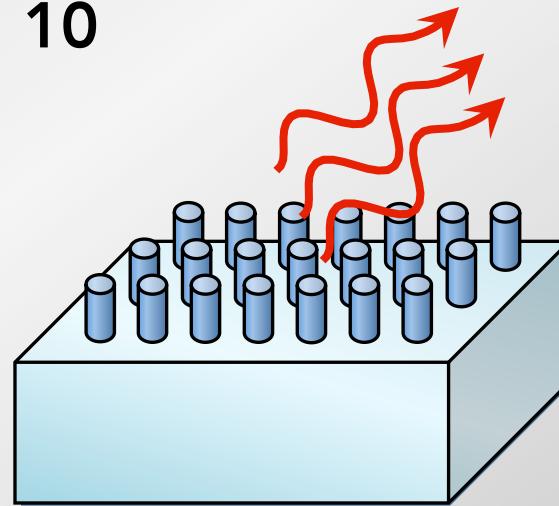
## Observation of trapped light within the radiation continuum

Chia Wei Hsu<sup>1,2\*</sup>, Bo Zhen<sup>1\*</sup>, Jeongwon Lee<sup>1</sup>, Song-Liang Chua<sup>1</sup>, Steven G. Johnson<sup>1,3</sup>, John D. Joannopoulos<sup>1</sup> & Marin Soljačić<sup>1</sup>

# Bound State in the Continuum



$$Q_{\text{monopole}} \approx 10^5$$
$$Q_{\text{dipole}} \approx 10$$



The pillar array has two radiative loss channels, both due to the dipole mode.

1

beam steering

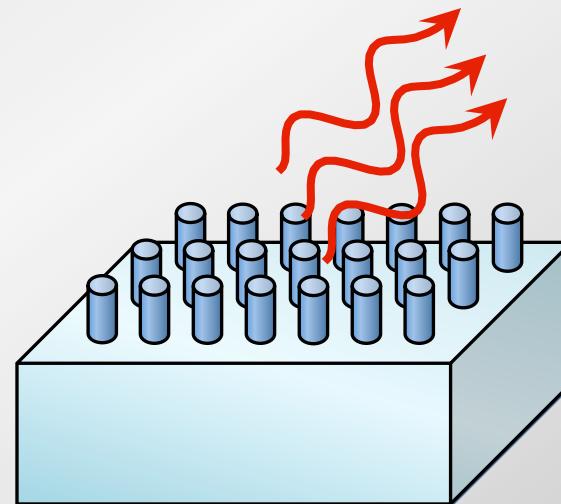
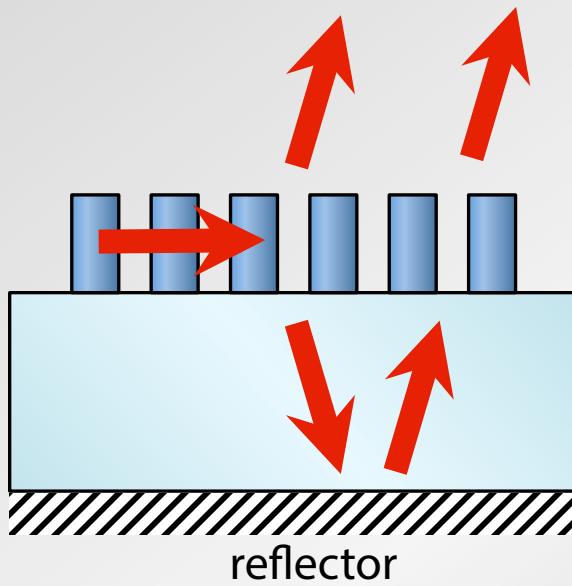
2

zero index

3

bound states

# Bound State in the Continuum



The pillar array has two radiative loss channels, both due to the dipole mode.

By interfering these channels, we can control (or eliminate) the radiation.

1

beam steering

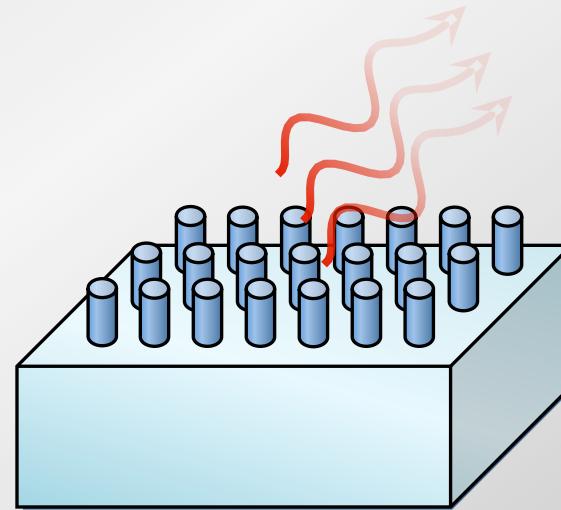
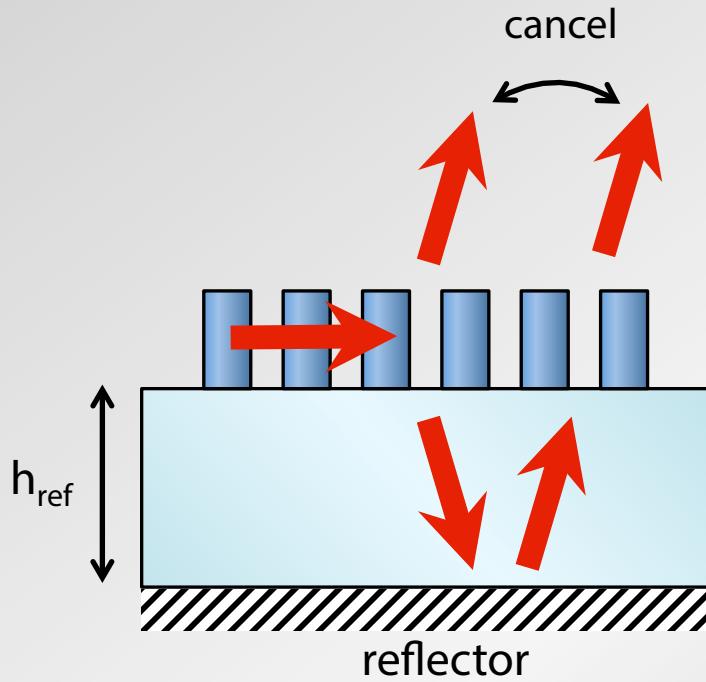
2

zero index

3

bound states

# Bound State in the Continuum



The pillar array has two radiative loss channels, both due to the dipole mode.

By interfering these channels, we can control (or eliminate) the radiation.

1

beam steering

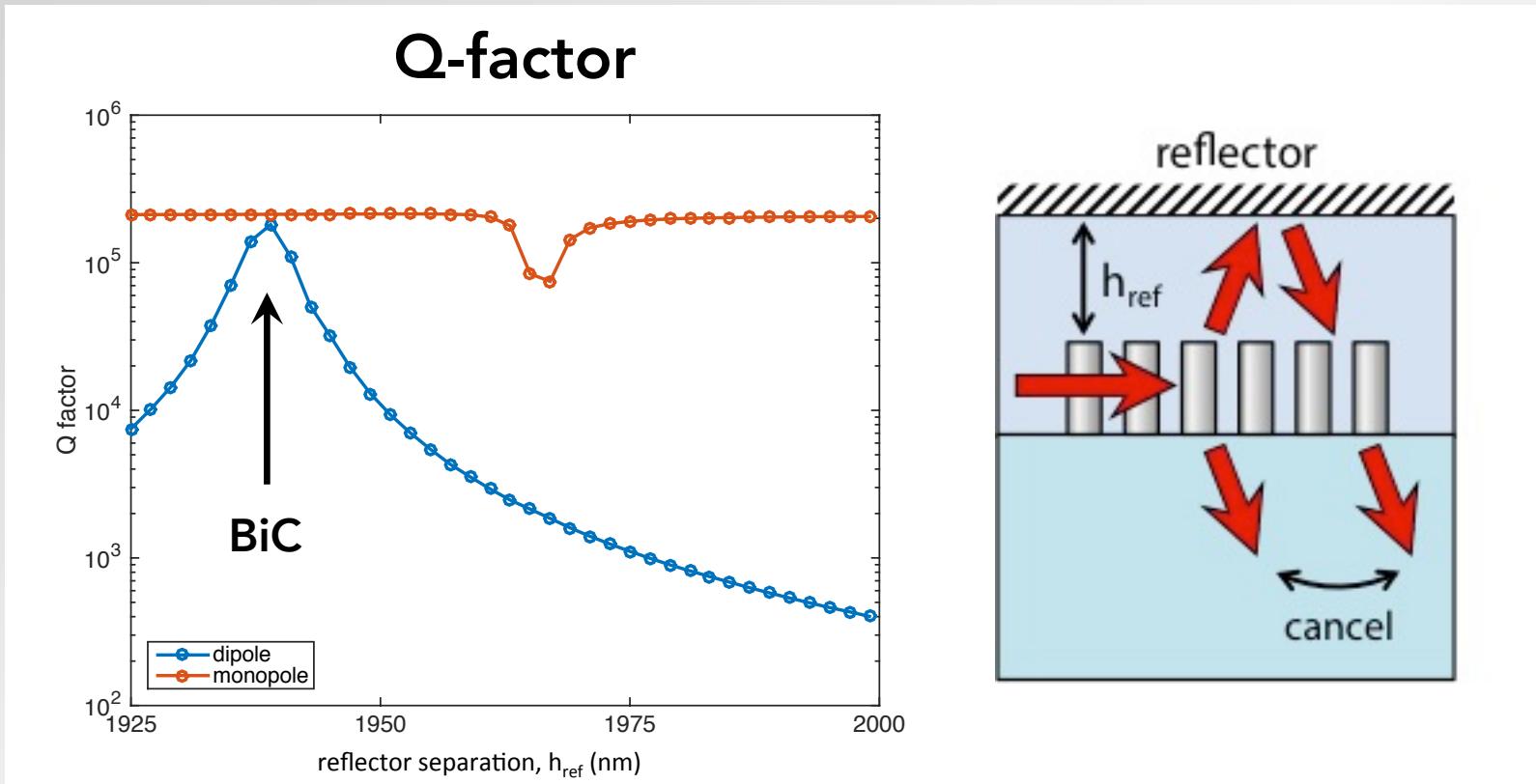
2

zero index

3

bound states

# Bound States with Zero Index



Tune the reflector height, looking for BiC

1

beam steering

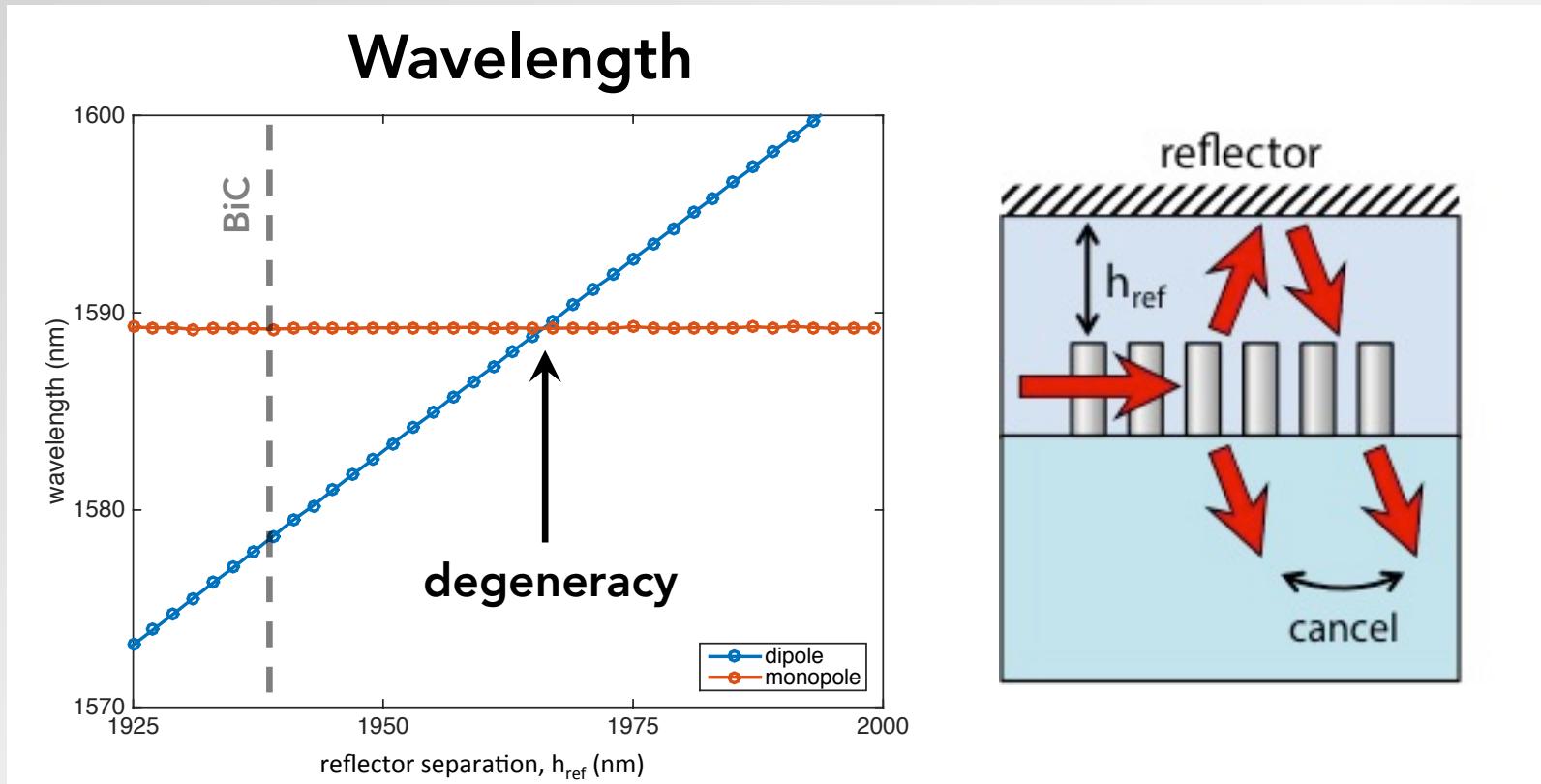
2

zero index

3

bound states

# Bound States with Zero Index



Changing the reflector height also changes the eigenfrequencies

1

beam steering

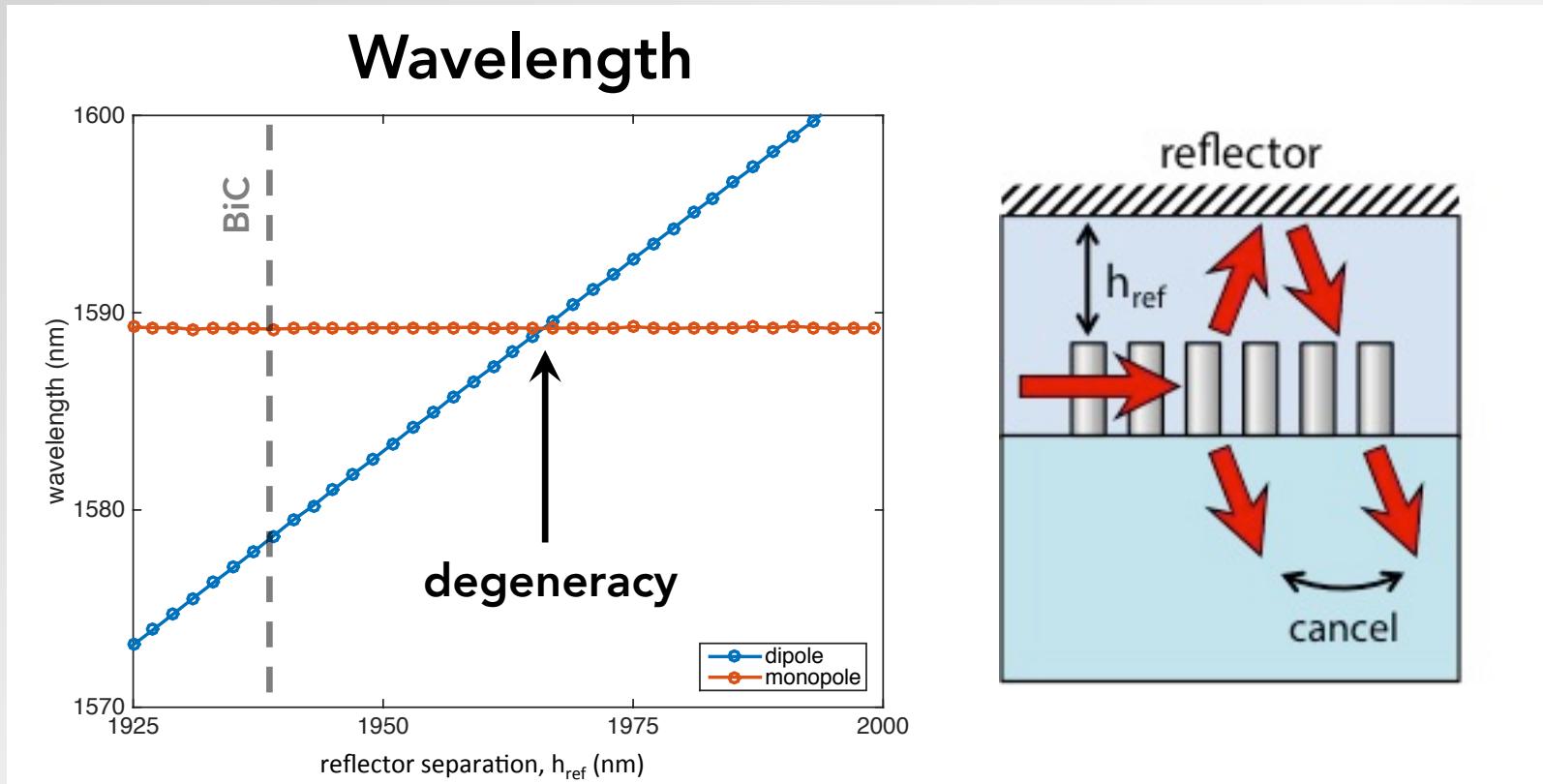
2

zero index

3

bound states

# Bound States with Zero Index



Changing the reflector height also changes the eigenfrequencies  
(just like radius)

1

beam steering

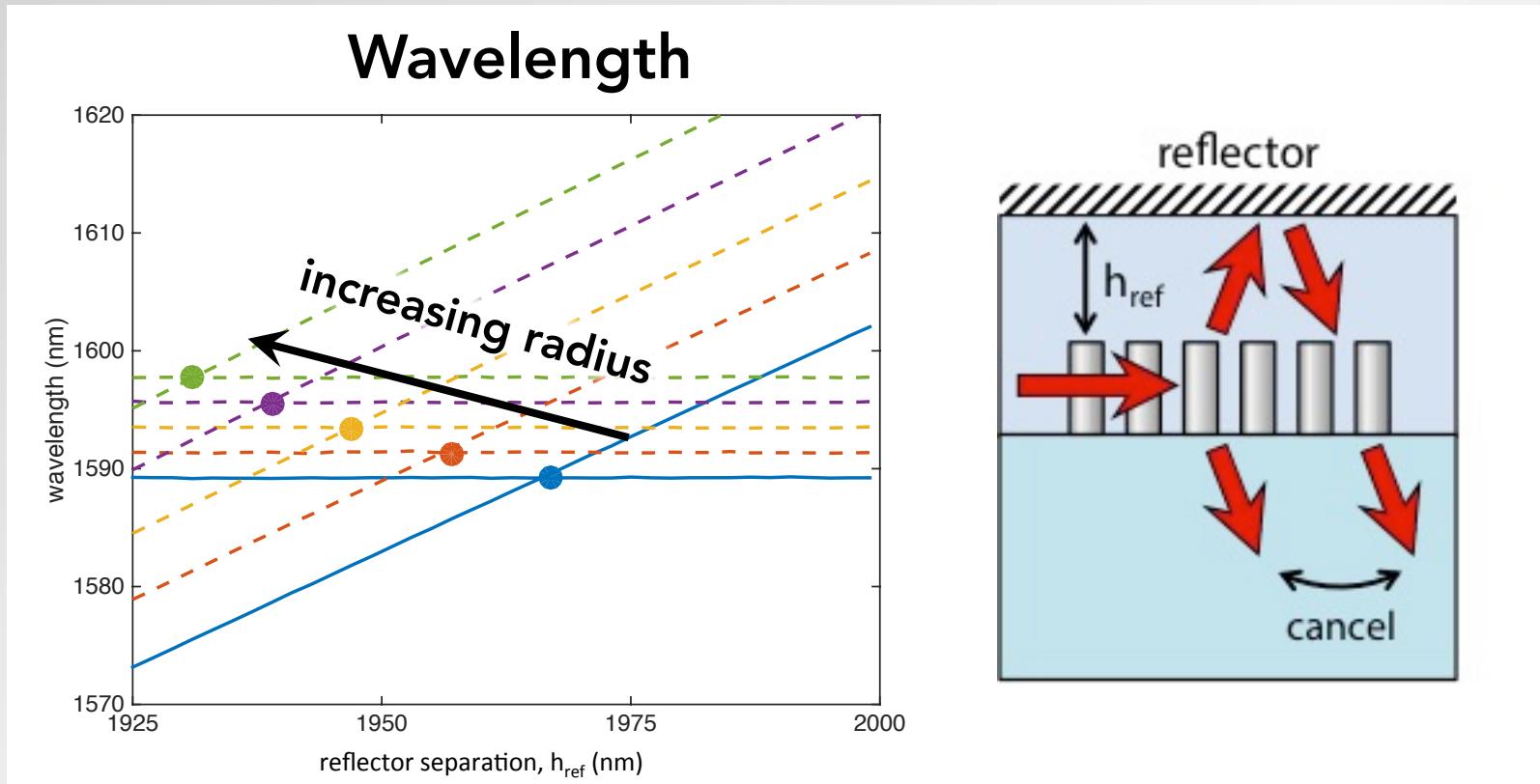
2

zero index

3

bound states

# Bound States with Zero Index



Try changing the reflector height and rod radius simultaneously

1

beam steering

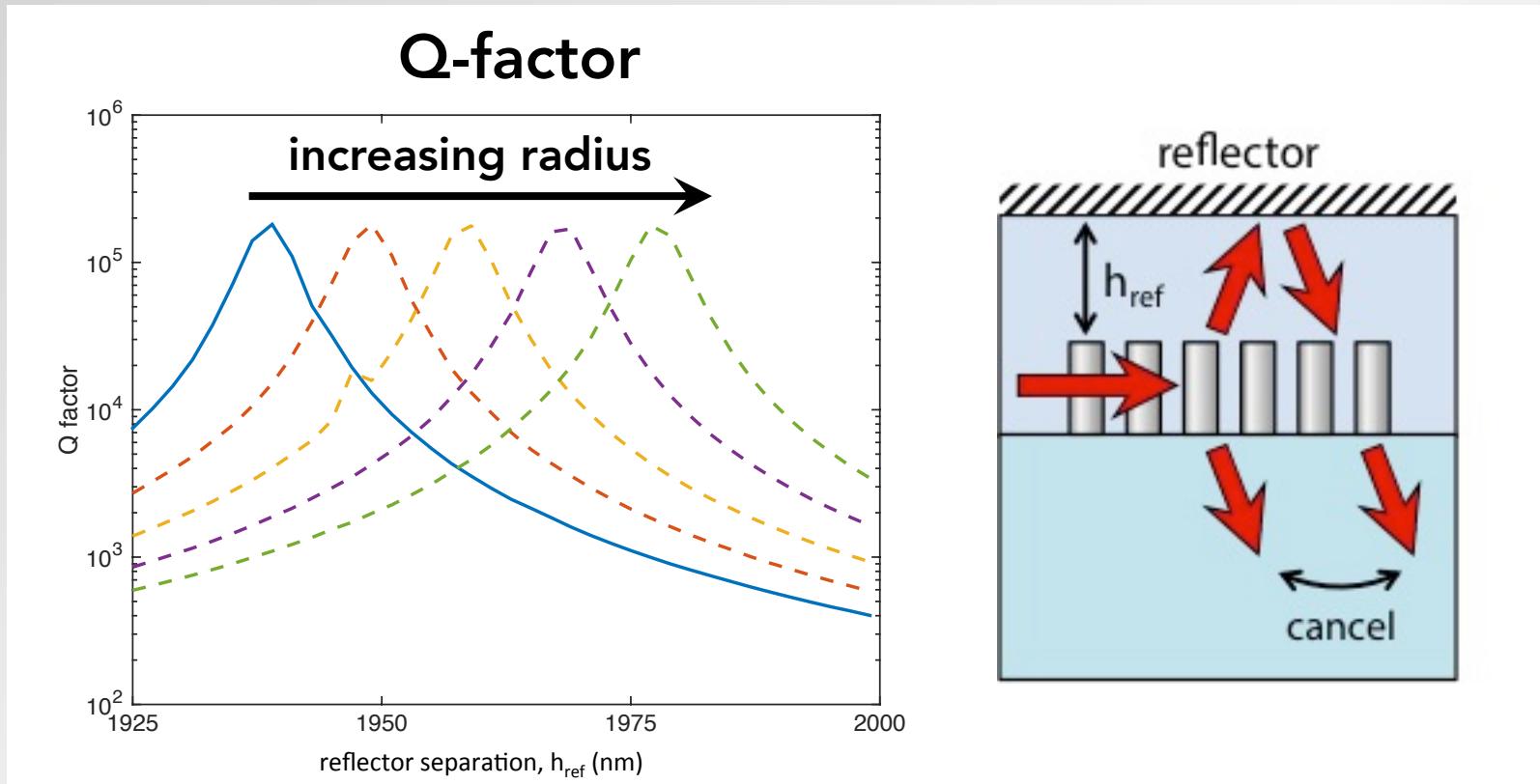
2

zero index

3

bound states

# Bound States with Zero Index



Try changing the reflector height and rod radius simultaneously

1

beam steering

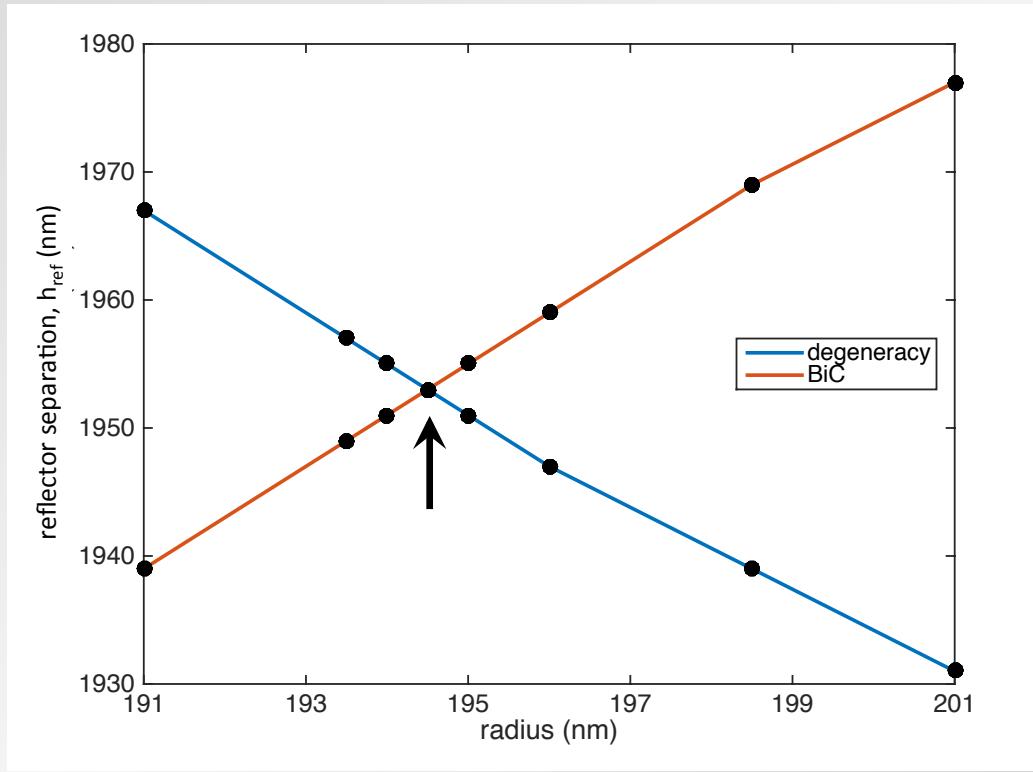
2

zero index

3

bound states

# Bound States with Zero Index



This design has a bound state with zero refractive index

1

beam steering

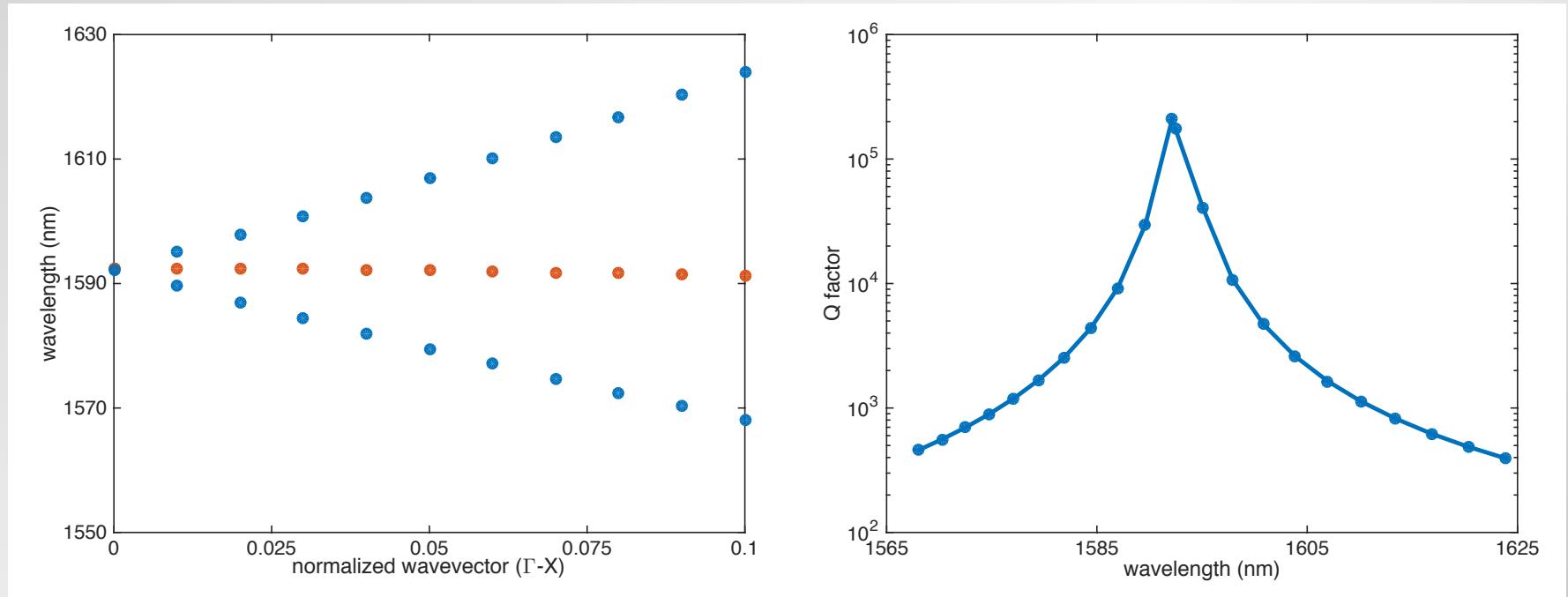
2

zero index

3

bound states

# Bound States with Zero Index



This approach allows independent control of the radiation rate at the  $\Gamma$ -point

Tuning parameters: rod radius, pitch, reflector spacing

1

beam steering

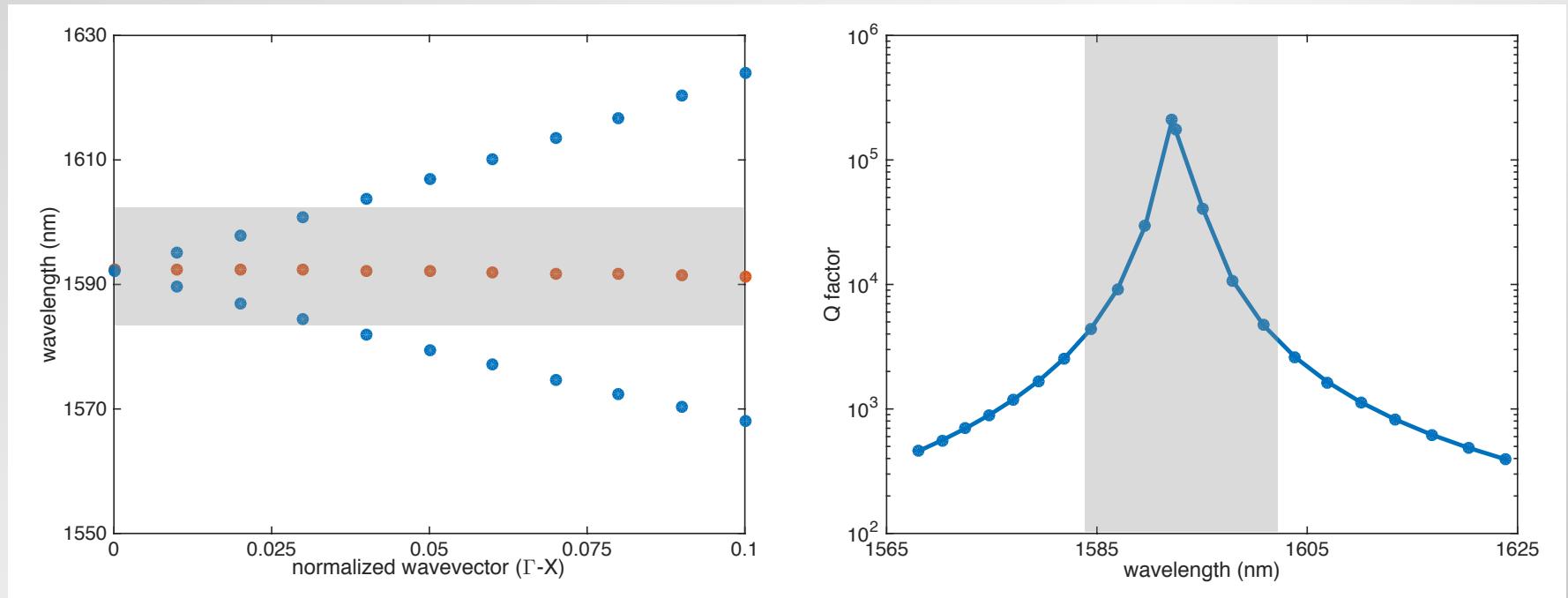
2

zero index

3

bound states

# Bound States with Nonzero Index



**Q-factor is very sensitive to wavelength**

1

beam steering

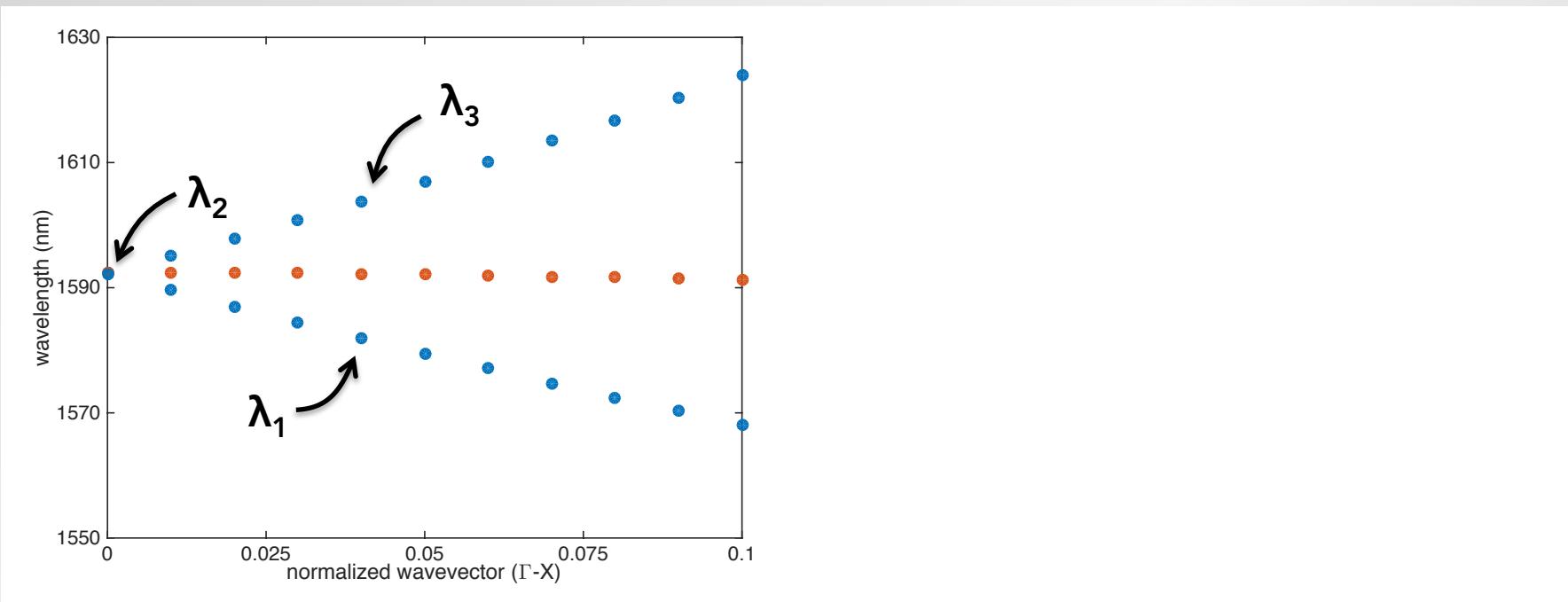
2

zero index

3

bound states

# Bound States with Nonzero Index



Consider non-zero wavevectors...

1

beam steering

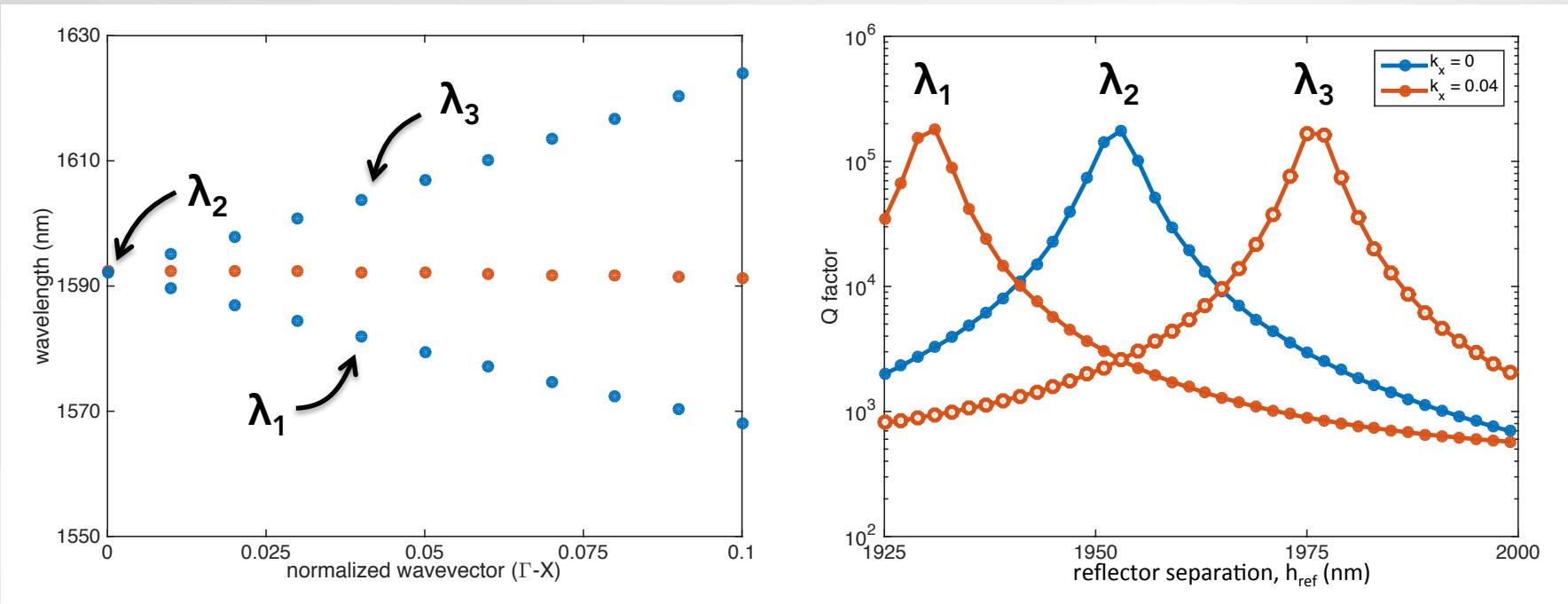
2

zero index

3

bound states

# Bound States with Nonzero Index



Consider non-zero wavevectors...

Each one becomes a bound state for a different reflector separation.

1

beam steering

2

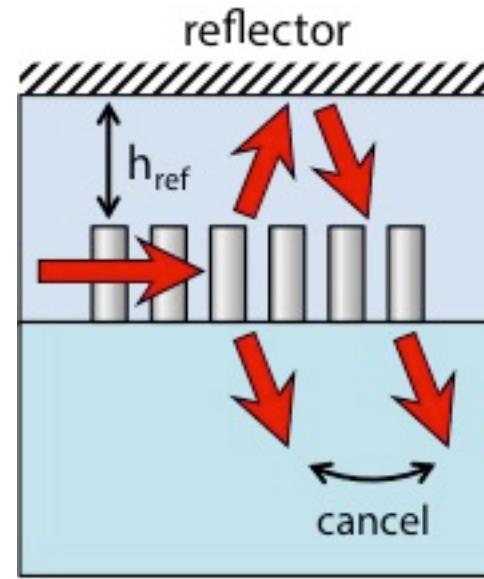
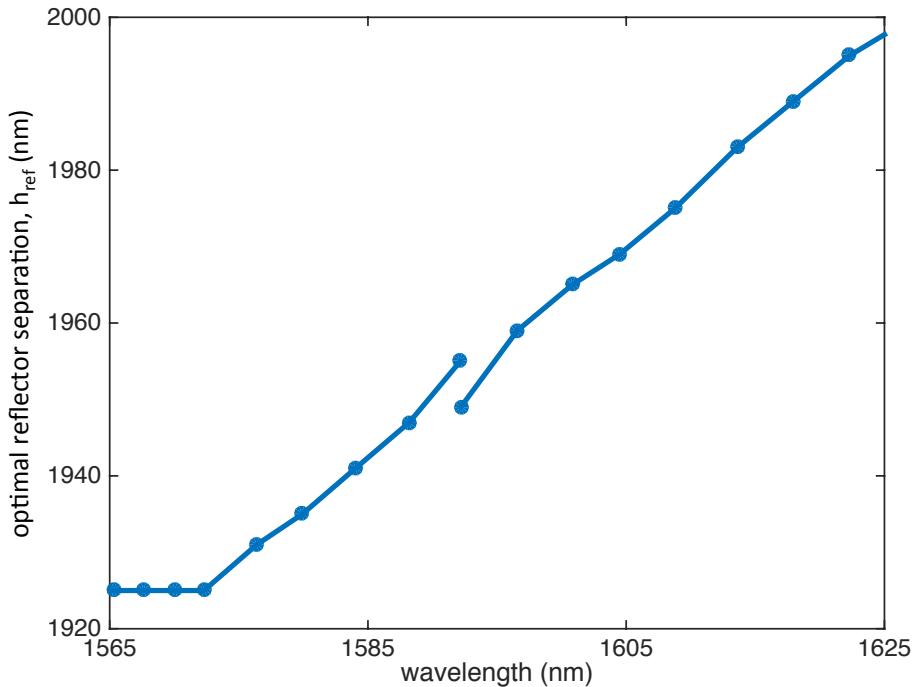
zero index

3

bound states

# Bound States with Nonzero Index

variable separation



What if we could choose a different thickness for every wavelength?

1

beam steering

2

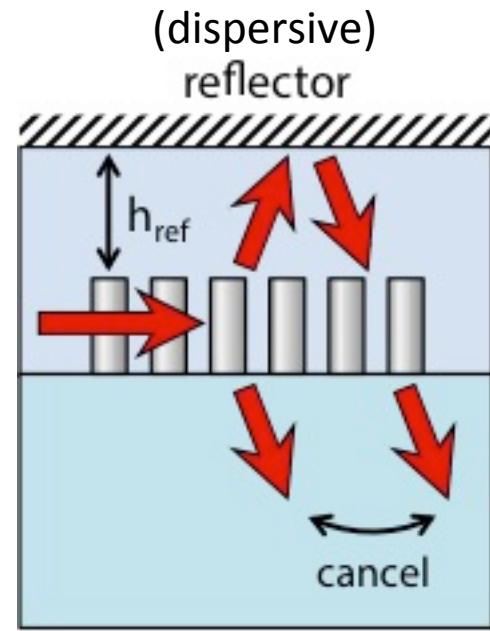
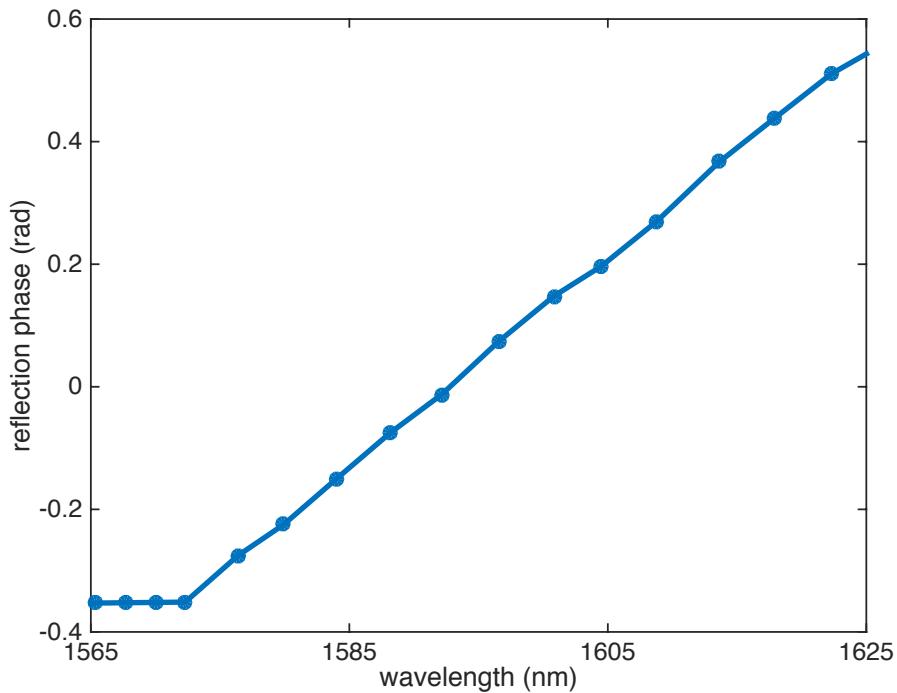
zero index

3

bound states

# Bound States with Nonzero Index

variable phase



Instead, just make the reflector dispersive

1

beam steering

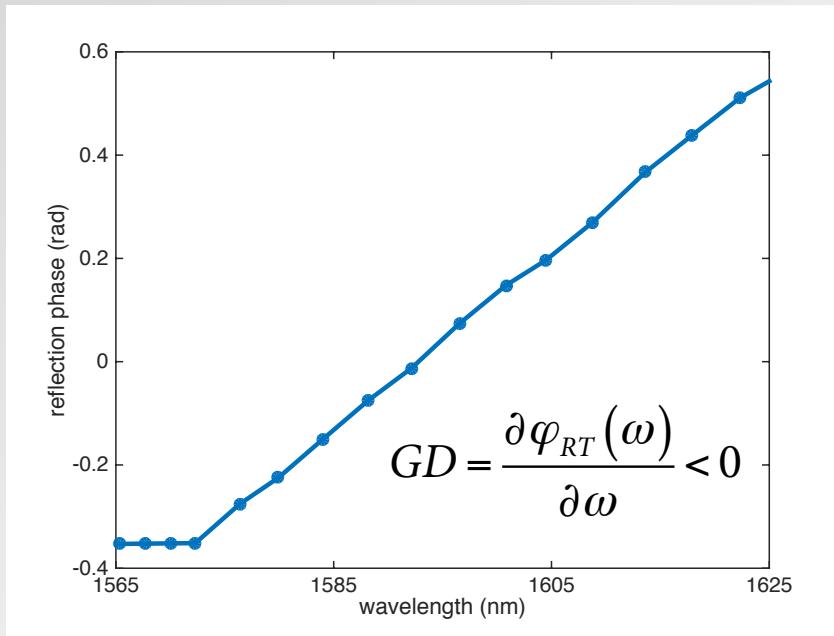
2

zero index

3

bound states

# Bound States with Nonzero Index



The reflector should exhibit  
a negative group delay.  
("Negative optical thickness")

1

beam steering

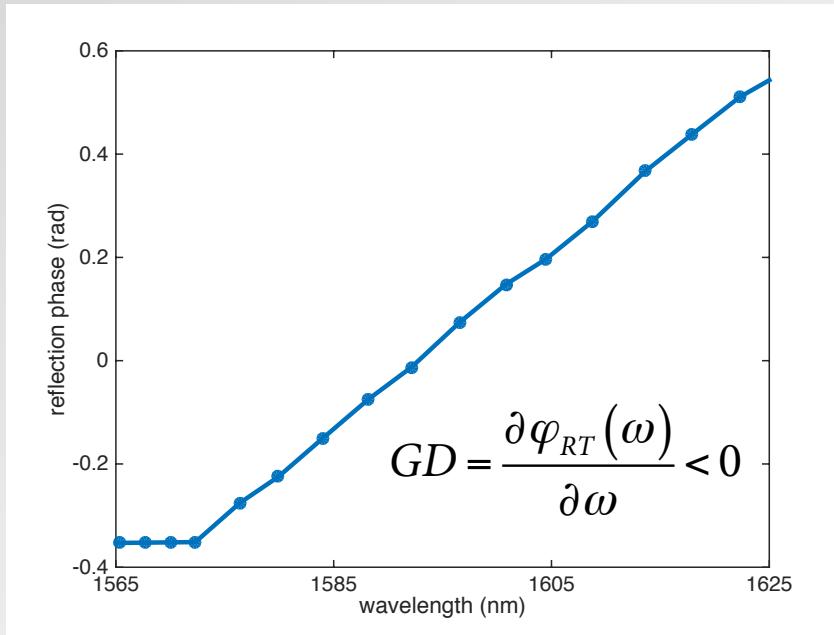
2

zero index

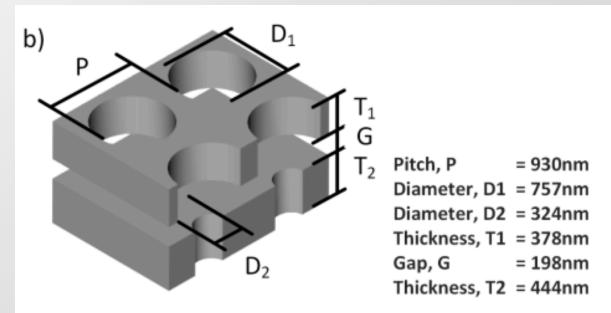
3

bound states

# Bound States with Nonzero Index



The reflector should exhibit  
a negative group delay.  
("Negative optical thickness")



Gellineau, A., et al. "Design of resonant mirrors with negative group delay", Optics Express, 2014

1

beam steering

2

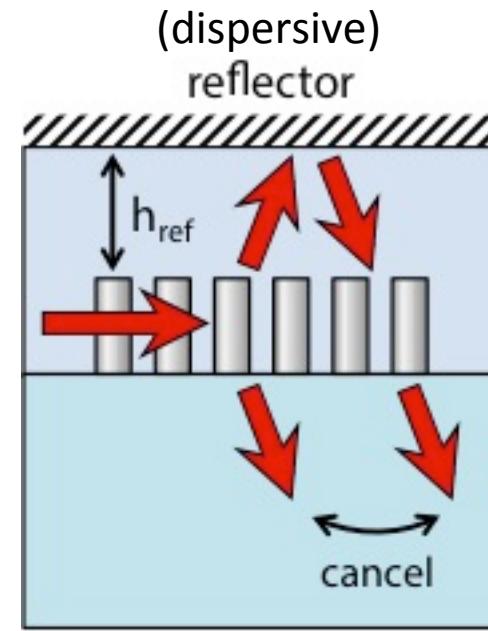
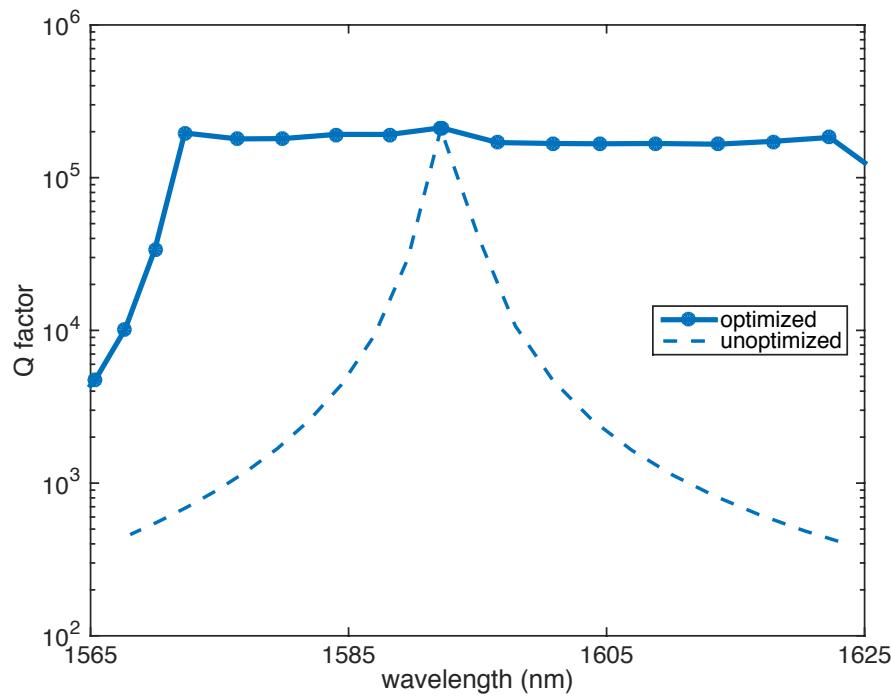
zero index

3

bound states

# Bound States with Nonzero Index

## broadband BiC



With the appropriate reflector, the BiC can be extended to a broad range of positive, zero, and negative values.

1

beam steering

2

zero index

3

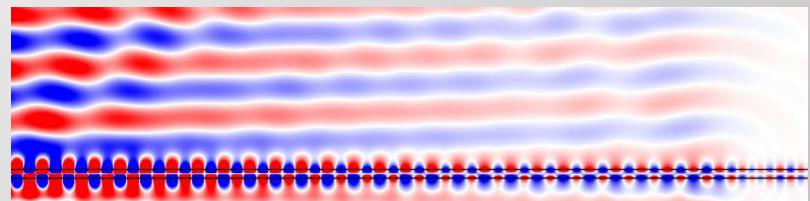
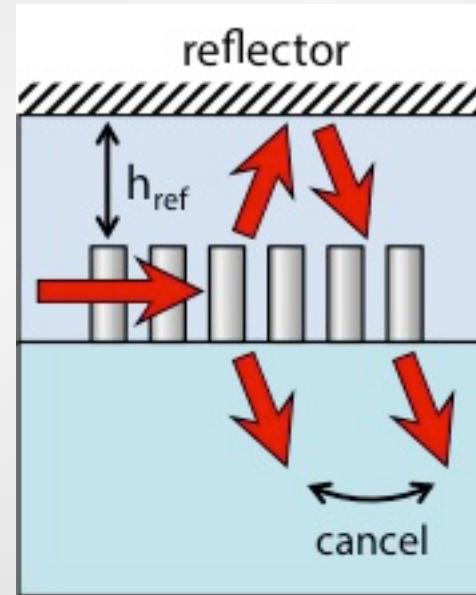
bound states

# Summary

Zero index metamaterials can access broadside radiation

All dielectric design enables efficient out-coupling.

Bound state in the continuum allows independent tuning of radiative Q-factor.

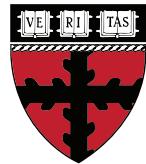
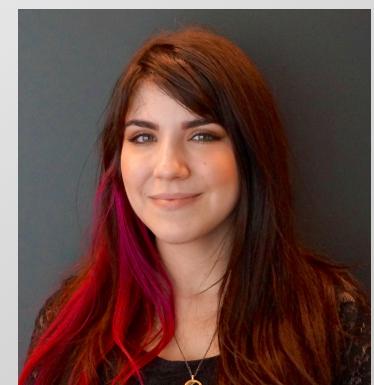
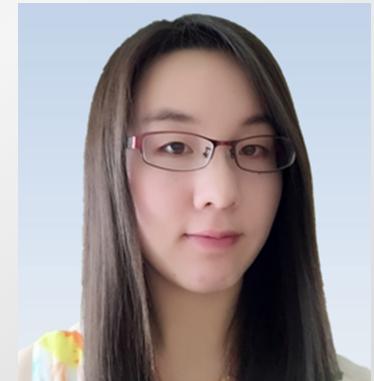


1 beam steering

2 zero index

3 bound states

# Thanks to the zero index team!



**HARVARD**  
John A. Paulson  
School of Engineering  
and Applied Sciences

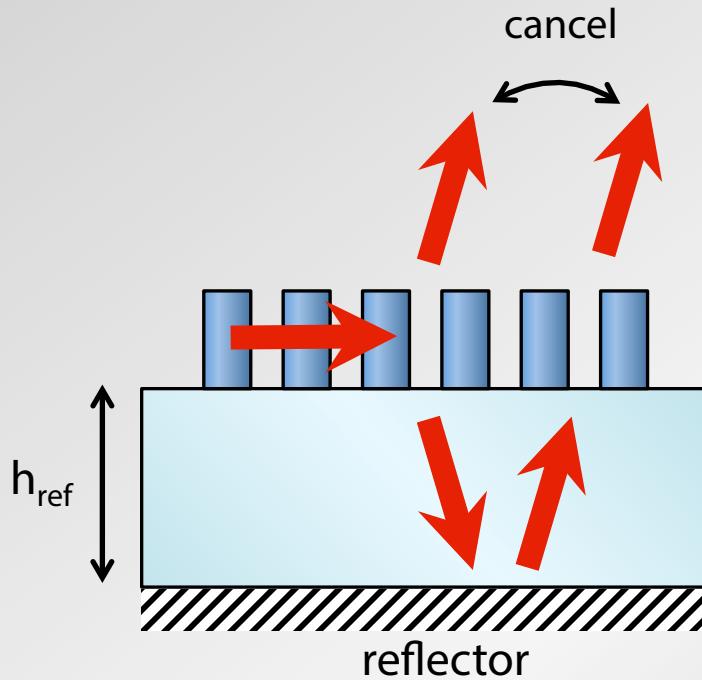


**Center for  
Nanoscale  
Systems**  
Harvard University





# Temporal Coupled Mode Theory



$2kh_{\text{ref}} + \pi = \text{round-trip phase}$   
 $r = \text{reflection coefficient}$   
 $t = \text{transmission coefficient}$

**BiC Condition:**

$$e^{-i2kh_{\text{ref}}} = t - r$$

Hsu, C., et al. Light 2013

We are guaranteed to find some reflector spacing,  $h_{\text{ref}}$ , that causes perfect cancellation.

1

beam steering

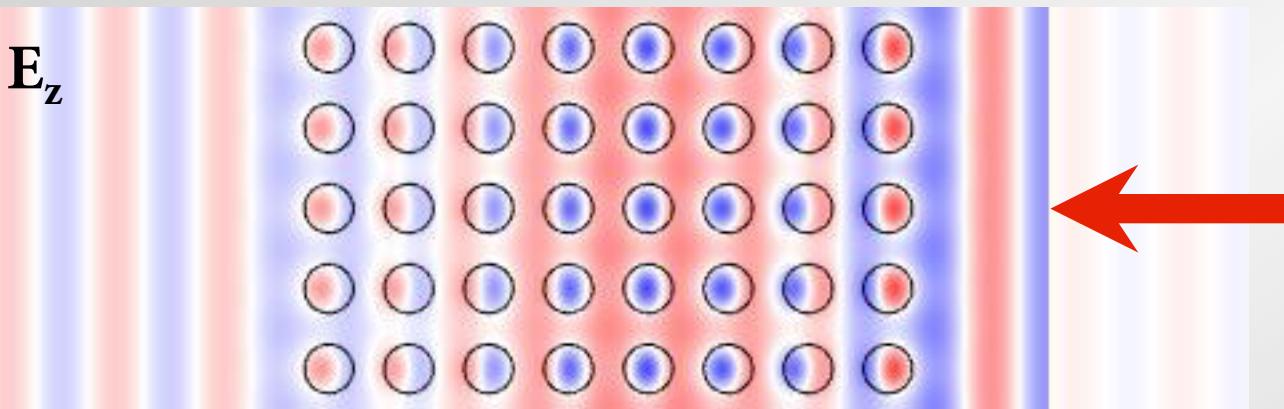
2

zero index

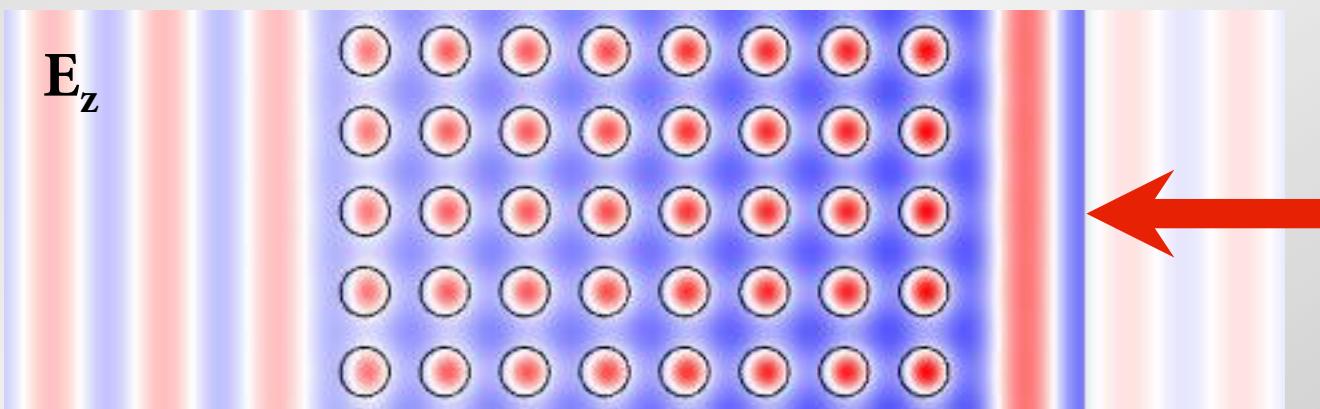
3

bound states

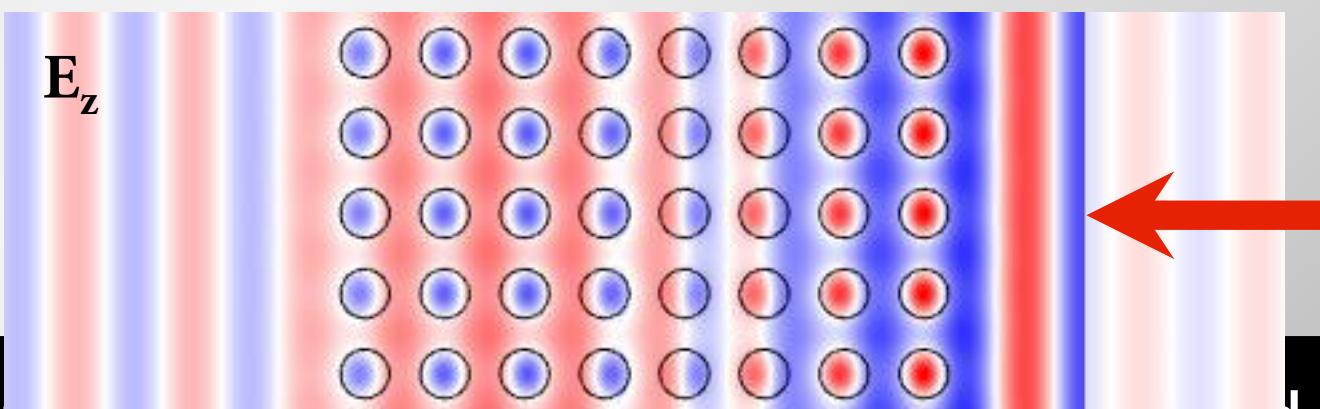
$\lambda_0 = 1530\text{nm}$   
 $n = 0.2$



$\lambda_0 = 1590\text{nm}$   
 $n = 0$



$\lambda_0 = 1650\text{nm}$   
 $n = -0.2$



1

beam steering

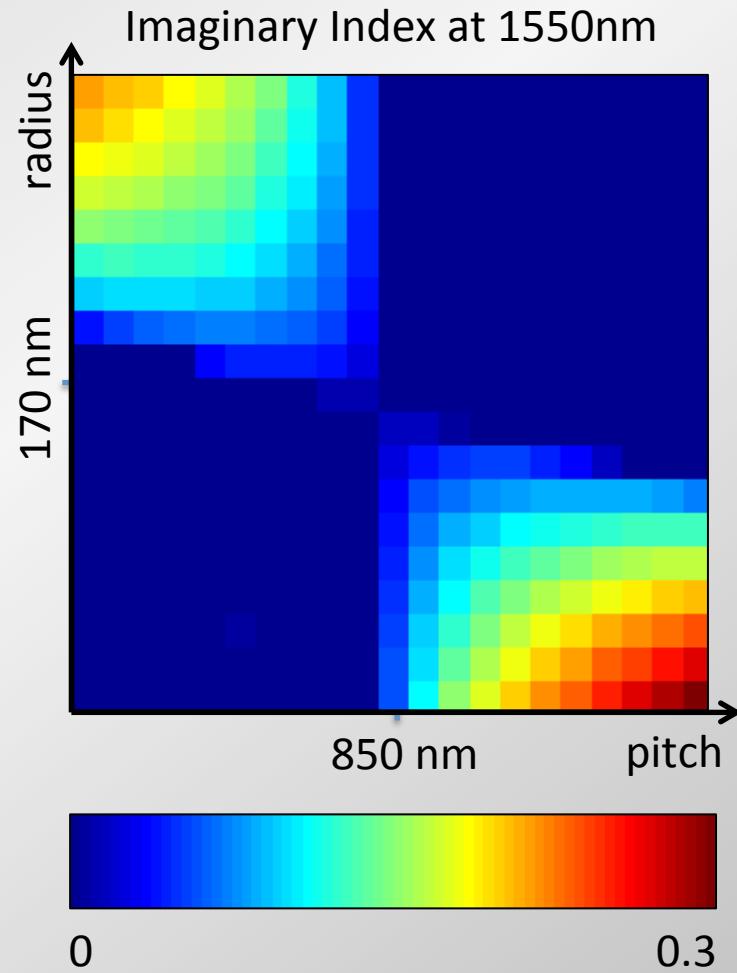
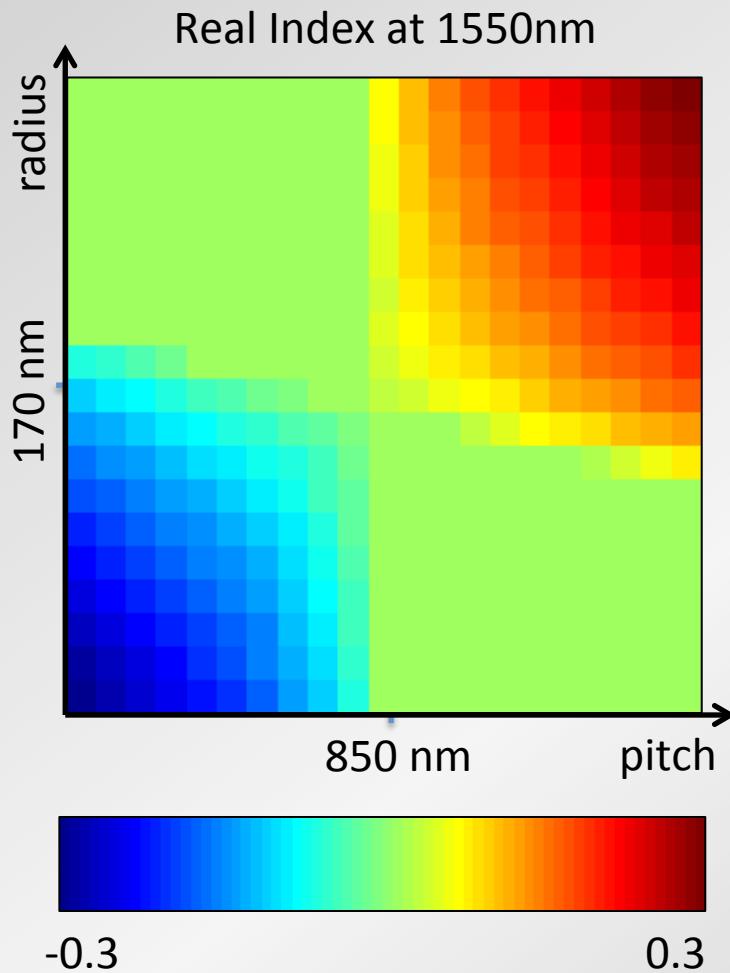
2

zero index

3

bound states

# Effective refractive index



1

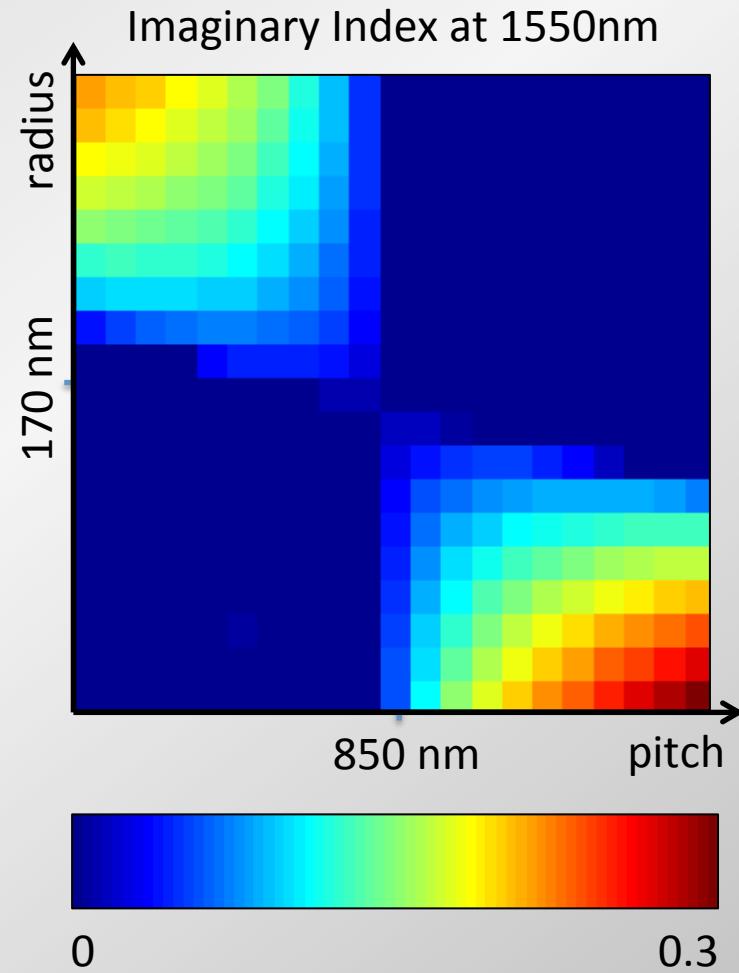
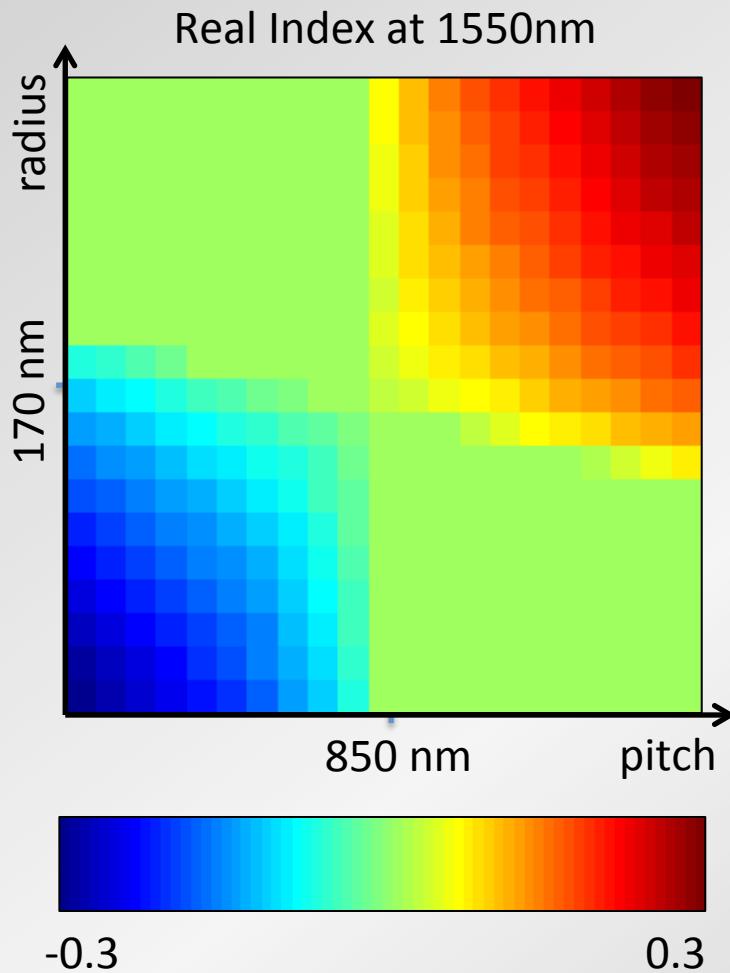
zero index

2

metamaterials

# Effective refractive index

$$n = n' + i n''$$



1

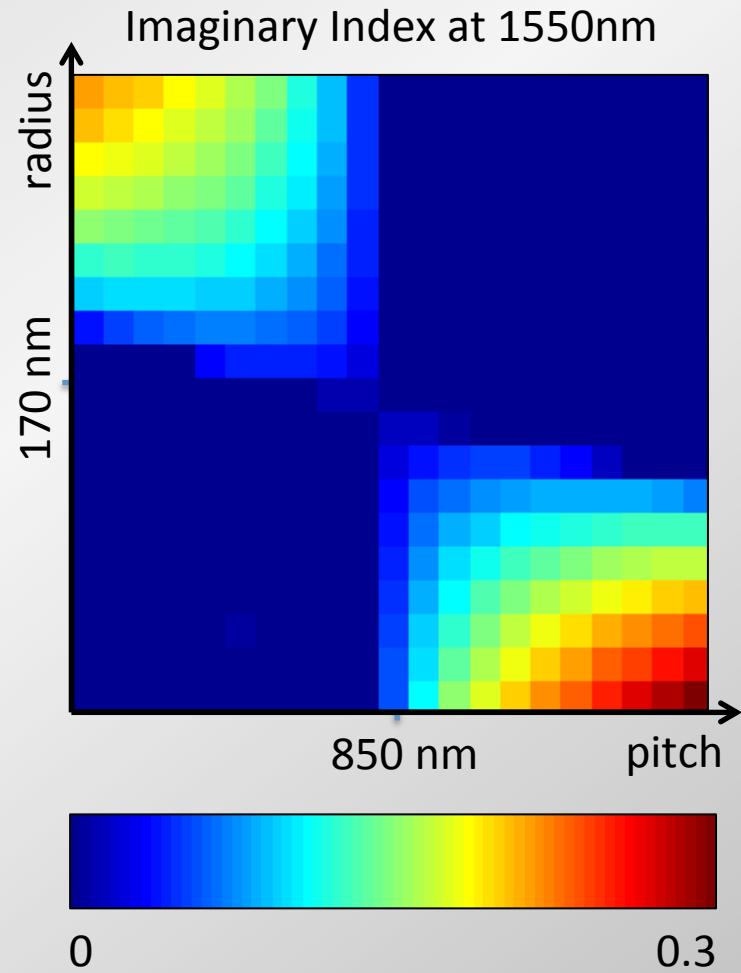
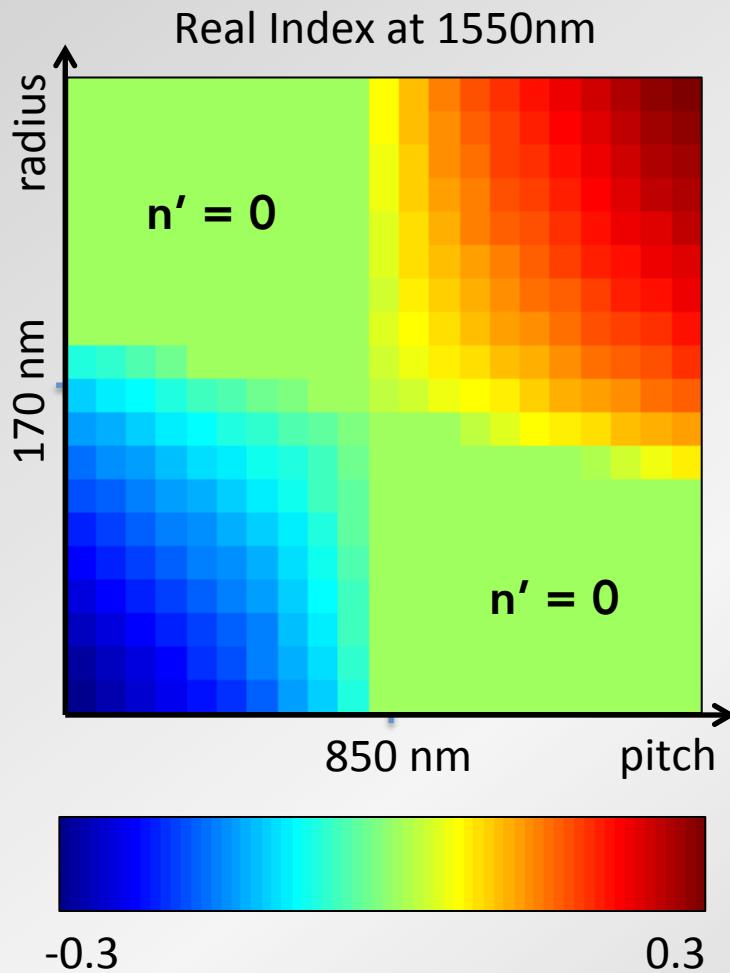
zero index

2

metamaterials

# Effective refractive index

$$n = n' + i n''$$



1

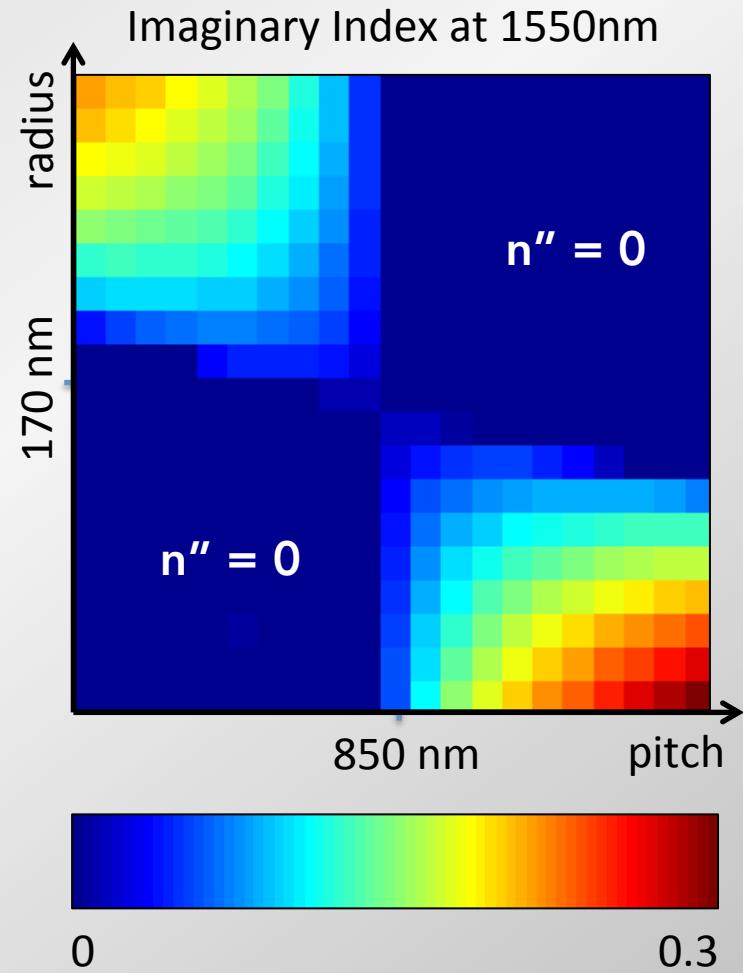
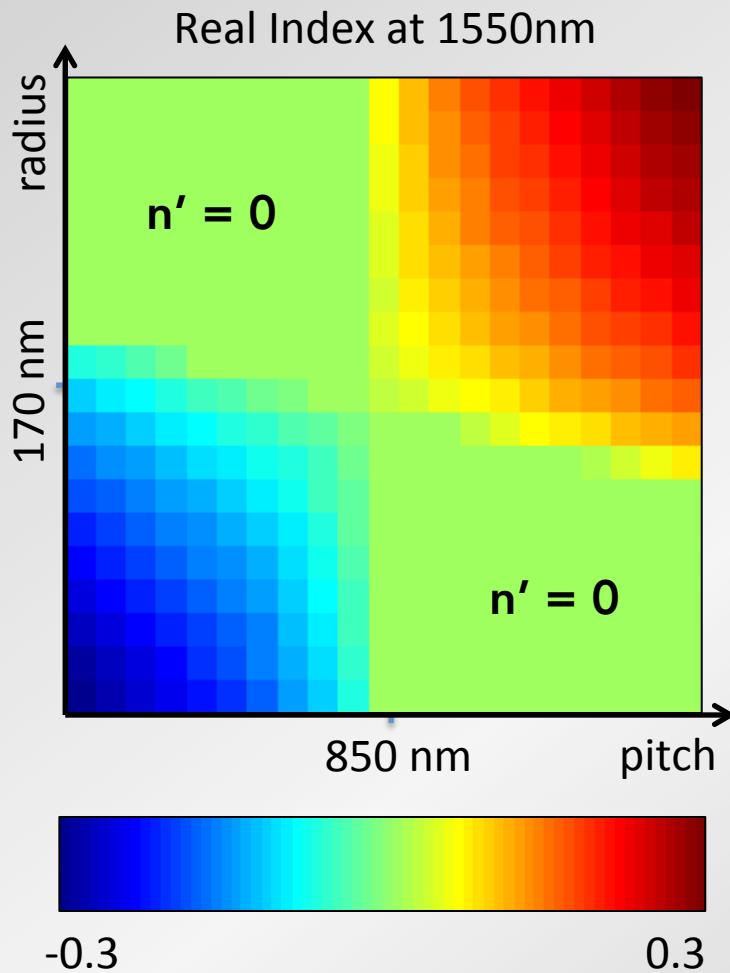
zero index

2

metamaterials

# Effective refractive index

$$n = n' + i n''$$



1

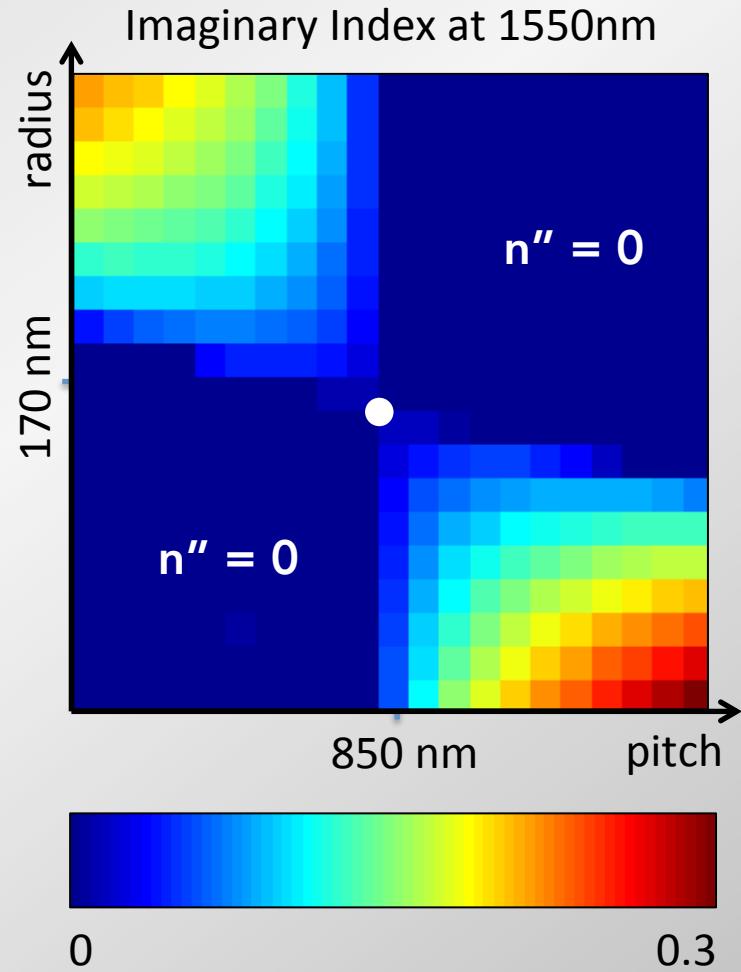
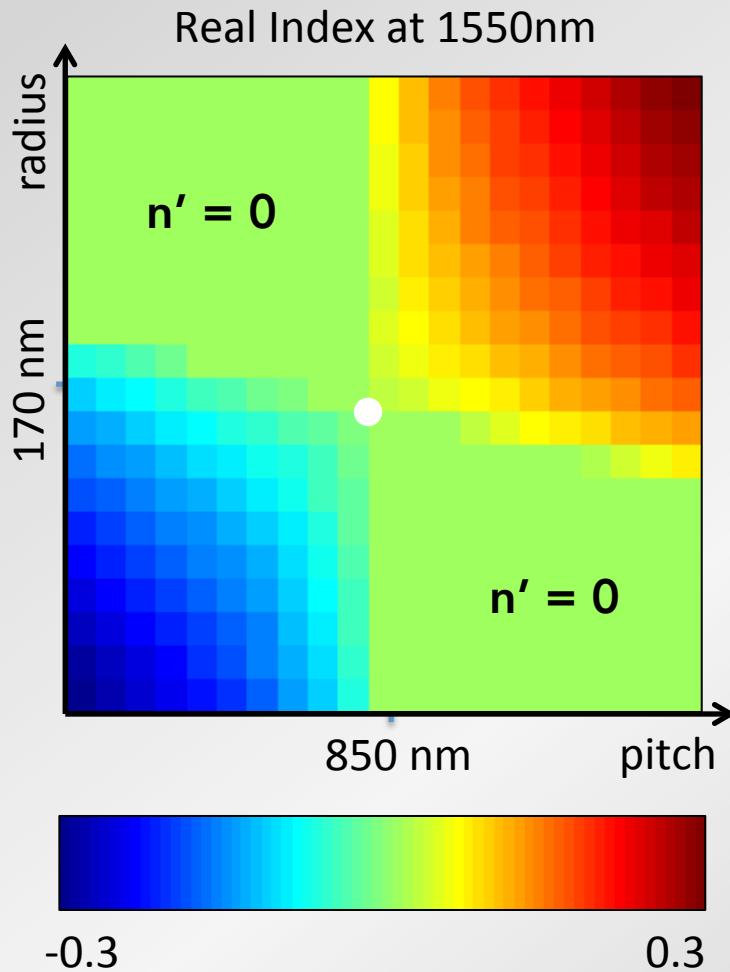
zero index

2

metamaterials

# Effective refractive index

$$n = n' + i n''$$



1

zero index

2

metamaterials

# Metamaterial Design

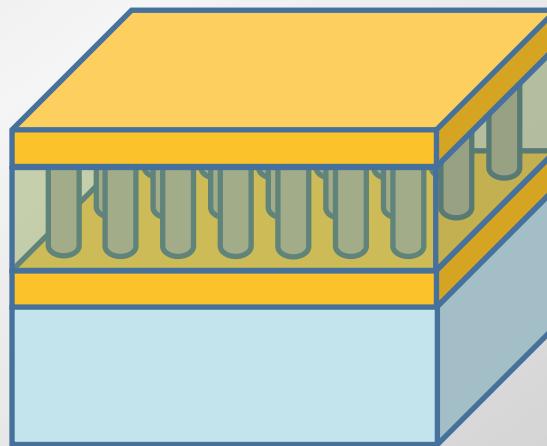
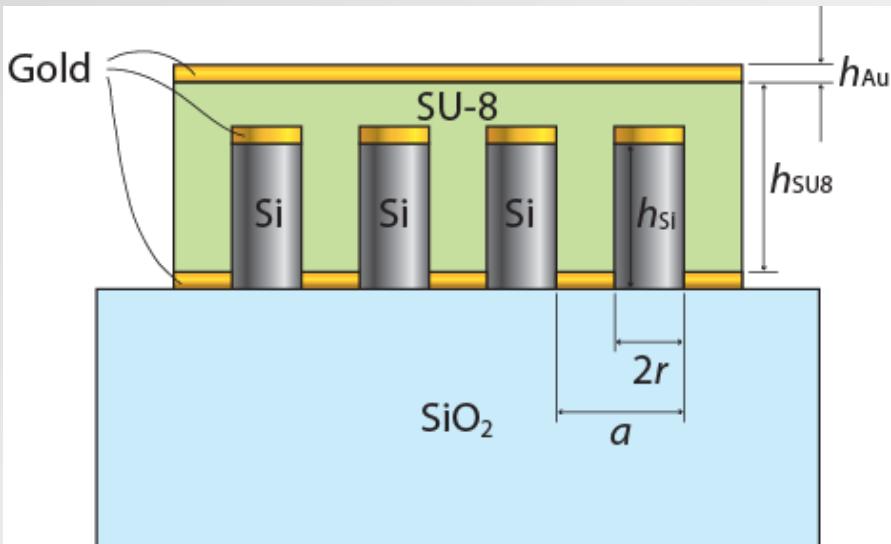
Gold

SU-8  
(polymer)

Silicon

Gold

Substrate  
( $\text{SiO}_2$ )



1

beam steering

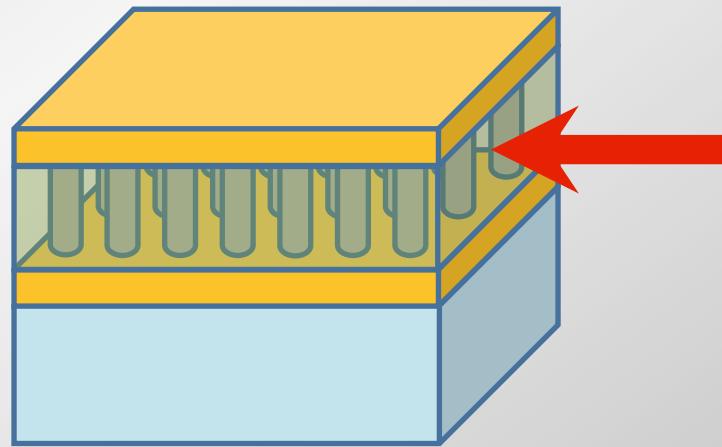
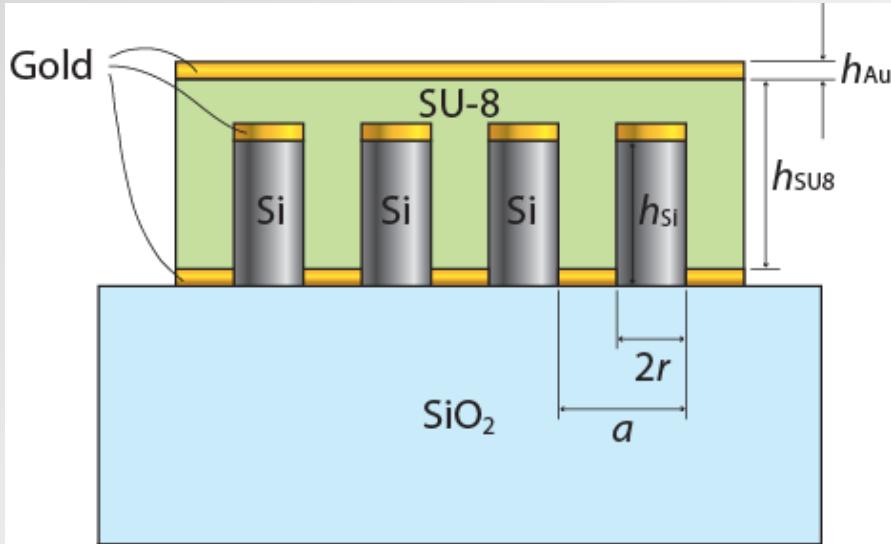
2

zero index

3

bound states

# Metamaterial Design



1

beam steering

2

zero index

3

bound states