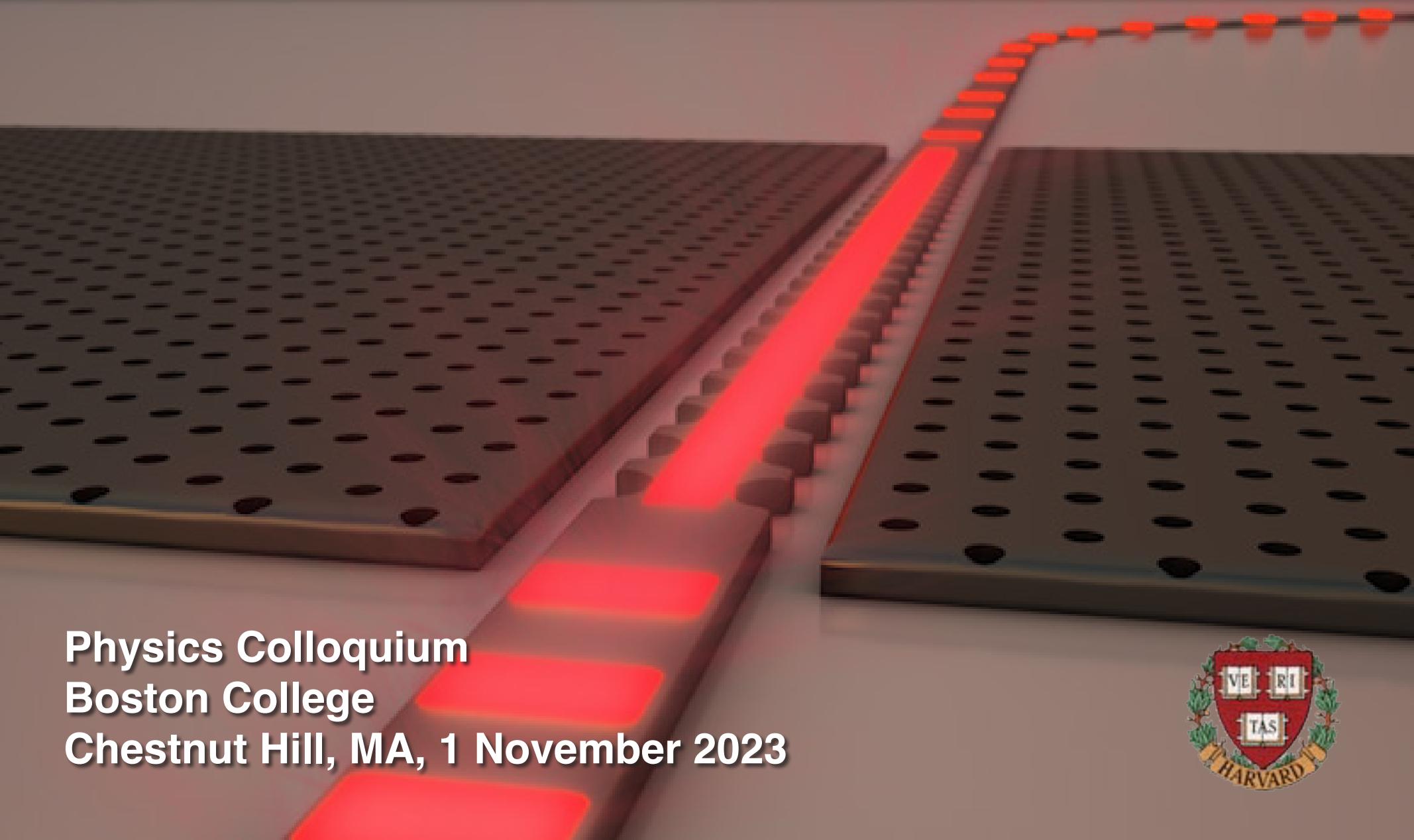


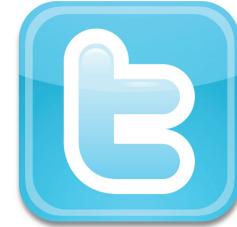
Metamaterials for extreme optics



**Physics Colloquium
Boston College
Chestnut Hill, MA, 1 November 2023**



Metamaterials for extreme optics



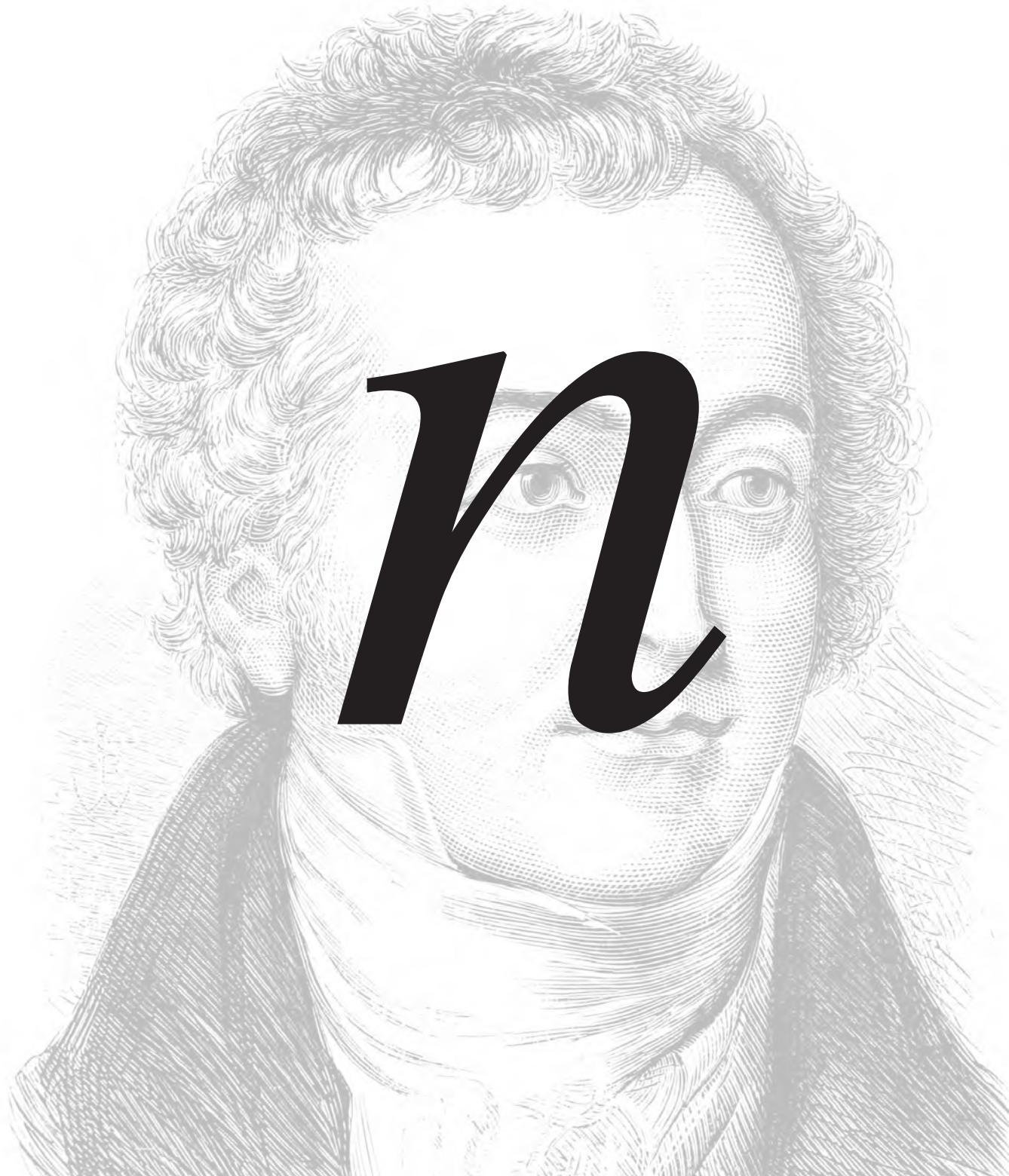
@eric_mazur

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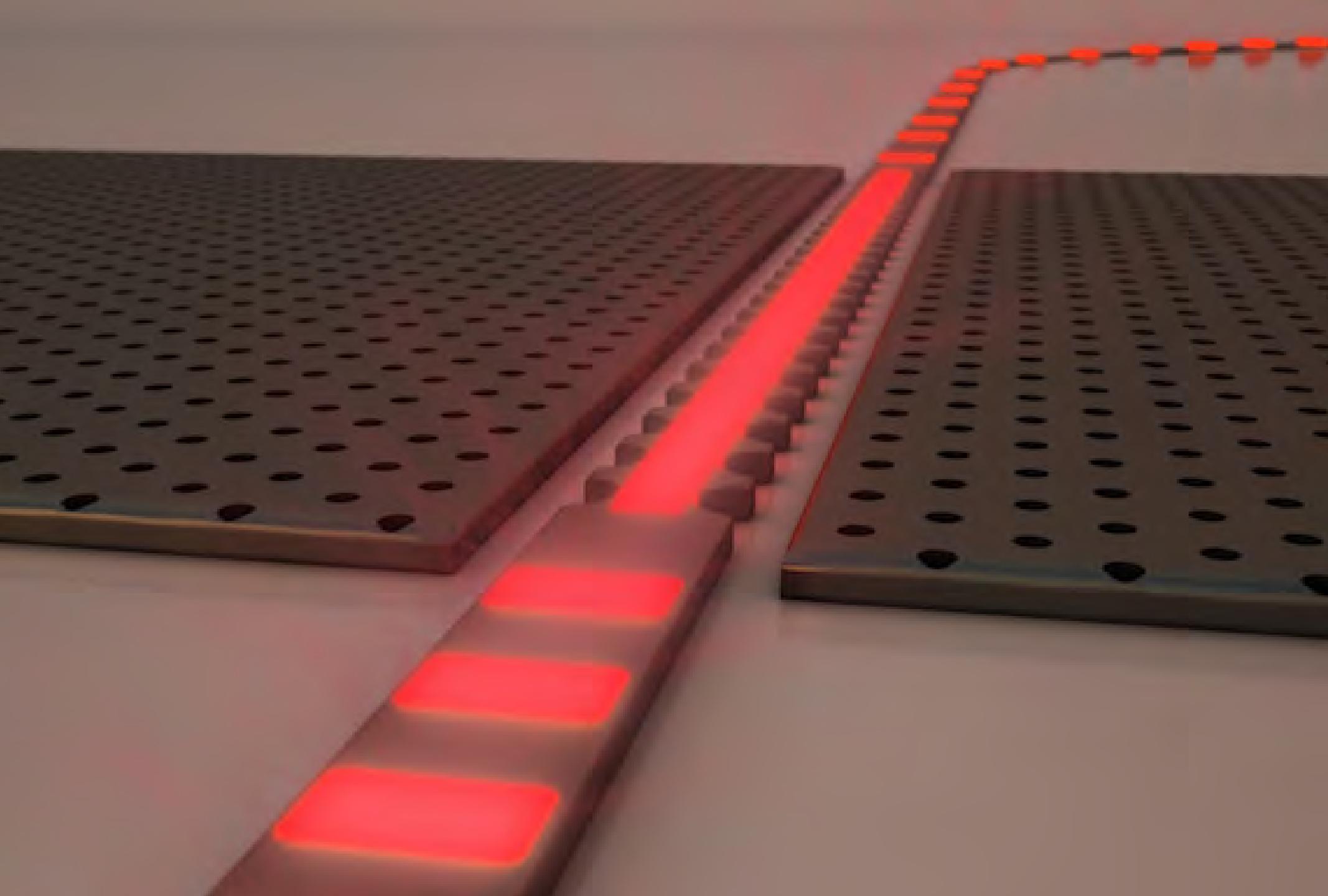




η



n



1 index

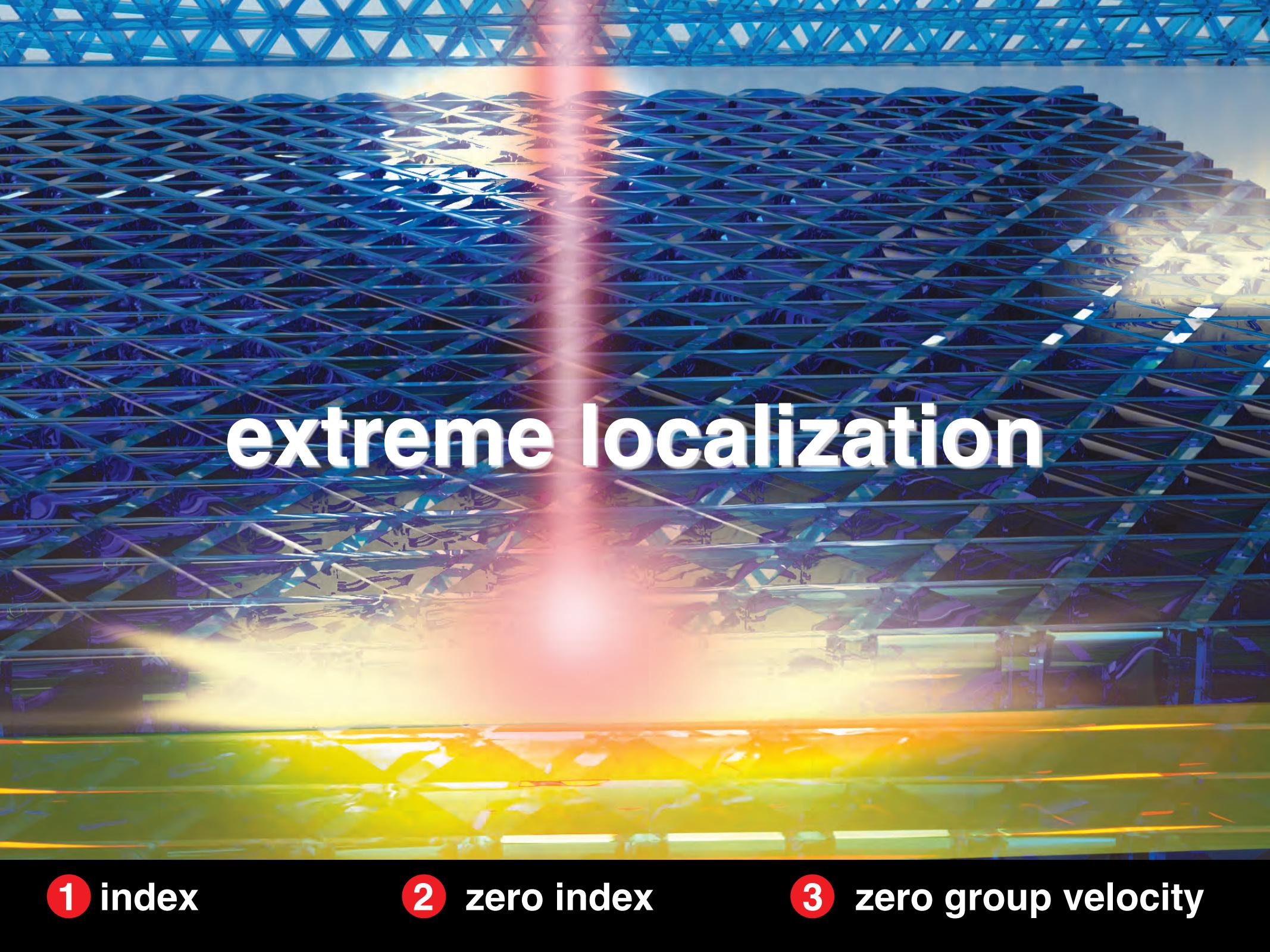
2 zero index

A photograph of a red laser beam passing through a metal grating. The beam is initially narrow and parallel, but as it moves along the grating, it spreads out into a series of bright, horizontal bands. The background is dark, and the laser beam is the primary light source.

extreme spreading

1 index

2 zero index



extreme localization

1 index

2 zero index

3 zero group velocity

Propagation of EM wave

Propagation of EM wave

governed by wave equation

$$\nabla^2 \vec{E} - \frac{\mu\epsilon}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

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In dispersive media $n = n(\omega)$.

Index of refraction

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

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So $n(\omega)$ determined by response of material to external fields

Index of refraction

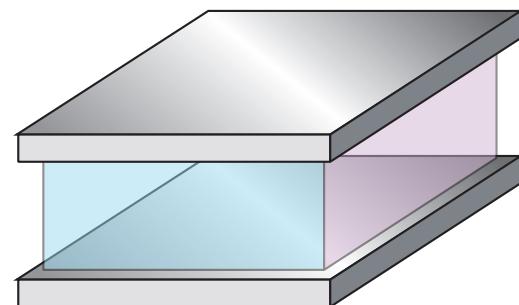
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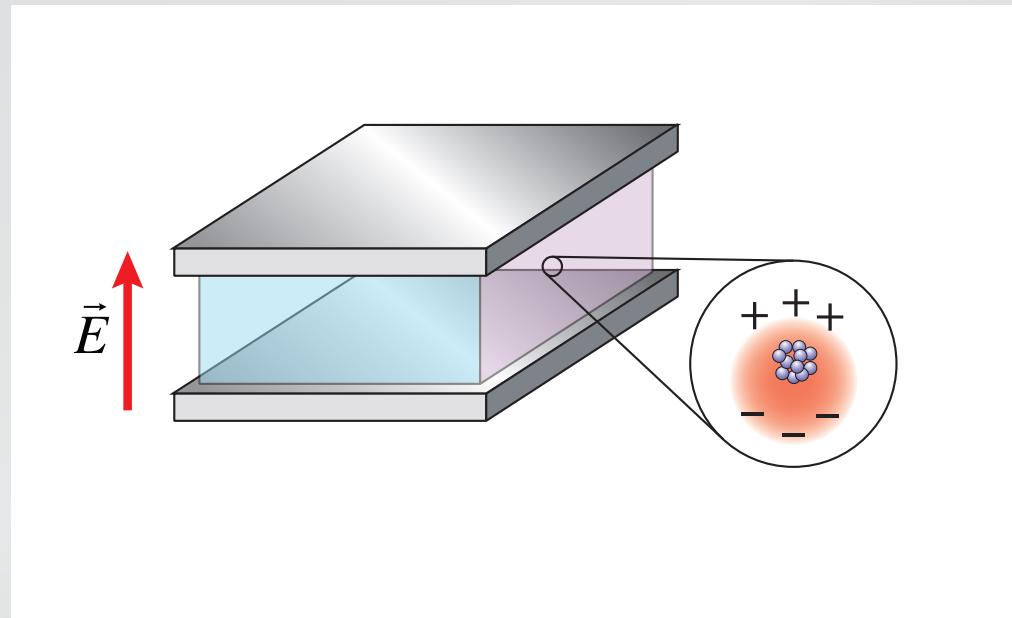
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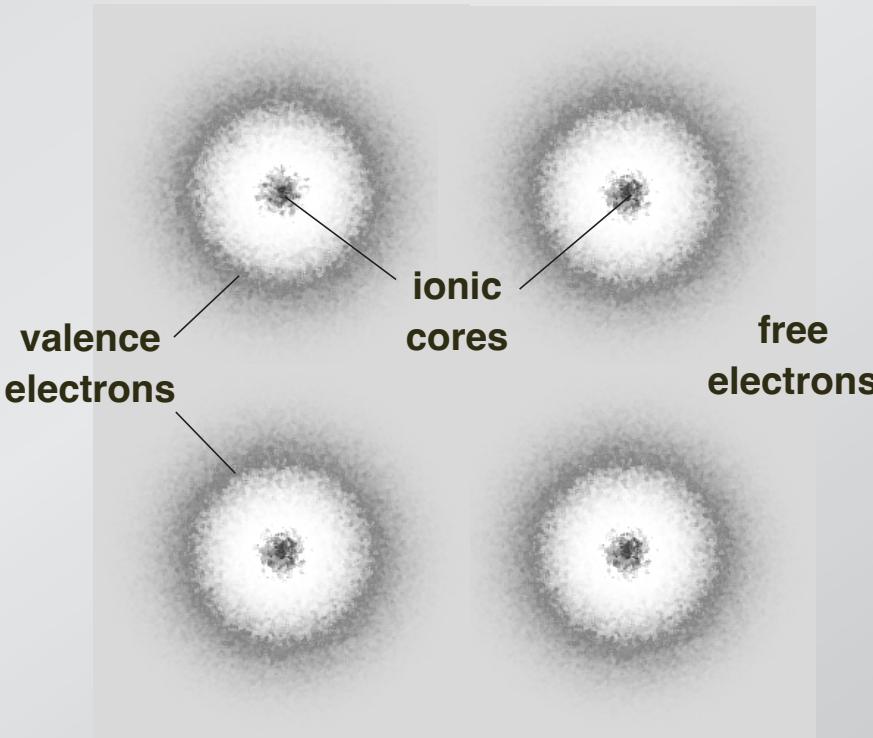


$\epsilon(\omega)$ measure of attenuation of electric field

Index of refraction

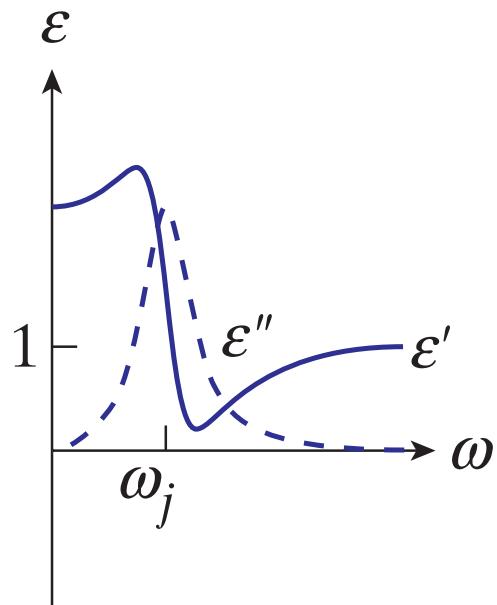
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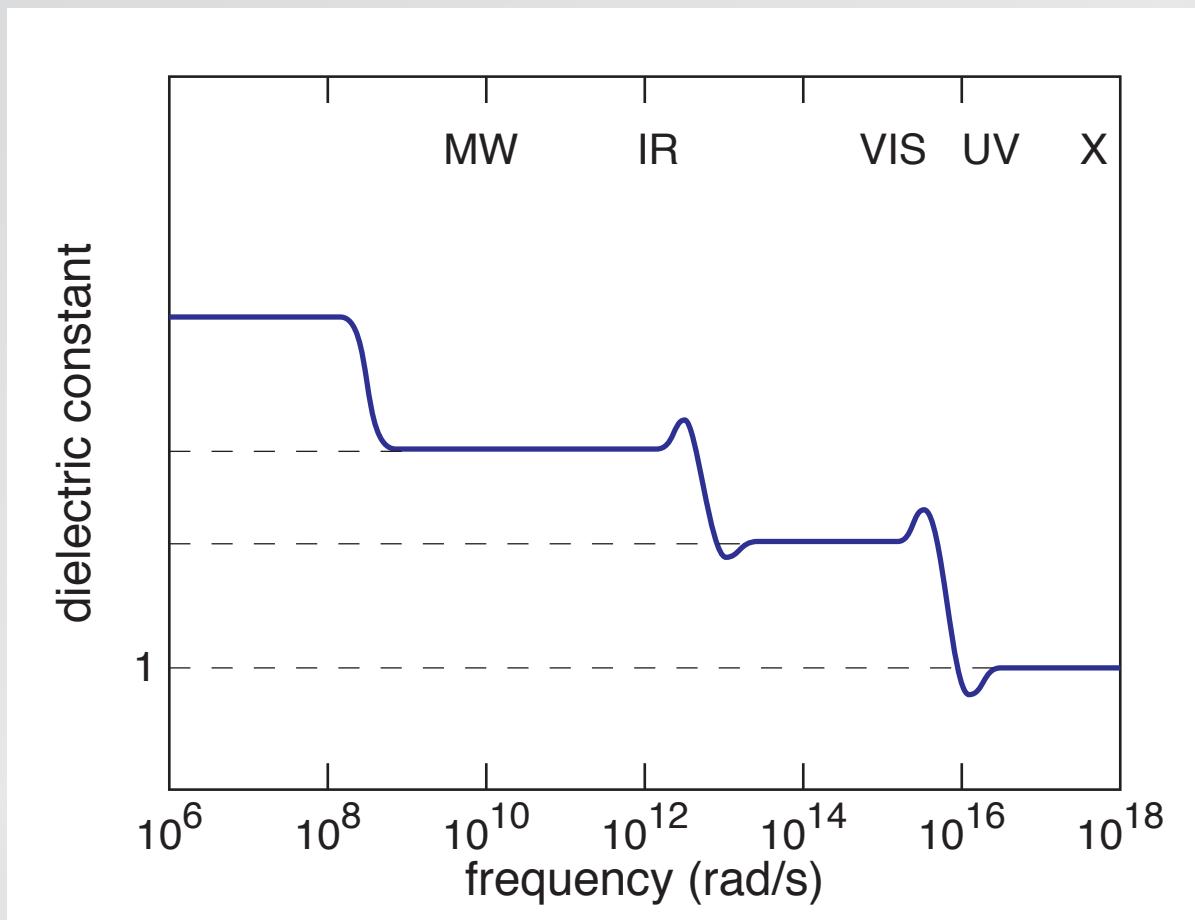


Dielectric constant

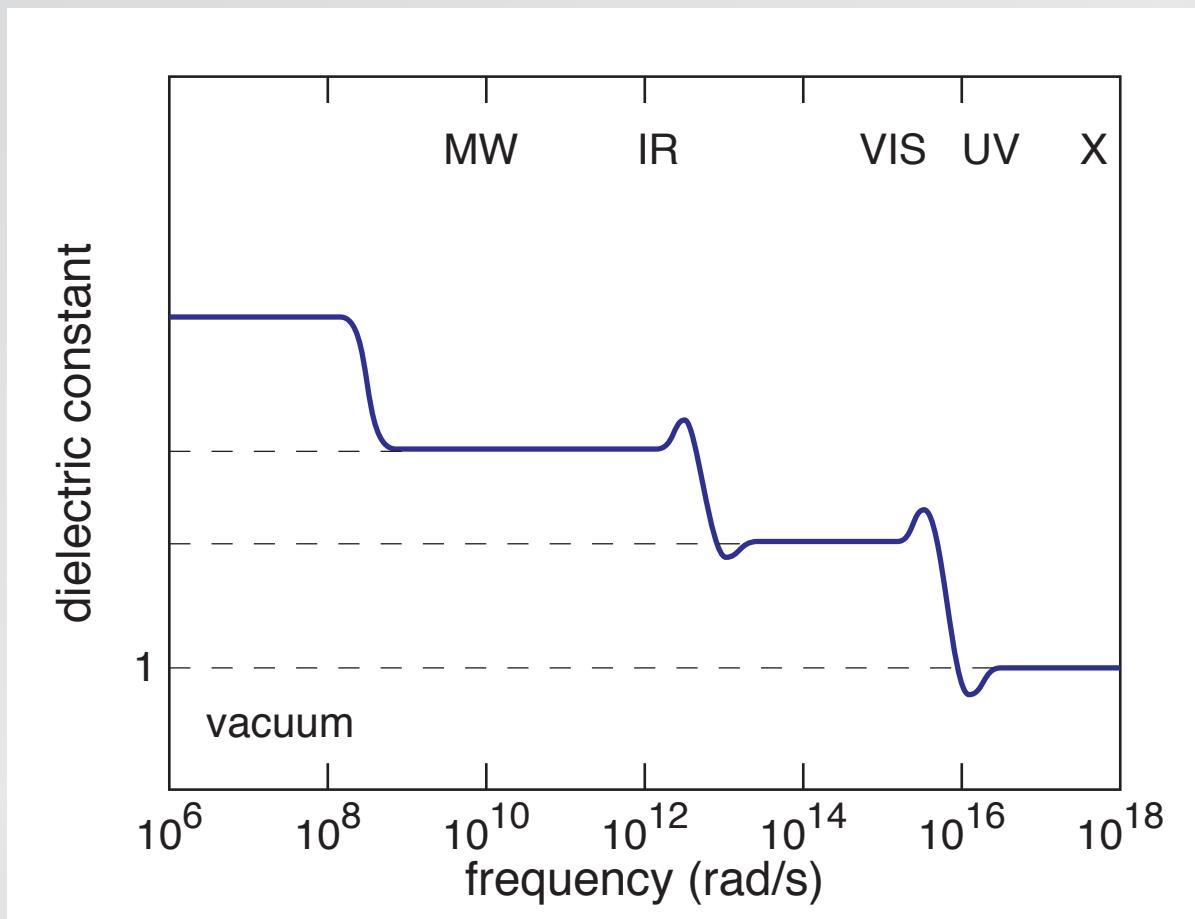
Lorentz oscillator



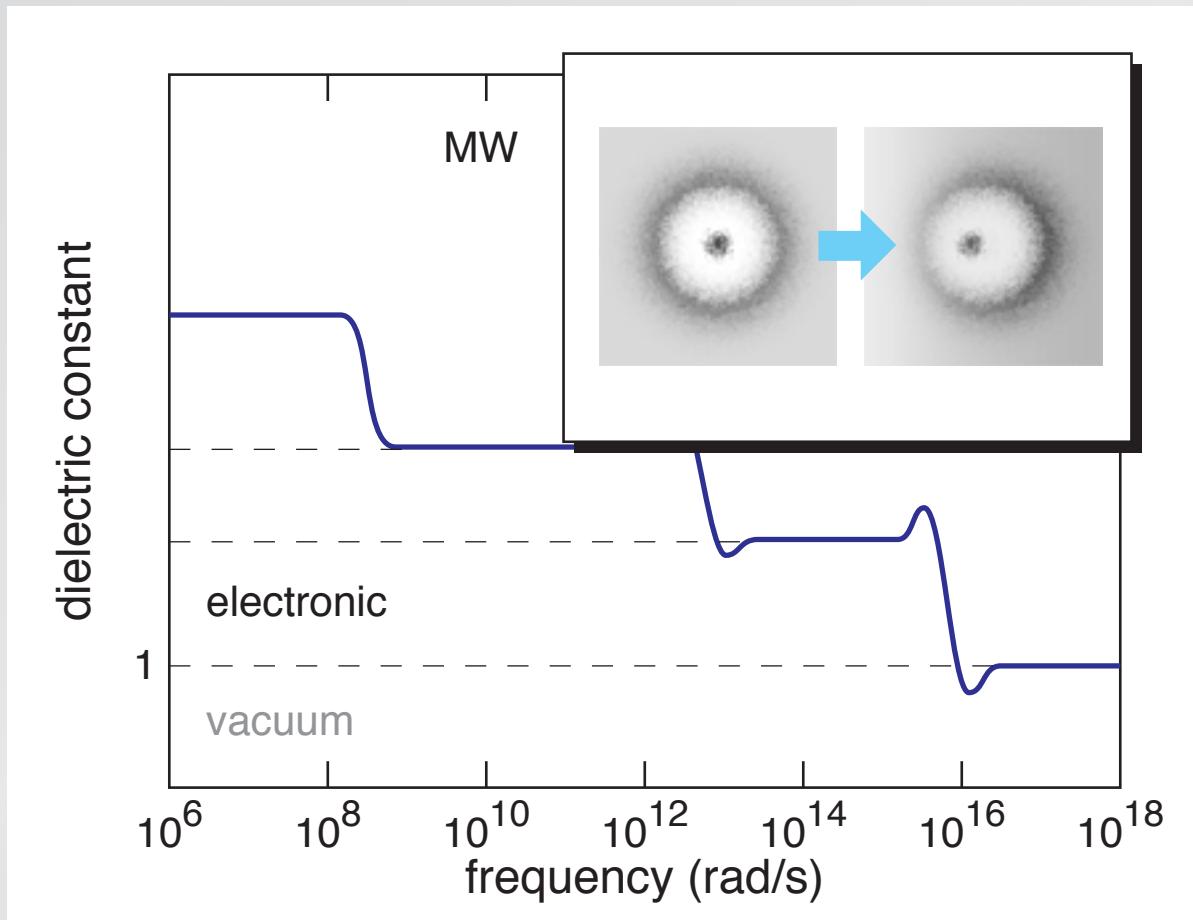
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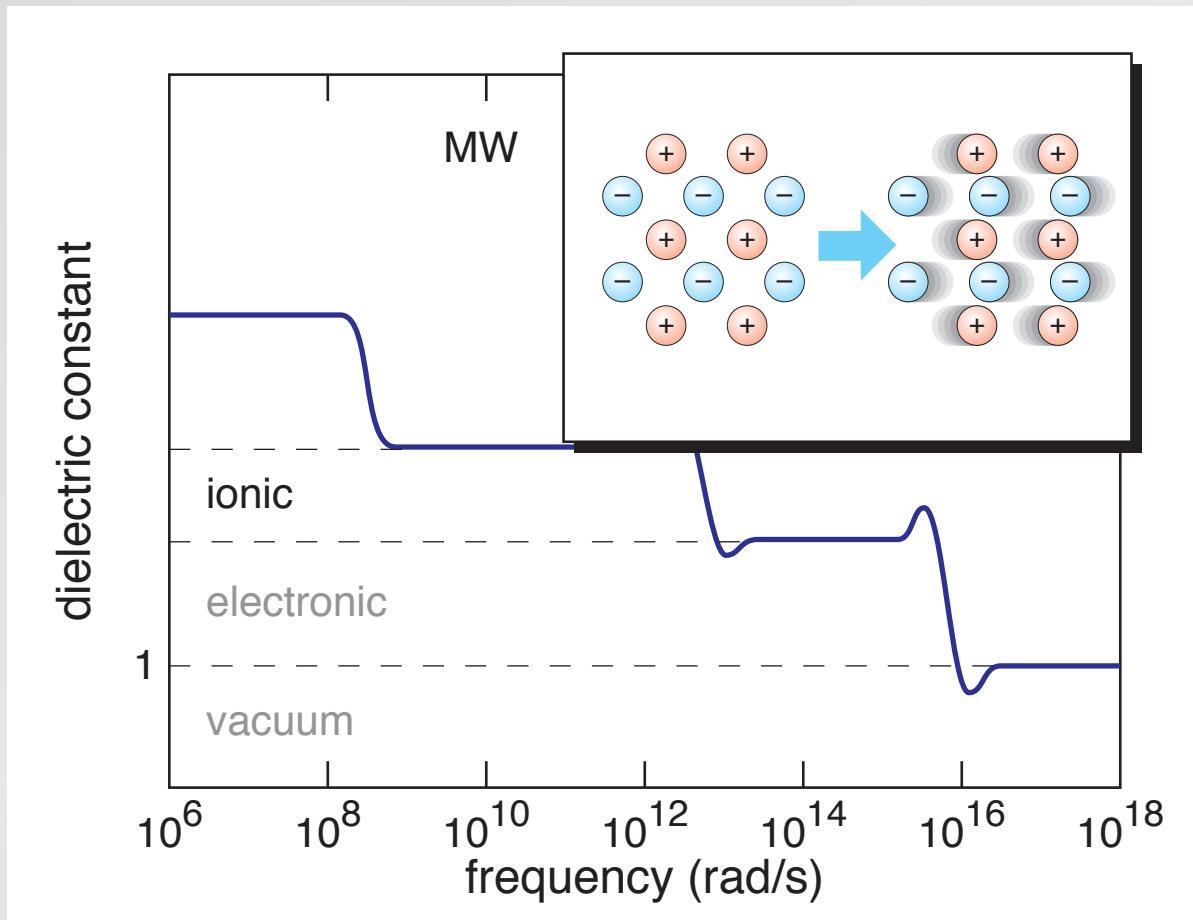
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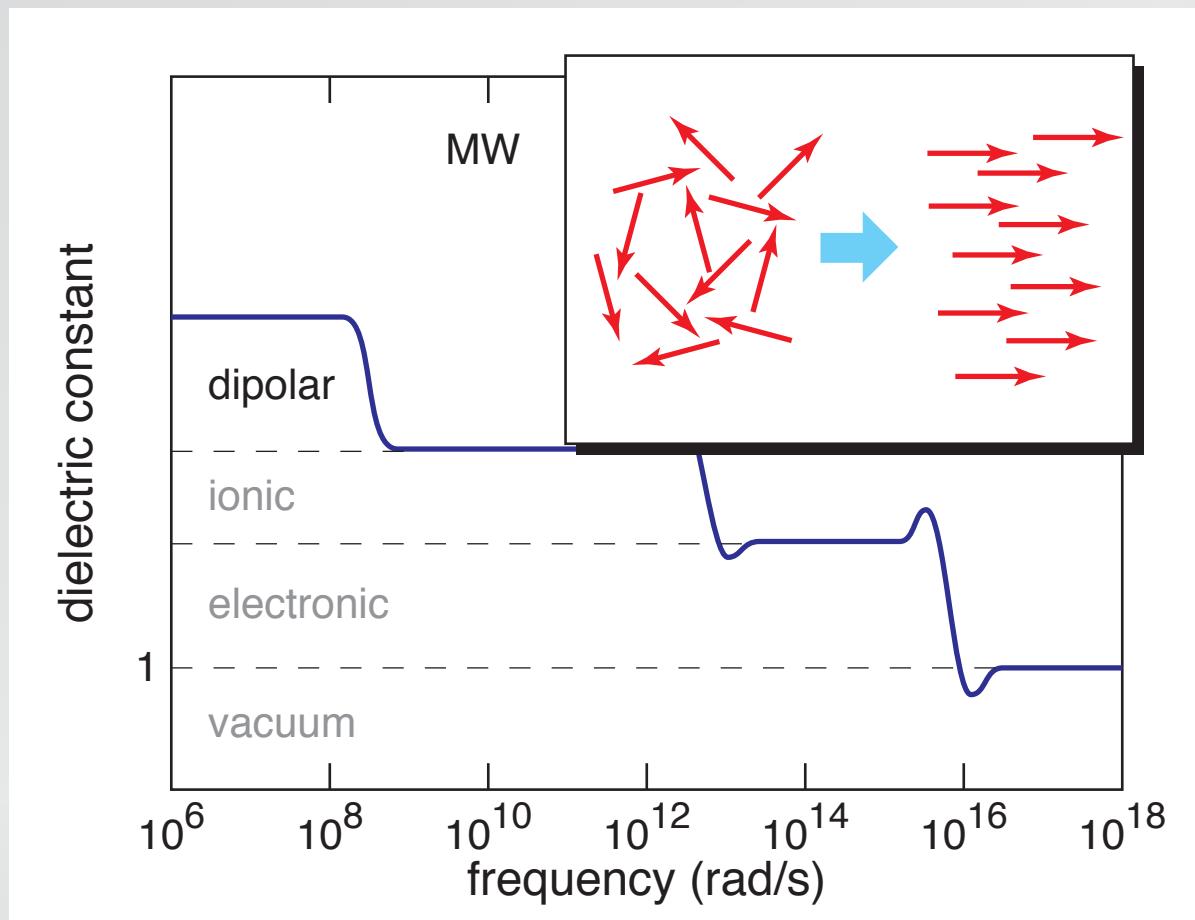
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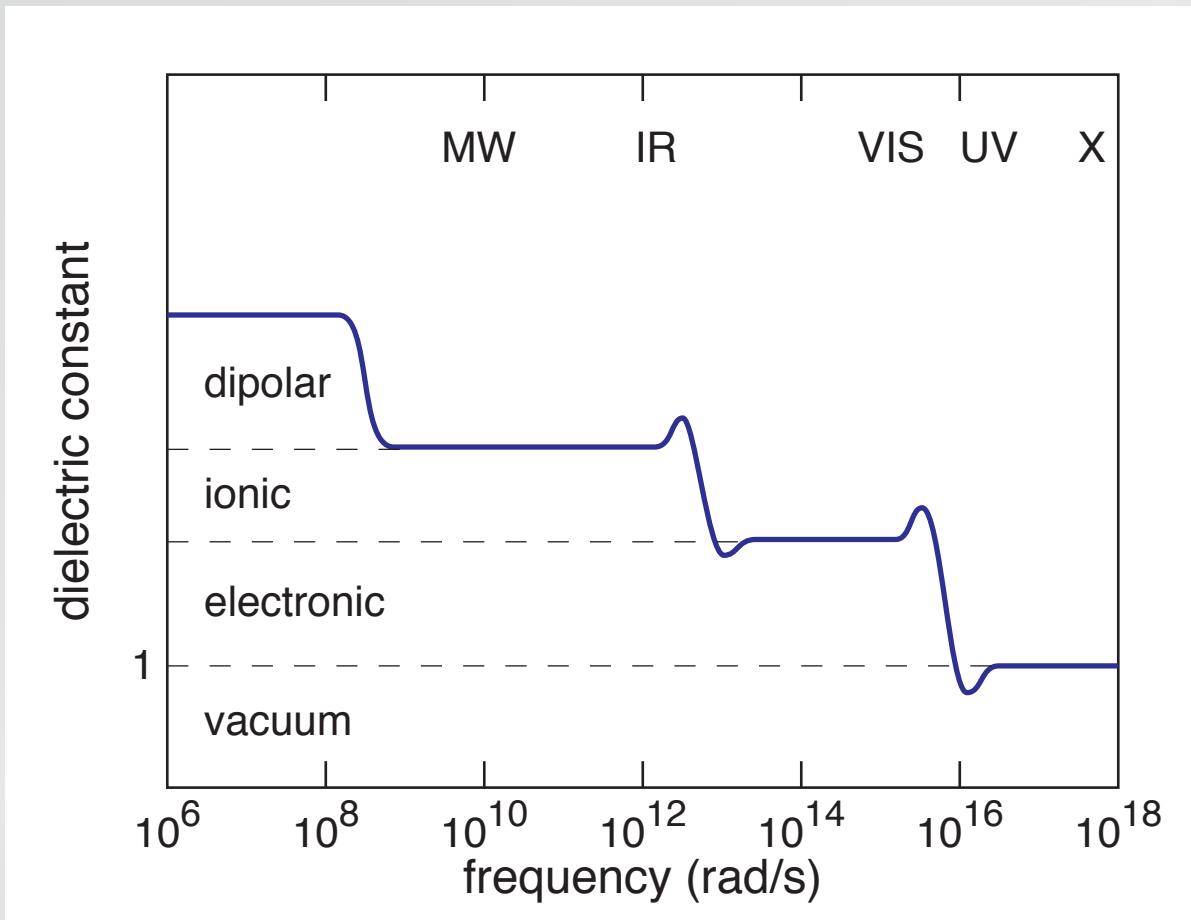
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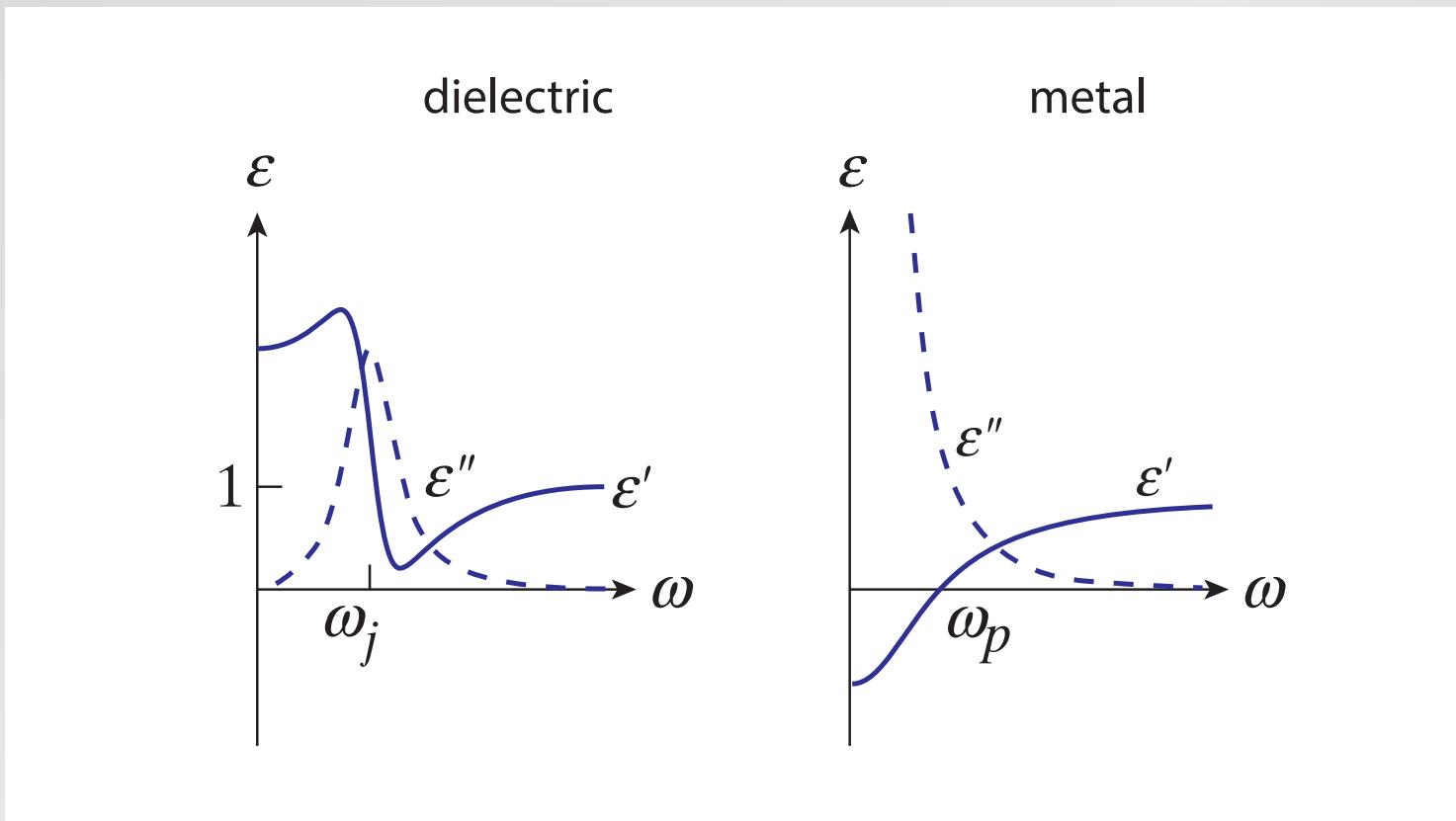
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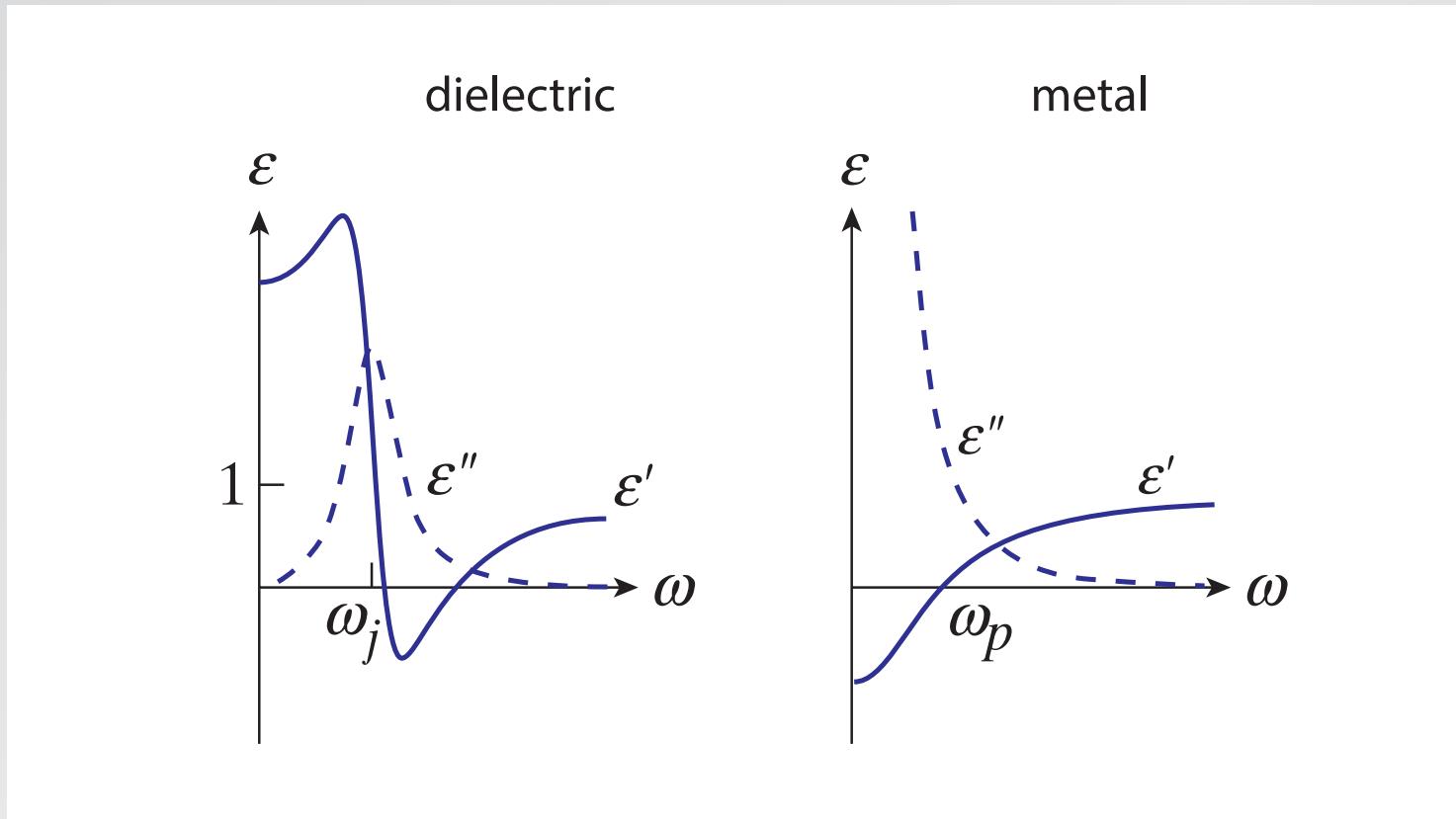


Lorentz and Drude models



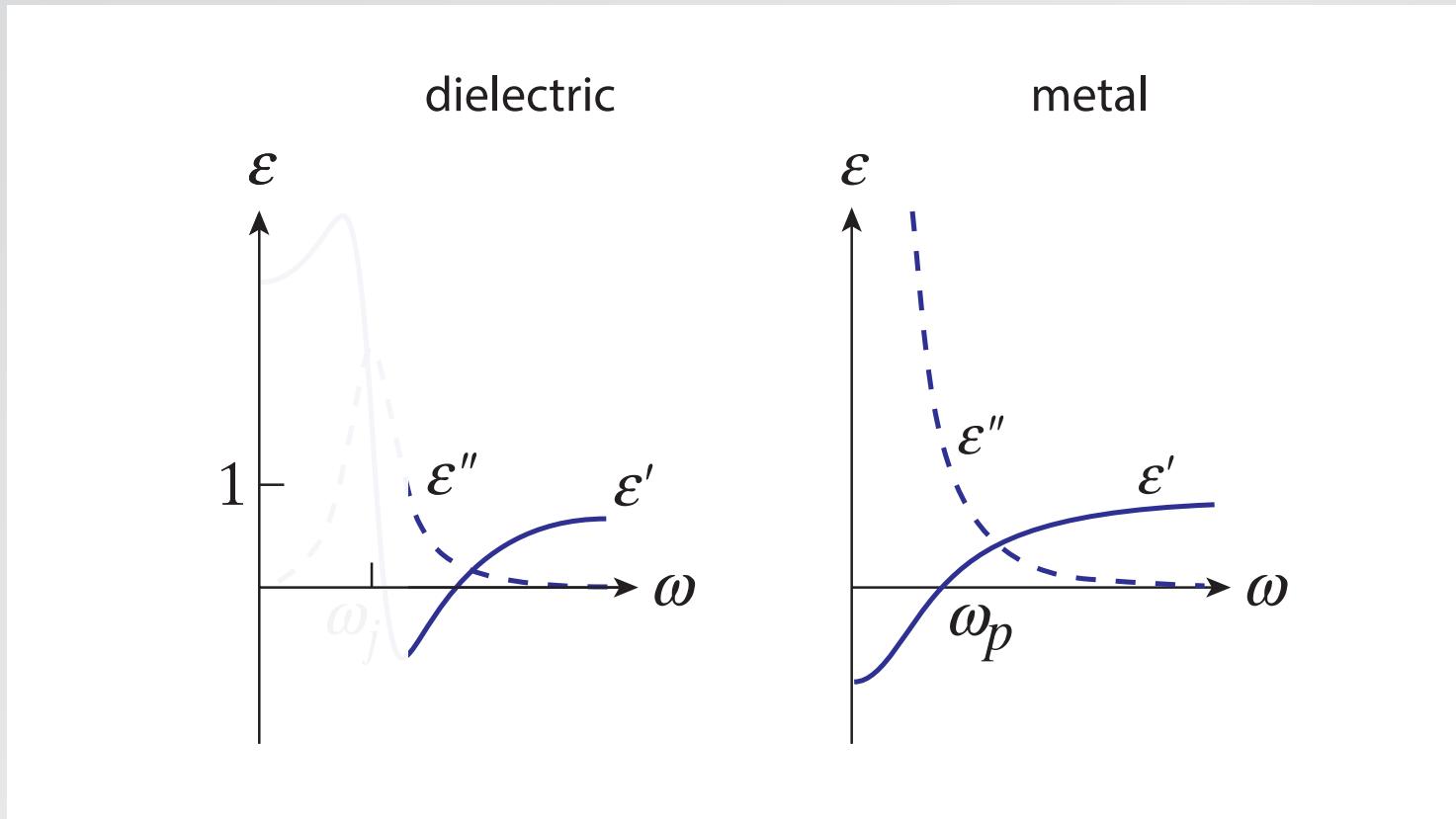
Lorentz and Drude models

for a strong (dielectric) resonance ε can become negative



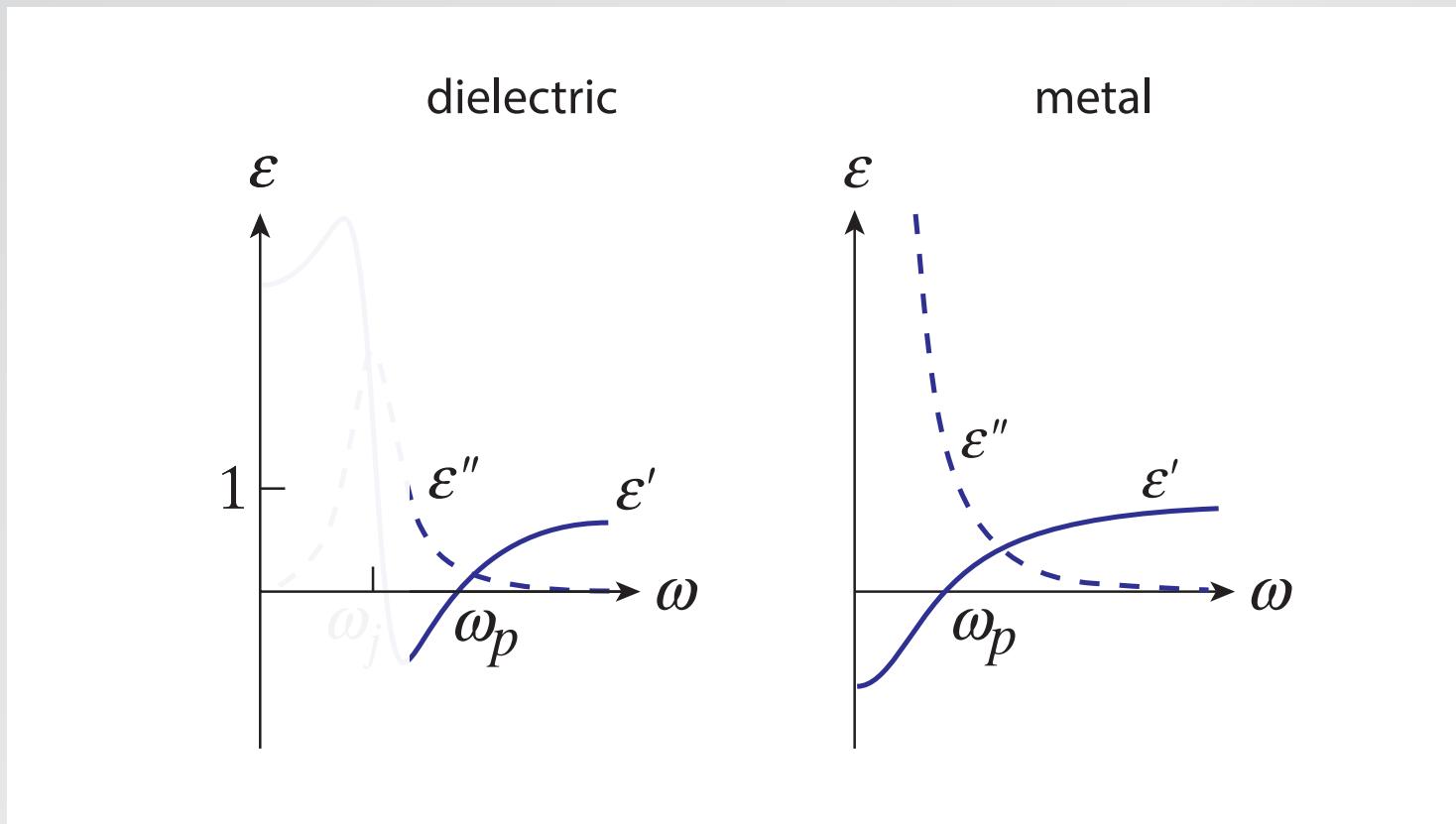
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valence electrons in dielectric then behave like a plasma



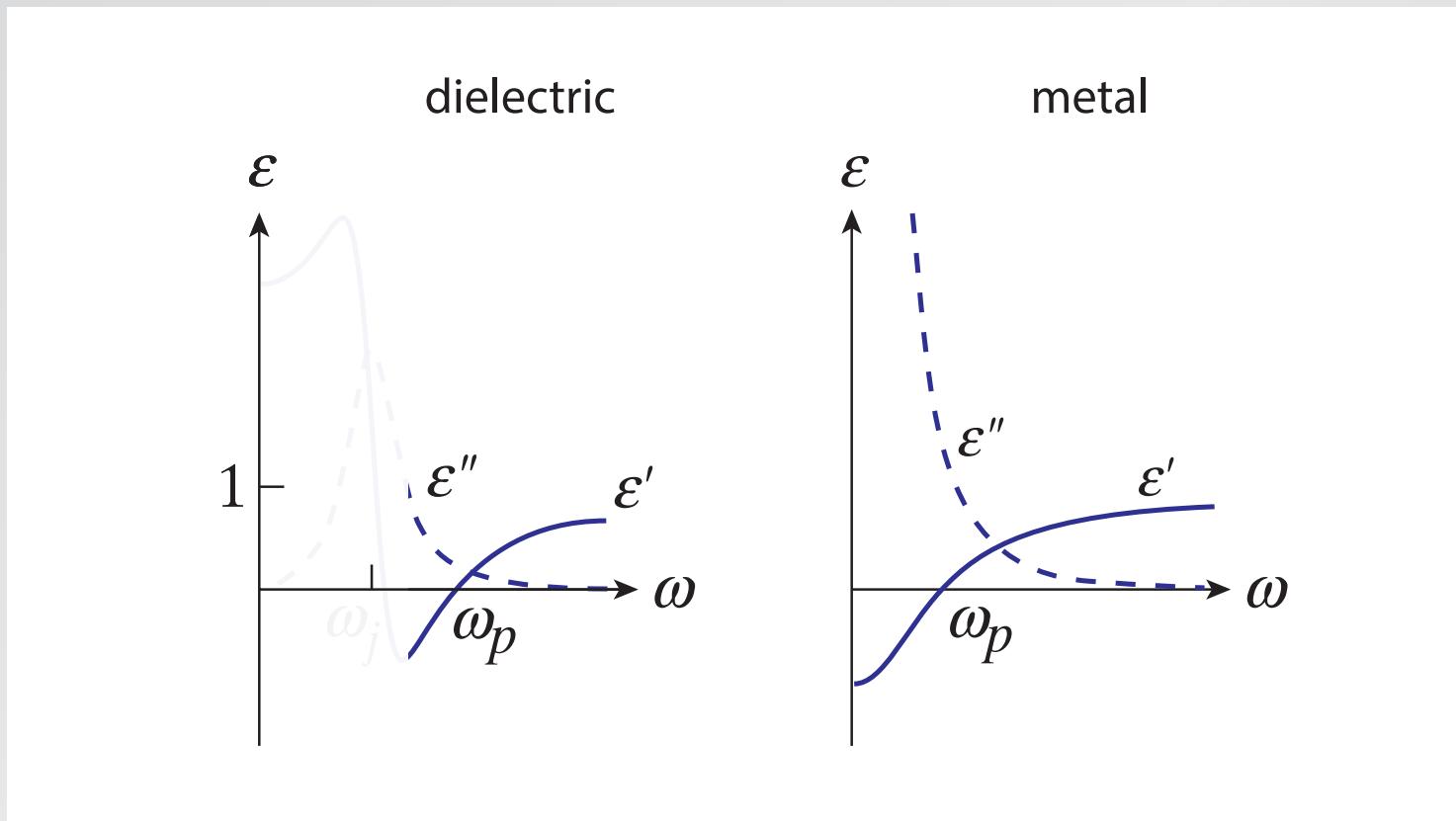
Lorentz and Drude models

with plasma frequency above the resonance



Lorentz and Drude models

(and far below the UV region)



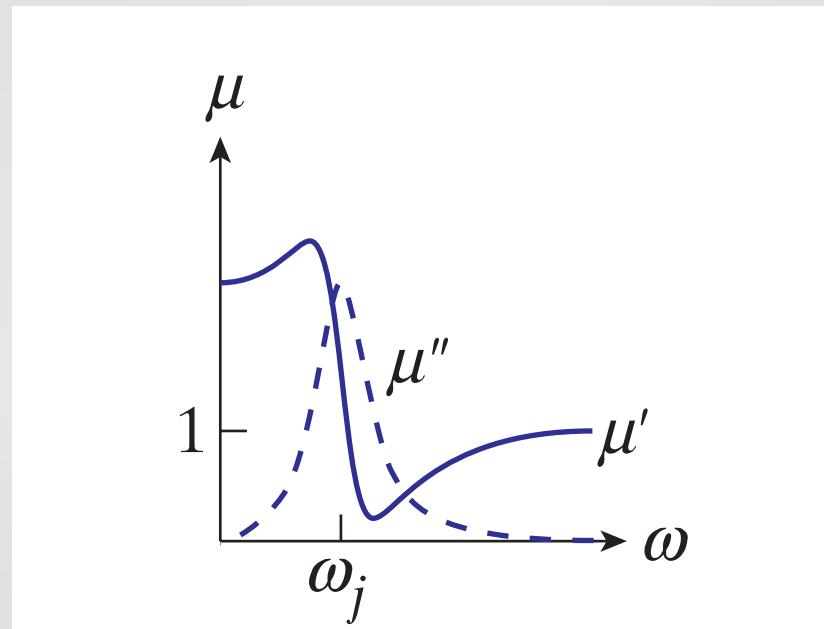
Index also determined by magnetic response

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

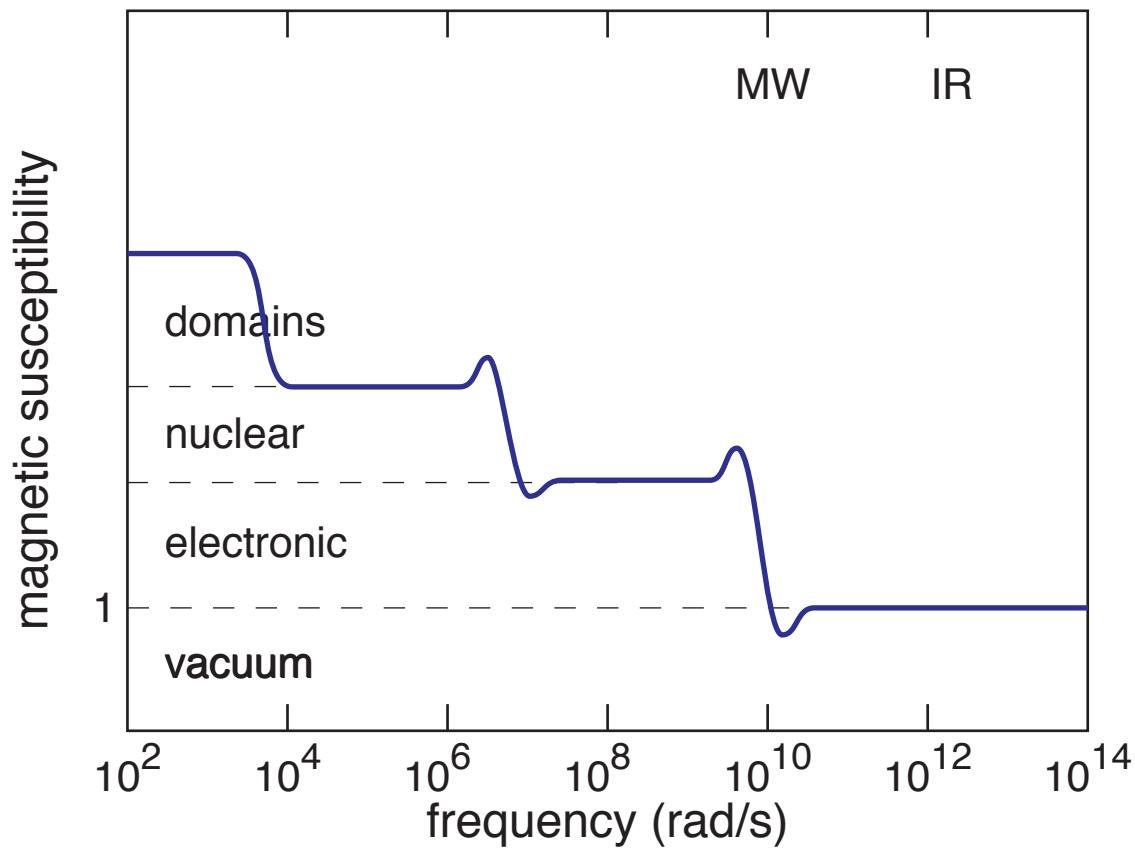
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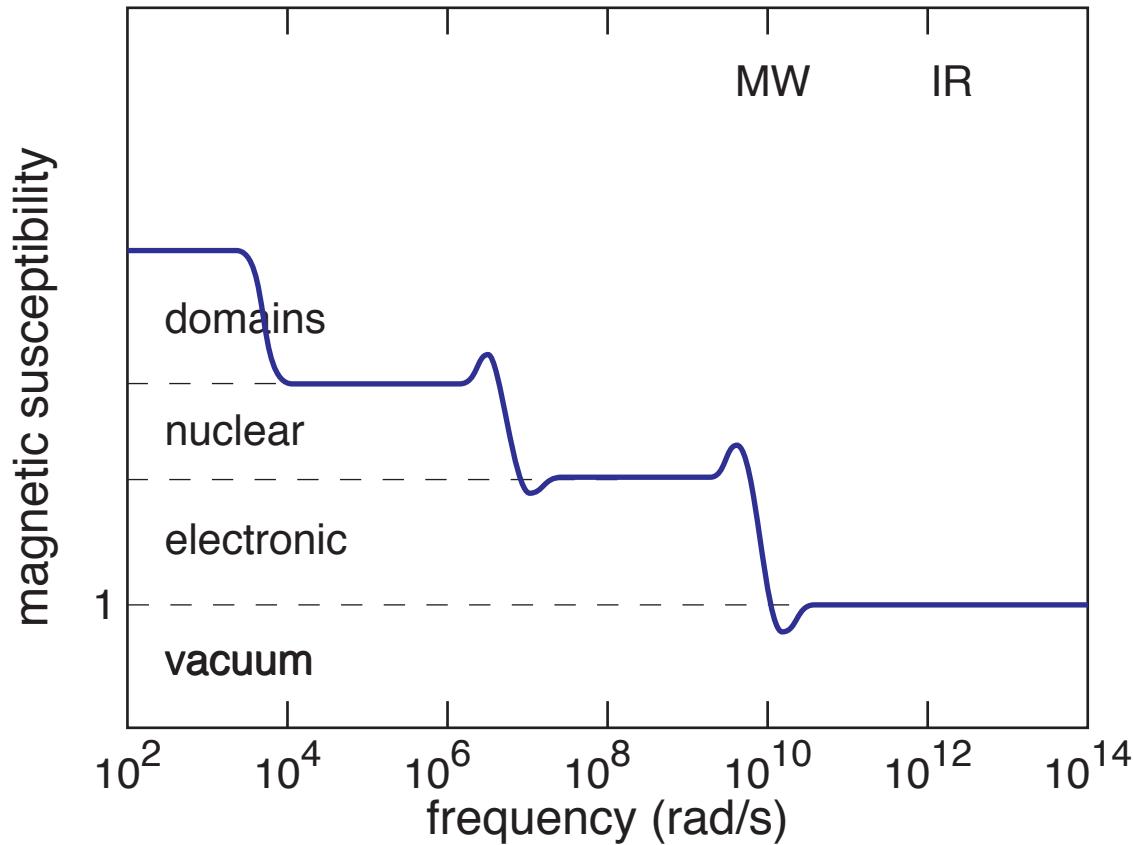


Magnetic response



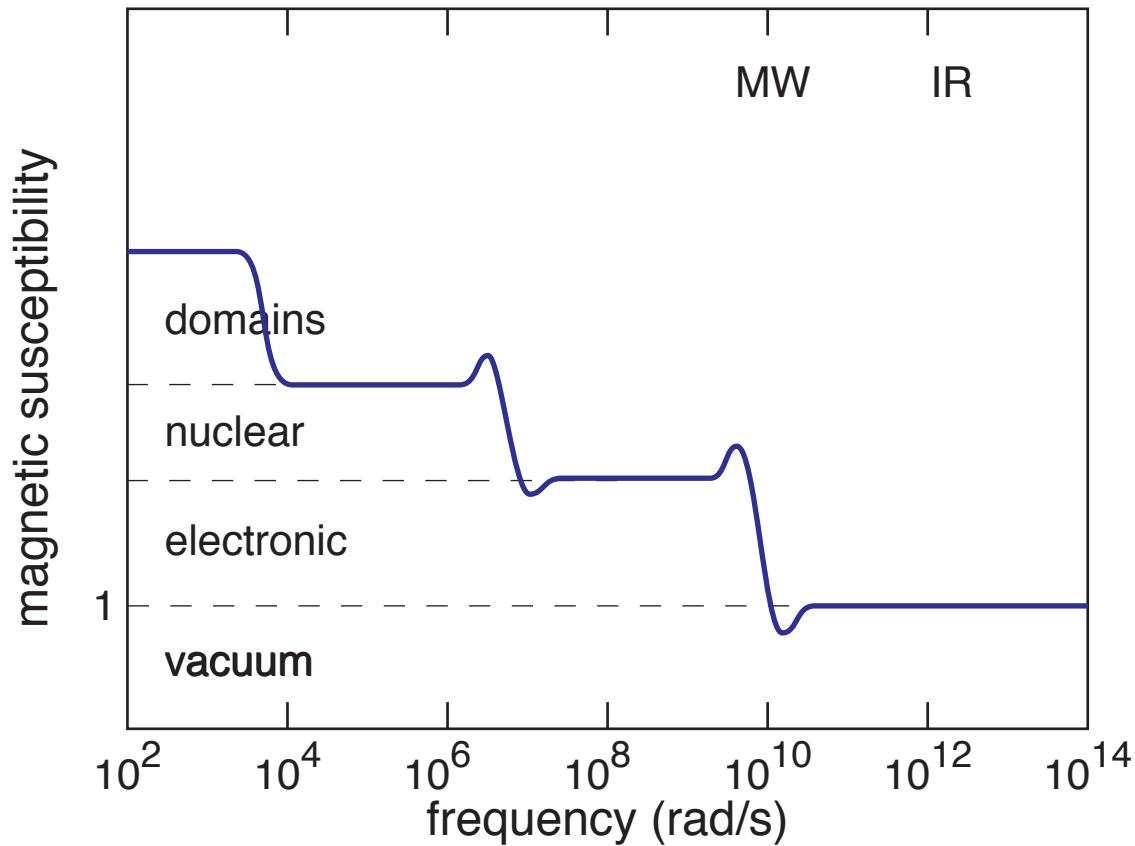
Magnetic response

but magnetic resonances occur below optical frequencies



Magnetic response

so, in optical regime, $\mu \approx 1$



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Both ϵ and μ are complex and their real parts can be negative.

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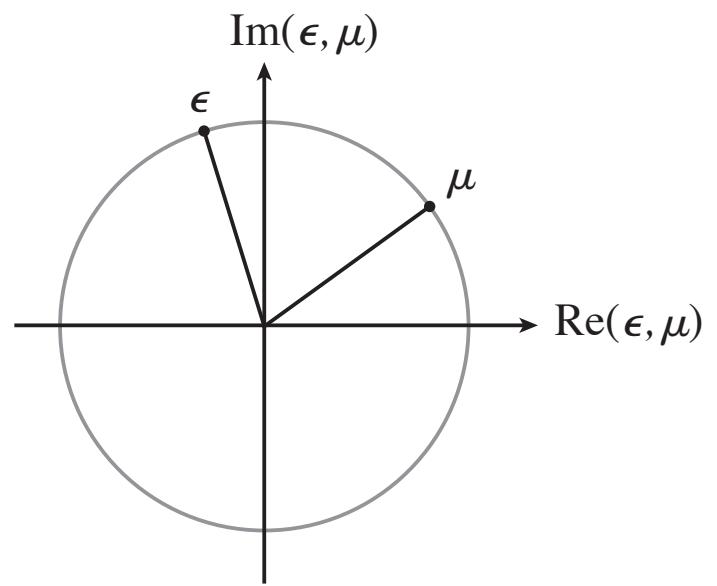
What happens when $\text{Re}\epsilon$ and/or $\text{Re}\mu$ is negative?

Write complex quantities as

$$\varepsilon = |\varepsilon| e^{i\theta} \quad \mu = |\mu| e^{i\phi}$$

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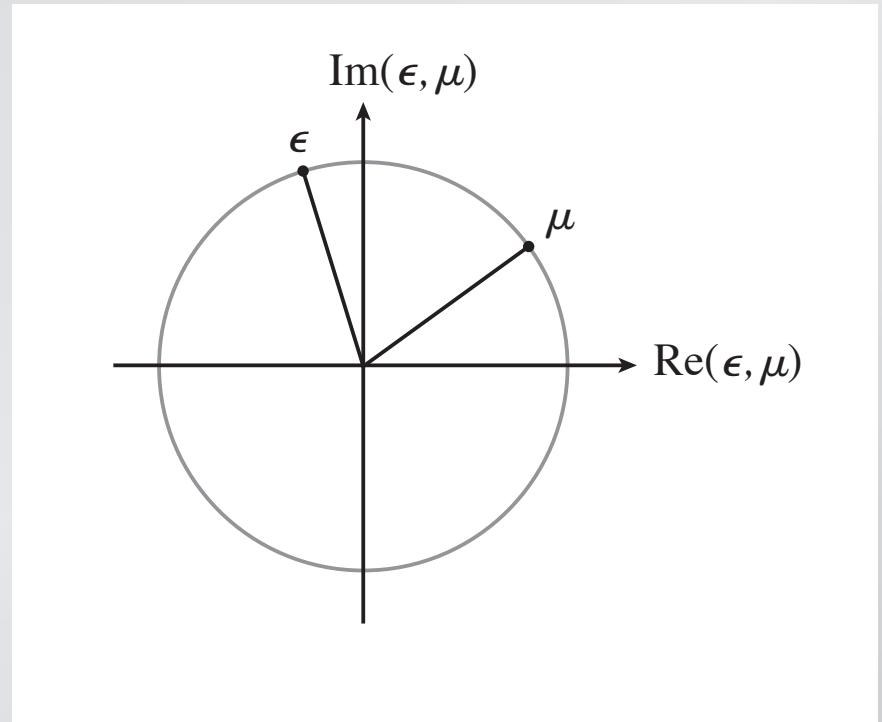


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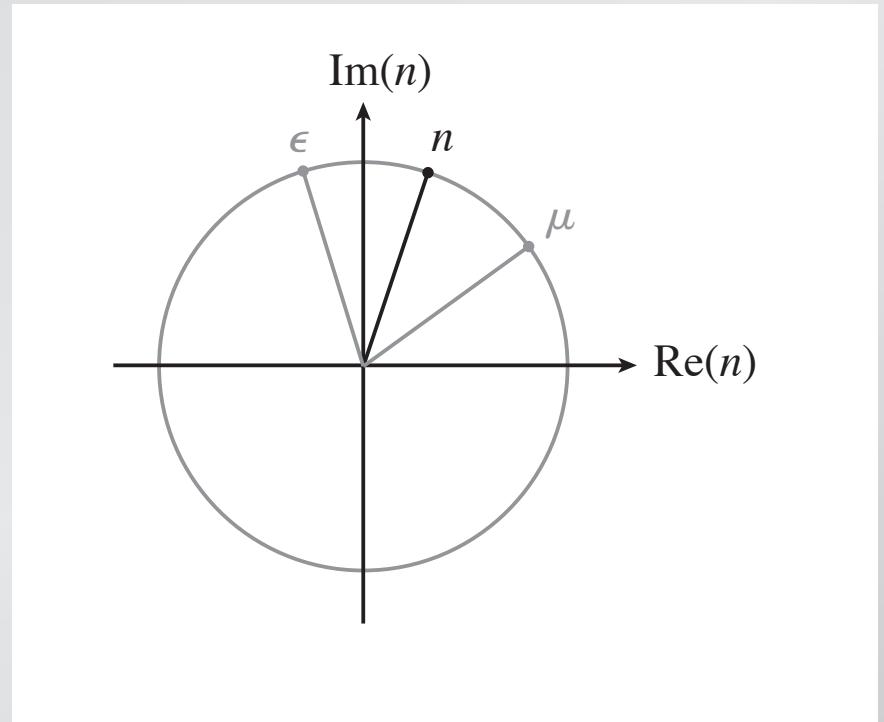


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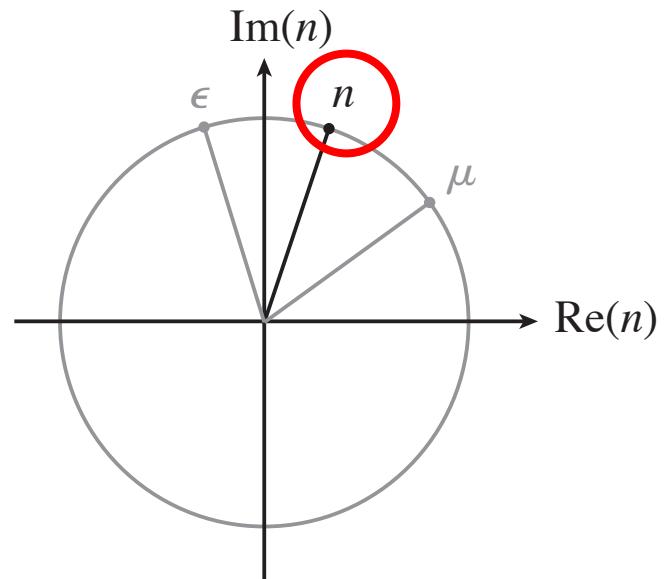
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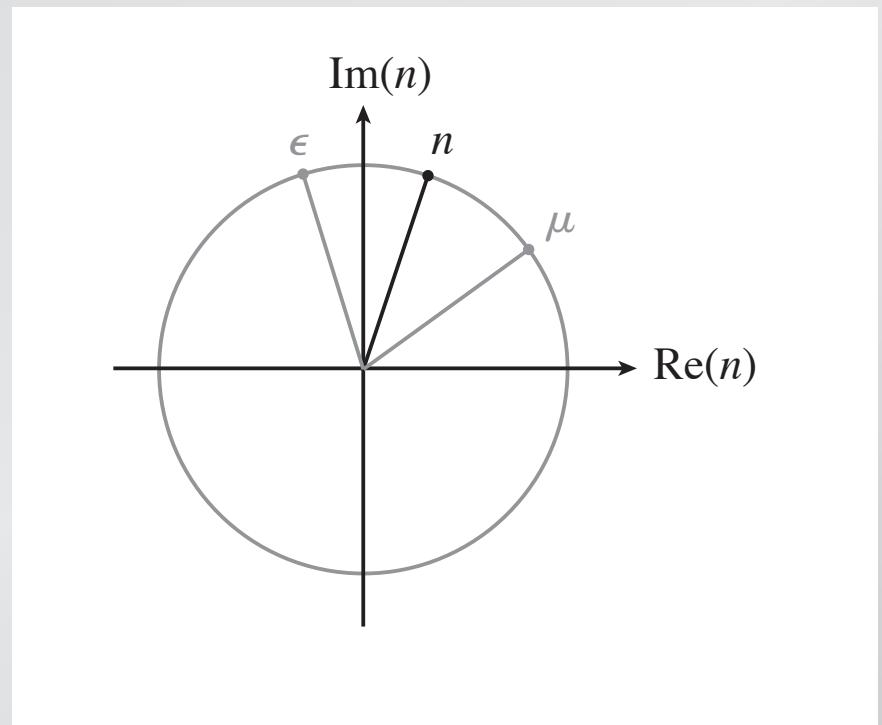
$$n = \sqrt{|\epsilon||\mu|} e^{i\frac{\theta+\phi}{2}}$$

Q: Is this only possible value?

1. yes
2. no, there's one more
3. there are many more
4. it depends



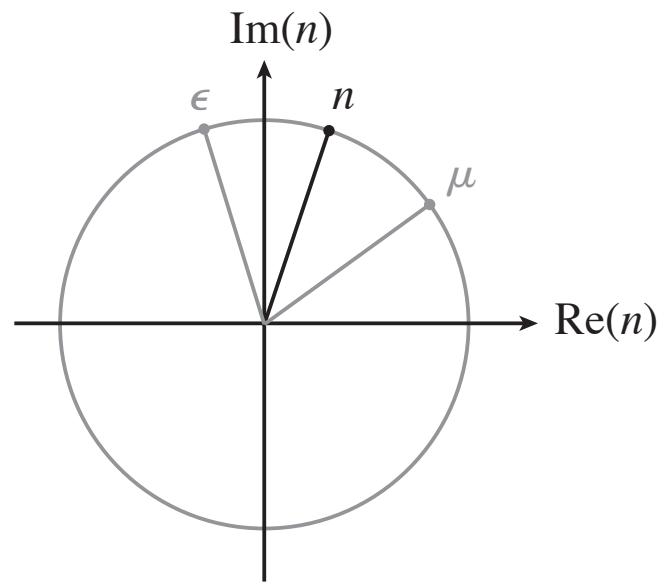
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Can add 2π to exponent

$$e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]}$$



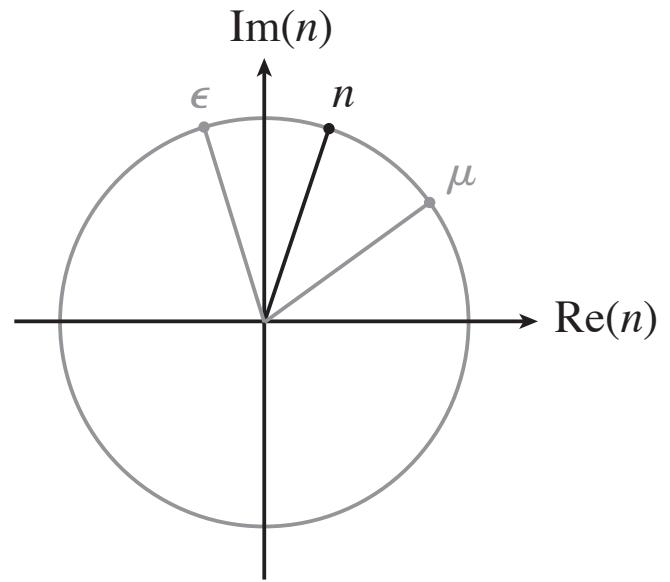
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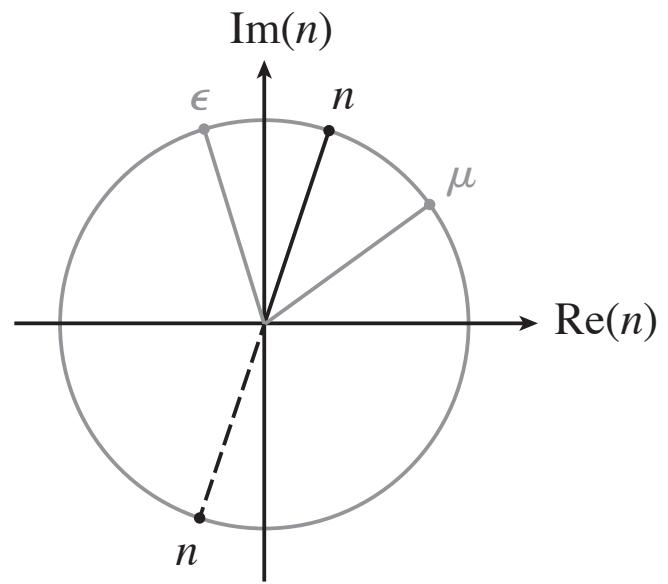
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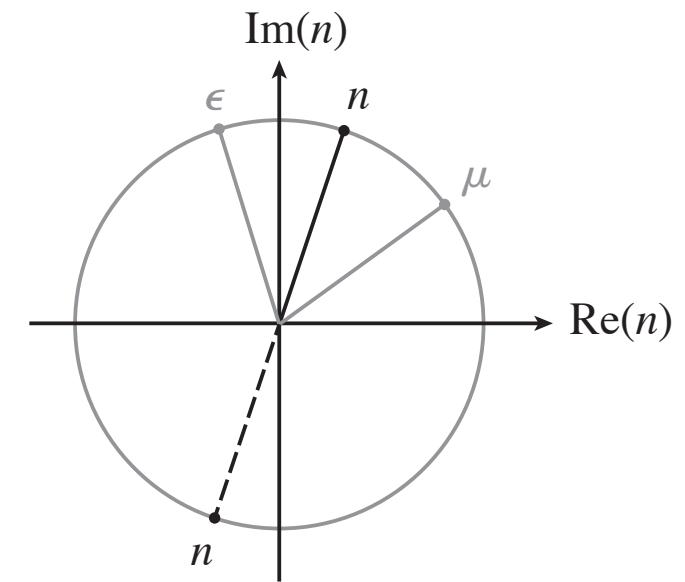
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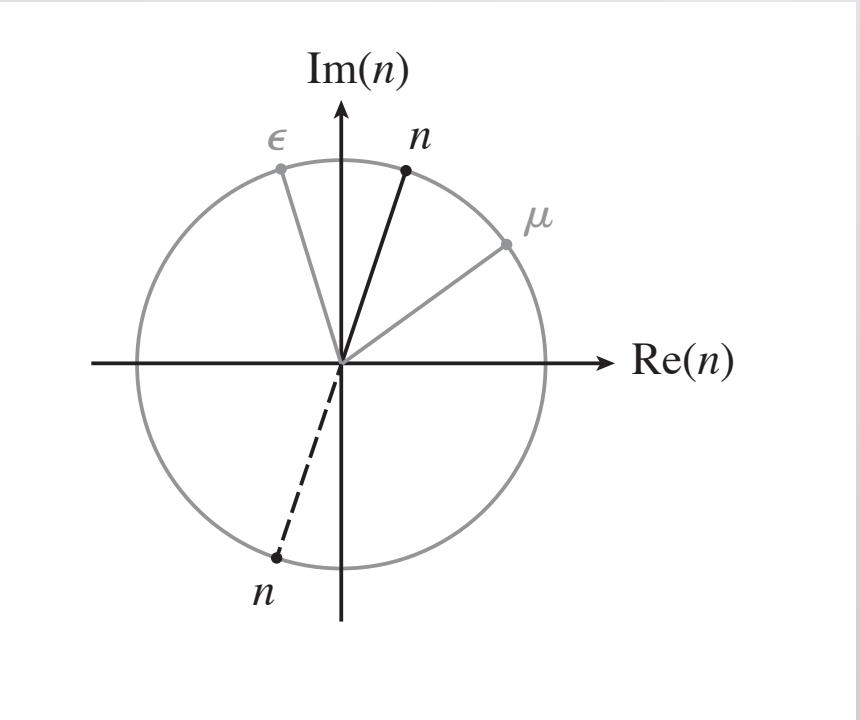
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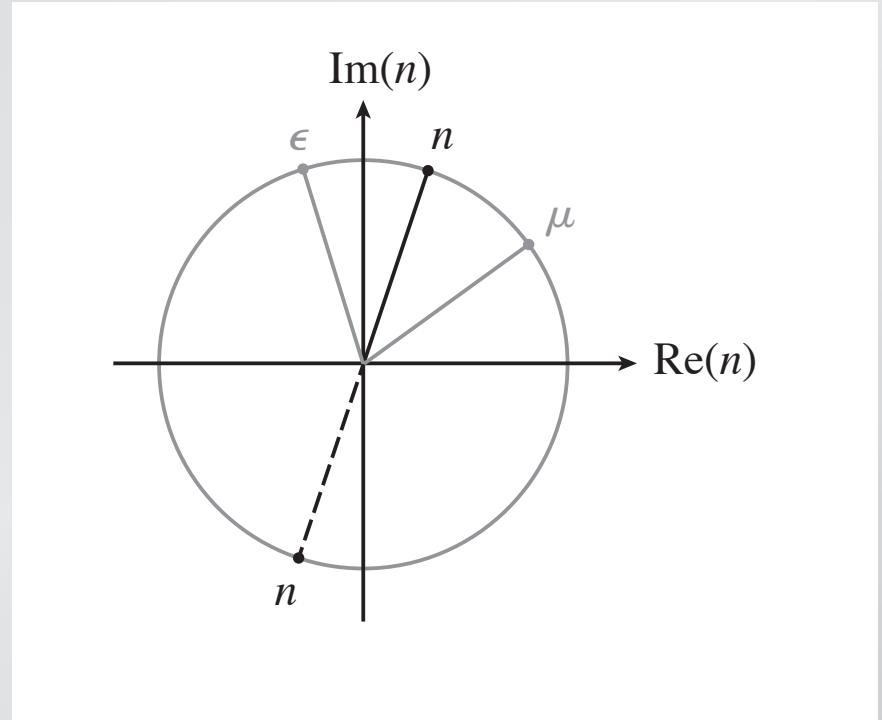
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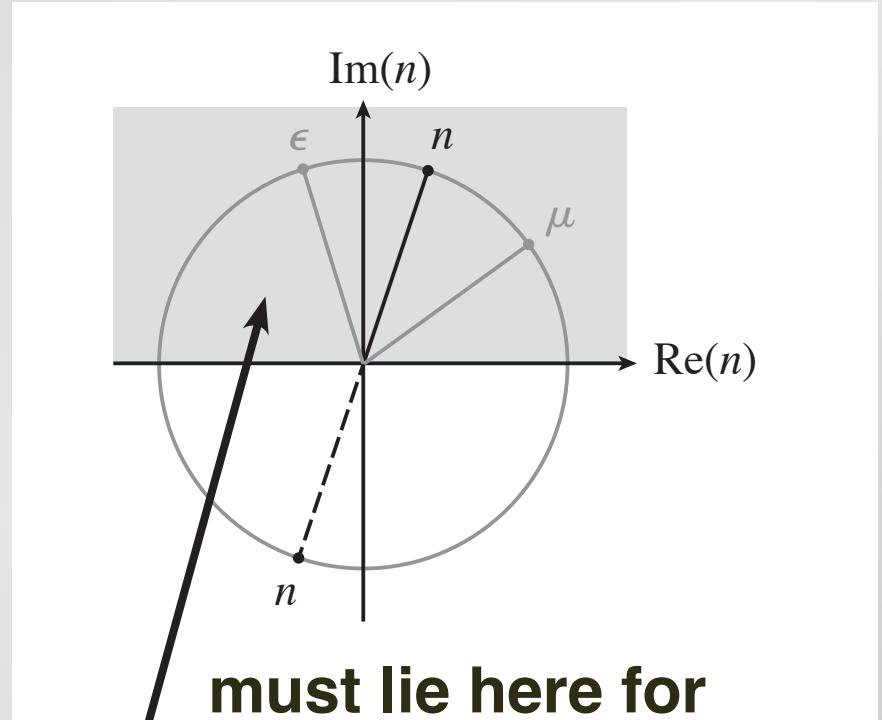
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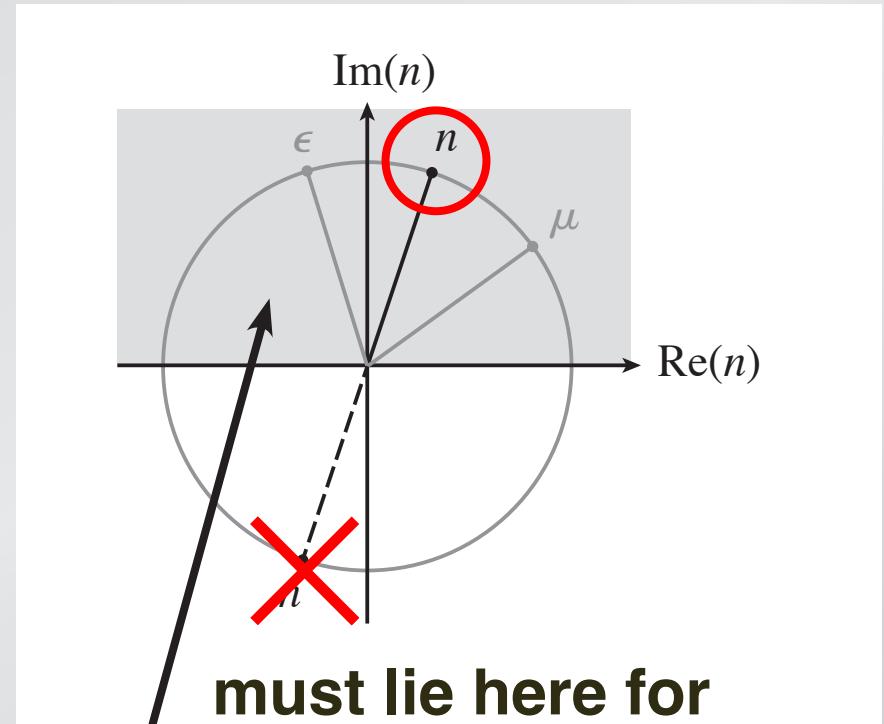
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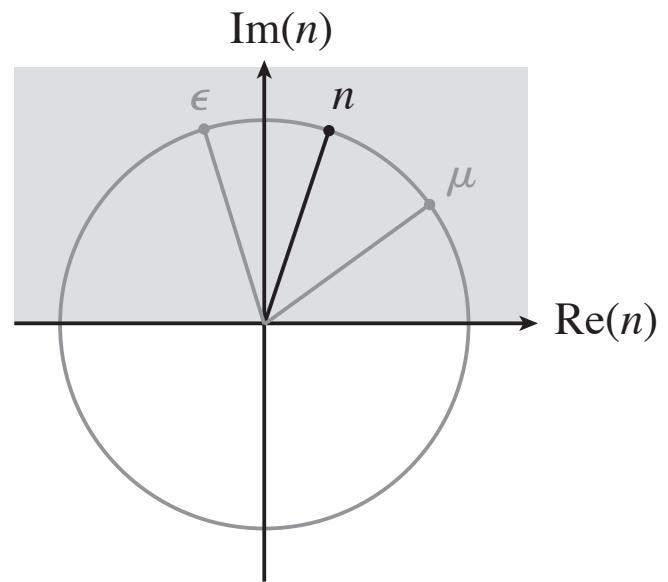
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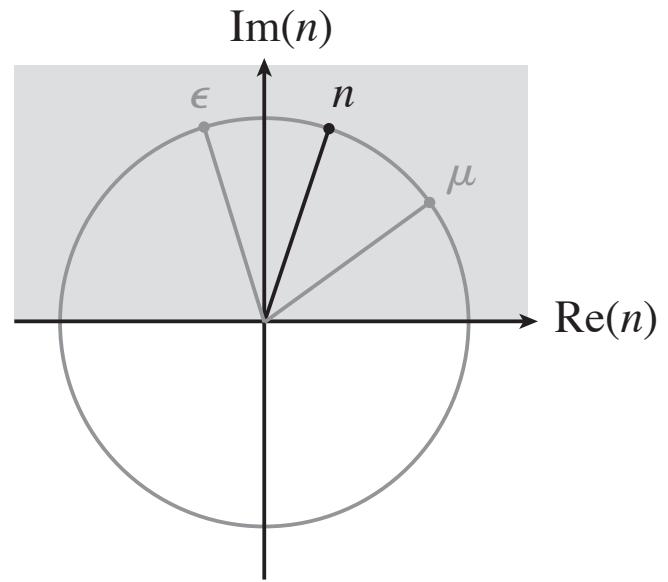
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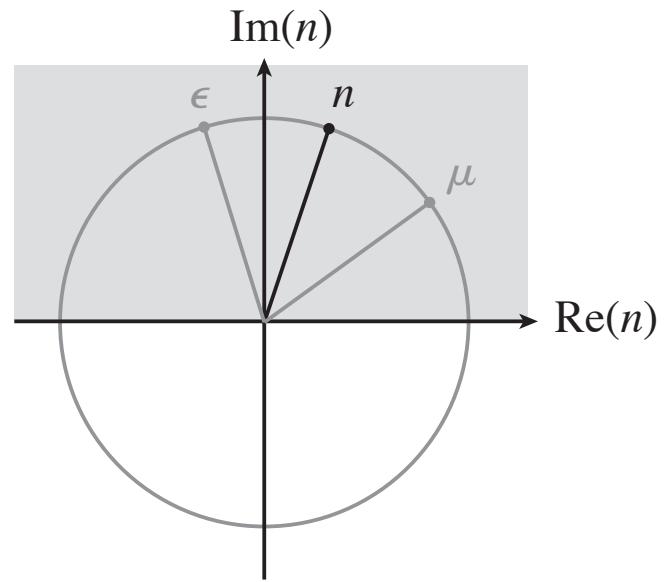
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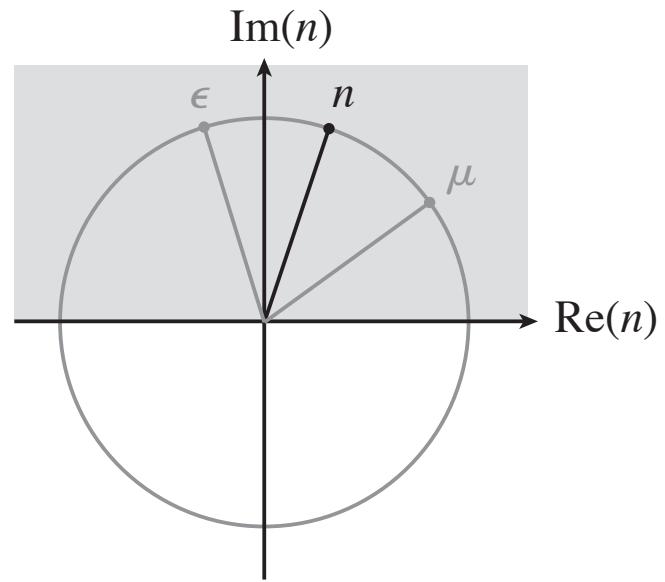
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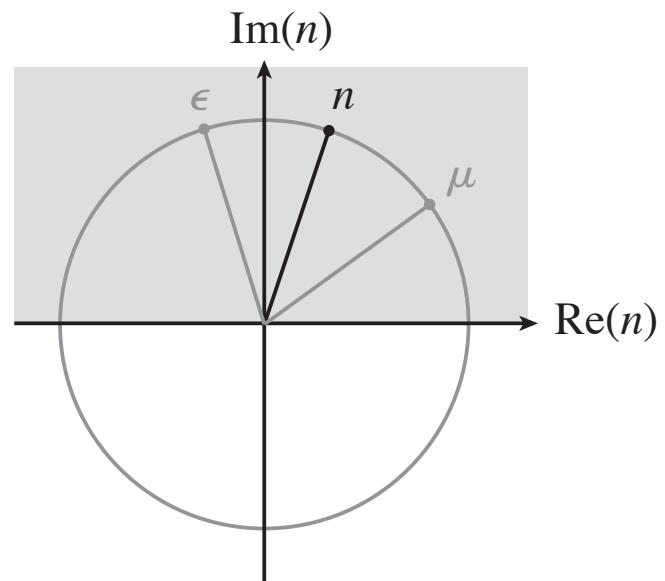
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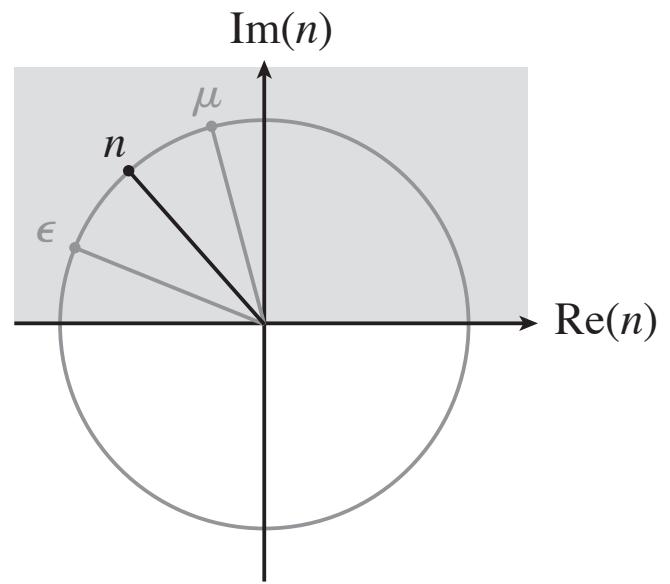
To find n (passive materials):

1. Draw line that bisects ϵ and μ
2. Choose upper branch



What happens when $\text{Re}\varepsilon$ and/or $\text{Re}\mu$ is negative?

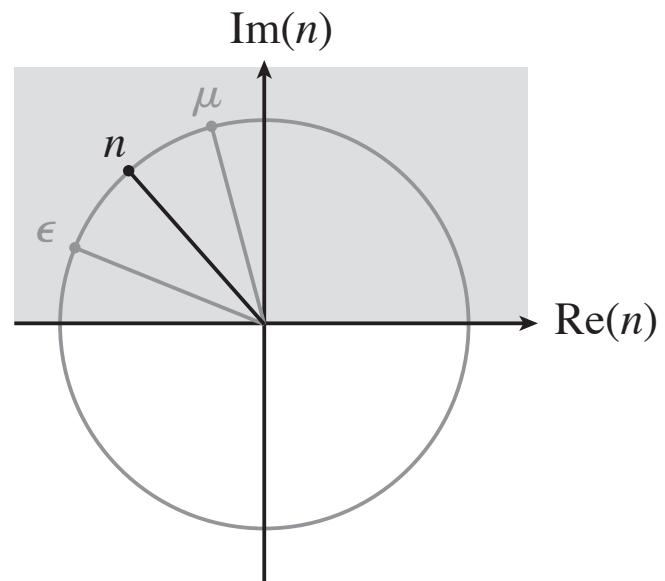
**For certain values of ε and μ
we can get a *negative* $\text{Re}(n)$!**



Q: Must both $\operatorname{Re}\varepsilon < 0$ and $\operatorname{Re}\mu < 0$

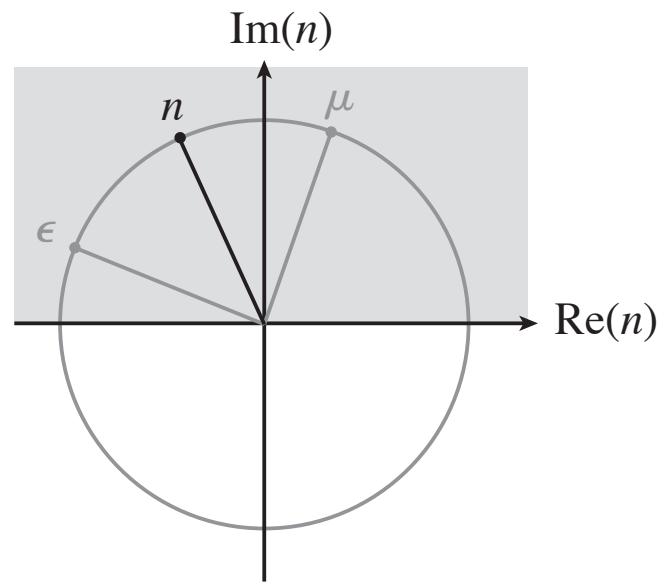
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- 1. yes**
- 2. no**

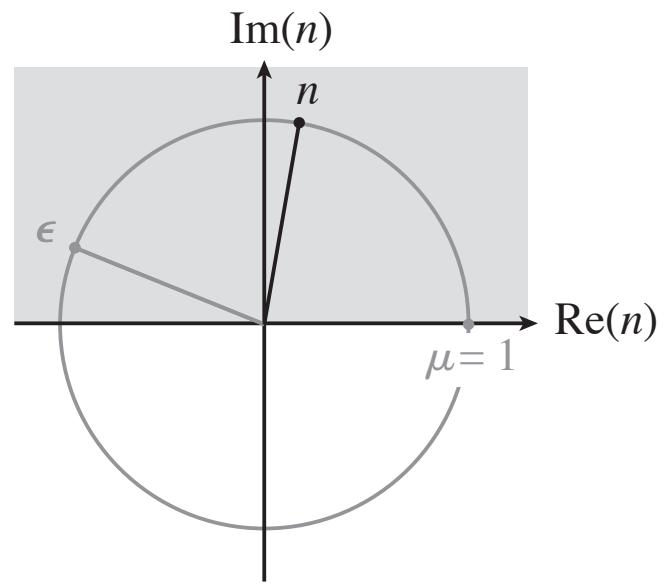


Q: Must both $\operatorname{Re}\epsilon < 0$ and $\operatorname{Re}\mu < 0$ to get a negative $\operatorname{Re}(n)$?

1. yes
2. no ✓



**However, need magnetic response
to achieve $\text{Re}(n) \leq 0$!**



What happens when $\text{Re}(n) < 0$?

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Remember

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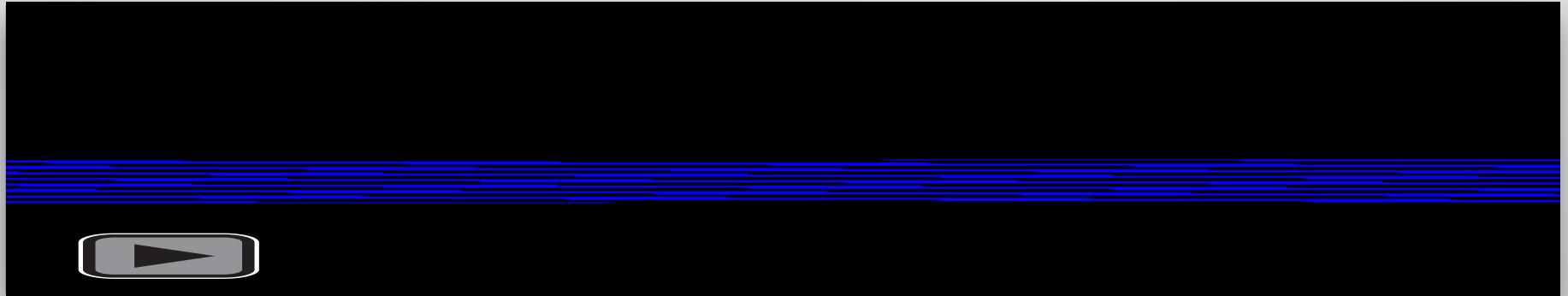
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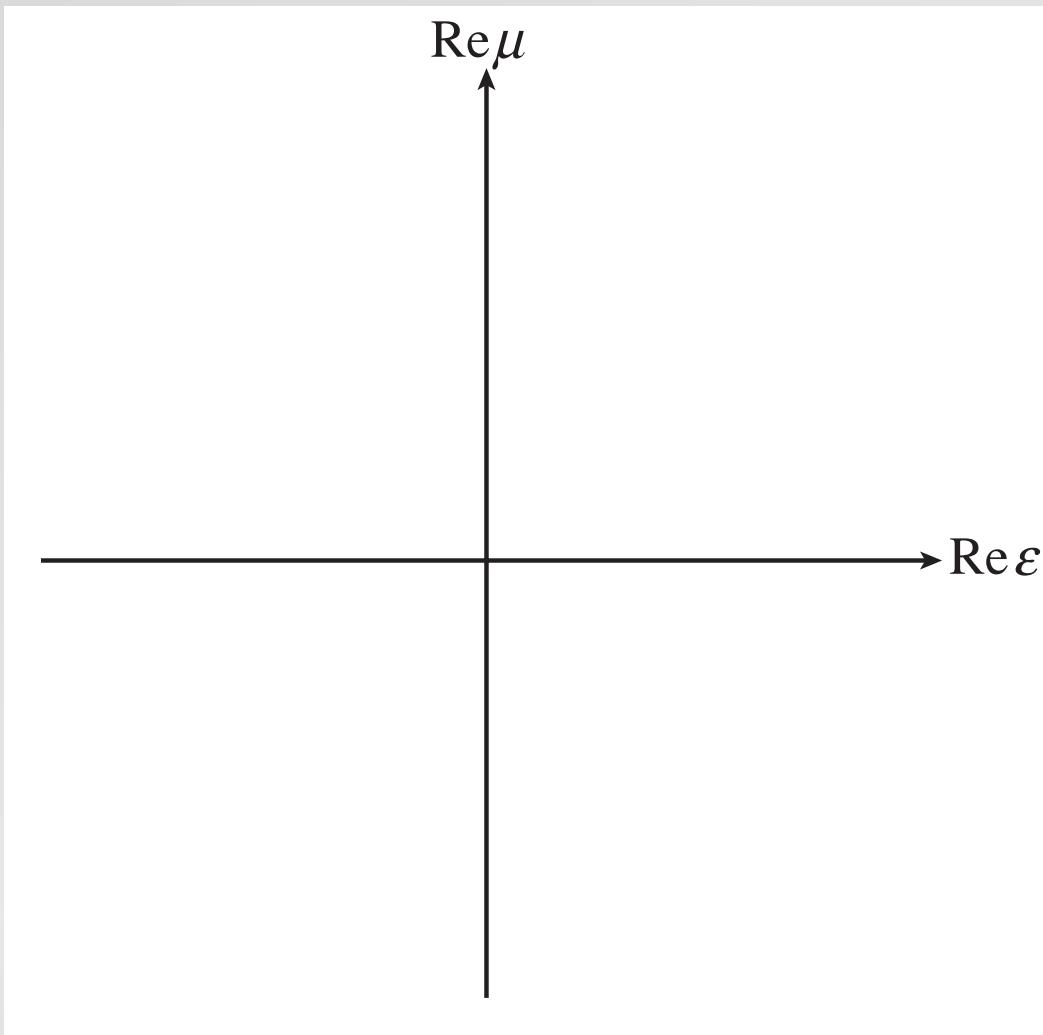
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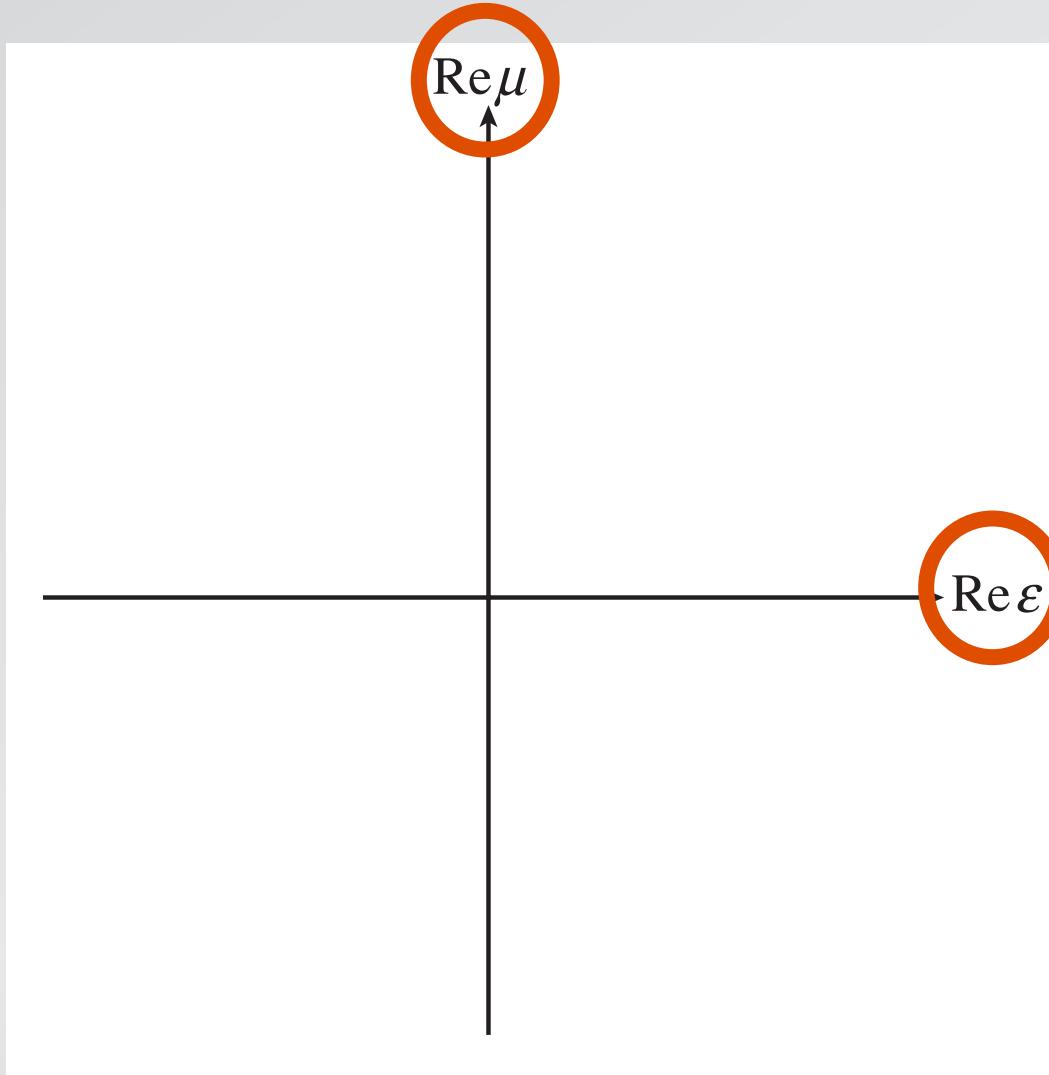


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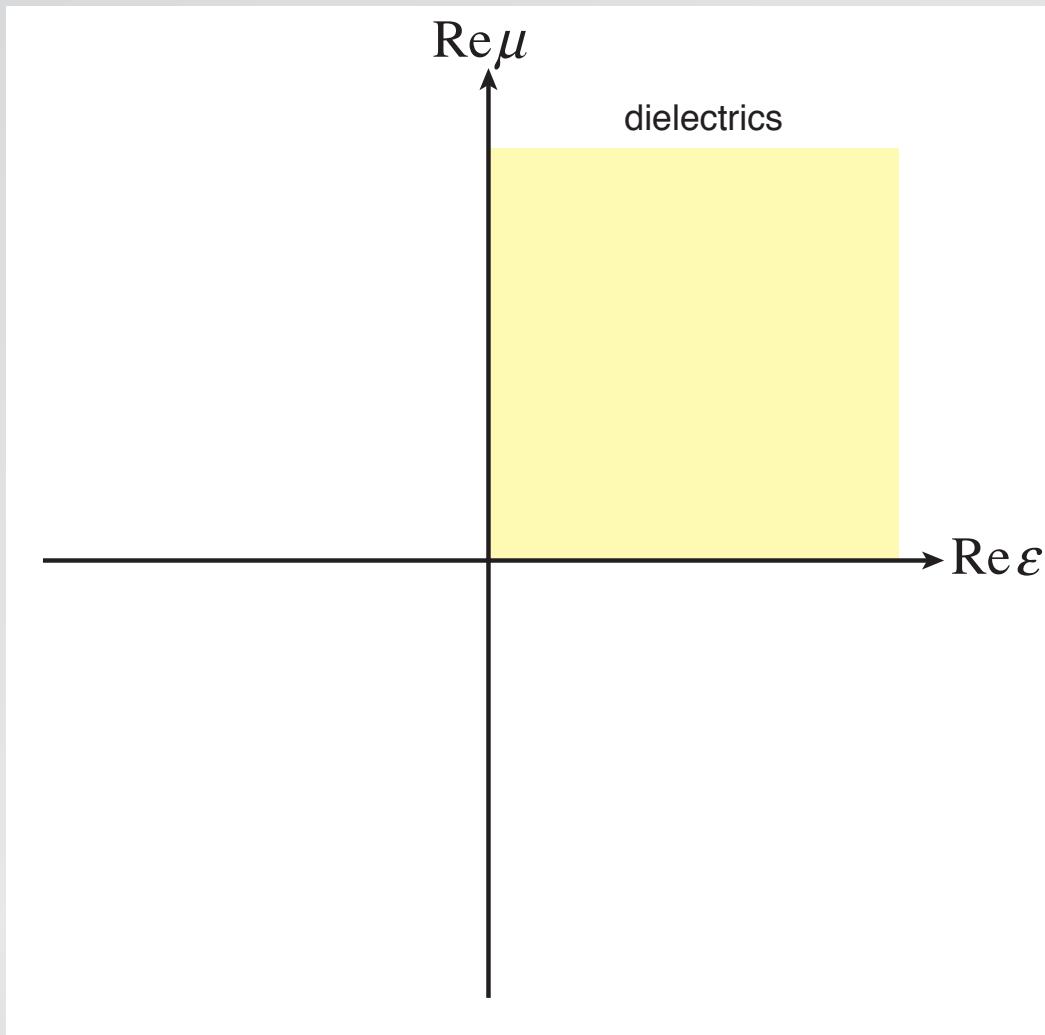
classification of (non-lossy) materials



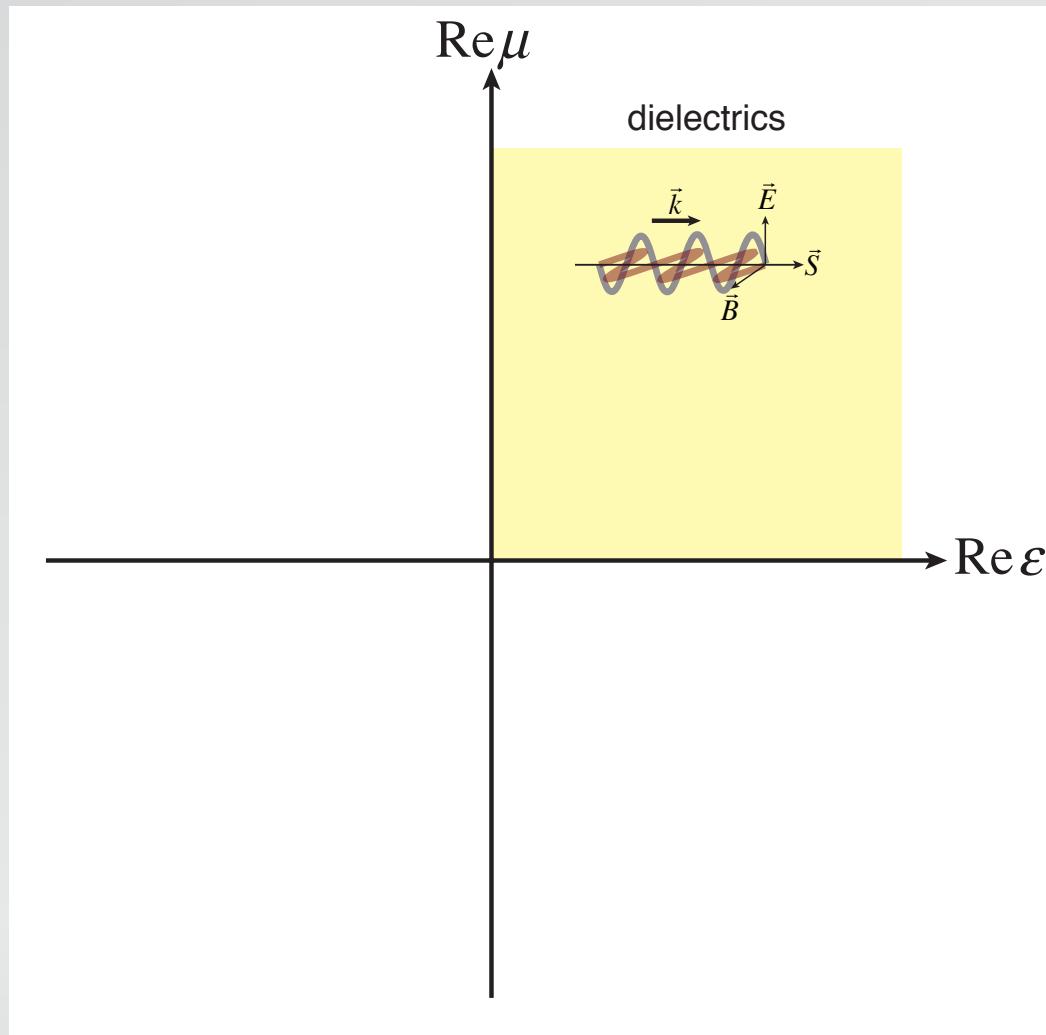
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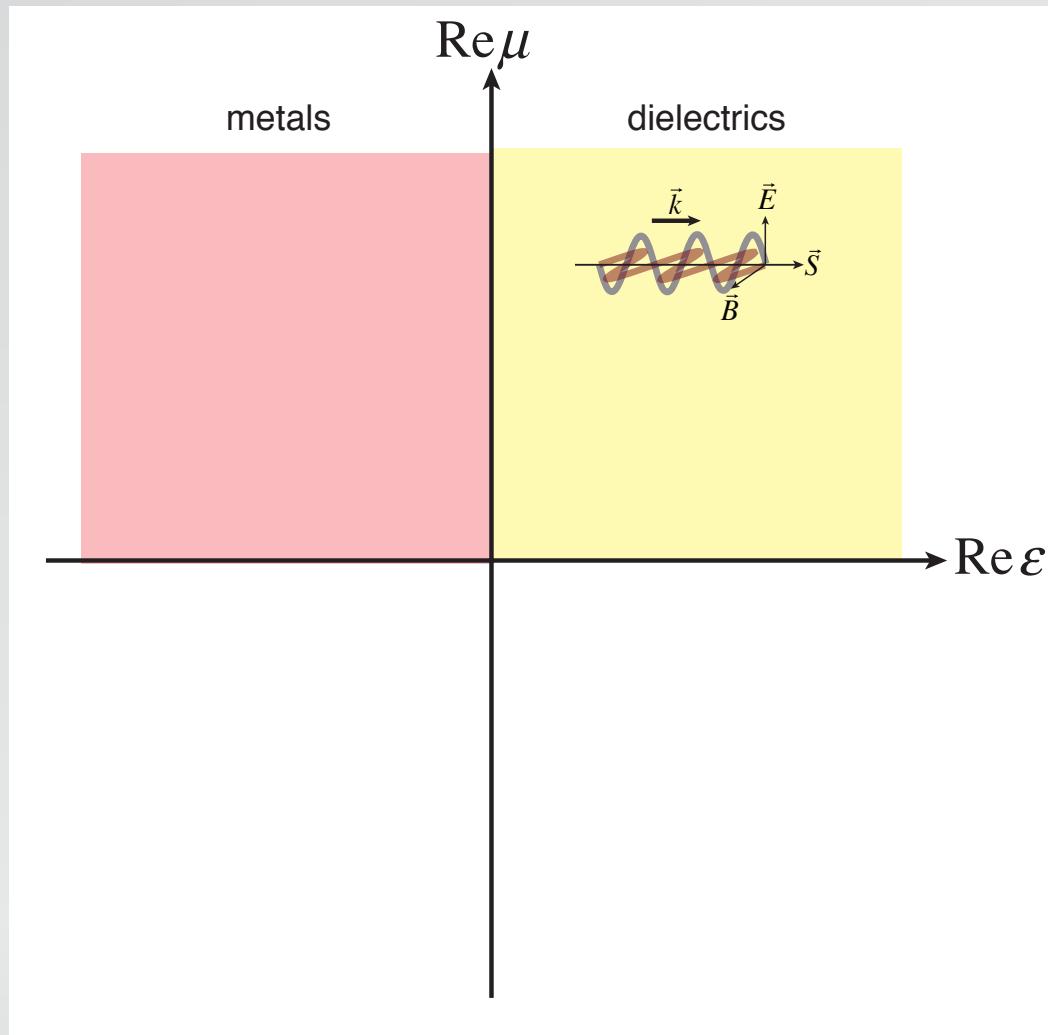
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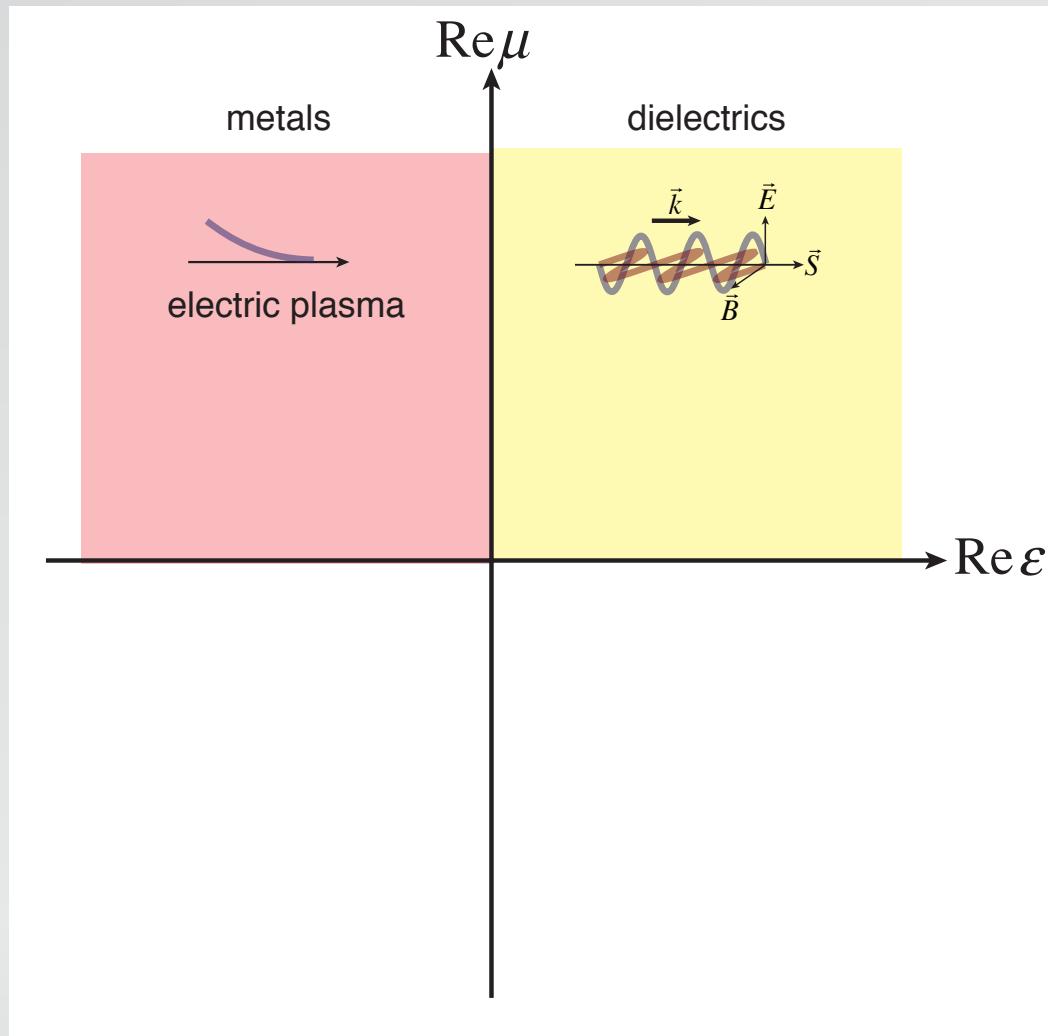
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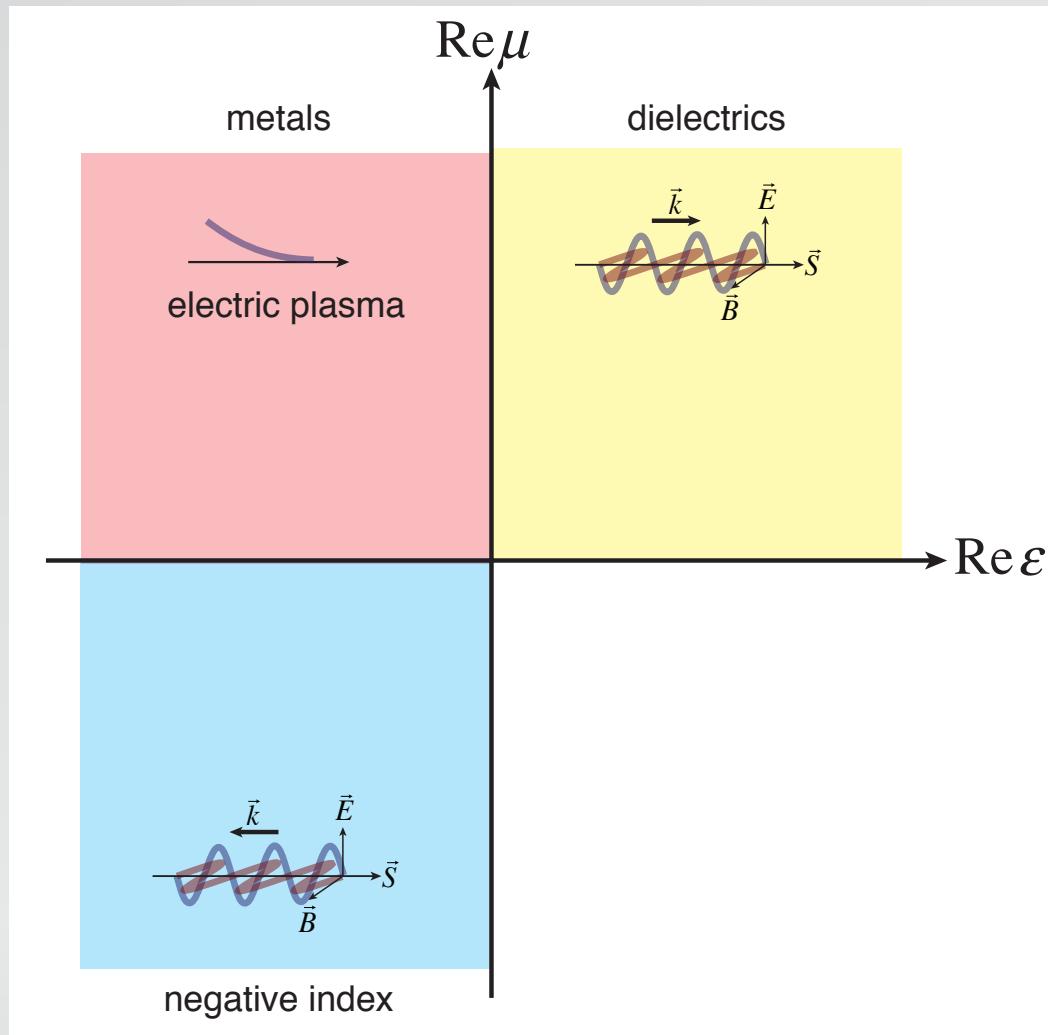
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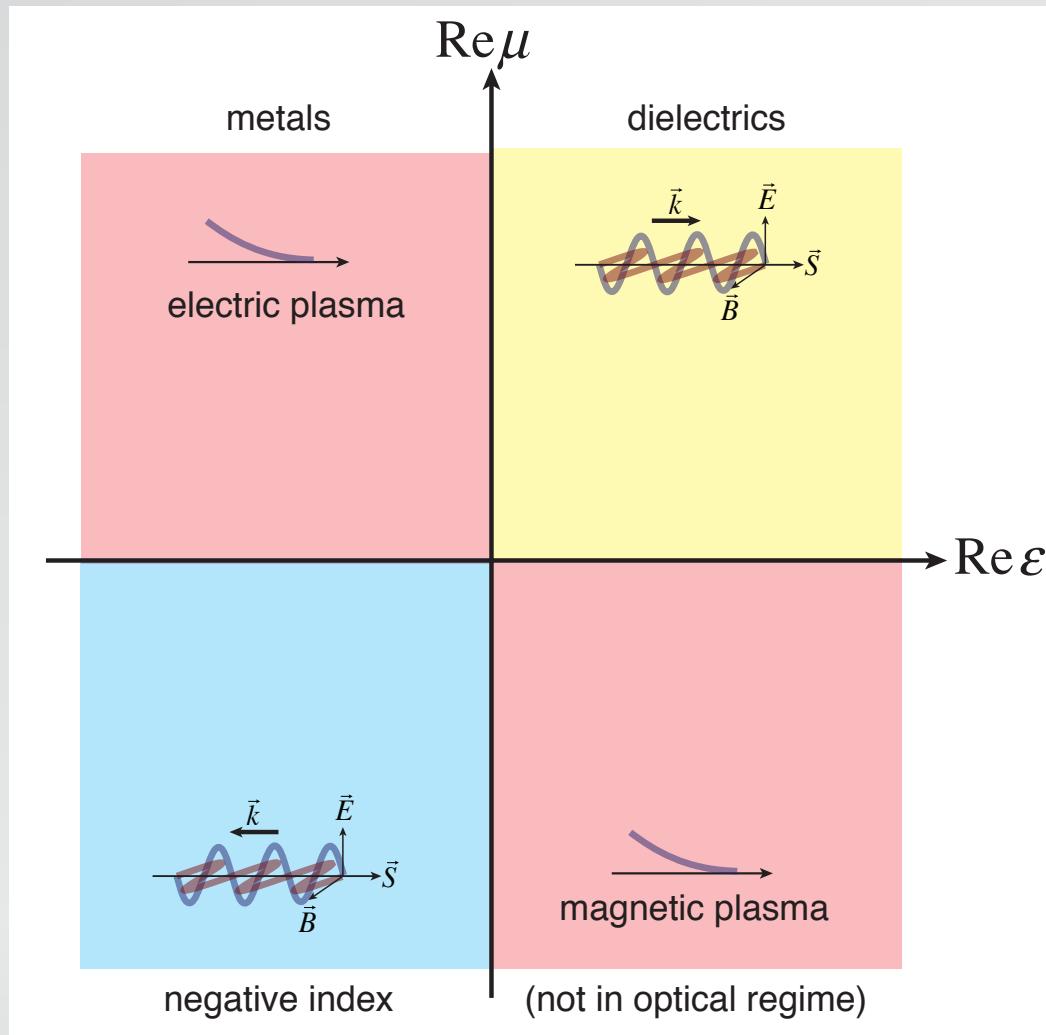
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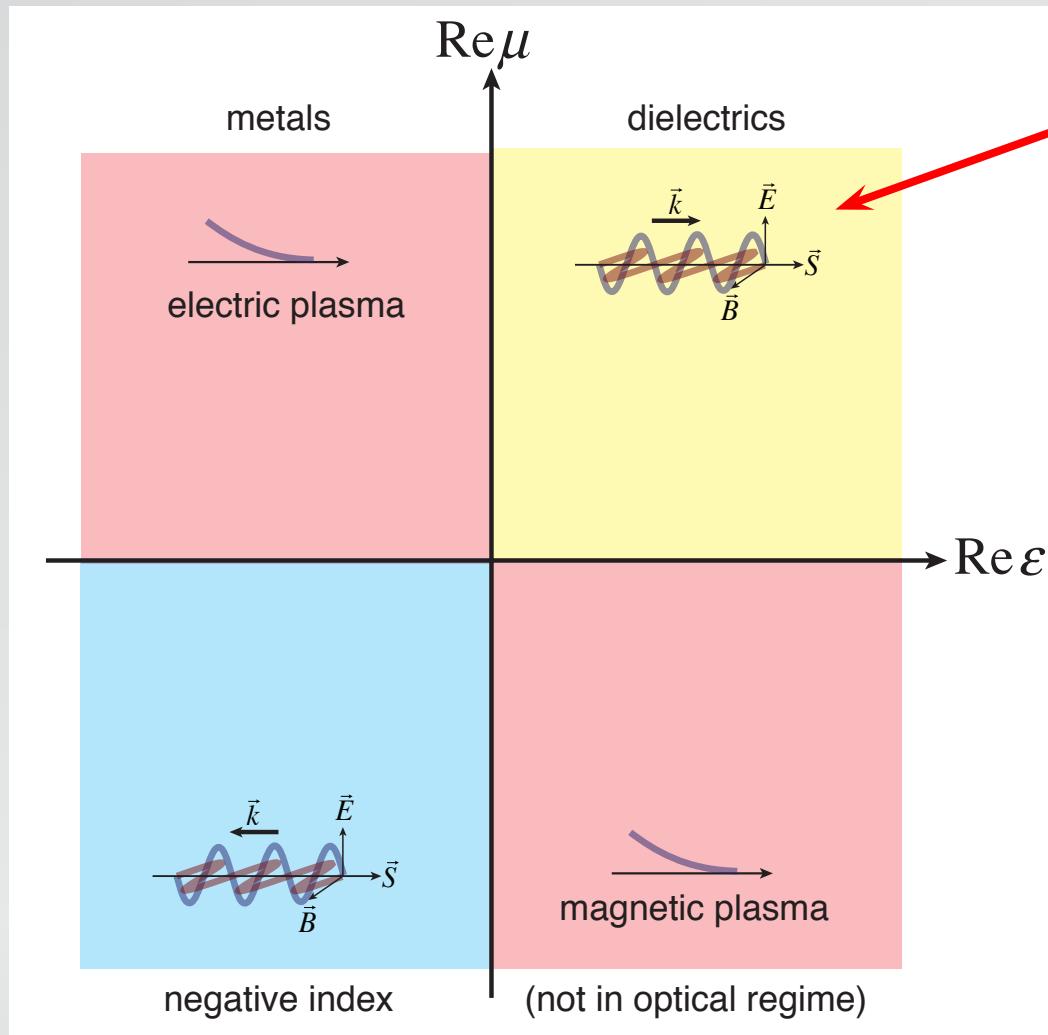
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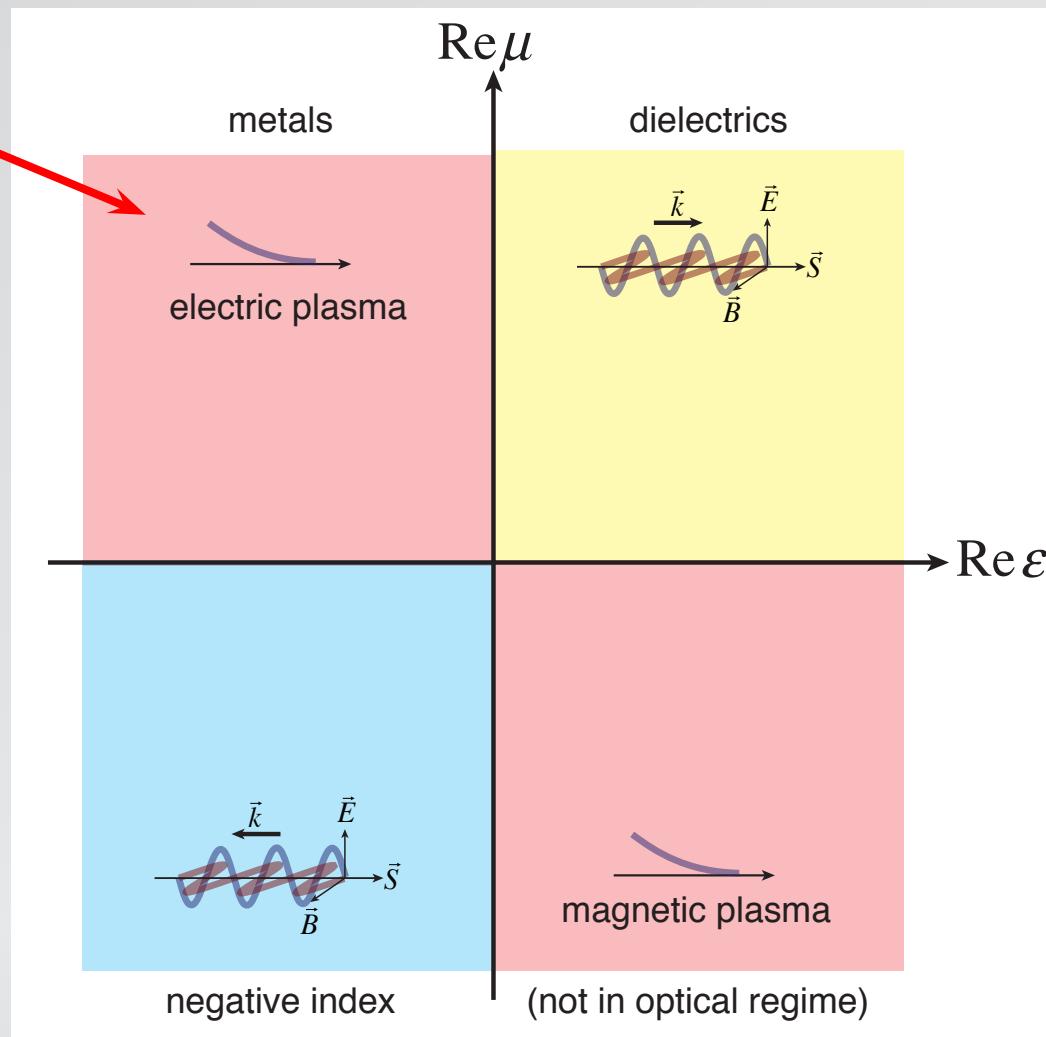
classification of (non-lossy) materials



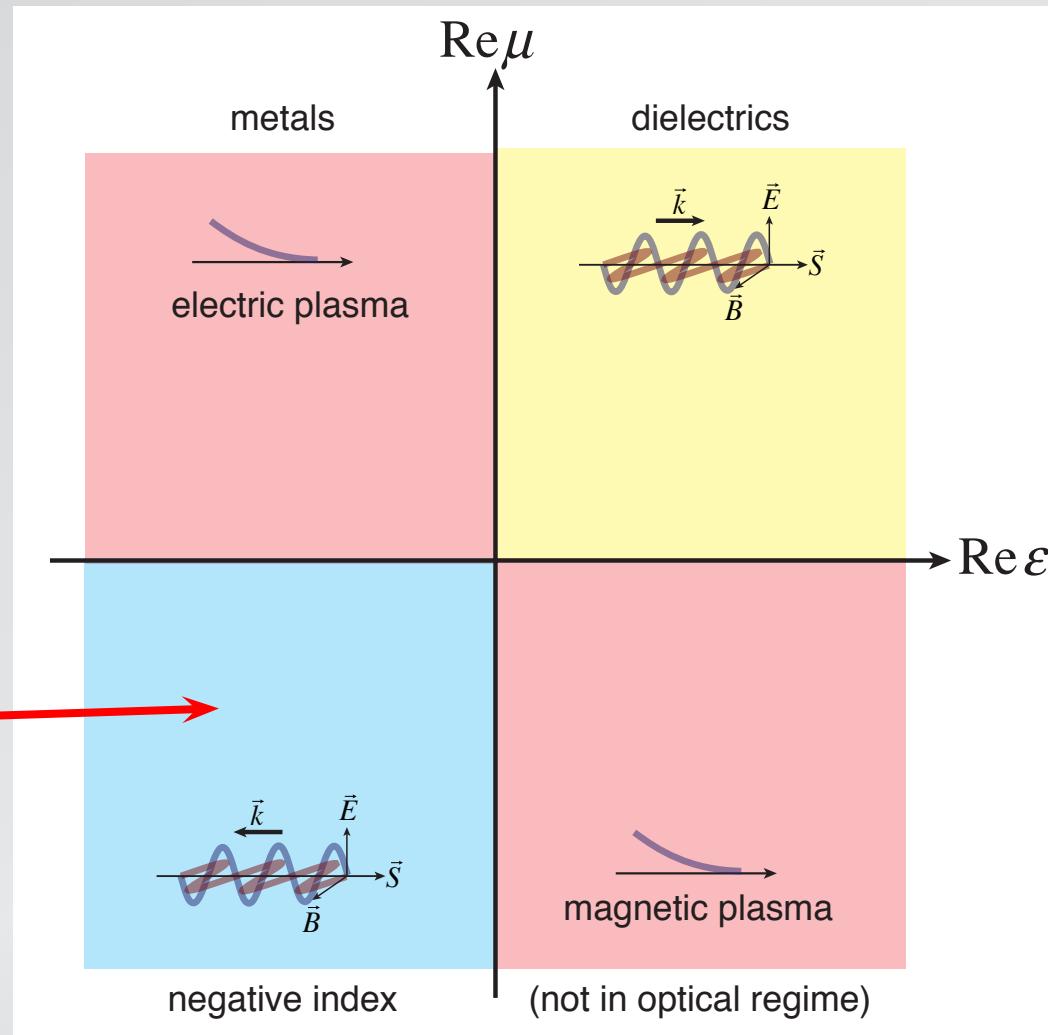
limited by
diffraction

classification of (non-lossy) materials

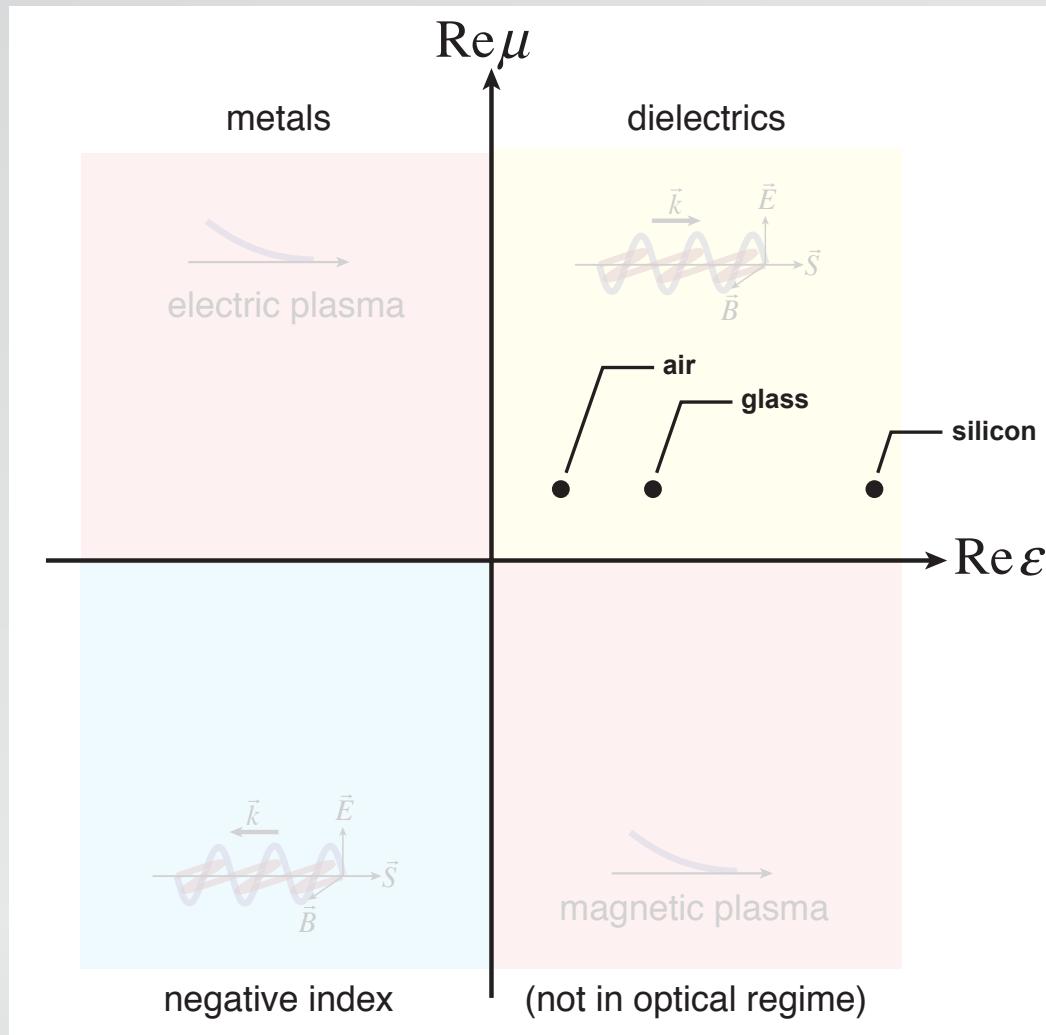
no propagation



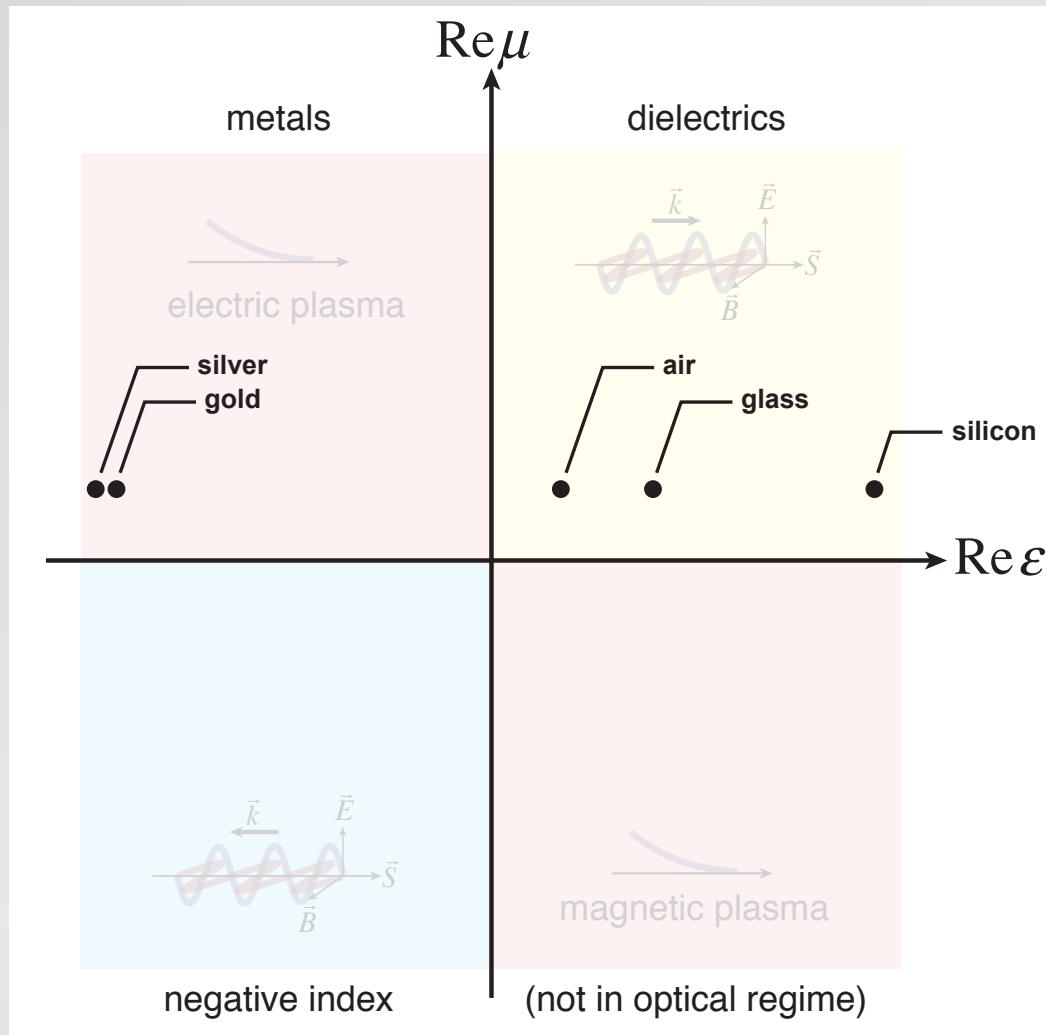
classification of (non-lossy) materials



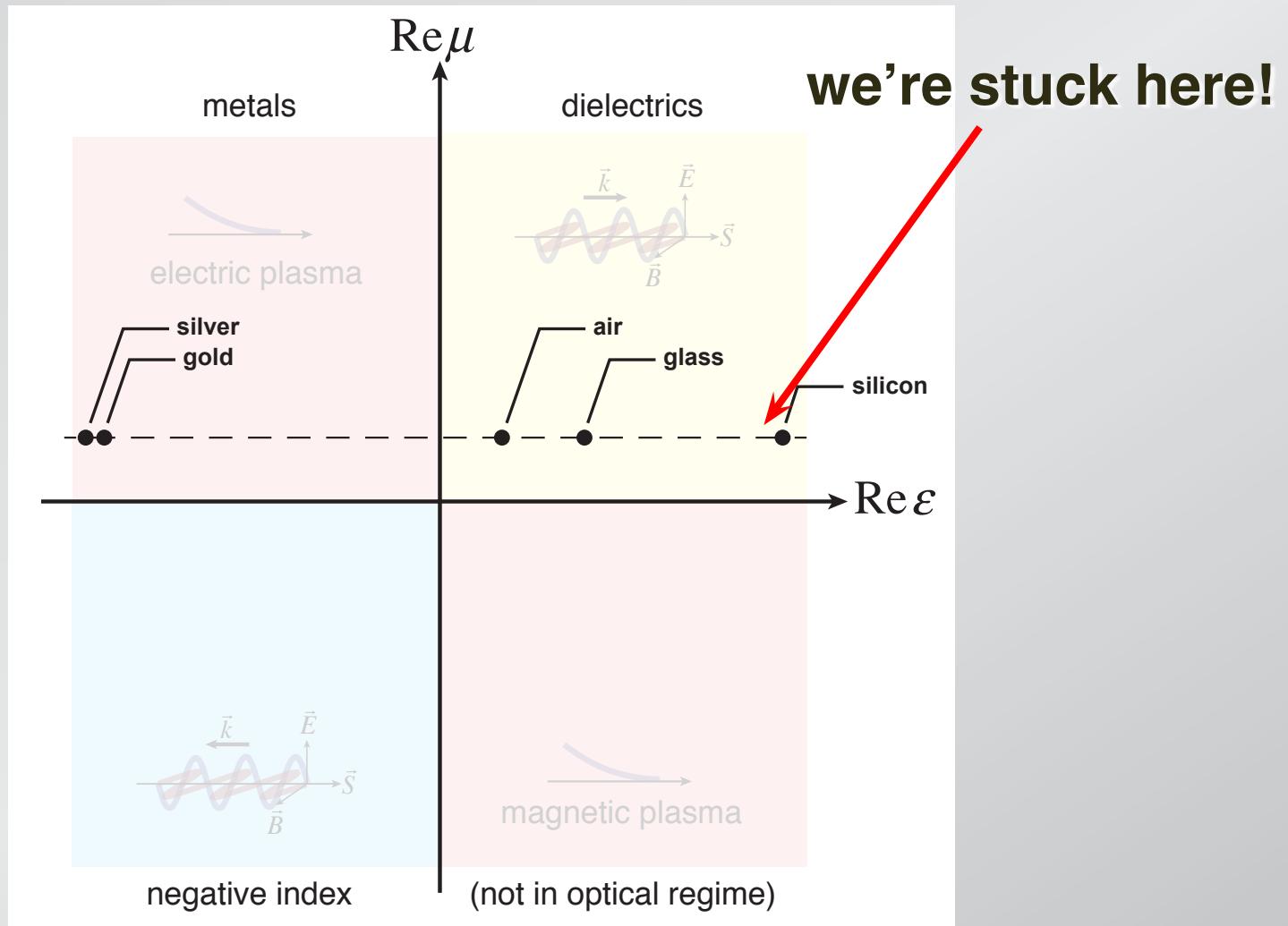
common materials very limited



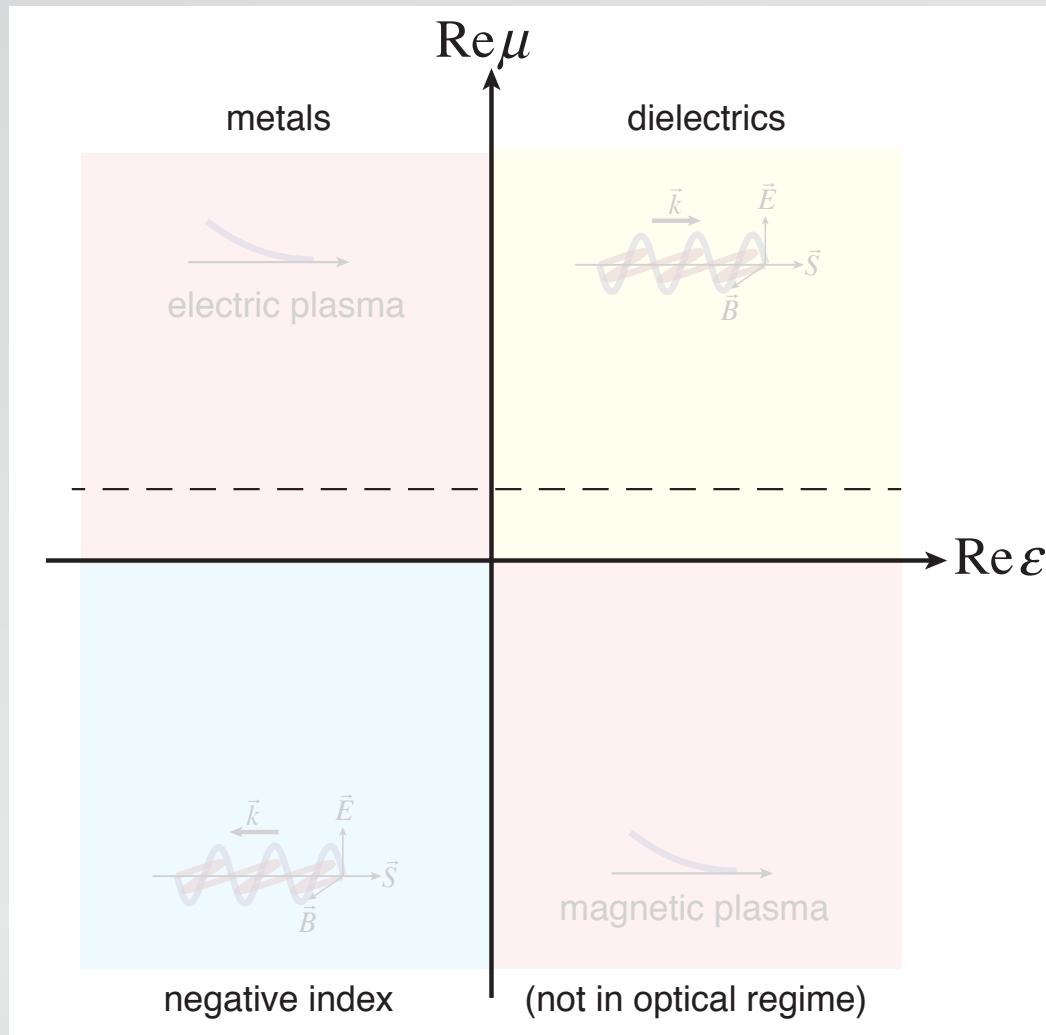
common materials very limited



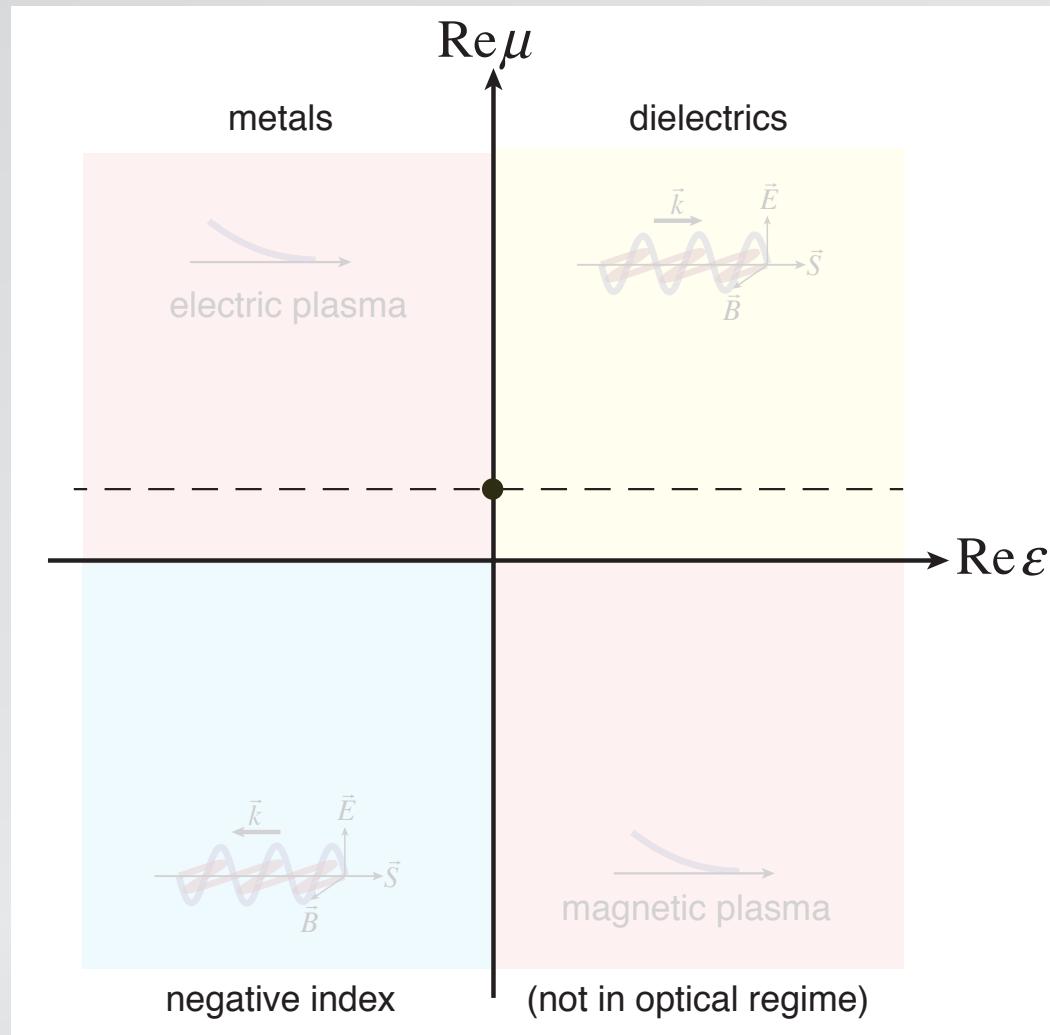
common materials very limited



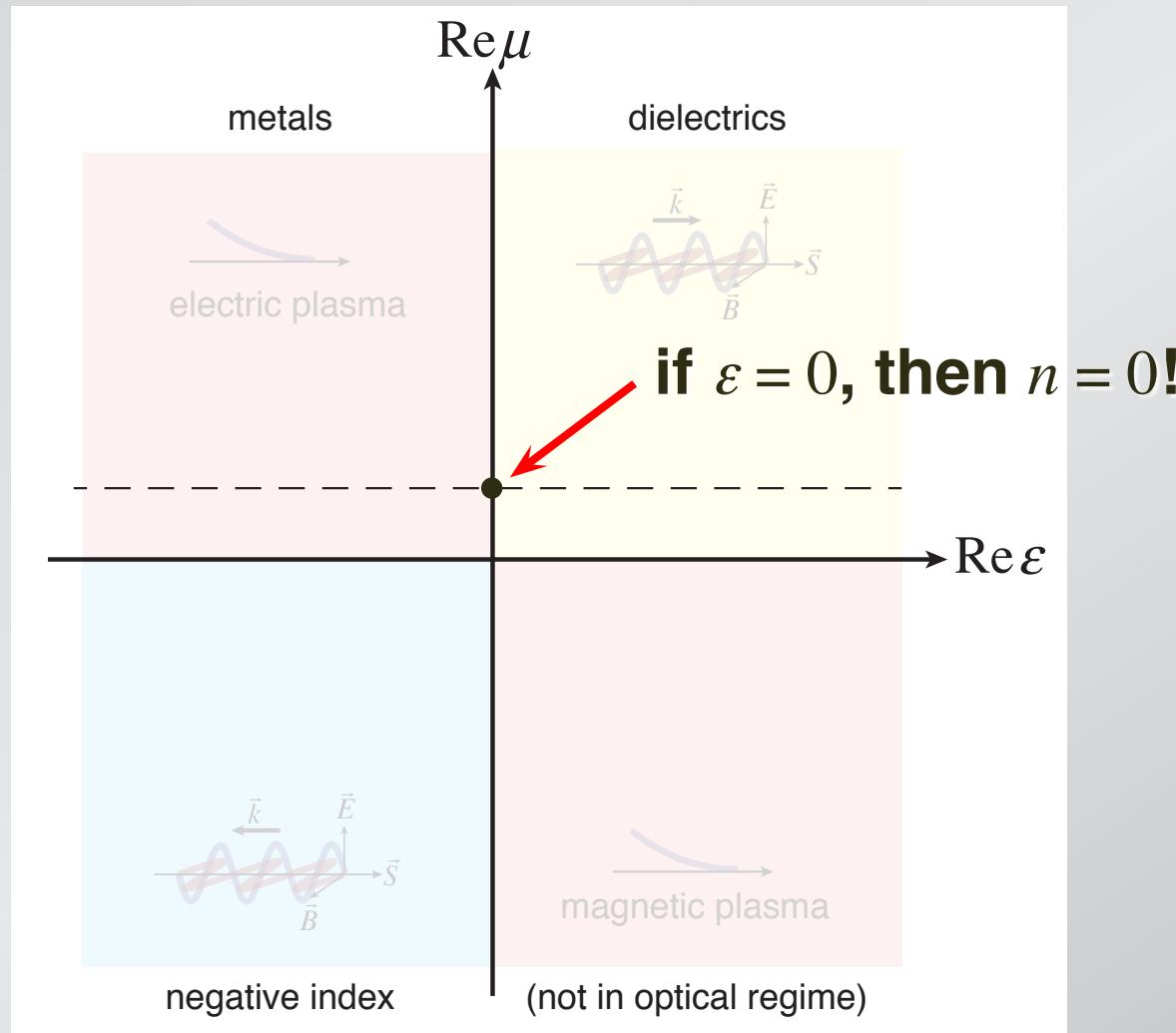
What happens on the axes?



what if we let $\varepsilon = 0$?



what if we let $\varepsilon = 0$?



1 index

2 zero index

Q: If $n = 0$, which of the following is true?

- 1. the frequency goes to zero.**
- 2. the phase velocity becomes infinite.**
- 3. both of the above.**
- 4. neither of the above.**

1 index

2 zero index

wave equation

$$\nabla^2 \vec{E} - \frac{\mu\epsilon}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

solution

$$\vec{E} = \vec{E}_o e^{i(kx - \omega t)}$$

where

$$\frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c$$

1 index

2 zero index

wave equation

$$\nabla^2 \vec{E} - \frac{\mu \epsilon \omega^2 \vec{E}}{c^2 n^2} = 0$$

solution

$$\vec{E} = \vec{E}_o e^{i(kx - \omega t)}$$

where

$$\frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c$$

1 index

2 zero index

wave equation

$$\nabla^2 \vec{E} - \frac{\mu \epsilon \omega^2 \vec{E}}{c^2 n^2} = 0$$

solution

$$\vec{E} = \vec{E}_o e^{i(kx - \omega t)} \rightarrow \vec{E} = \vec{E}_o e^{-i\omega t}$$

where

$$\frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c$$

1 index

2 zero index

wave equation

$$\nabla^2 \vec{E} - \frac{\mu \epsilon \omega^2 \vec{E}}{c^2 n^2} = 0$$

solution

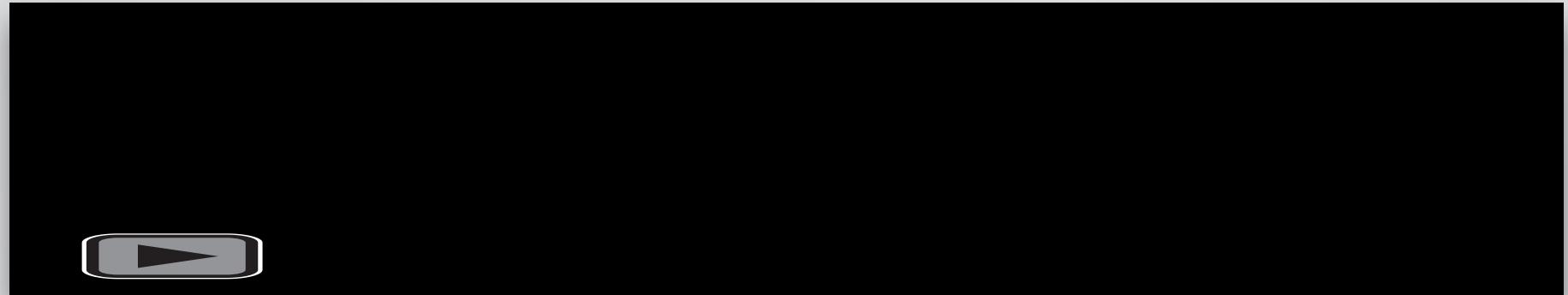
$$\vec{E} = \vec{E}_o e^{i(kx - \omega t)} \longrightarrow \vec{E} = \vec{E}_o e^{-i\omega t}$$

where

$$\frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c \longrightarrow \infty$$

① index

② zero index



1 index

2 zero index



“Superluminal”?!

1 index

2 zero index

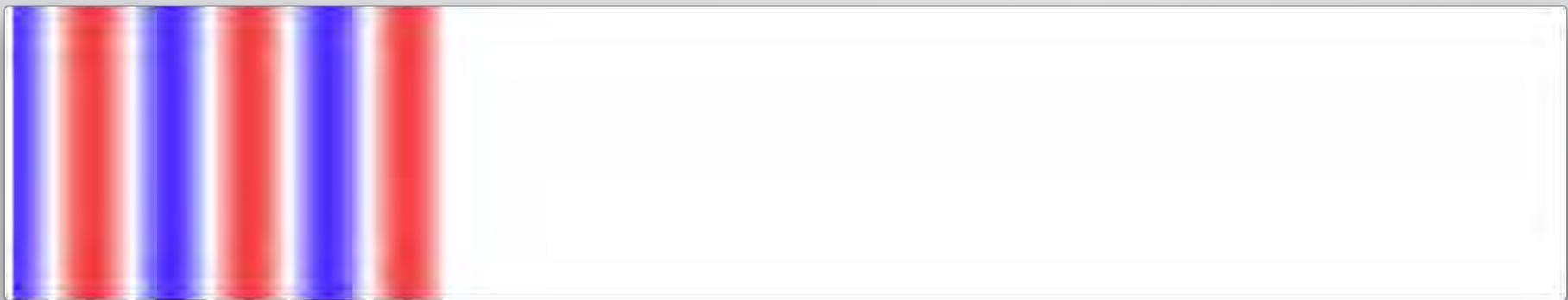
What about

WAVE PROPAGATION AND GROUP VELOCITY

LÉON BRILLOUIN

Member of the National Academy of Sciences

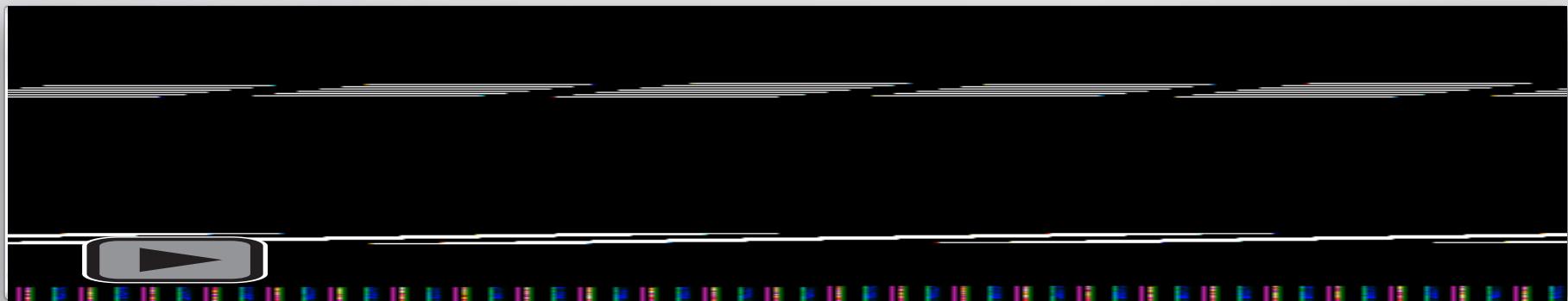
What about causality?



1 index

2 zero index

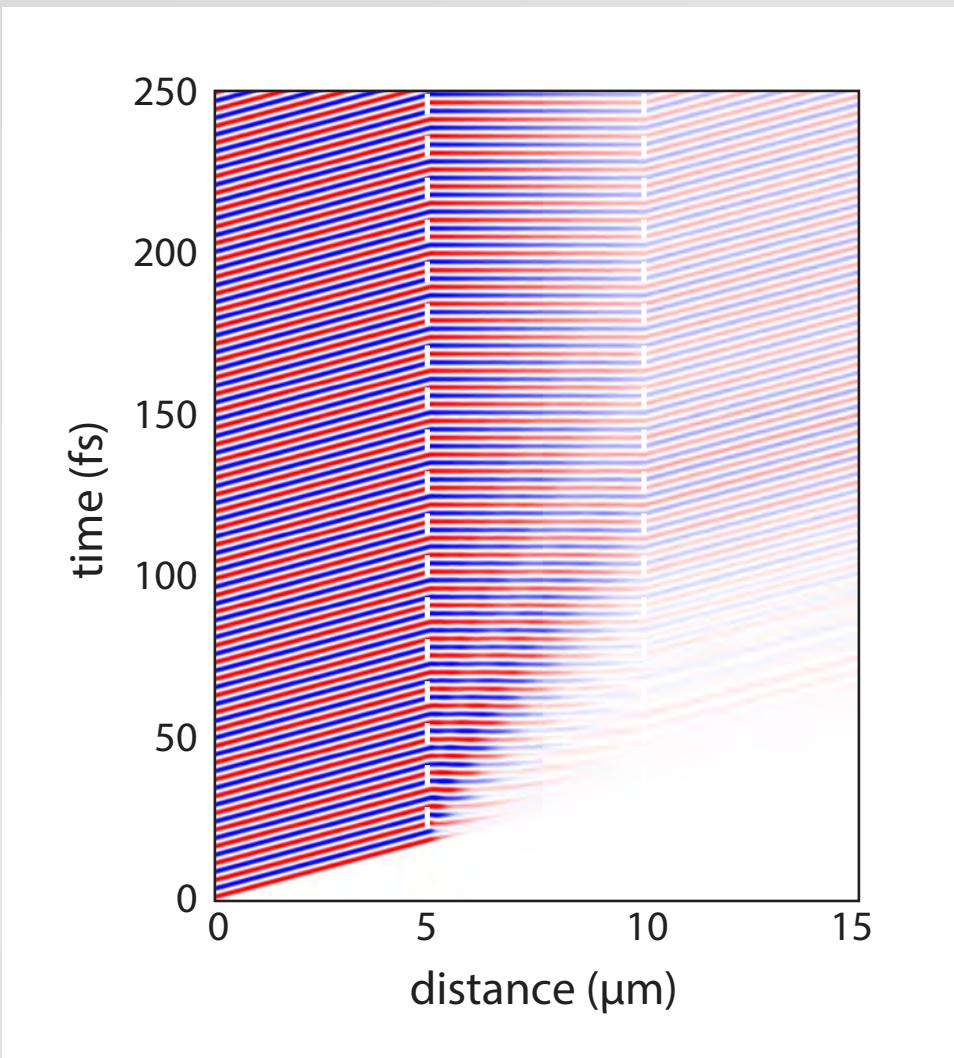
What about causality?



1 index

2 zero index

What about causality?

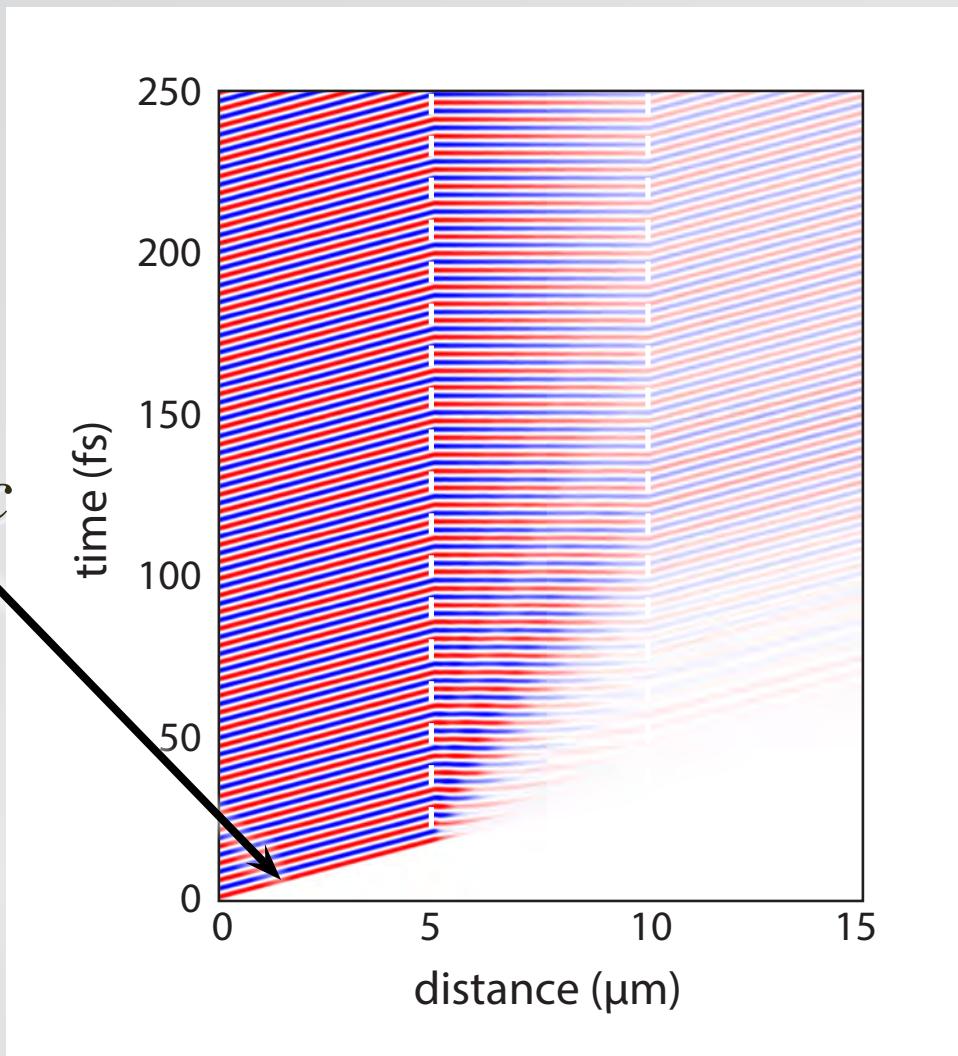


1 index

2 zero index

What about causality?

speed of light c

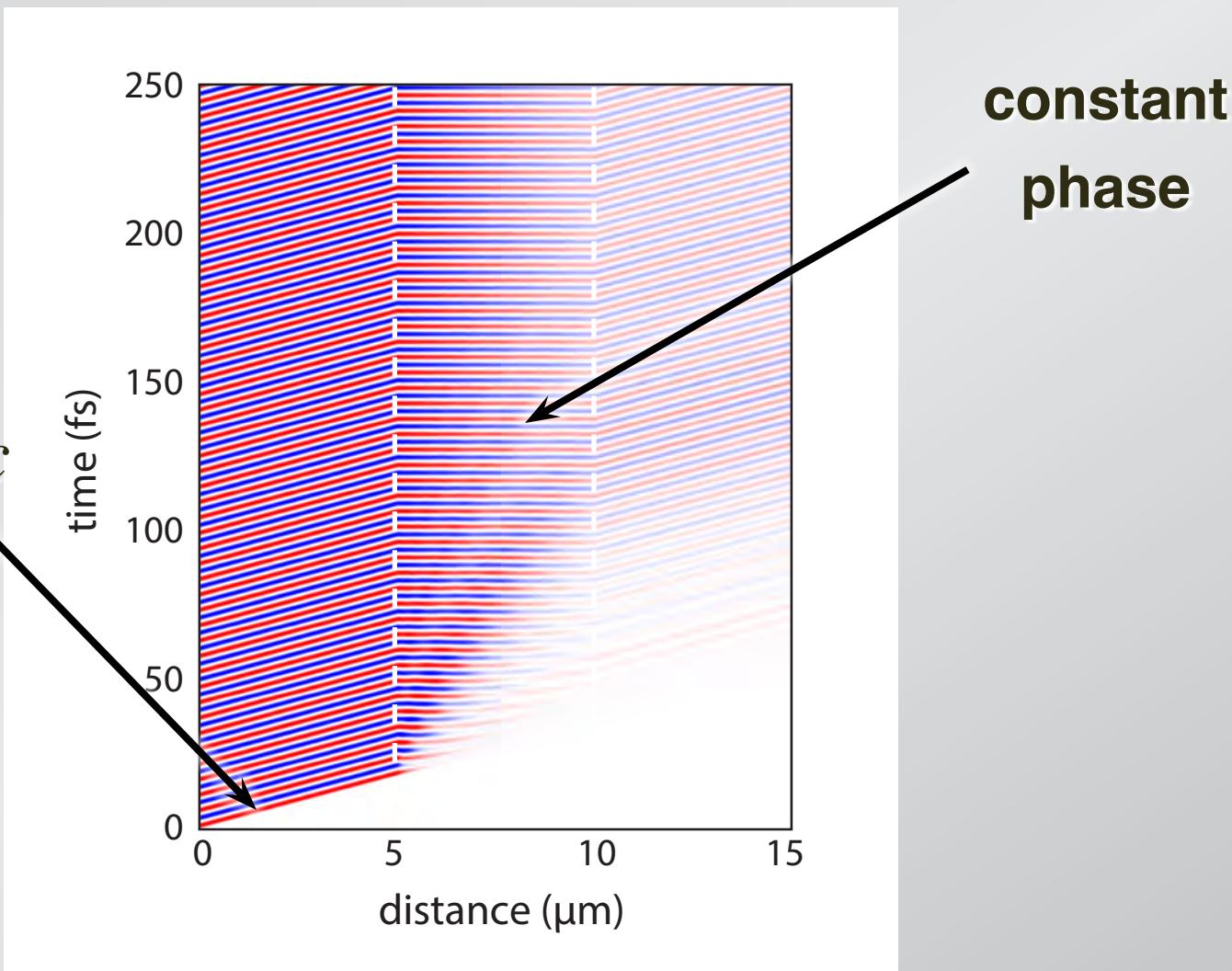


1 index

2 zero index

What about causality?

speed of light c



1 index

2 zero index

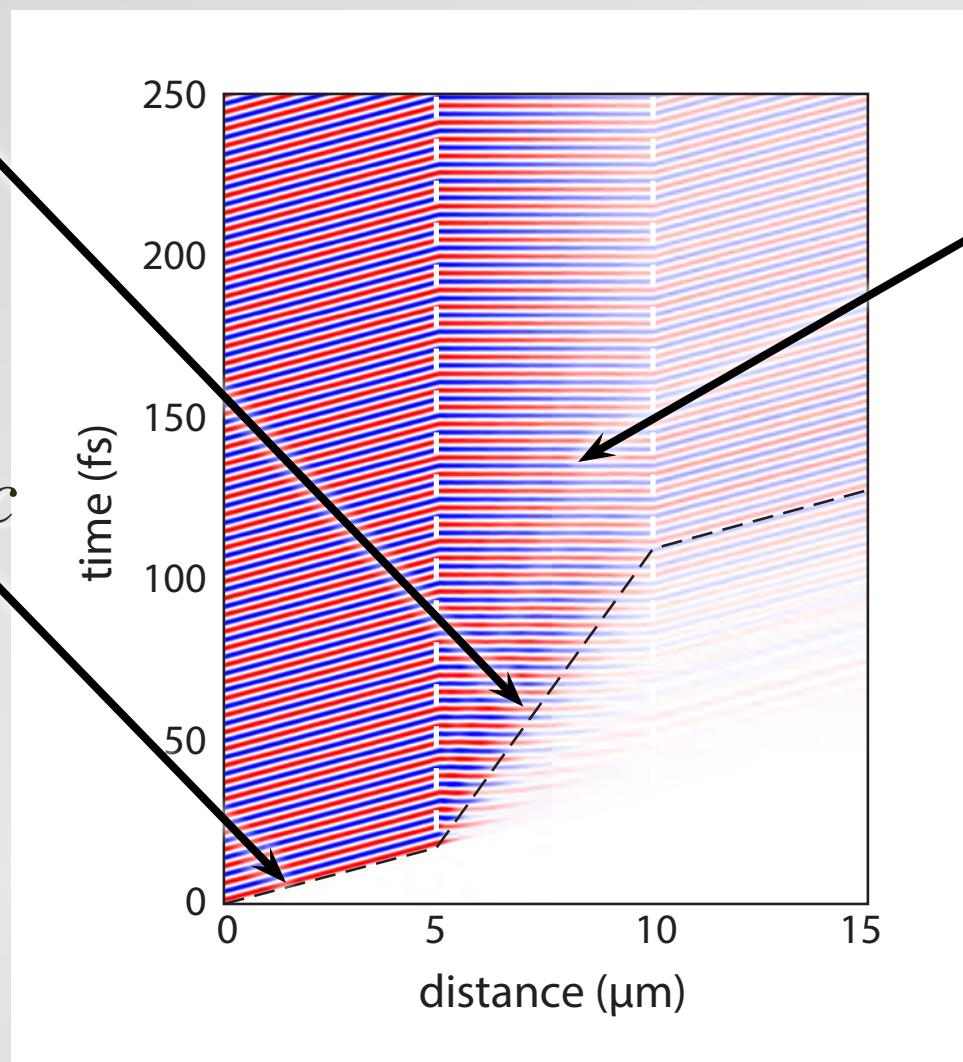
What about causality?

group velocity

$$v_g < c$$

speed of light c

constant phase



1 index

2 zero index

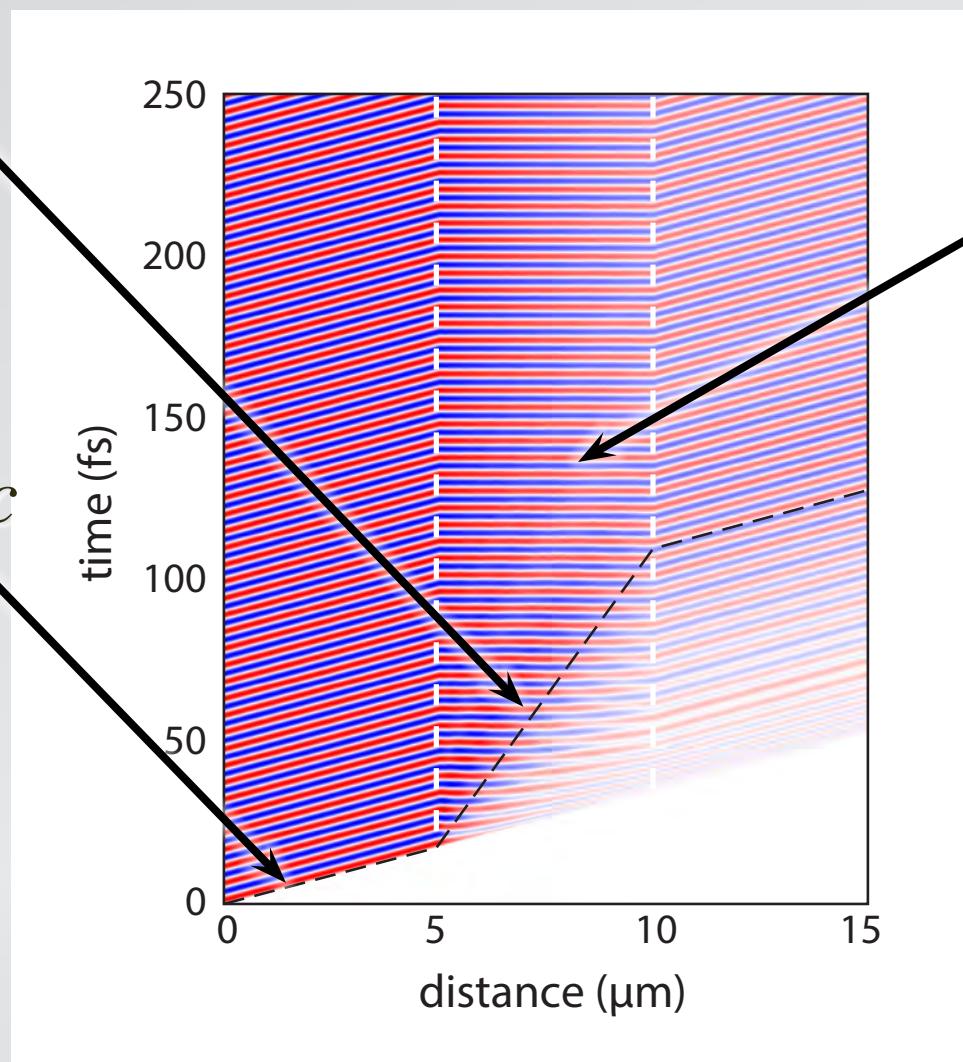
What about causality?

group velocity

$$v_g < c$$

speed of light c

constant phase



1 index

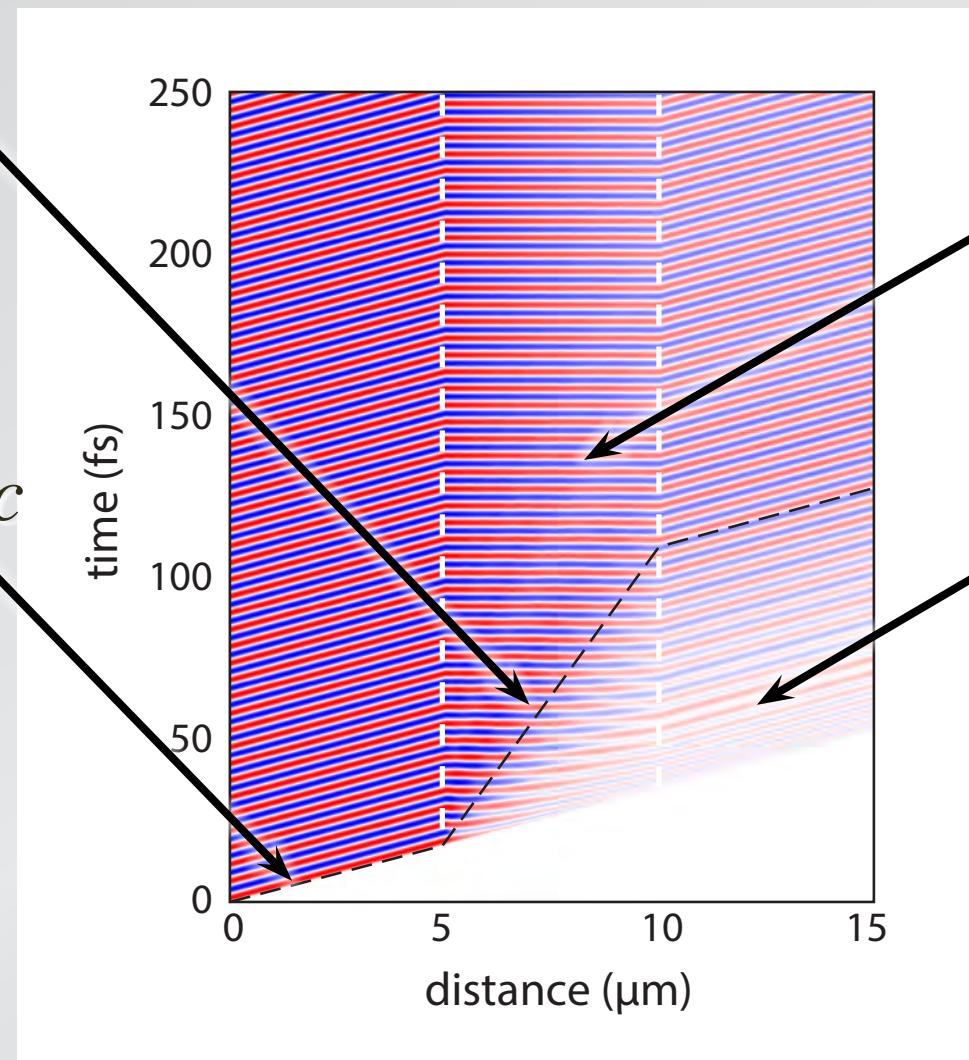
2 zero index

What about causality?

group velocity

$$v_g < c$$

speed of light c



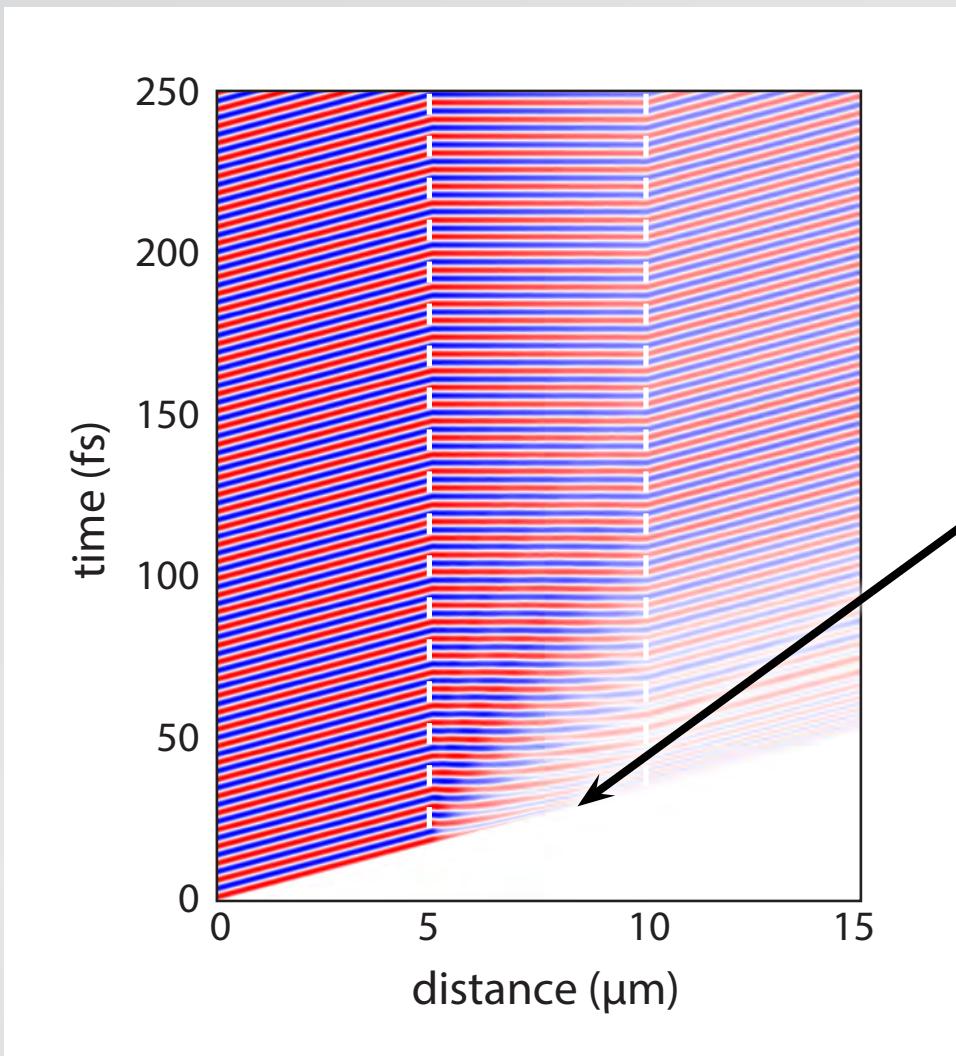
constant
phase

high-frequency
precursors

1 index

2 zero index

What about causality?

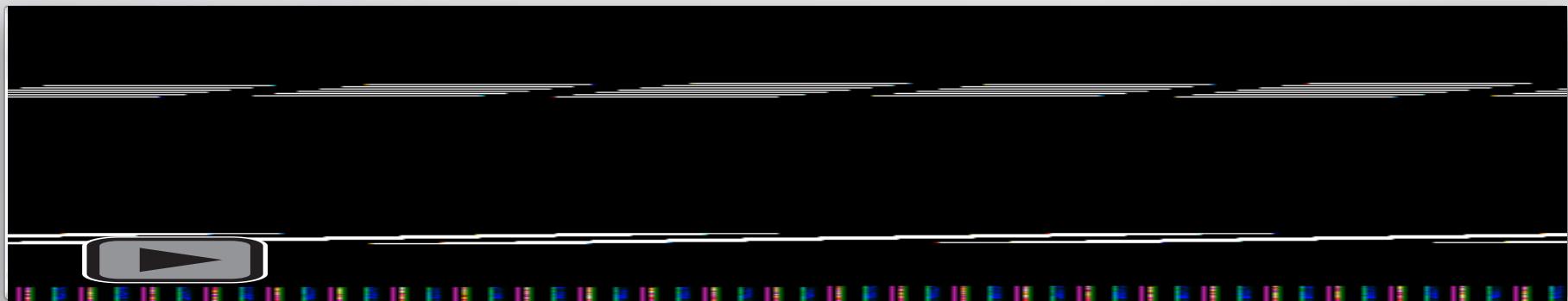


**signal *always*
travels at speed c !**

1 index

2 zero index

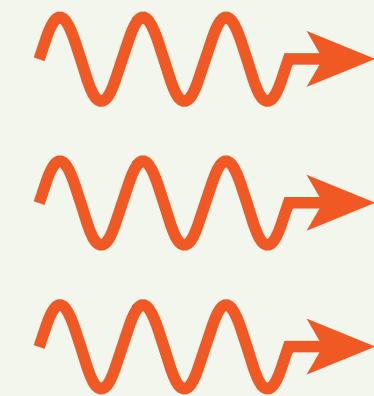
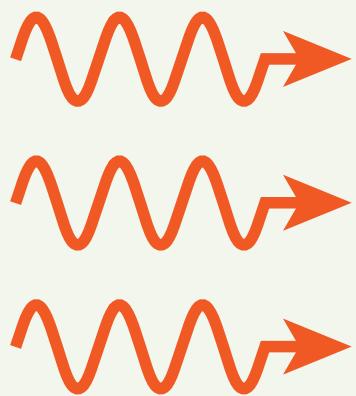
What about causality?



1 index

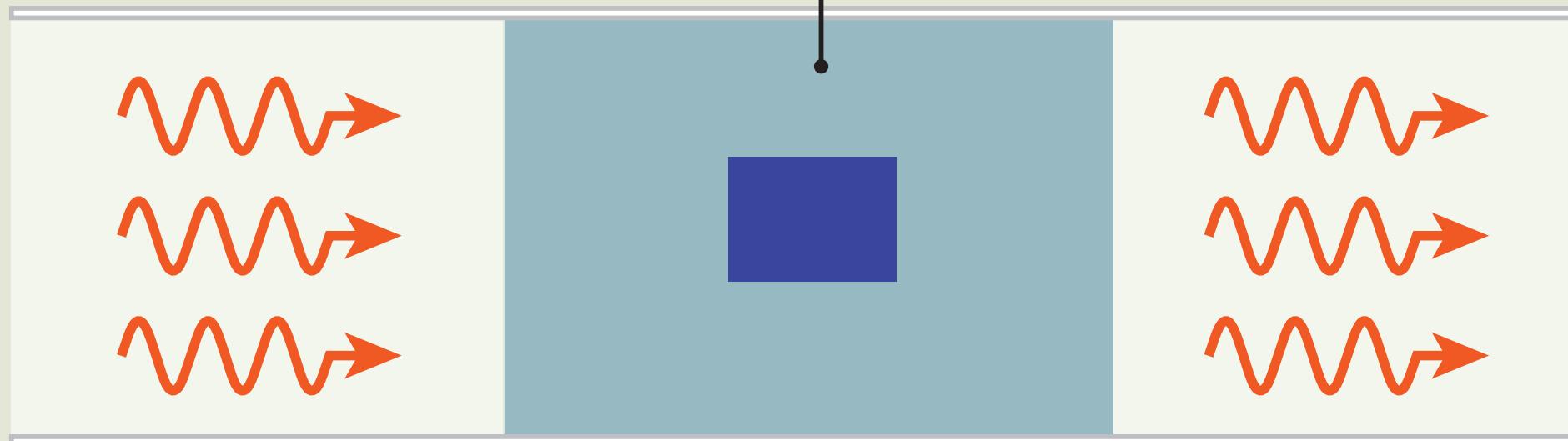
2 zero index

$n = 0$



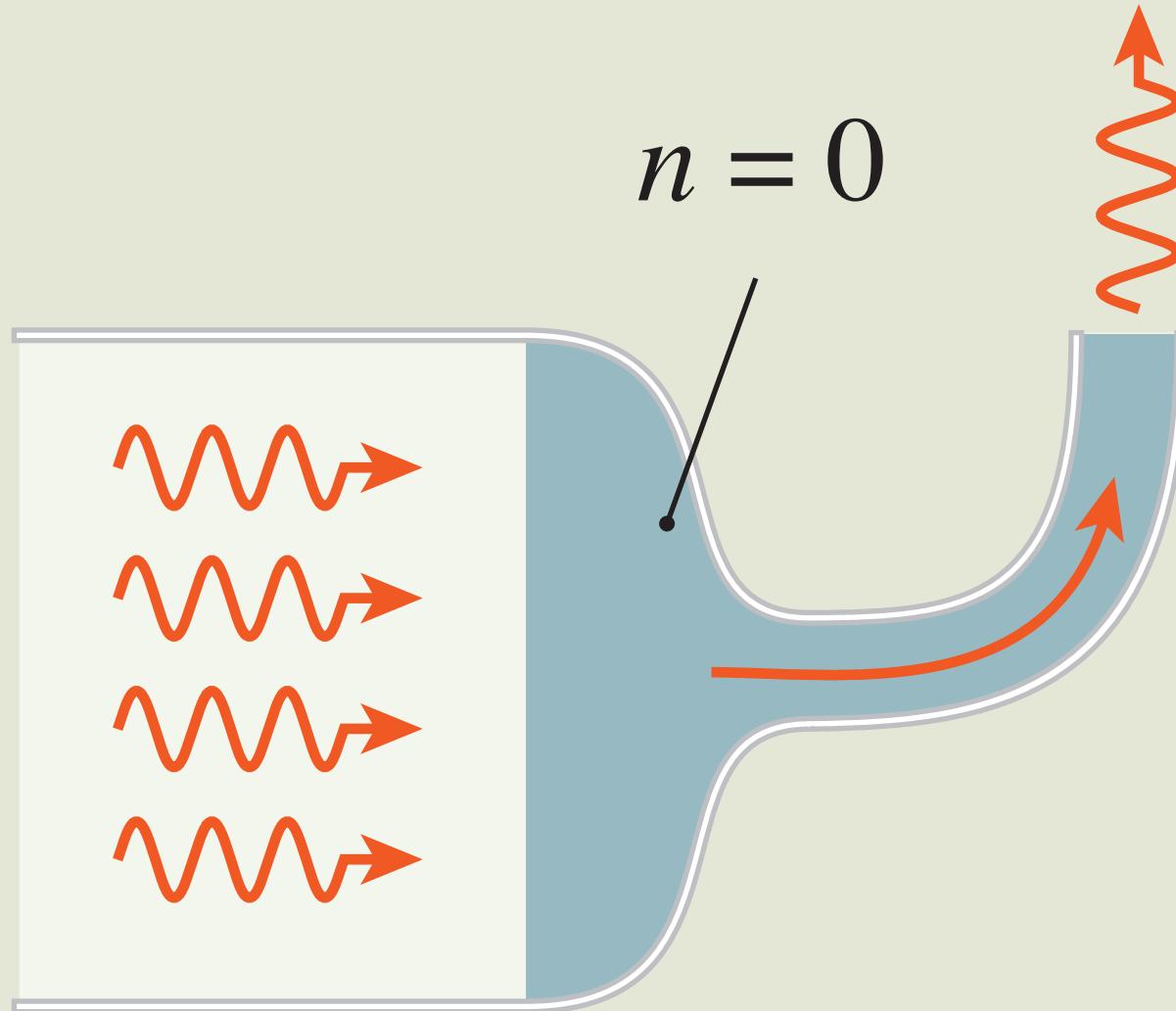
1 index

2 zero index

$n = 0$ 

1 index

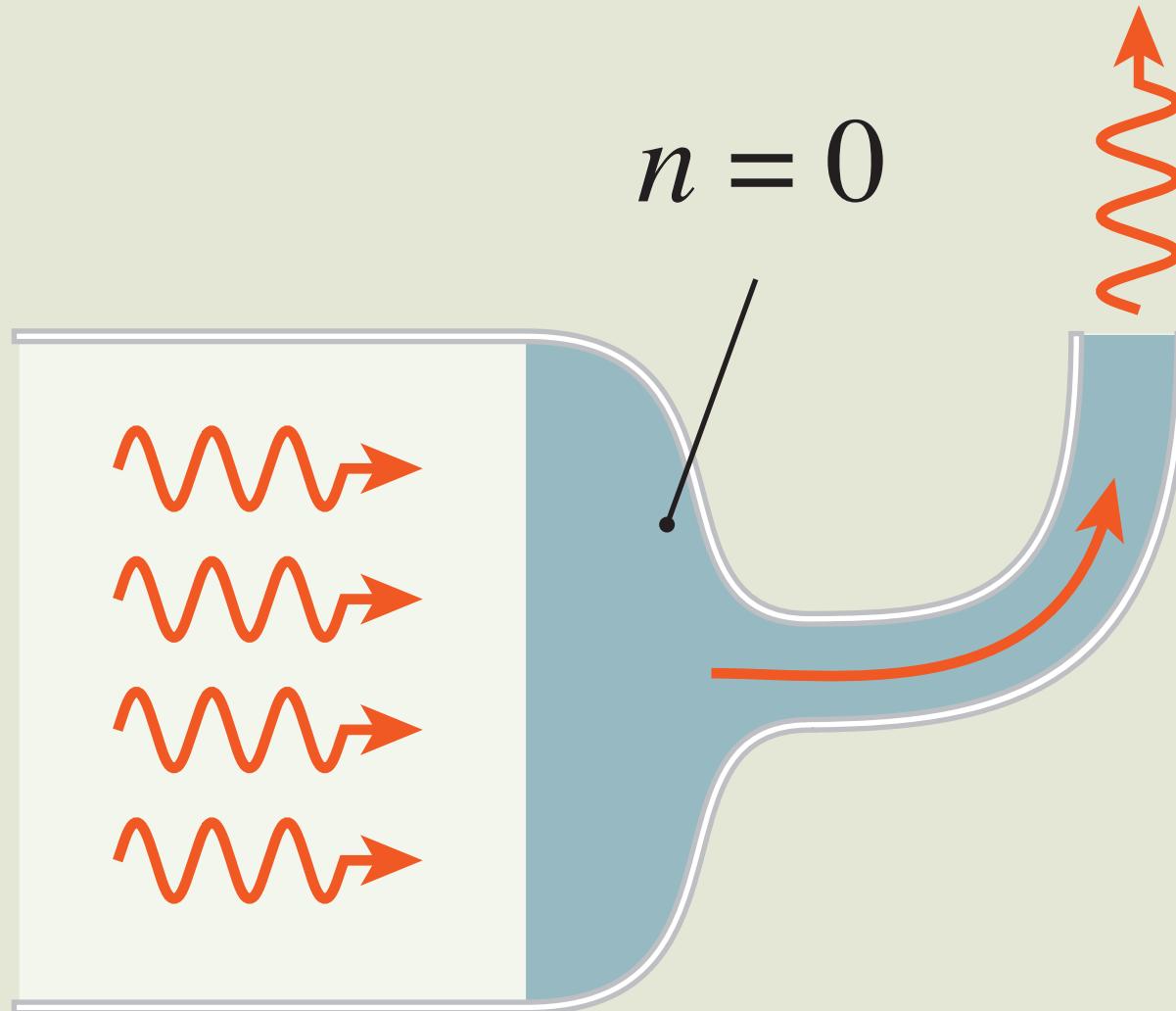
2 zero index



1 index

2 zero index

“tunneling with infinite decay length”



1 index

2 zero index

how?

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

but ϵ and μ also determine reflectivity

$$R = \frac{Z-1}{Z+1}$$

1 index

2 zero index

how?

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

but ϵ and μ also determine reflectivity

$$R = \frac{Z - 1}{Z + 1}$$

where

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

1 index

2 zero index

how?

$$\varepsilon, \mu \rightarrow 0$$

$$n = \sqrt{\varepsilon\mu} \rightarrow 0$$

but ε and μ also determine reflectivity

$$R = \frac{Z - 1}{Z + 1}$$

where

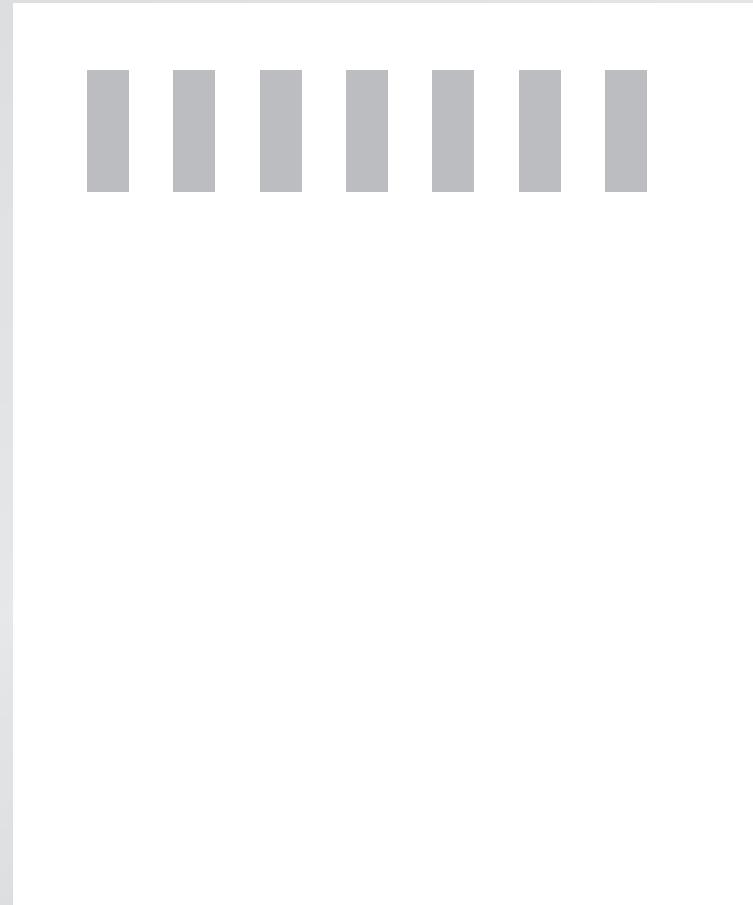
$$Z = \sqrt{\frac{\mu}{\varepsilon}} \quad \text{finite!}$$

1 index

2 zero index

Engineering a magnetic response

use array of dielectric rods

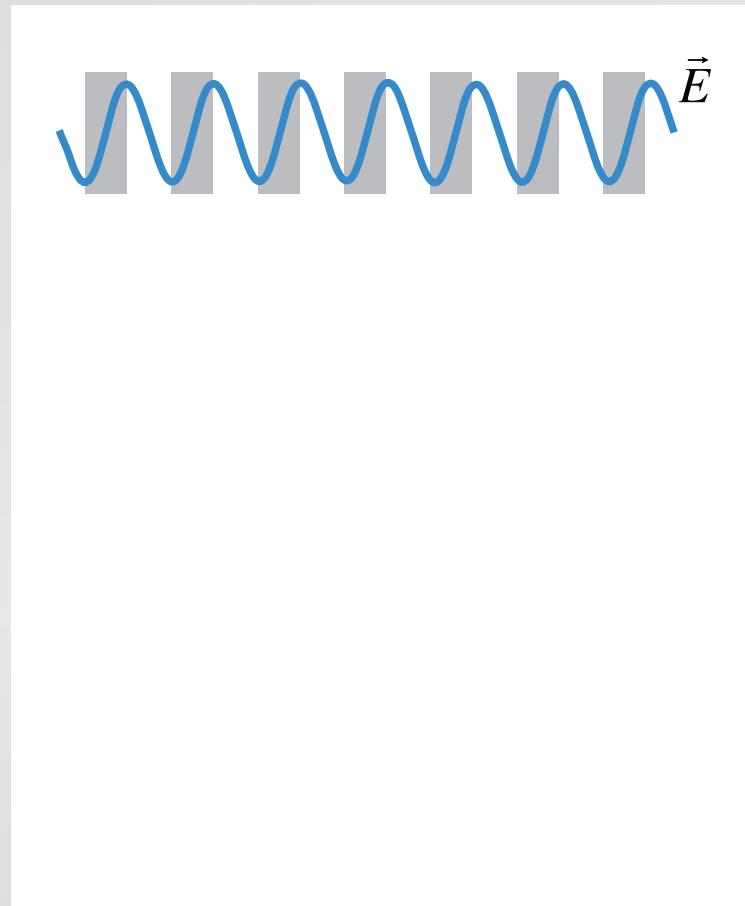


1 index

2 zero index

Engineering a magnetic response

incident electromagnetic wave ($\lambda_{\text{eff}} \approx a$)

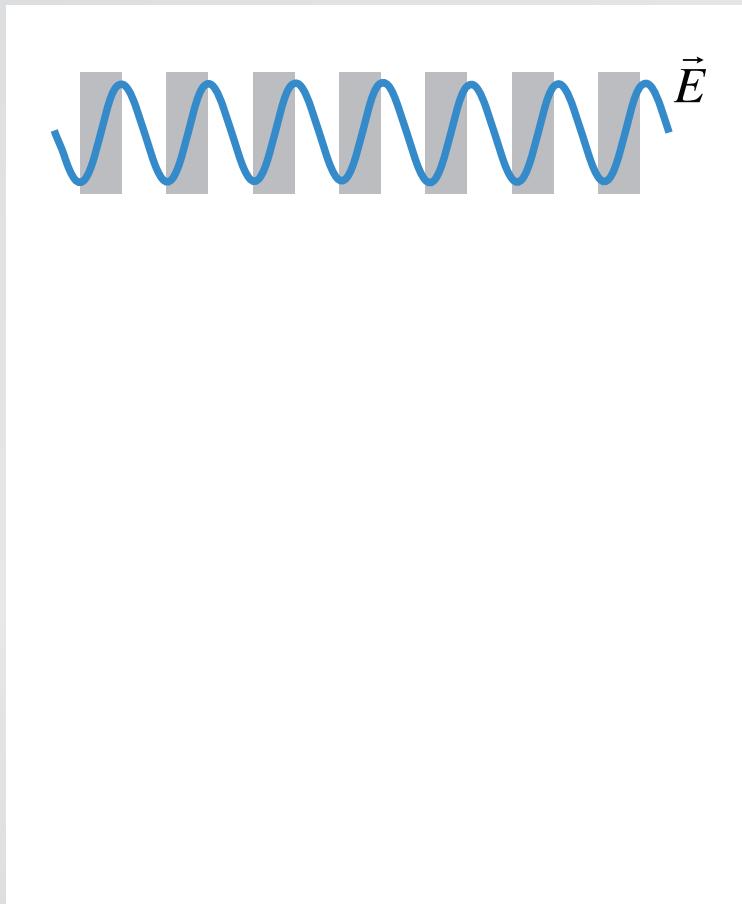


1 index

2 zero index

Engineering a magnetic response

produces an electric response...

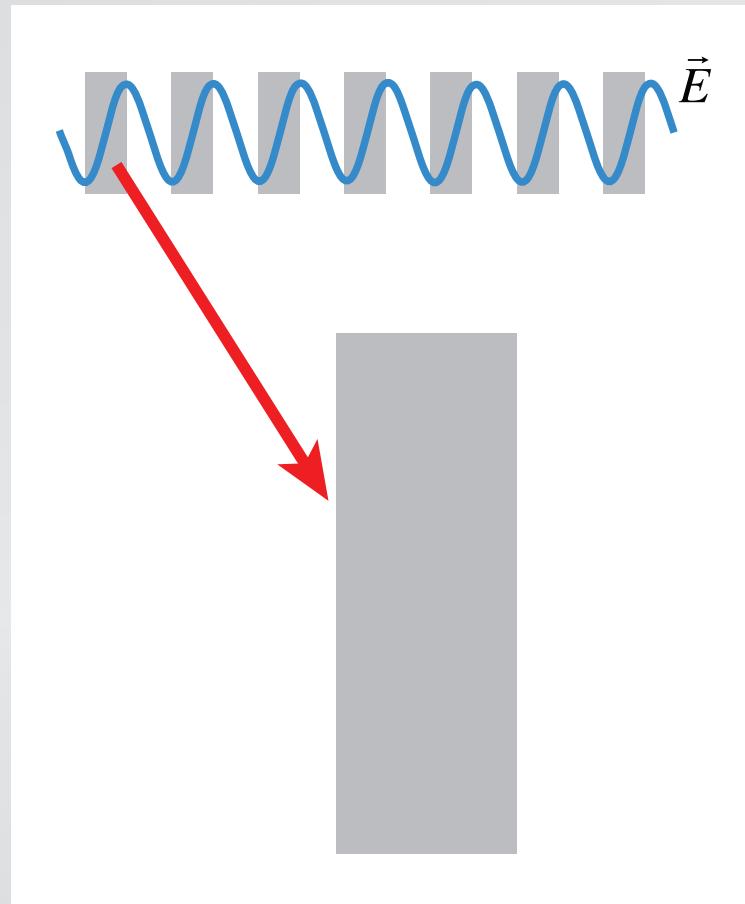


1 index

2 zero index

Engineering a magnetic response

... but different electric fields front and back...

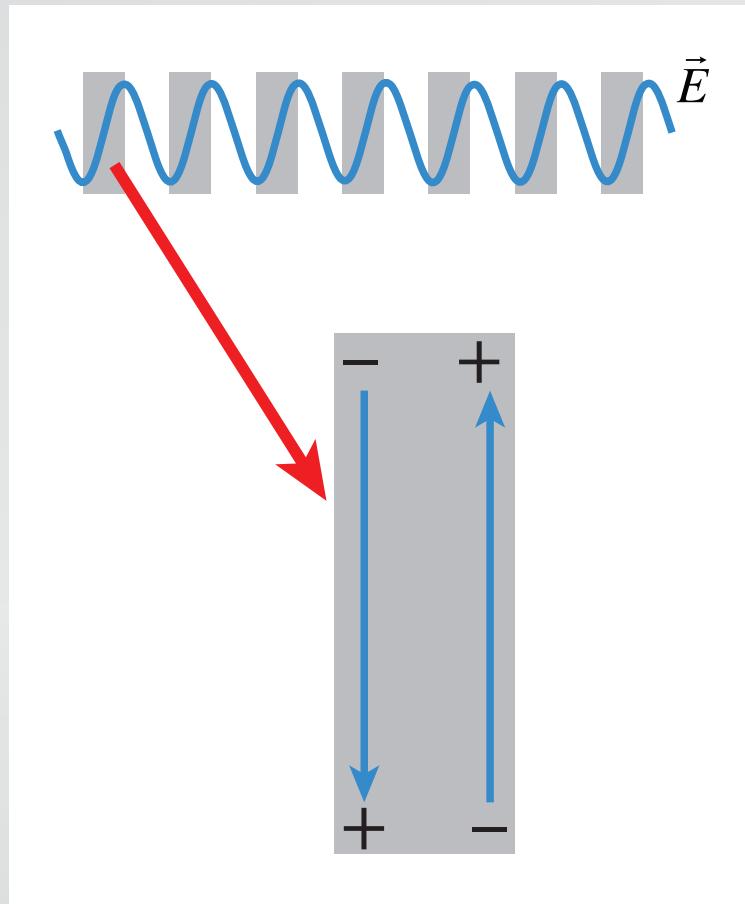


1 index

2 zero index

Engineering a magnetic response

...induce different polarizations on opposite sides...

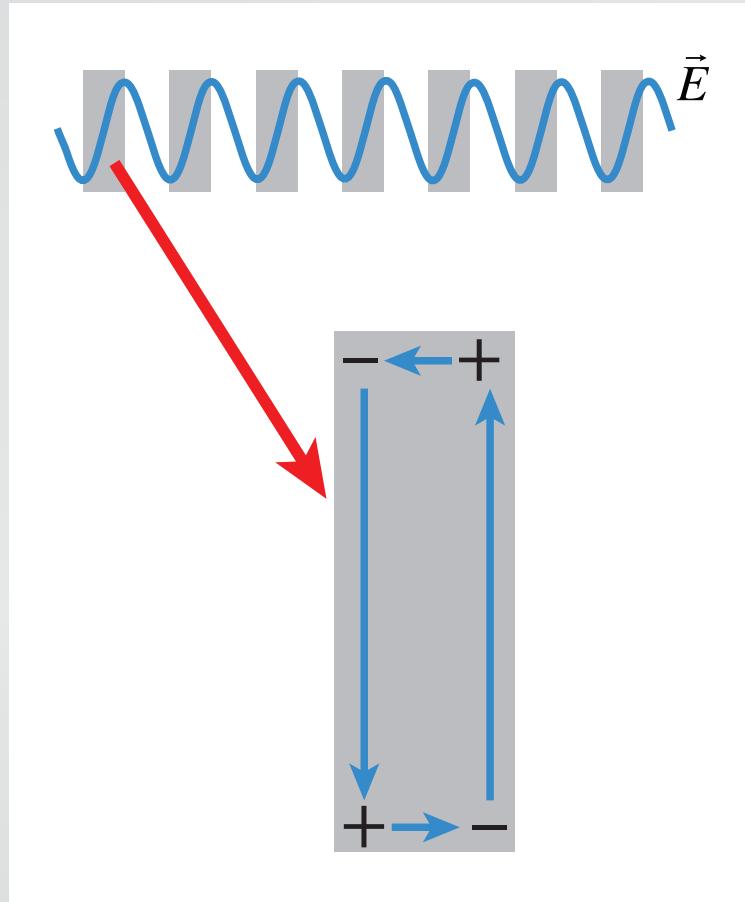


1 index

2 zero index

Engineering a magnetic response

...causing a current loop...

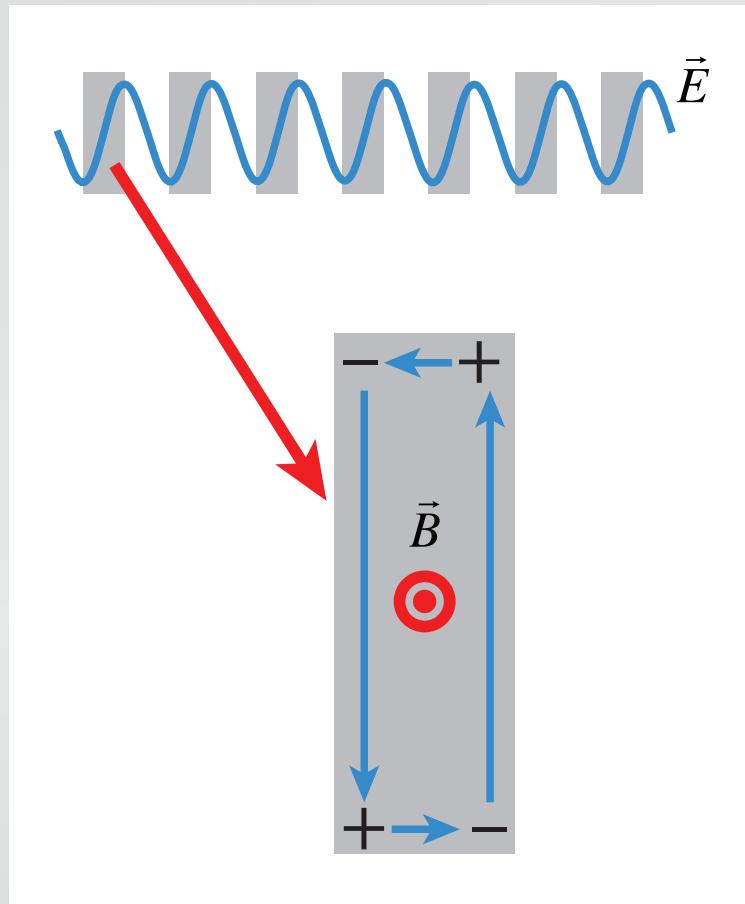


1 index

2 zero index

Engineering a magnetic response

...which, in turn, produces an induced magnetic field

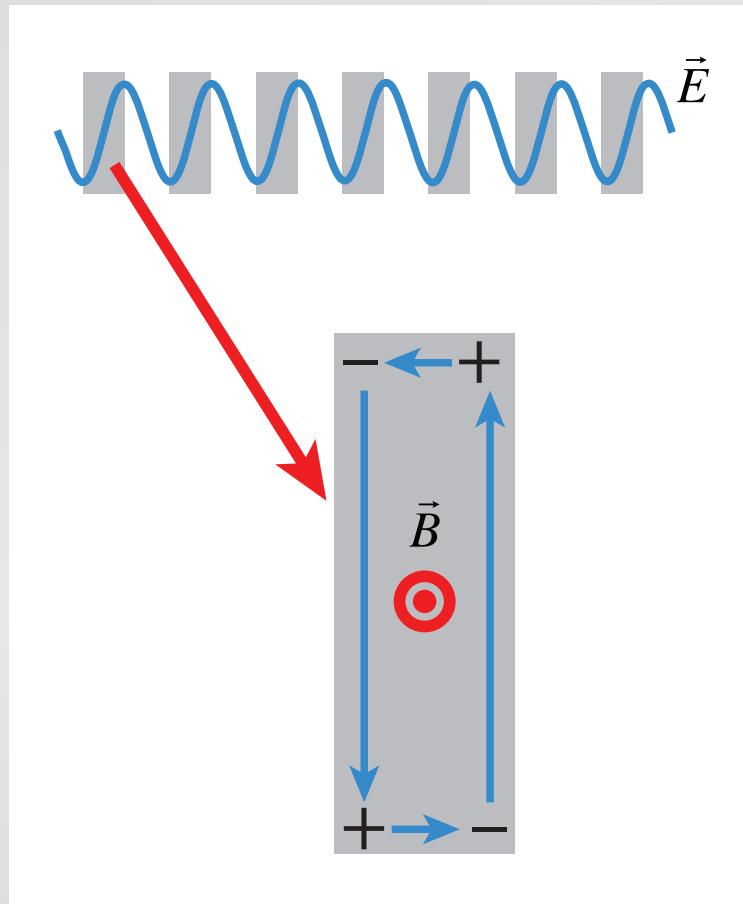


1 index

2 zero index

Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide



1 index

2 zero index

Engineering a magnetic response

adjustable parameters



1 index

2 zero index

Engineering a magnetic response

adjustable parameters

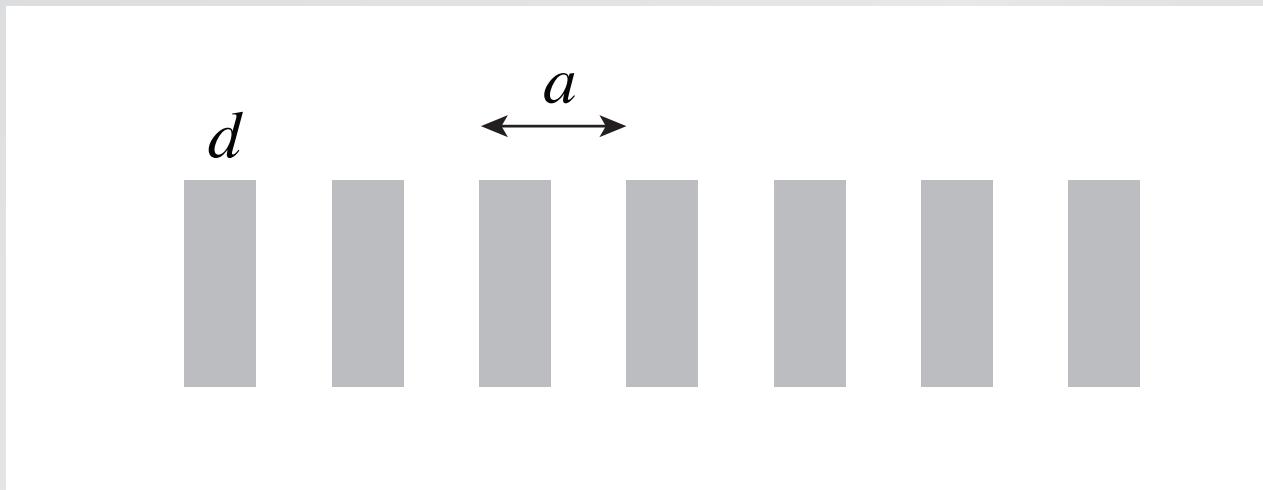


1 index

2 zero index

Engineering a magnetic response

adjustable parameters

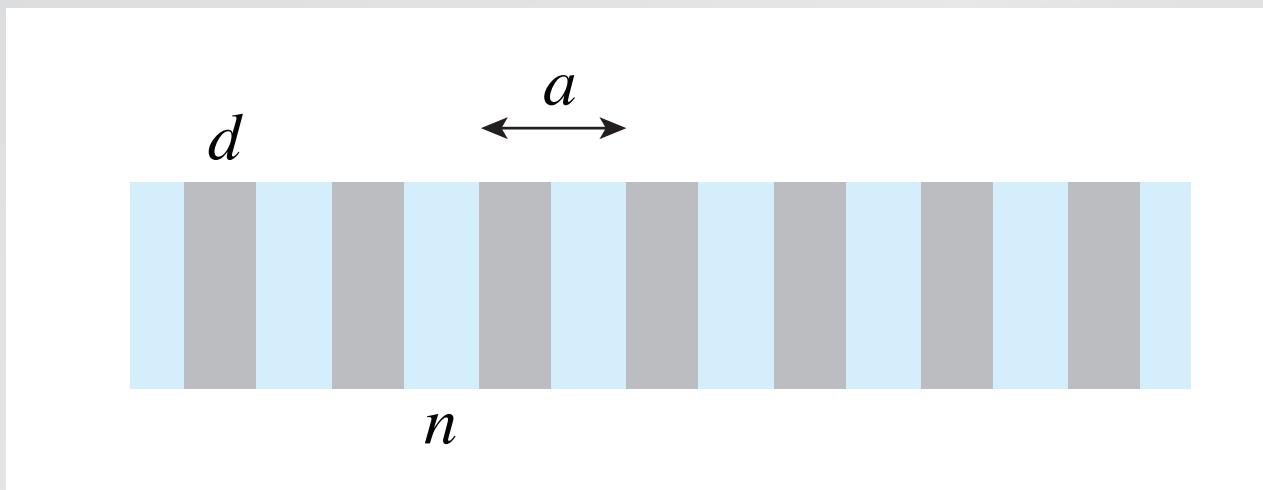


1 index

2 zero index

Engineering a magnetic response

adjustable parameters

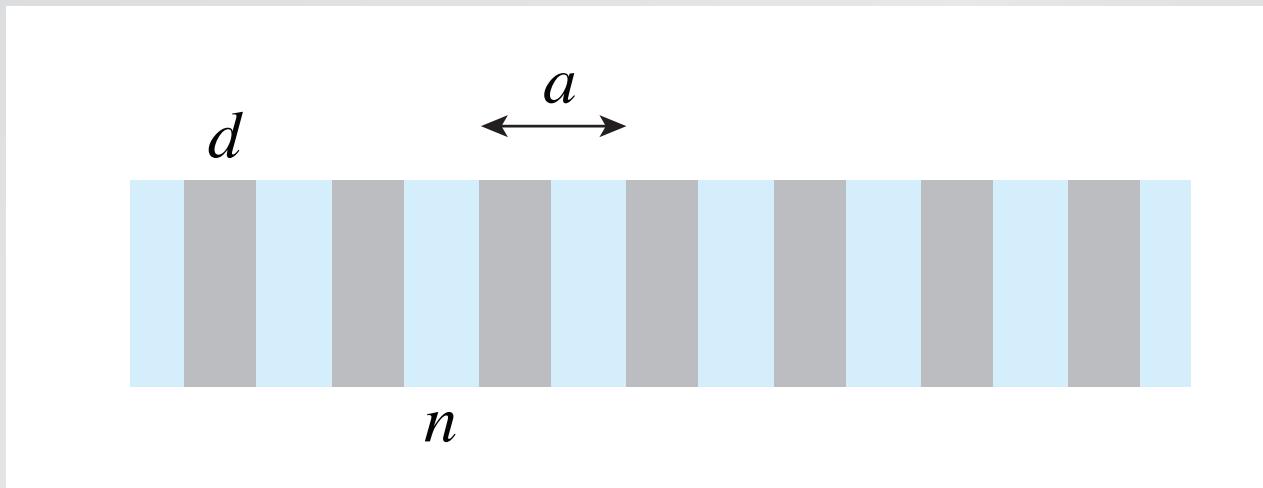


1 index

2 zero index

Engineering a magnetic response

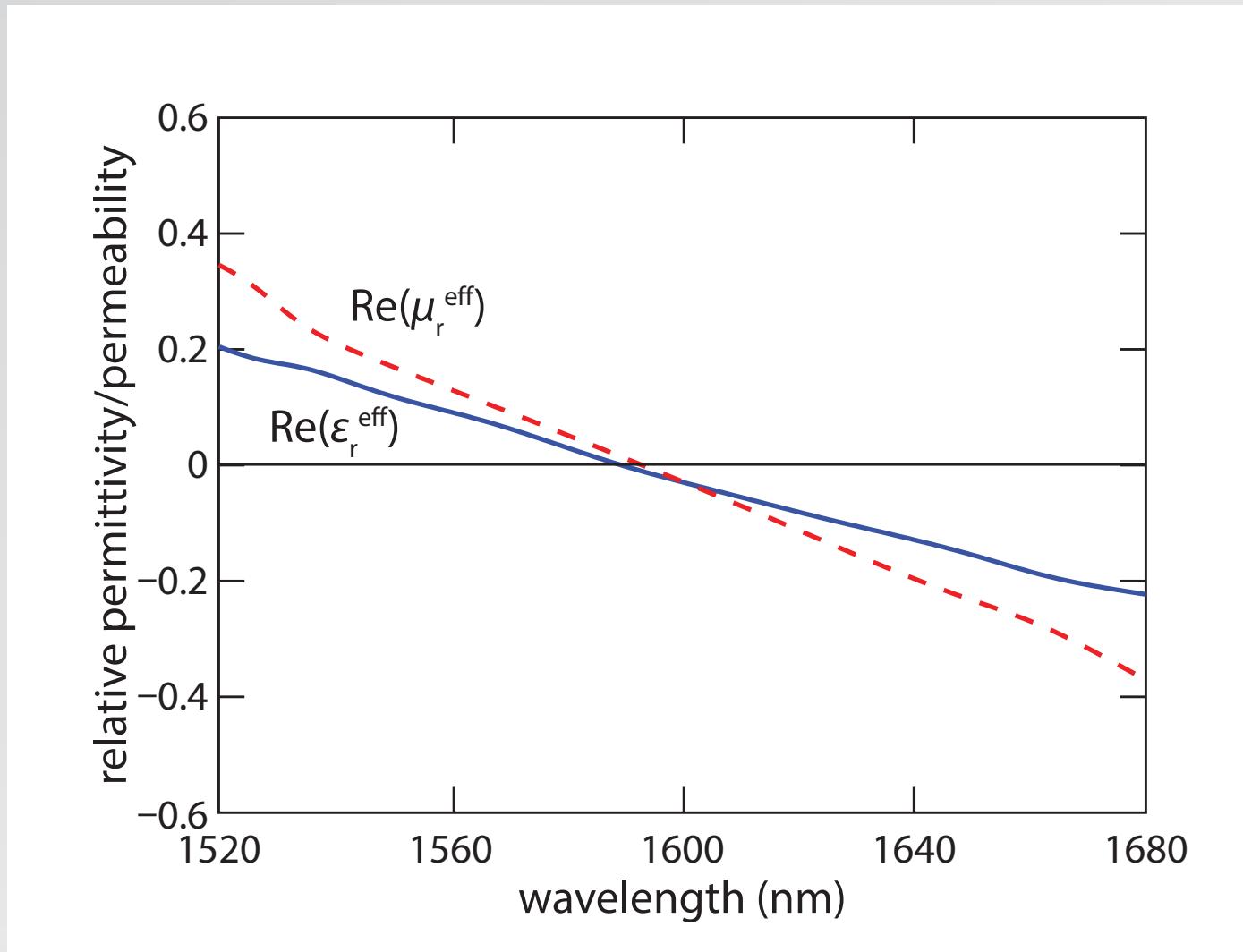
adjustable parameters



$$d = 422 \text{ nm}, \quad a = 690 \text{ nm}, \quad n = 1.57 \text{ (SU8)}$$

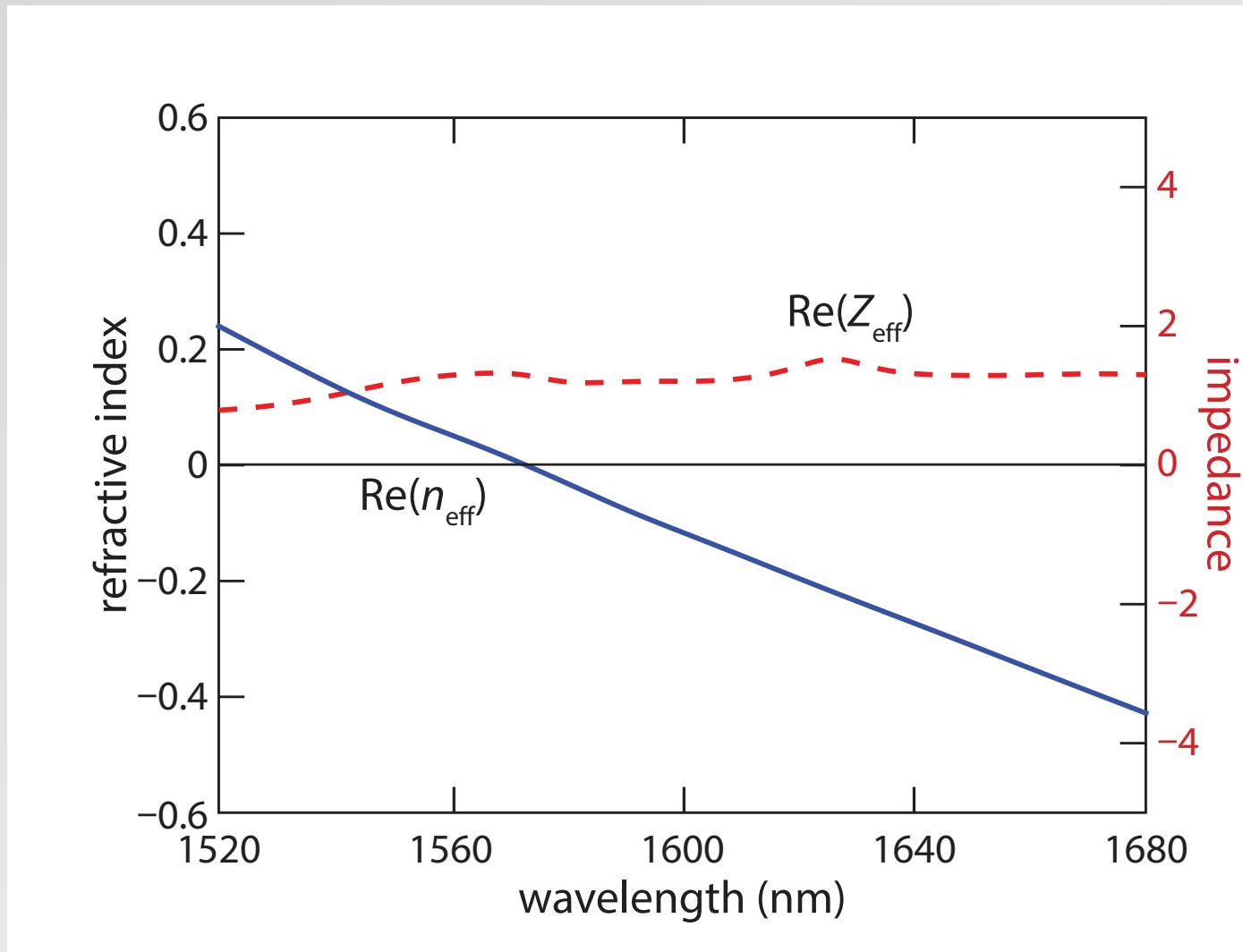
1 index

2 zero index



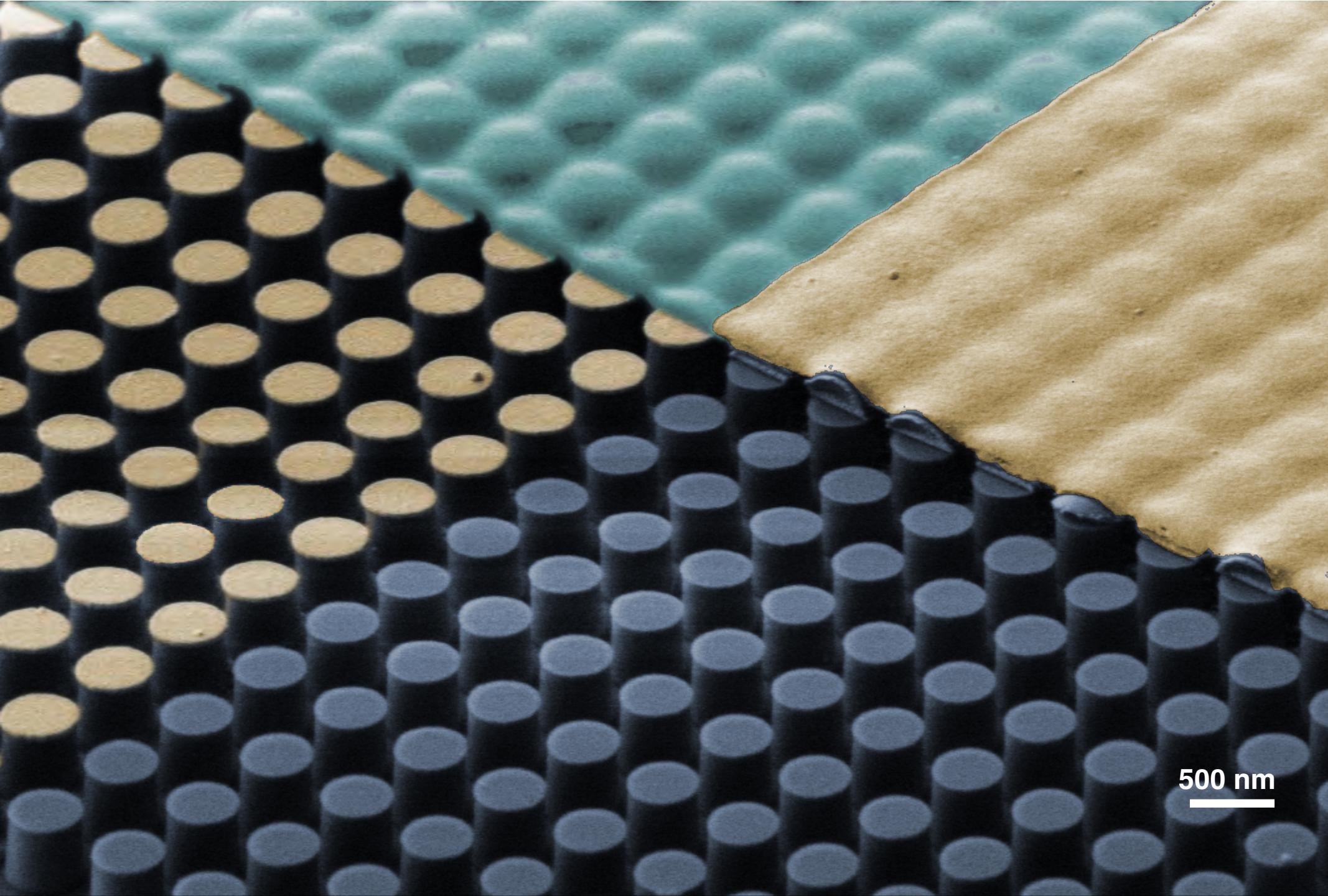
1 index

2 zero index



1 index

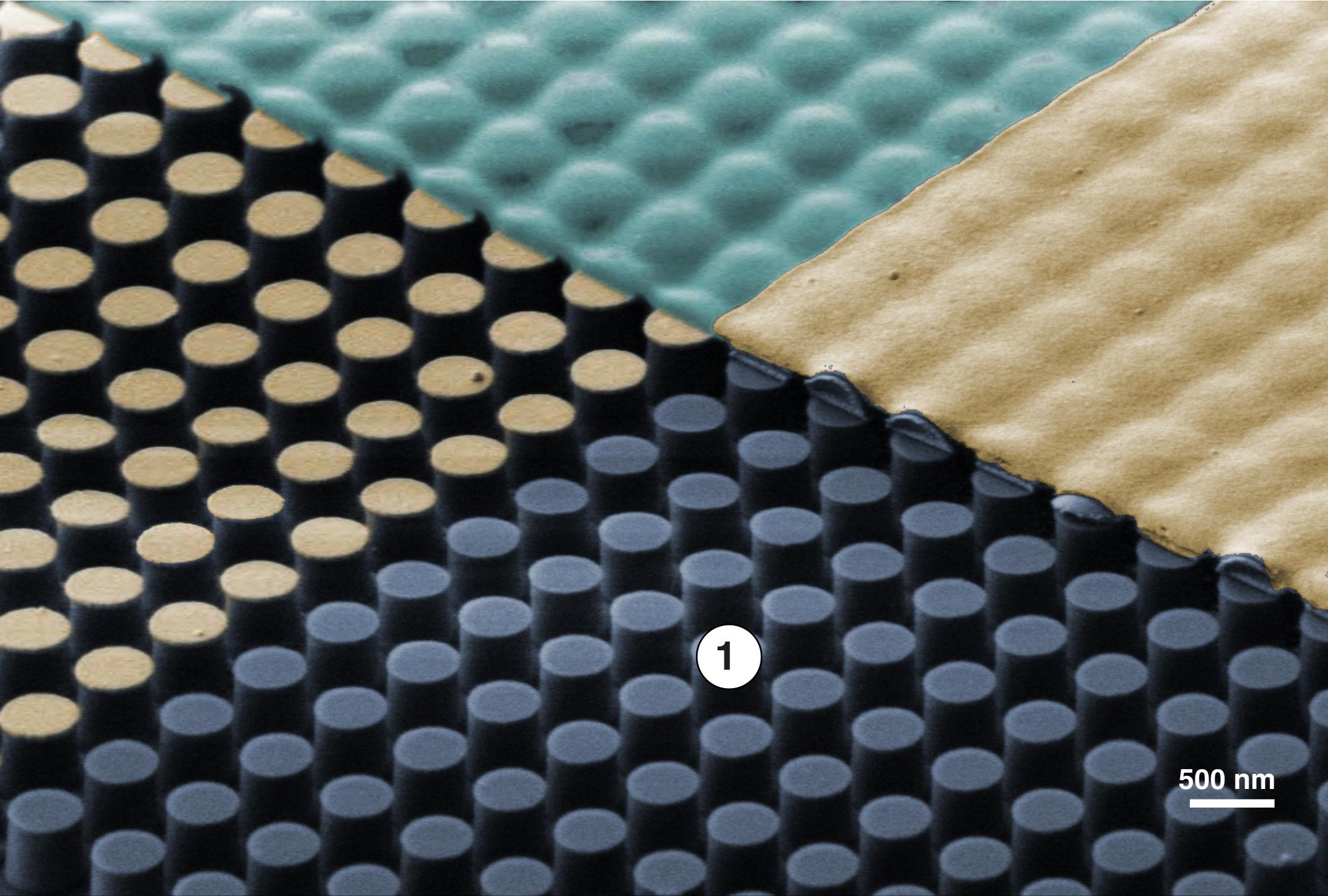
2 zero index



1 index

2 zero index

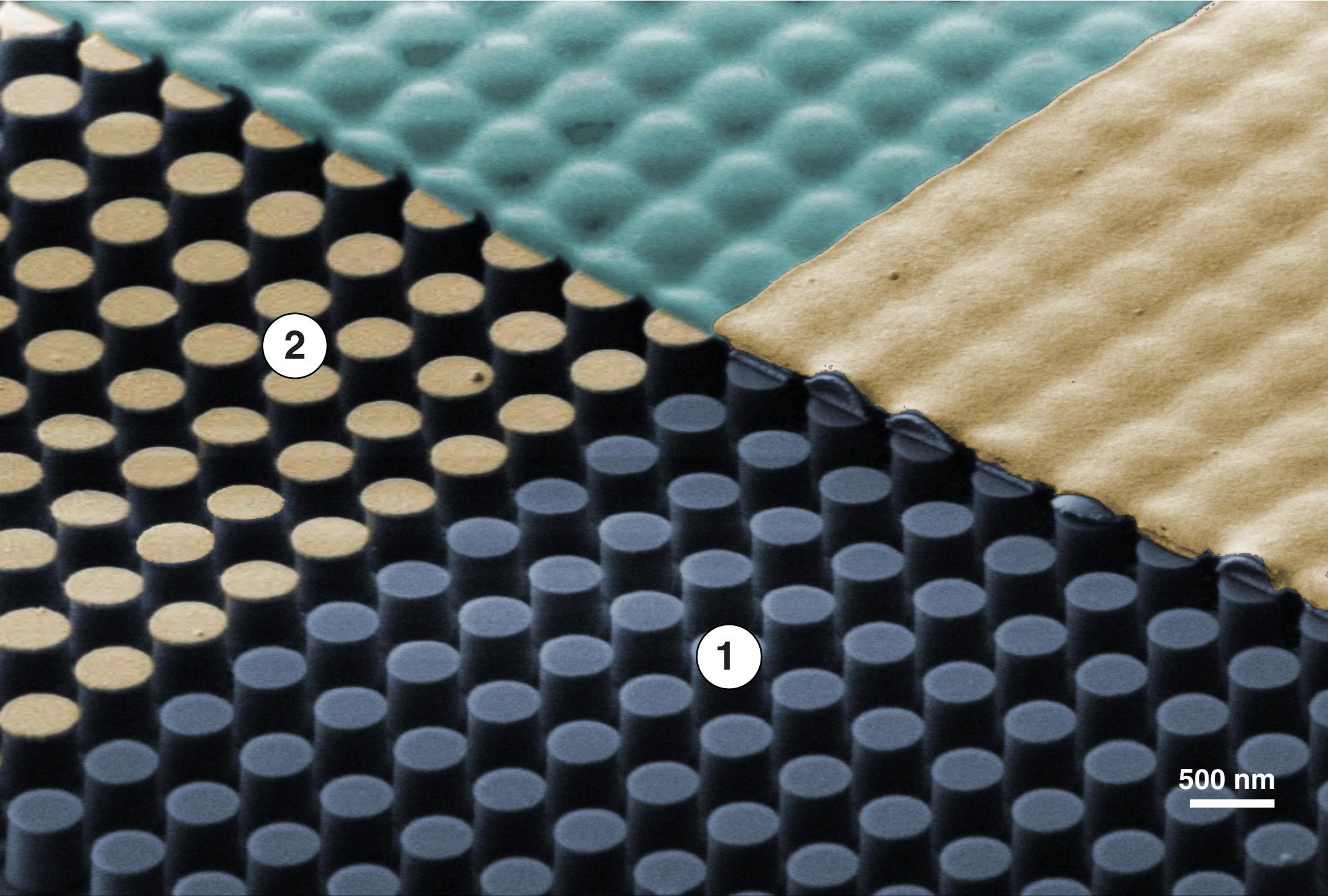
500 nm



1 index

2 zero index

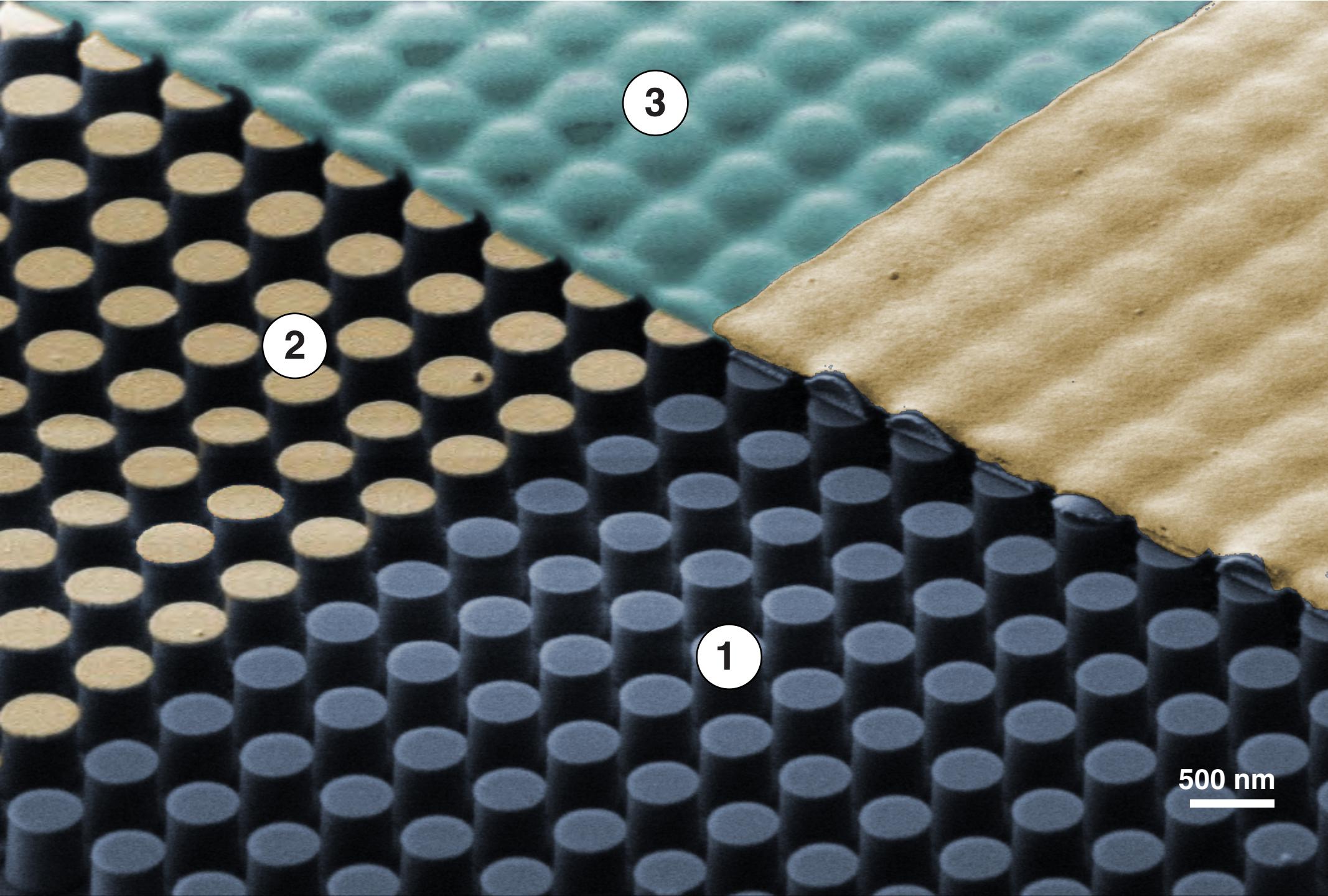
500 nm



1 index

2 zero index

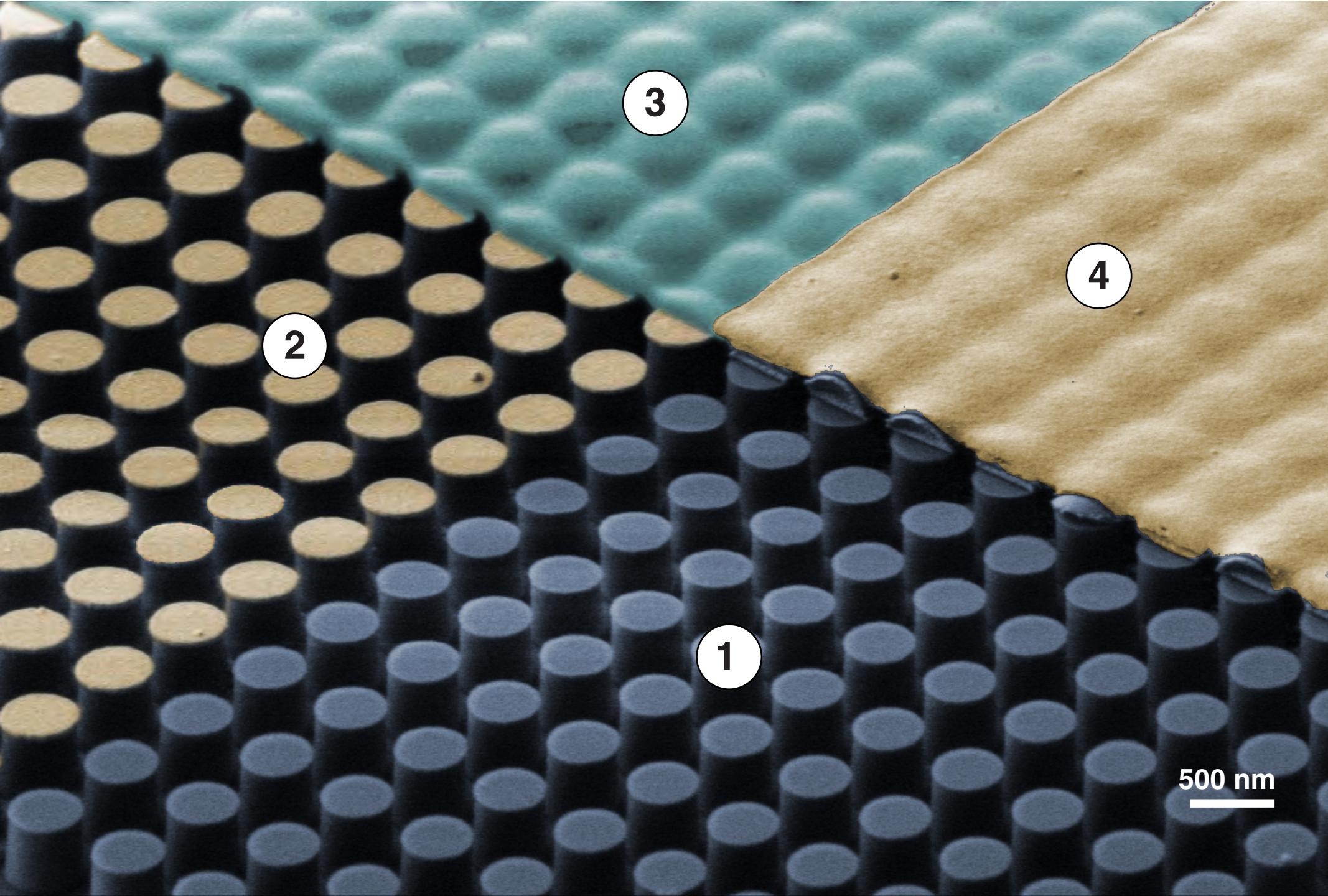
500 nm



1 index

2 zero index

500 nm



1 index

2 zero index

500 nm

Can make this in any shape!

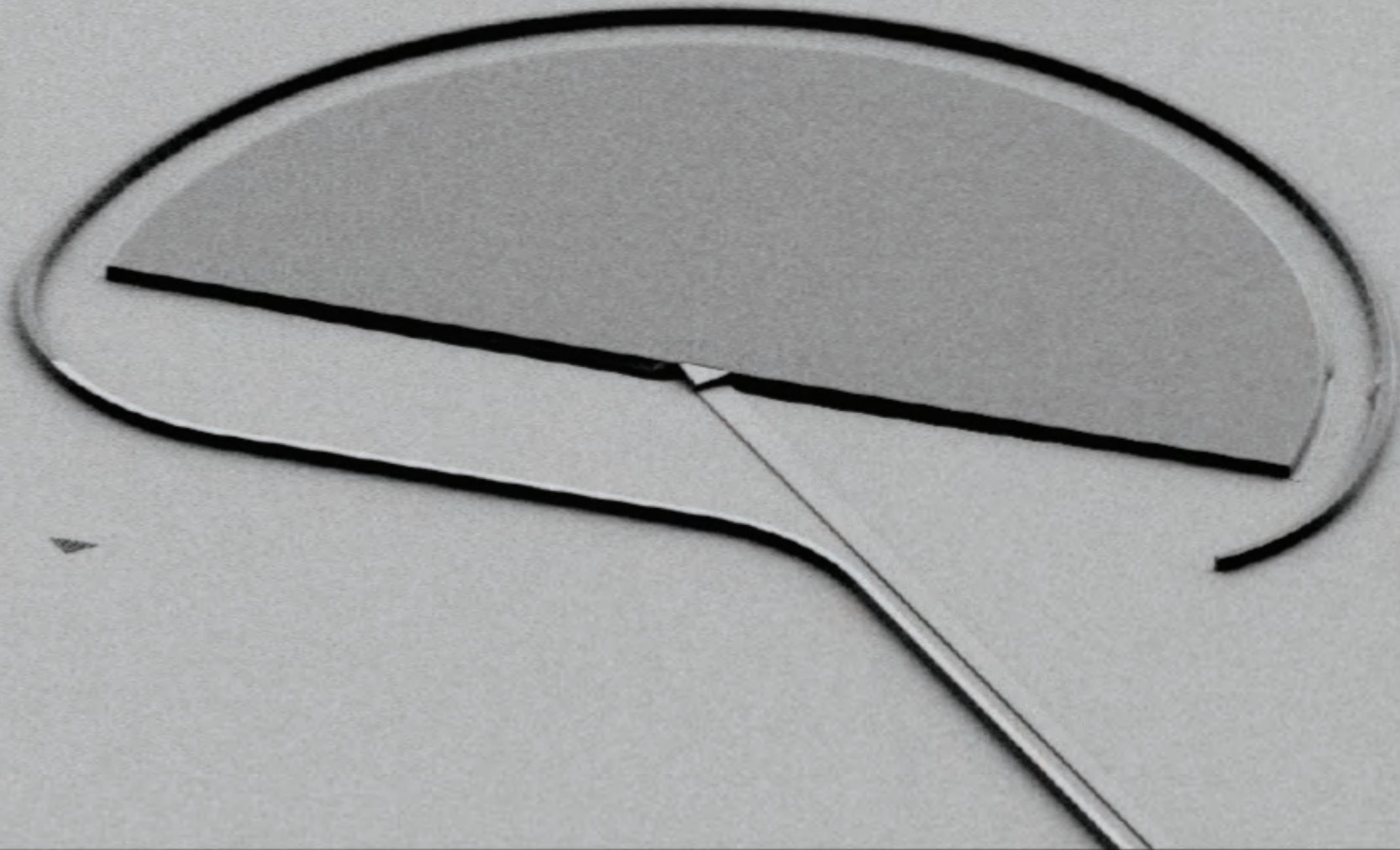
1 index

2 zero index



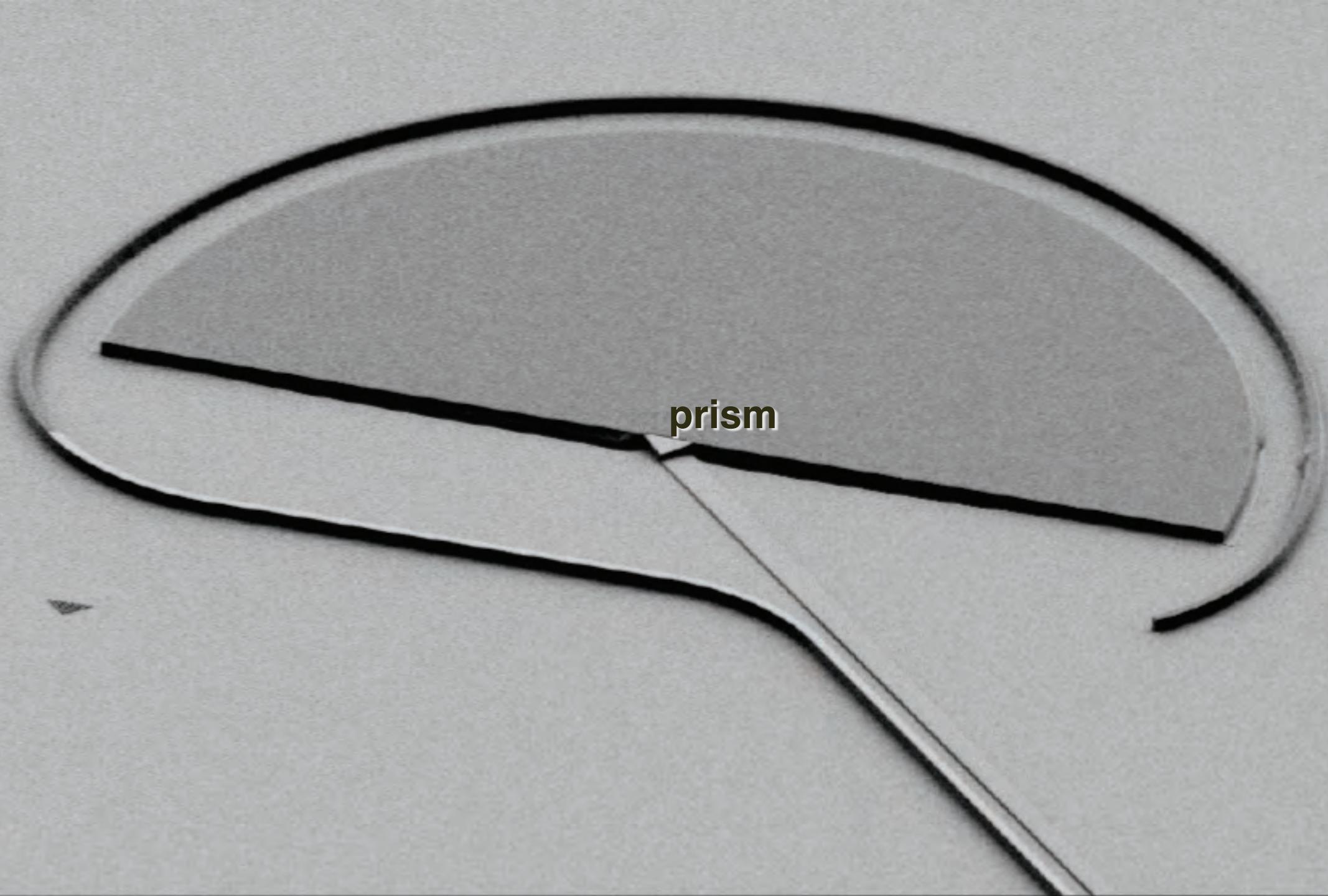
1 index

2 zero index



1 index

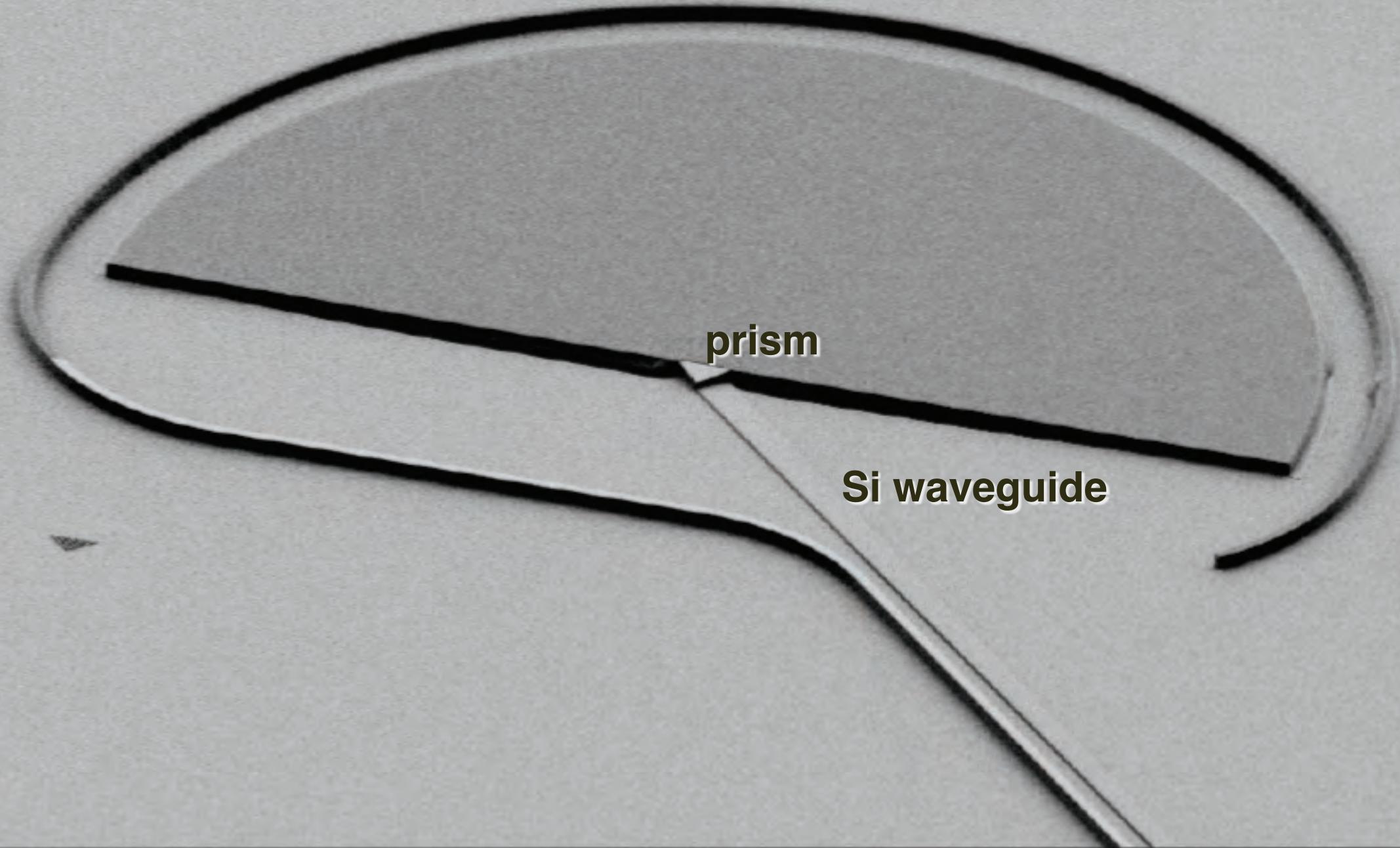
2 zero index



prism

1 index

2 zero index

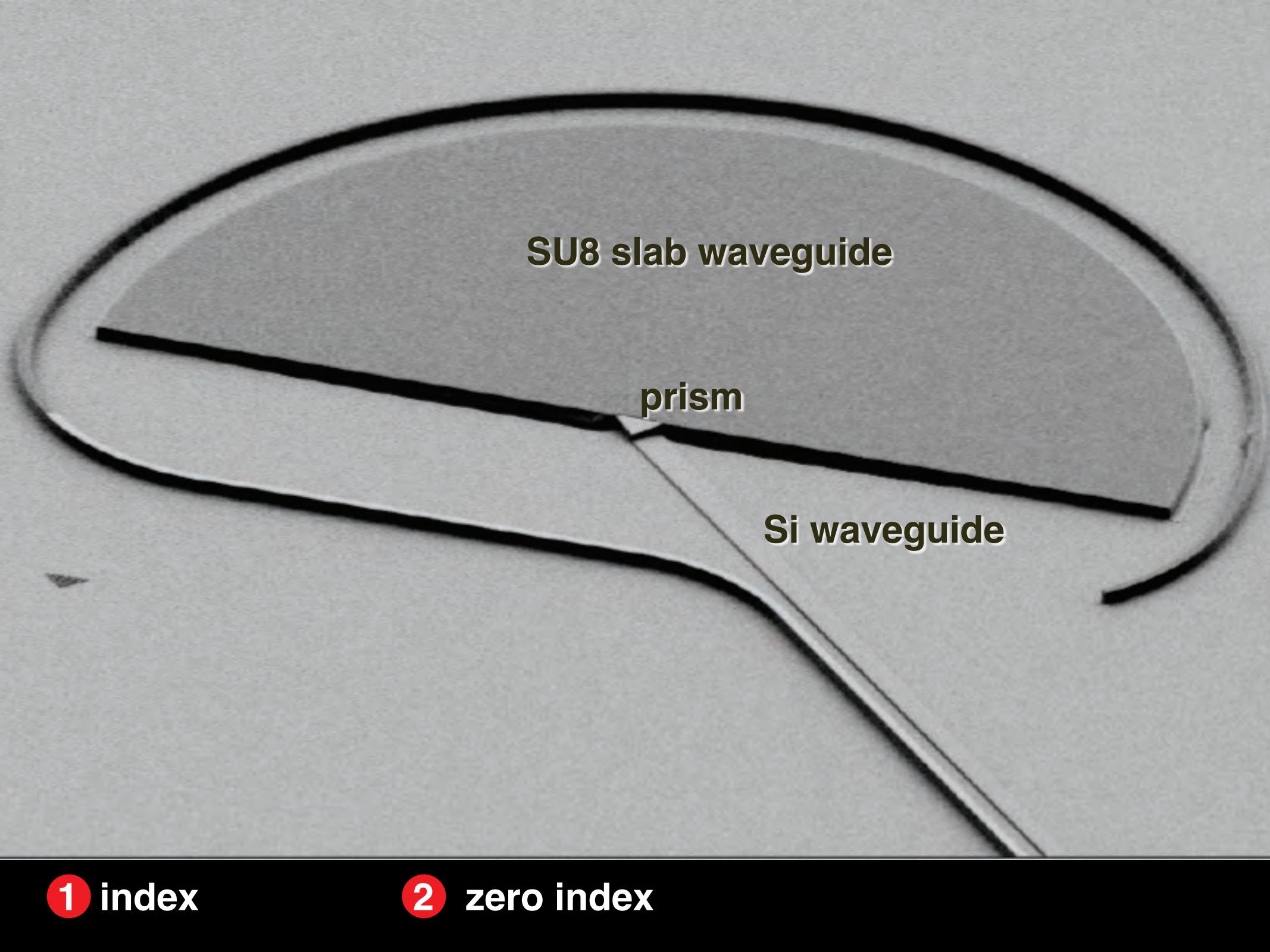


prism

Si waveguide

1 index

2 zero index

A scanning electron micrograph (SEM) showing a waveguide structure. A large, thick, curved waveguide is labeled "SU8 slab waveguide". A smaller, thinner waveguide that splits off from the main one is labeled "Si waveguide". The two waveguides meet at a junction point. The word "prism" is written vertically along the main waveguide curve.

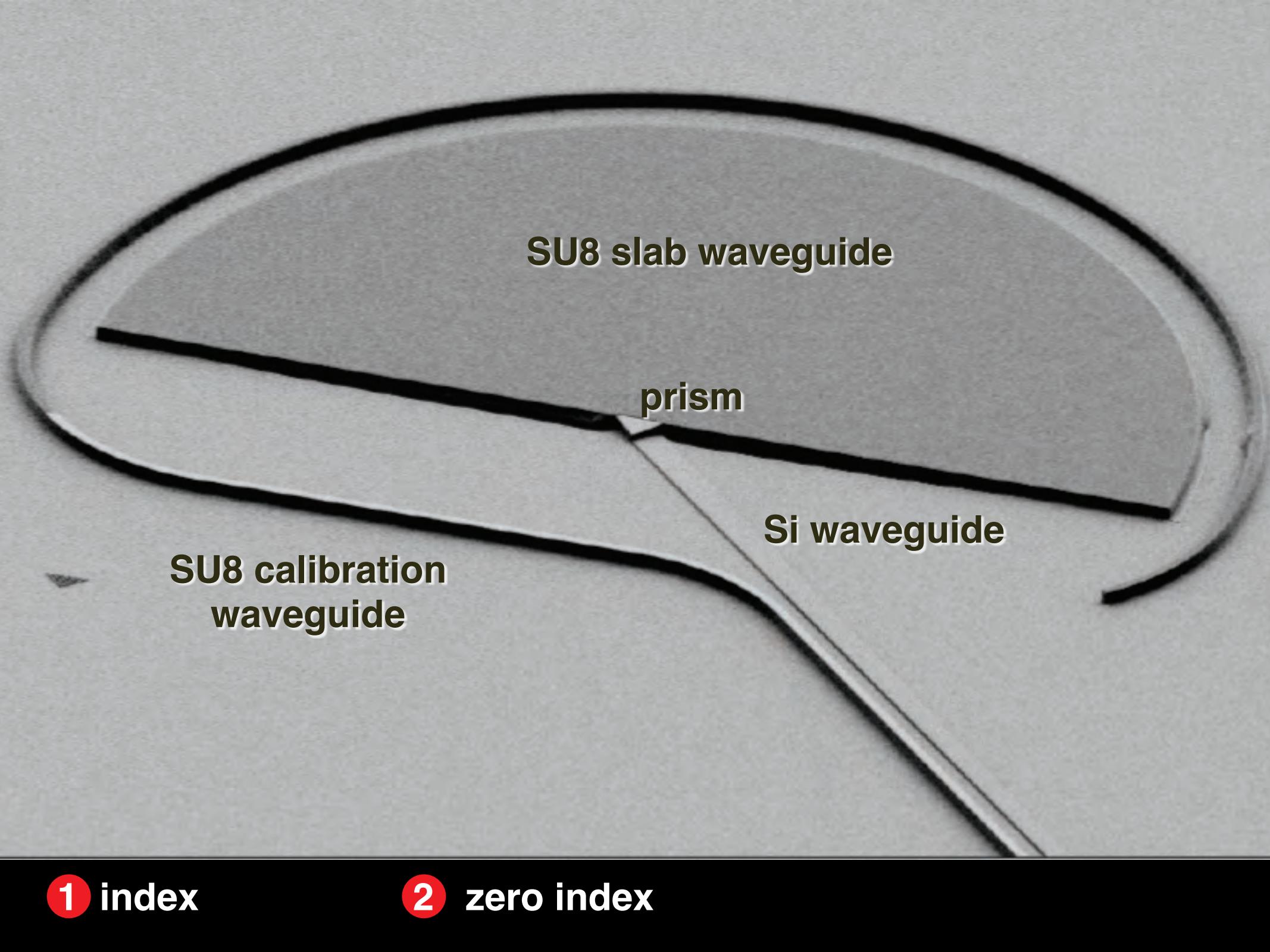
SU8 slab waveguide

prism

Si waveguide

1 index

2 zero index

A grayscale SEM image showing a cross-section of a waveguide structure. A thick, curved SU8 slab waveguide is at the top. Below it, a thinner Si waveguide is partially embedded in the SU8. A horizontal line labeled 'prism' extends from the Si waveguide towards the left. A calibration scale bar is visible on the far left.

SU8 slab waveguide

prism

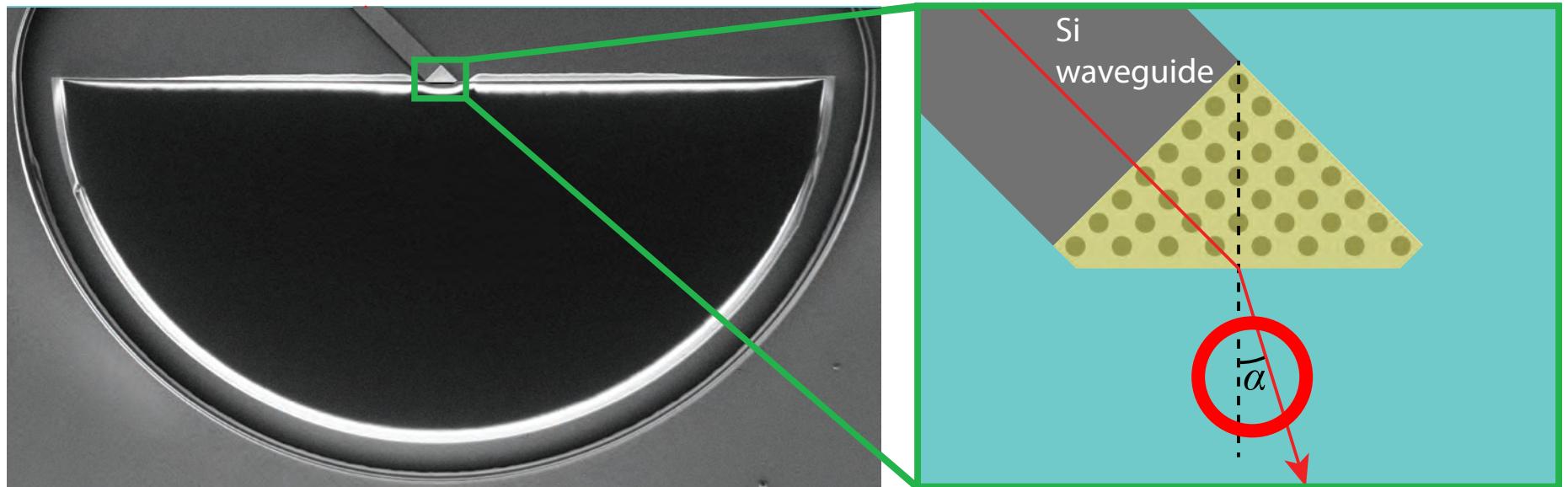
**SU8 calibration
waveguide**

Si waveguide

1 index

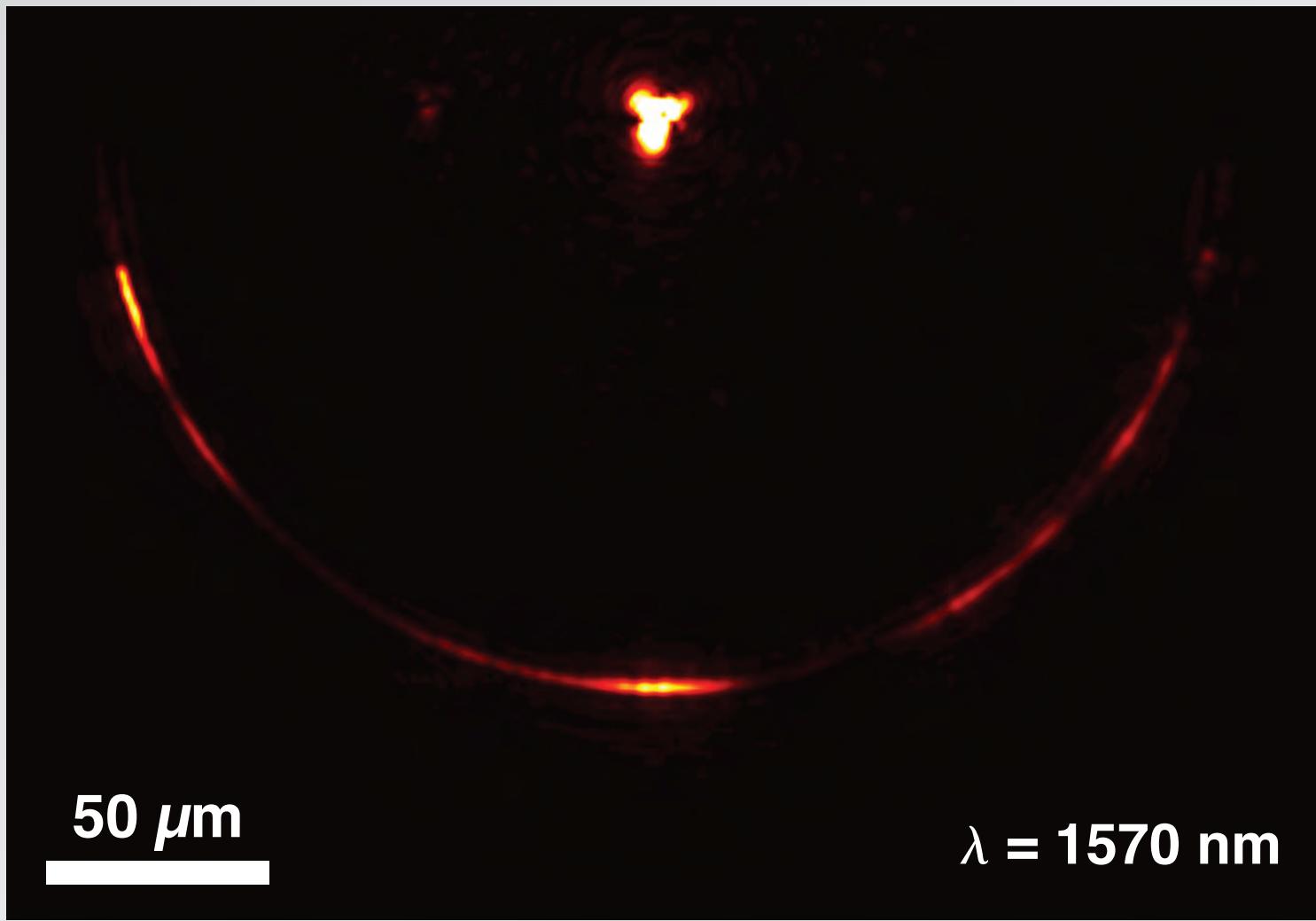
2 zero index

On-chip zero-index prism



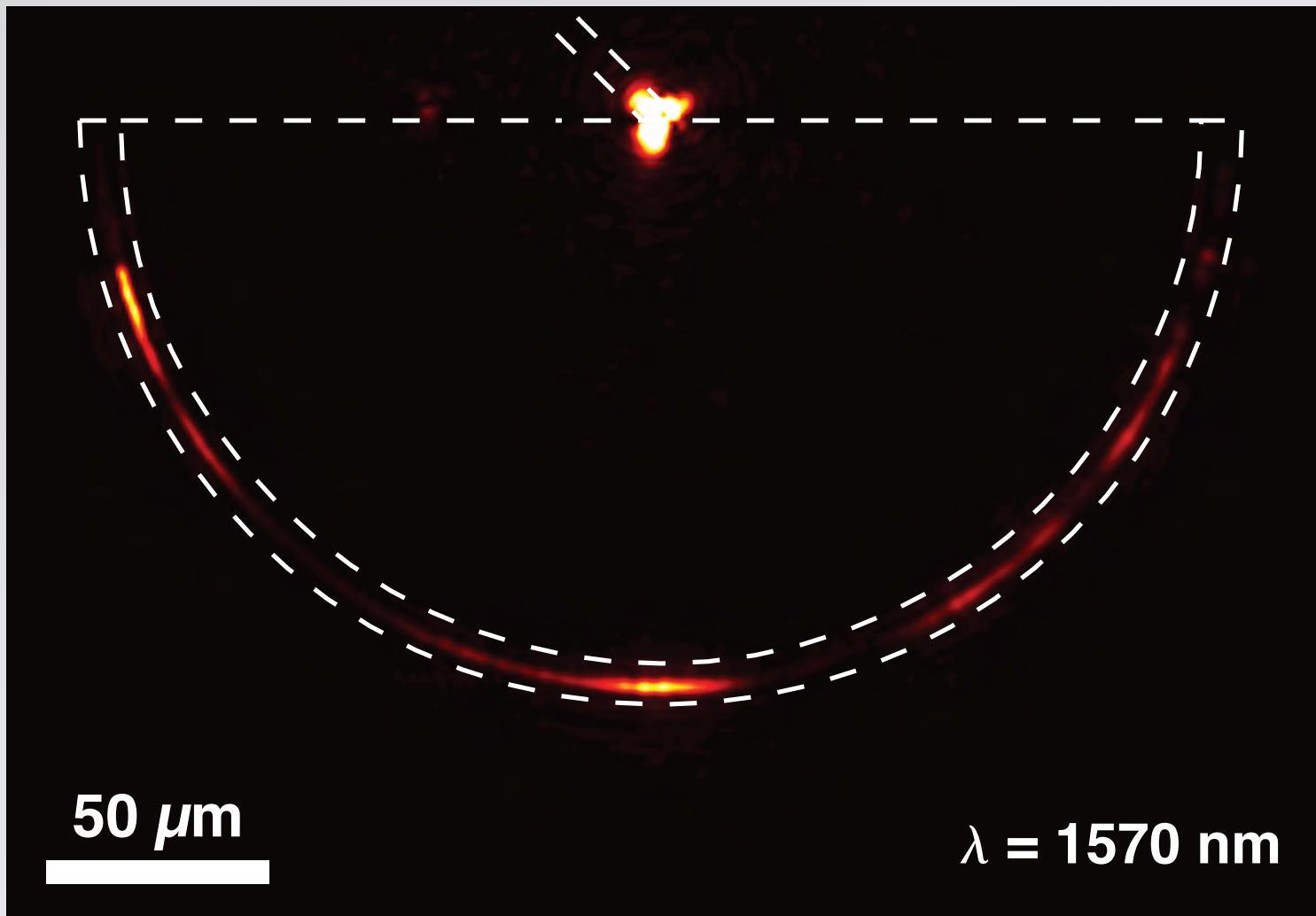
1 index

2 zero index



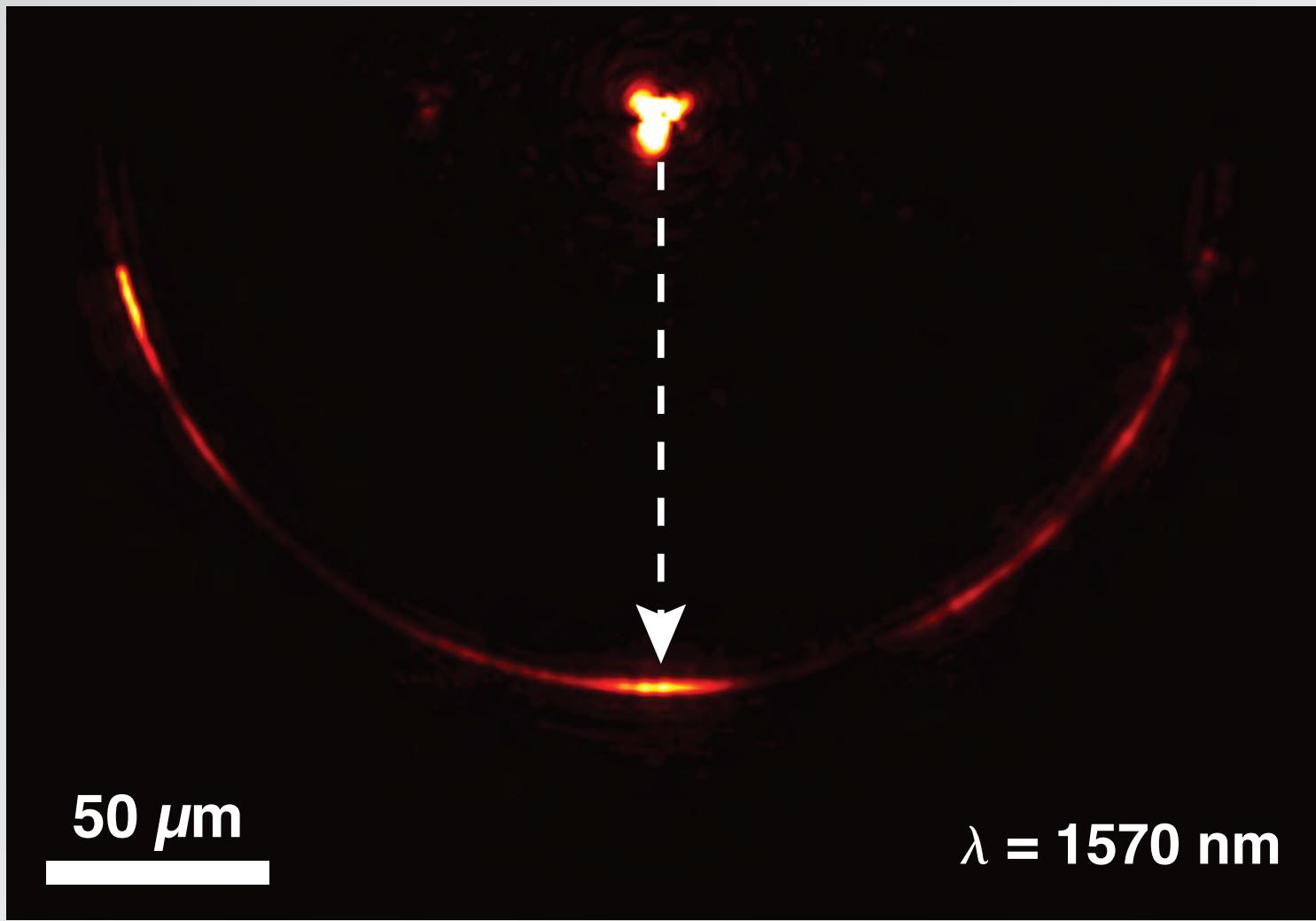
1 index

2 zero index



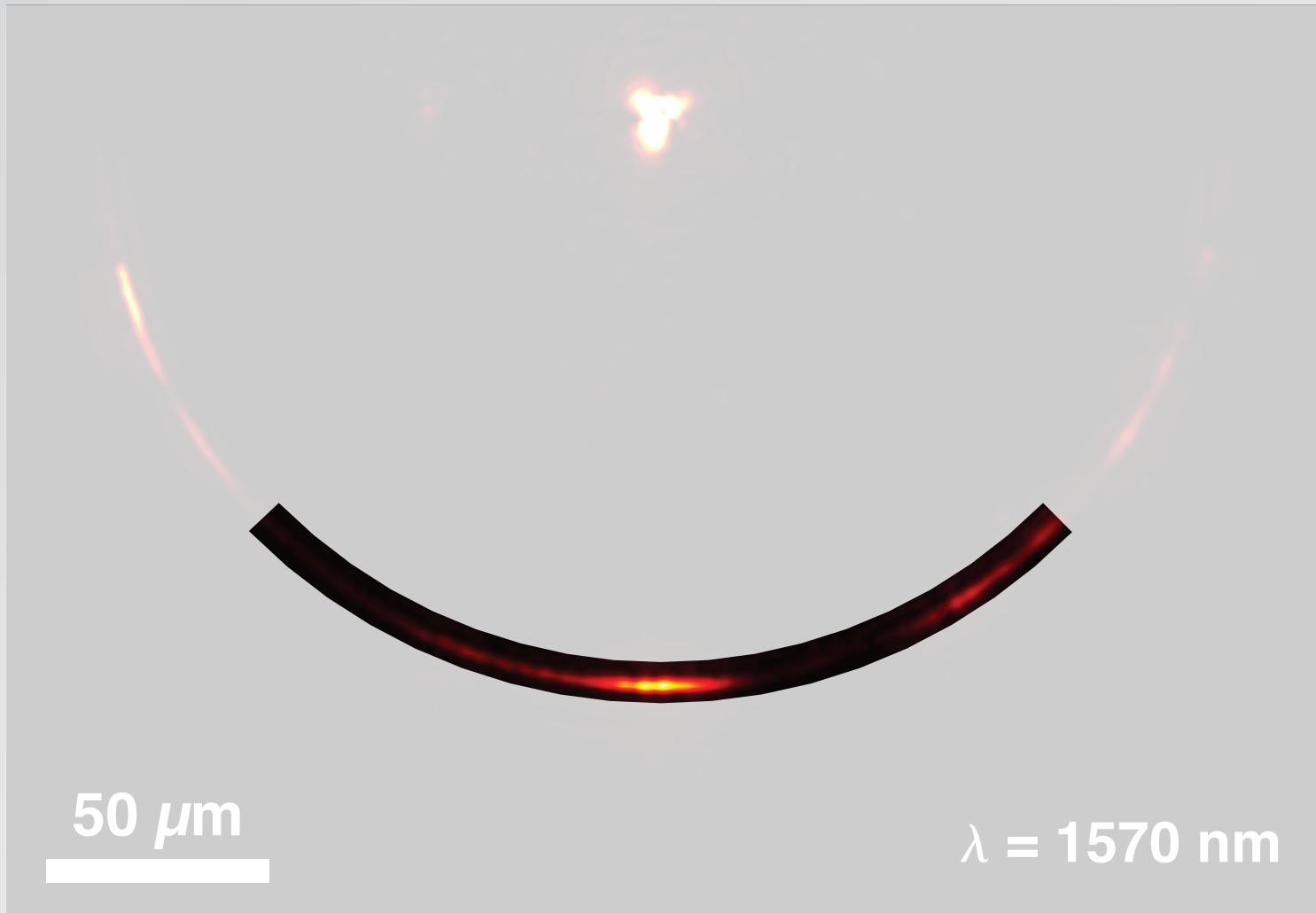
1 index

2 zero index



1 index

2 zero index



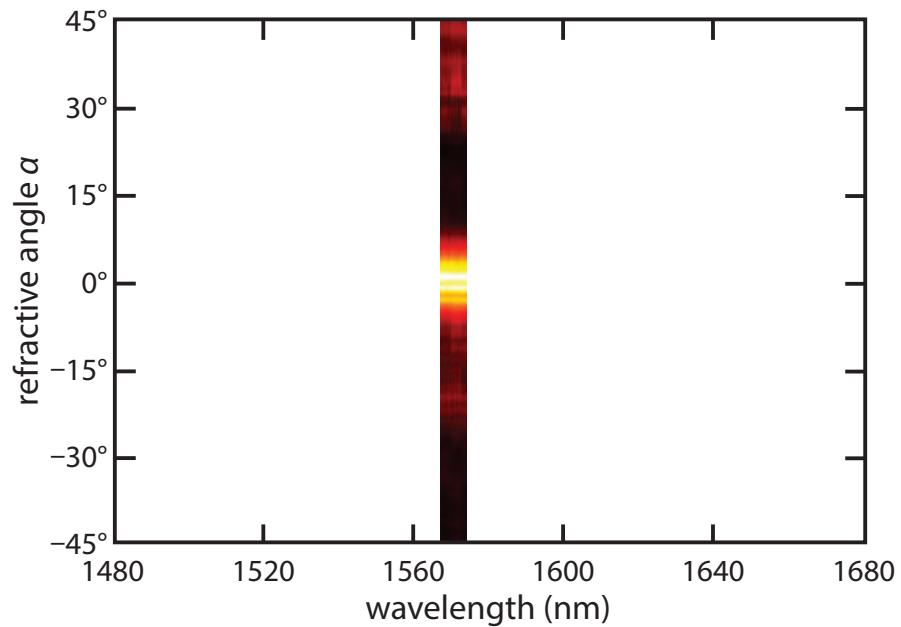
50 μm

$\lambda = 1570 \text{ nm}$

1 index

2 zero index

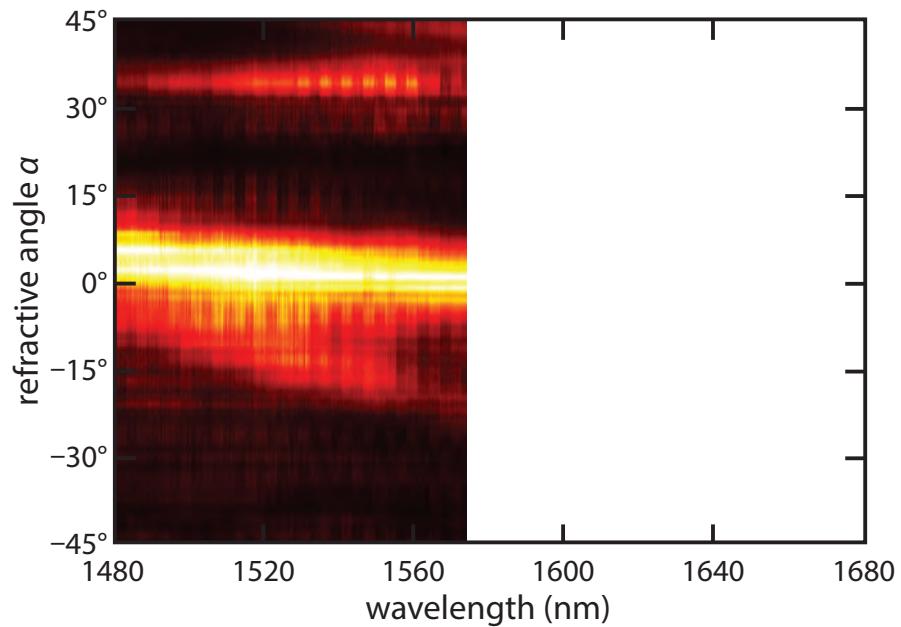
Wavelength dependence of refraction angle



1 index

2 zero index

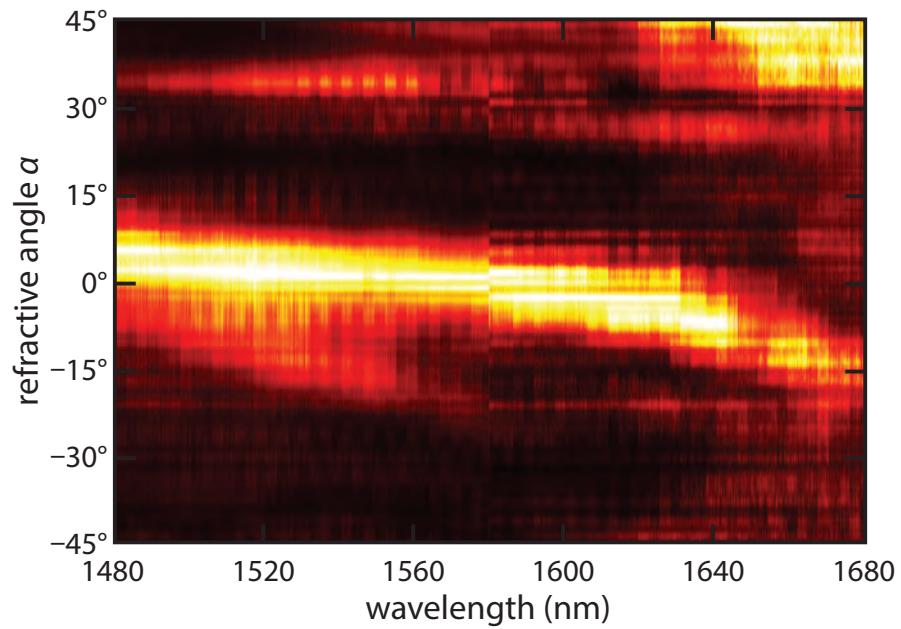
Wavelength dependence of refraction angle



1 index

2 zero index

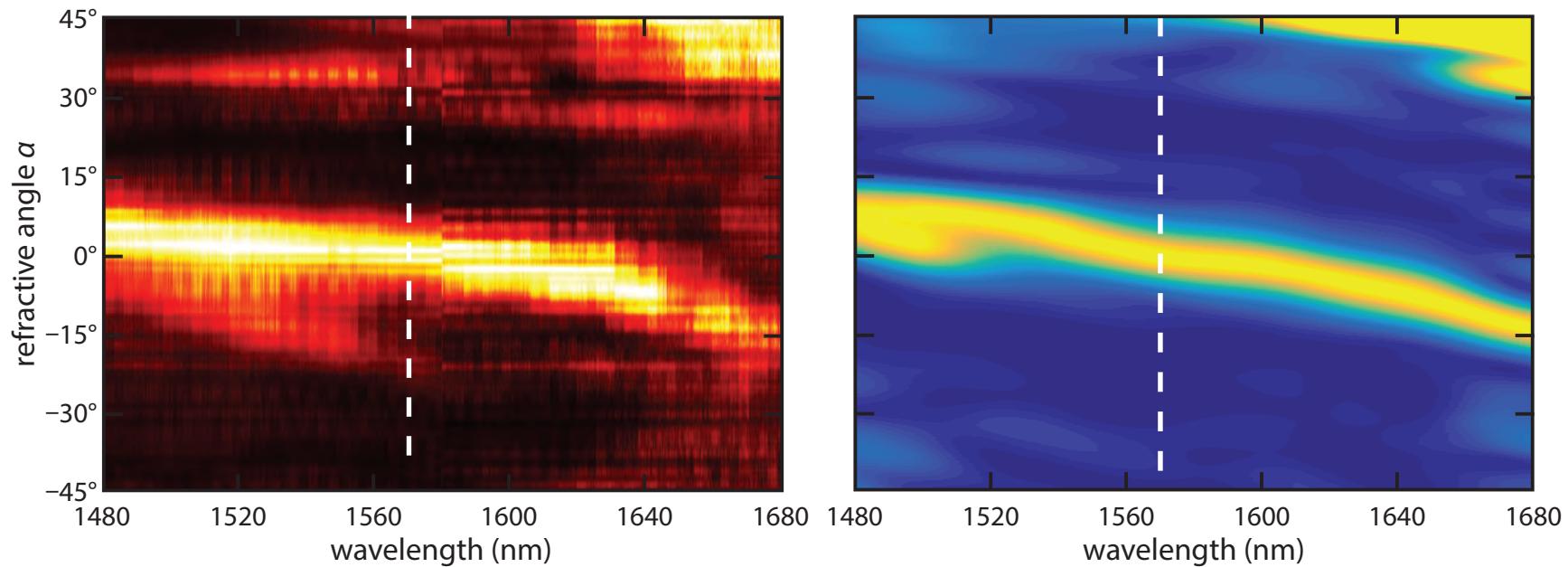
Wavelength dependence of refraction angle



1 index

2 zero index

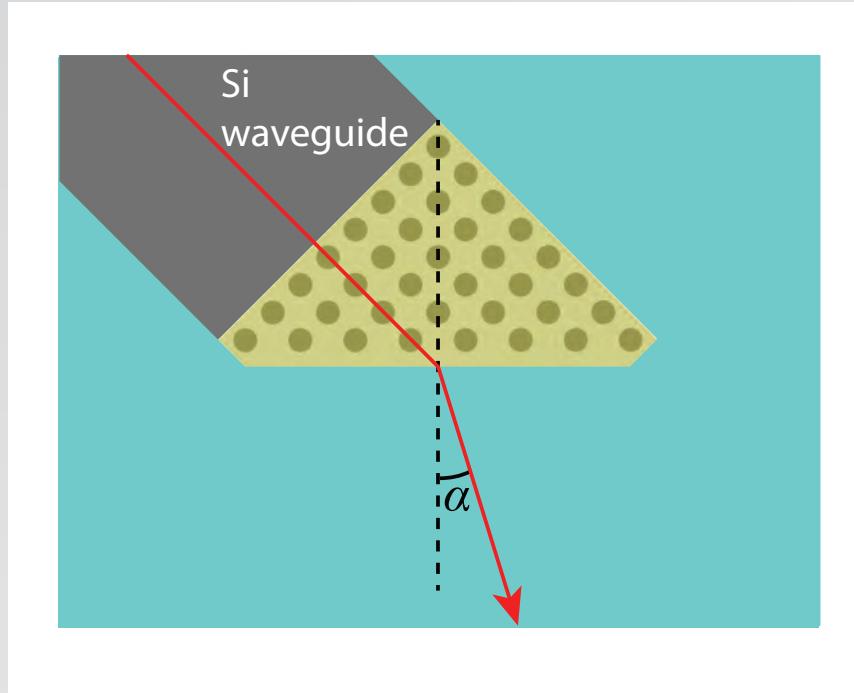
Wavelength dependence of refraction angle



1 index

2 zero index

Wavelength dependence of index

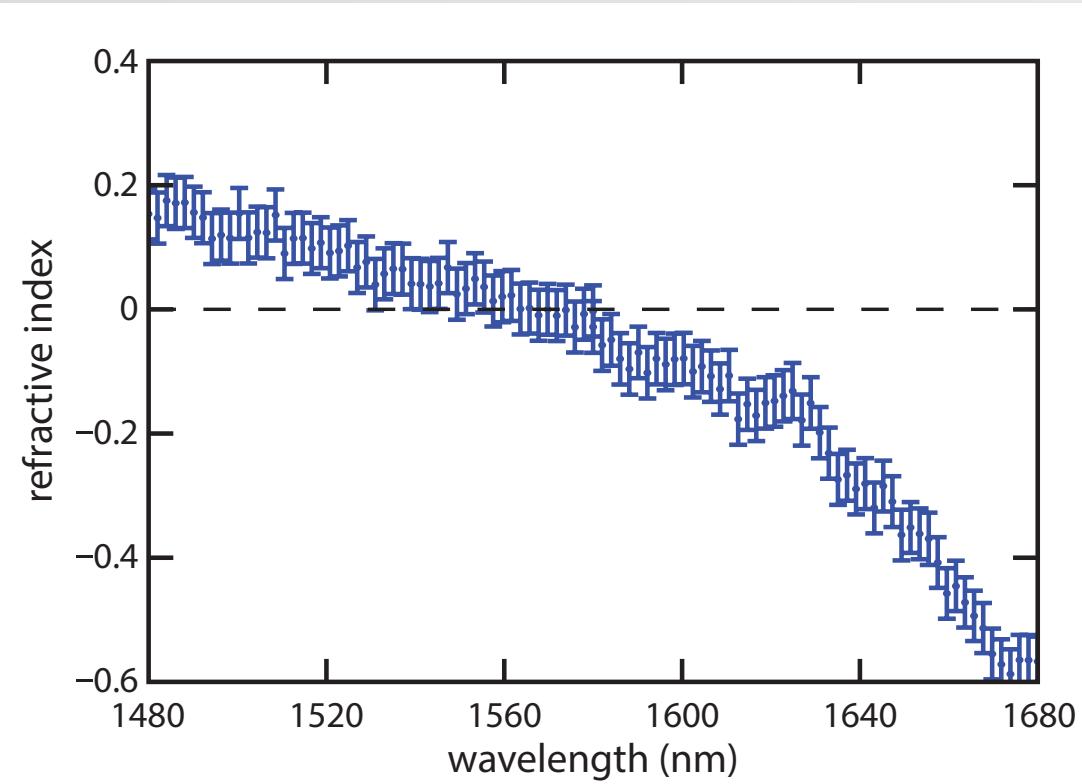


$$n_{\text{prism}} = n_{\text{slab}} \frac{\sin \alpha}{\sin 45^\circ}$$

1 index

2 zero index

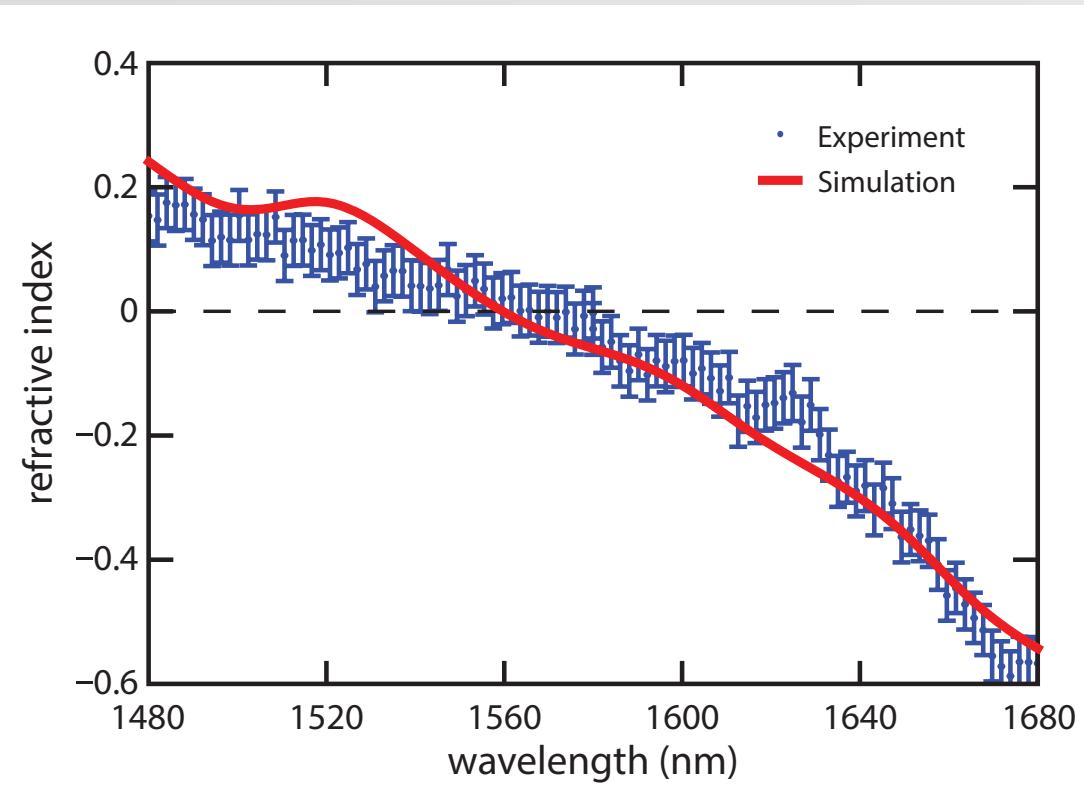
Wavelength dependence of index



1 index

2 zero index

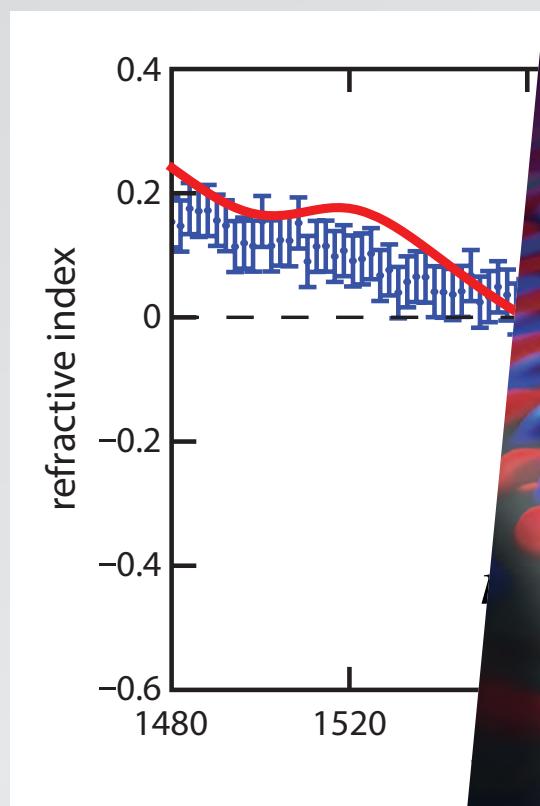
Wavelength dependence of index



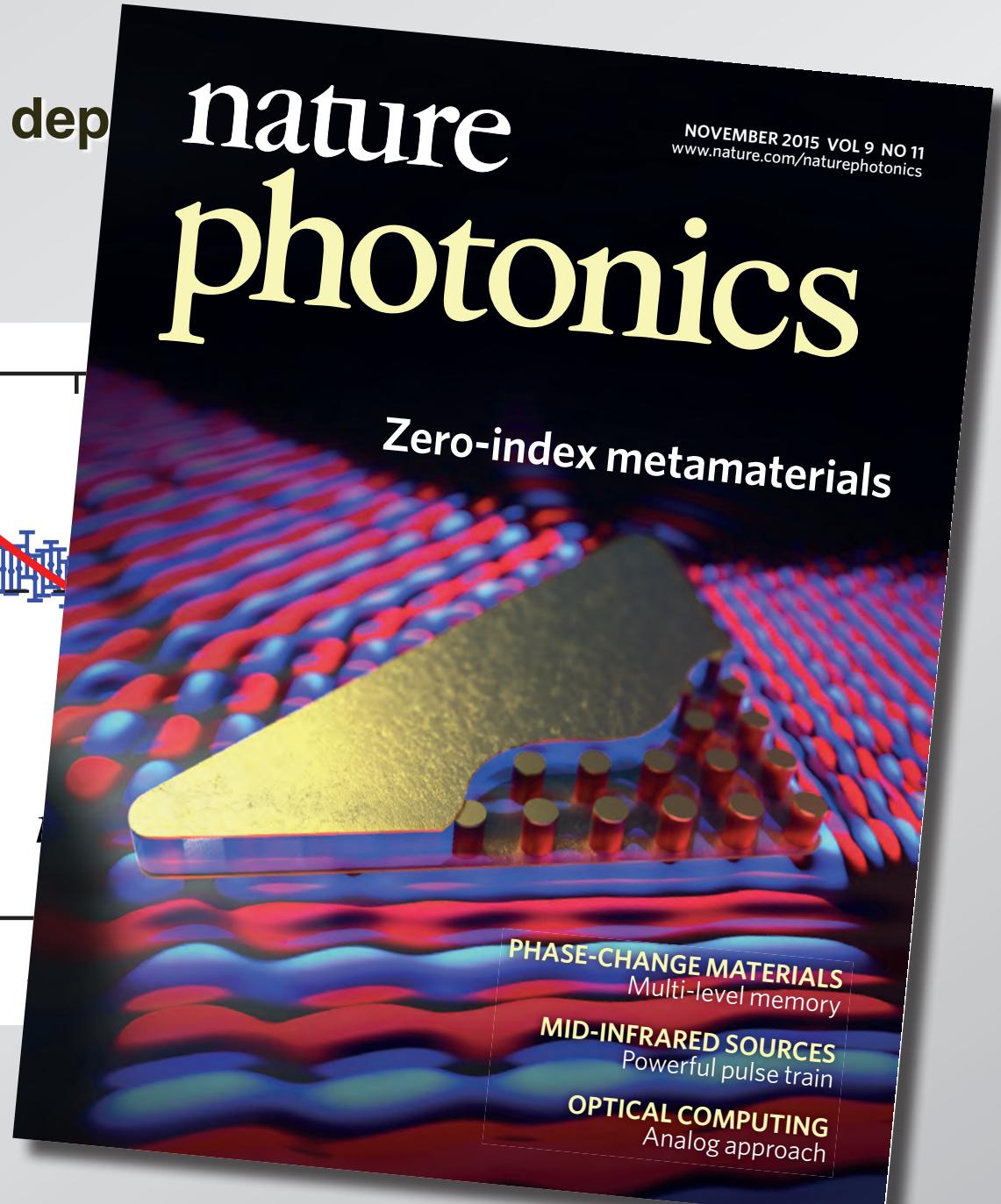
1 index

2 zero index

Wavelength dep



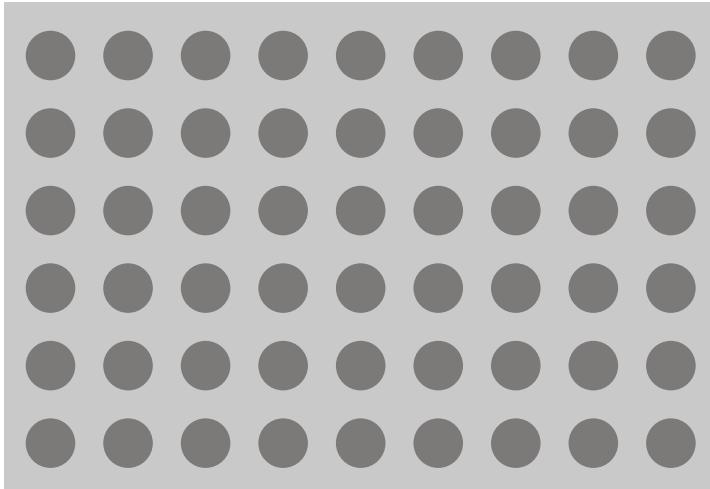
2 zero index



1 index

simplify fabrication

pillar array

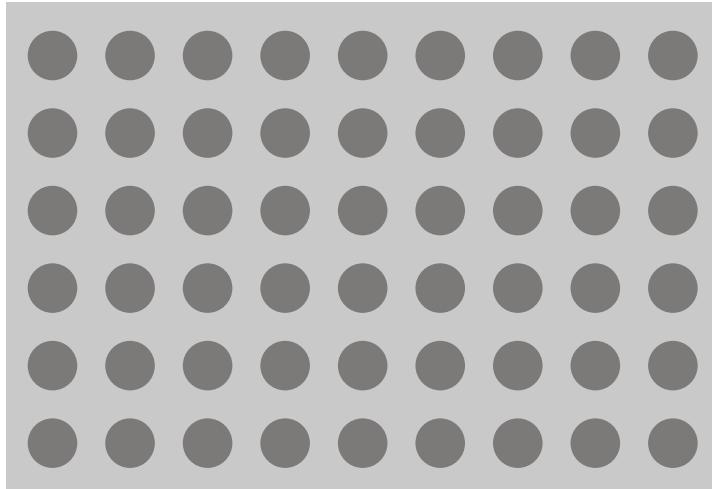


1 index

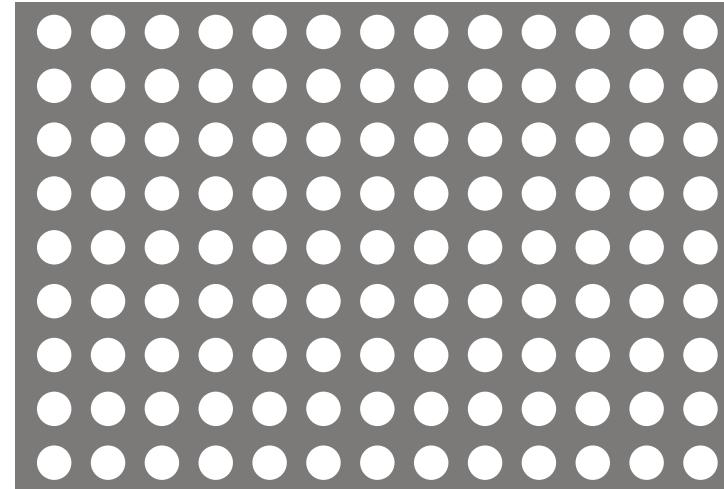
2 zero index

simplify fabrication

pillar array



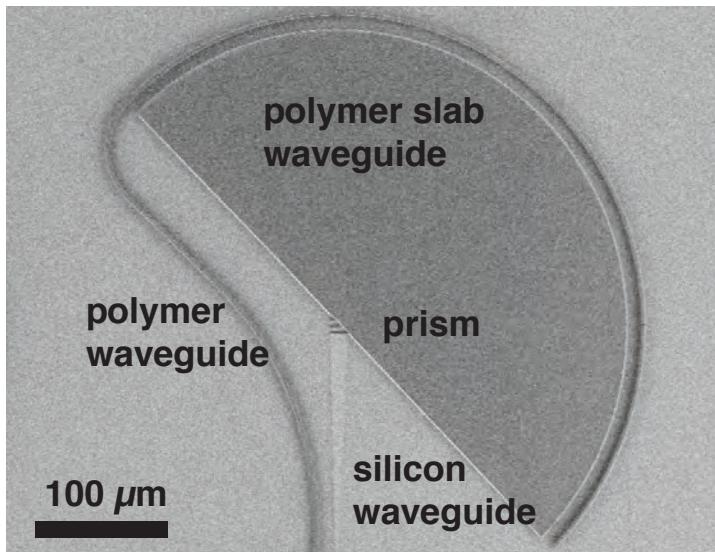
airhole array



1 index

2 zero index

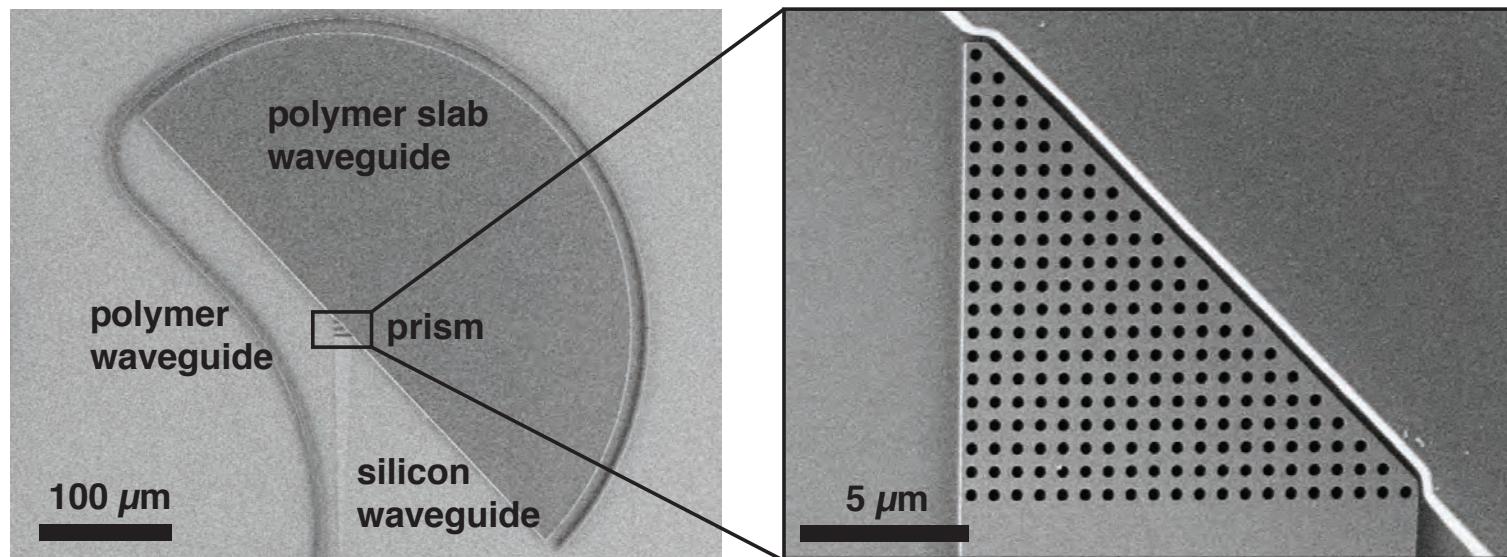
simplify fabrication



1 index

2 zero index

simplify fabrication

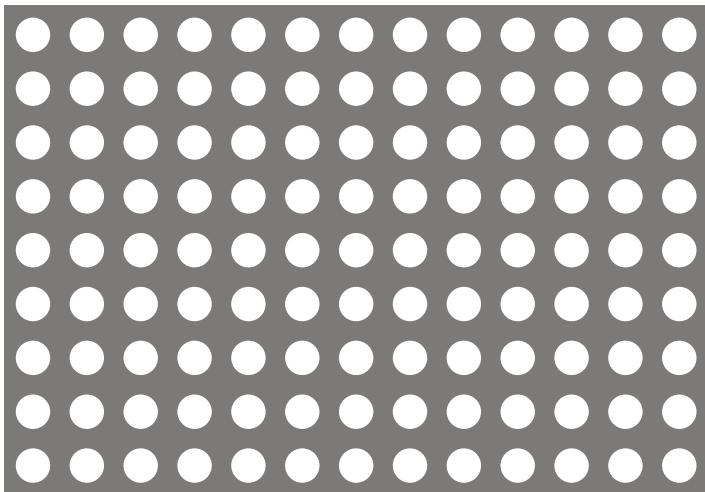


1 index

2 zero index

simplify further!

airhole array

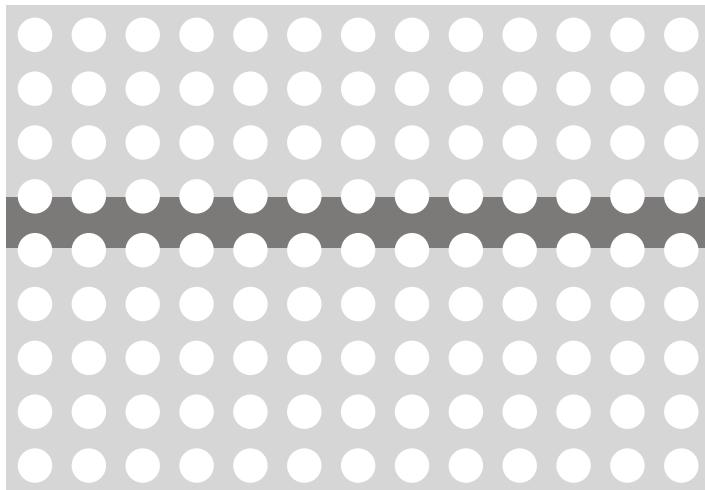


1 index

2 zero index

simplify further!

airhole array

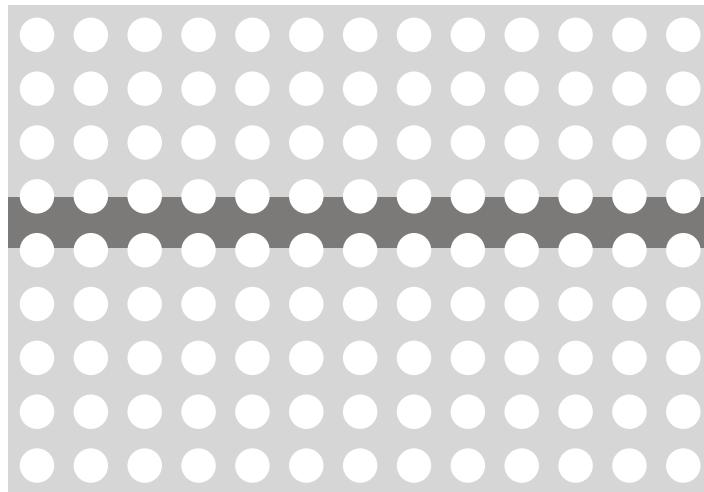


1 index

2 zero index

simplify further!

airhole array



1D ZIM waveguide

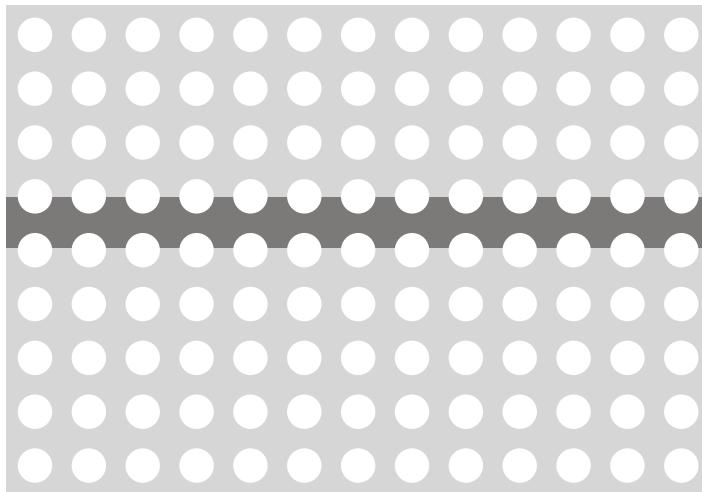


1 index

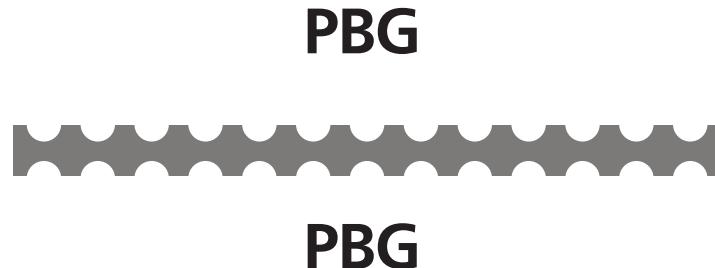
2 zero index

simplify further!

airhole array



1D ZIM waveguide



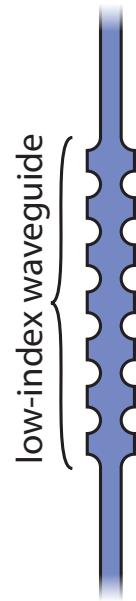
PBG

PBG

1 index

2 zero index

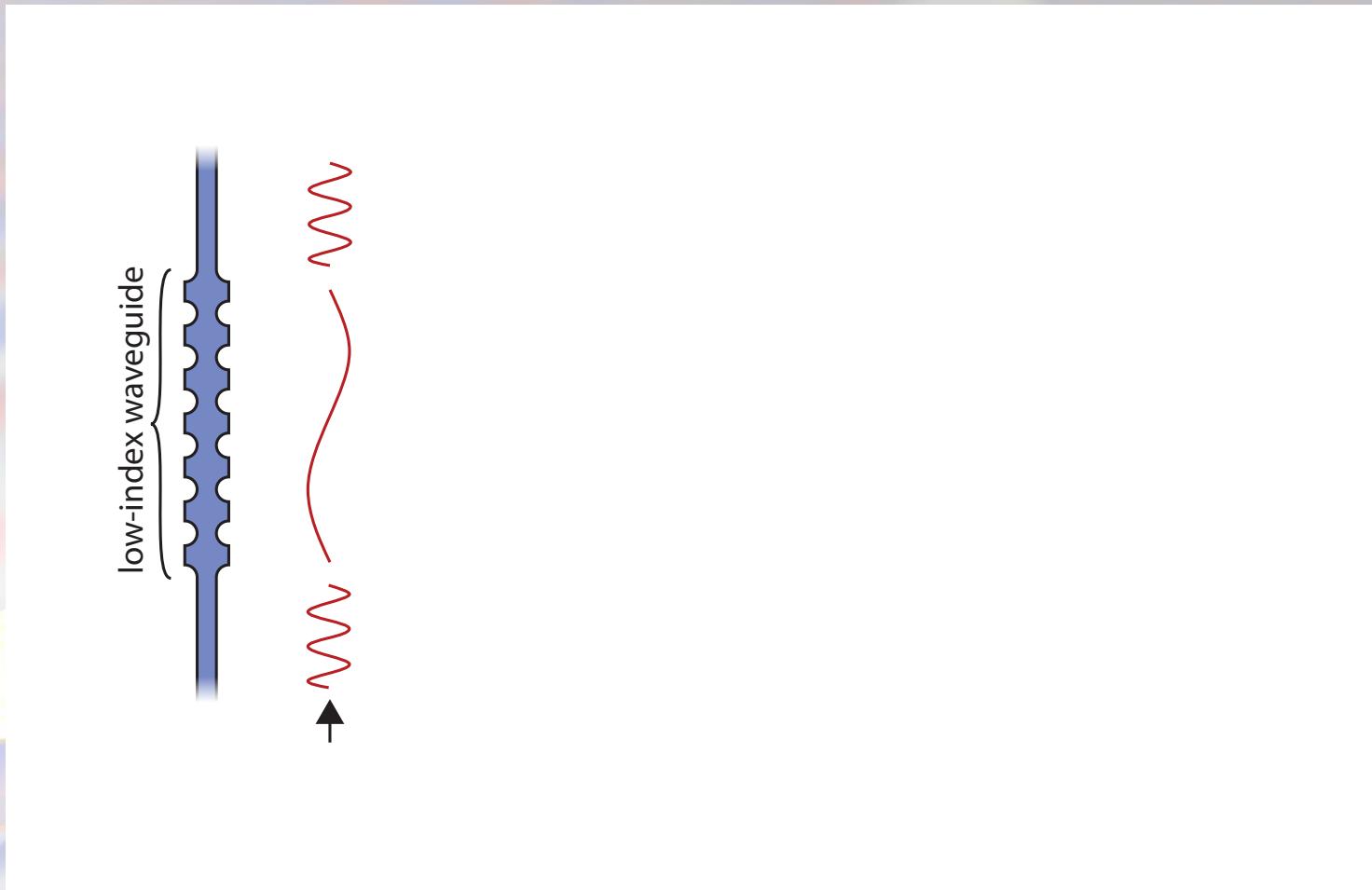
waveguiding



1 index

2 zero index

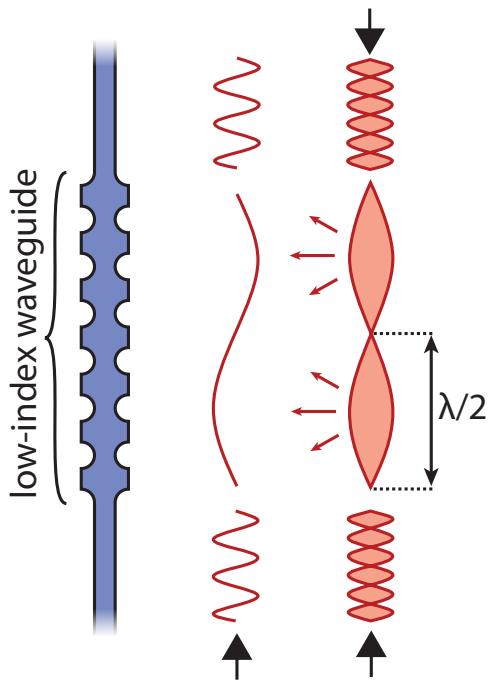
waveguiding



1 index

2 zero index

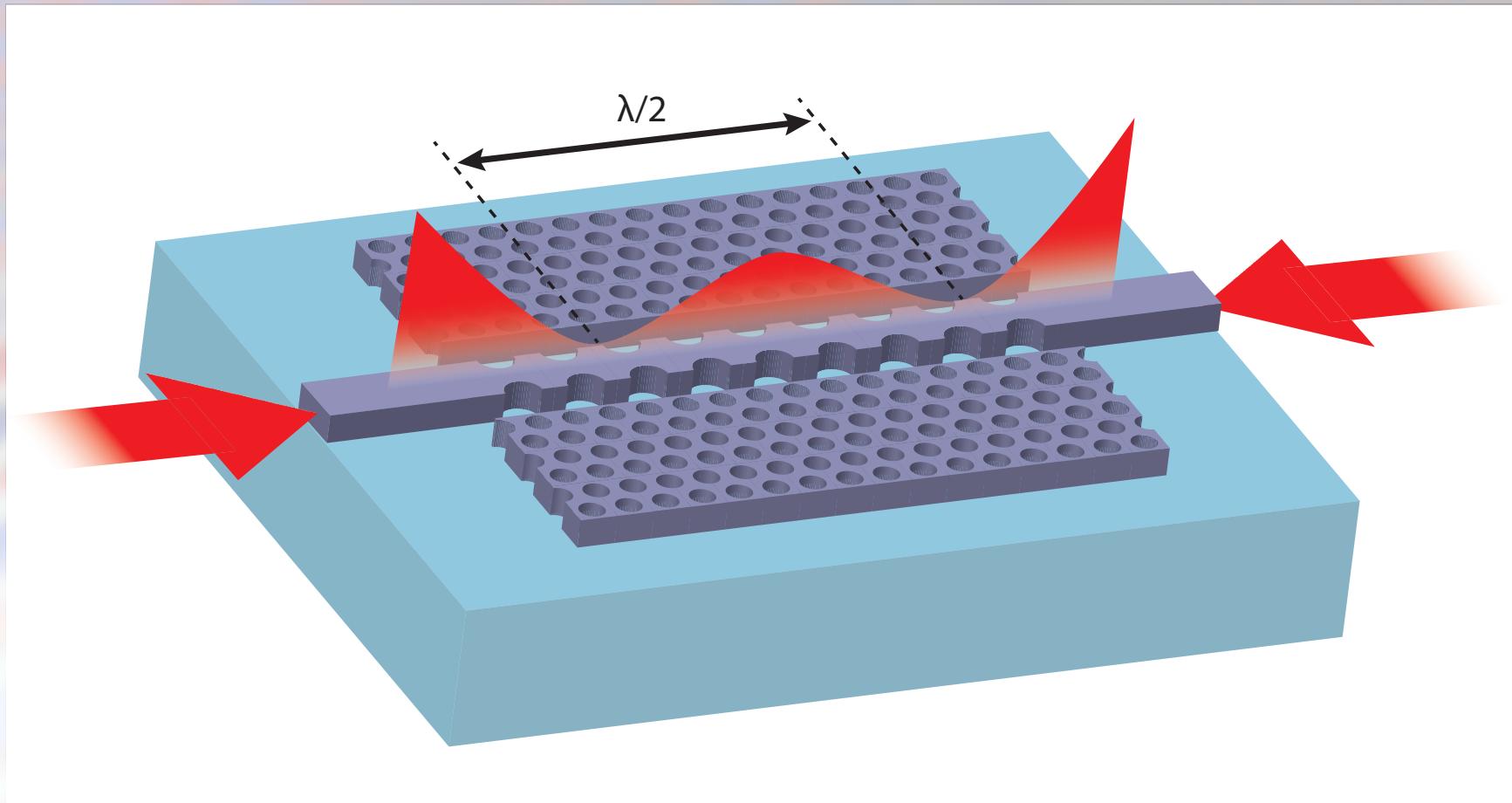
waveguiding



1 index

2 zero index

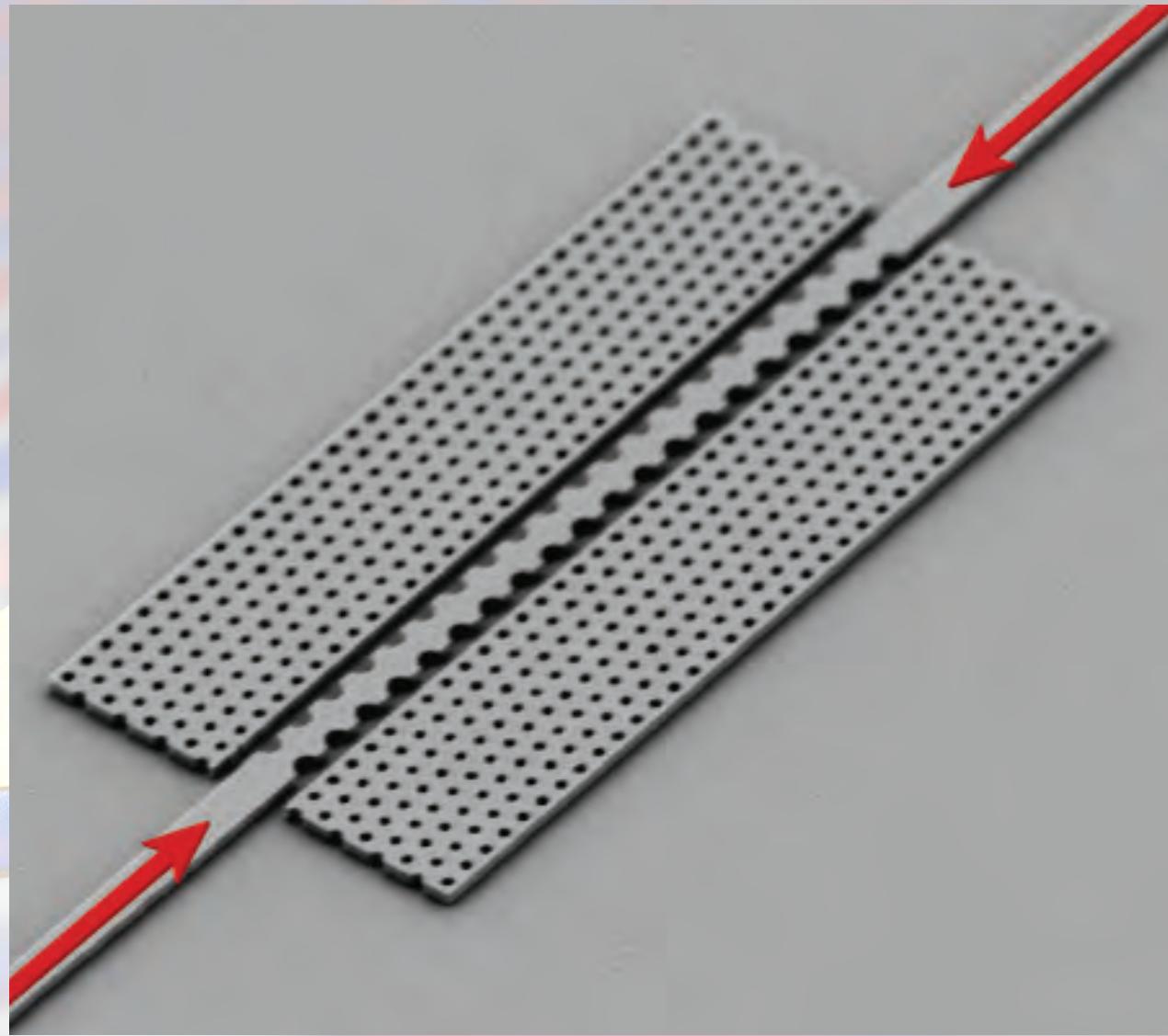
look at standing waves



1 index

2 zero index

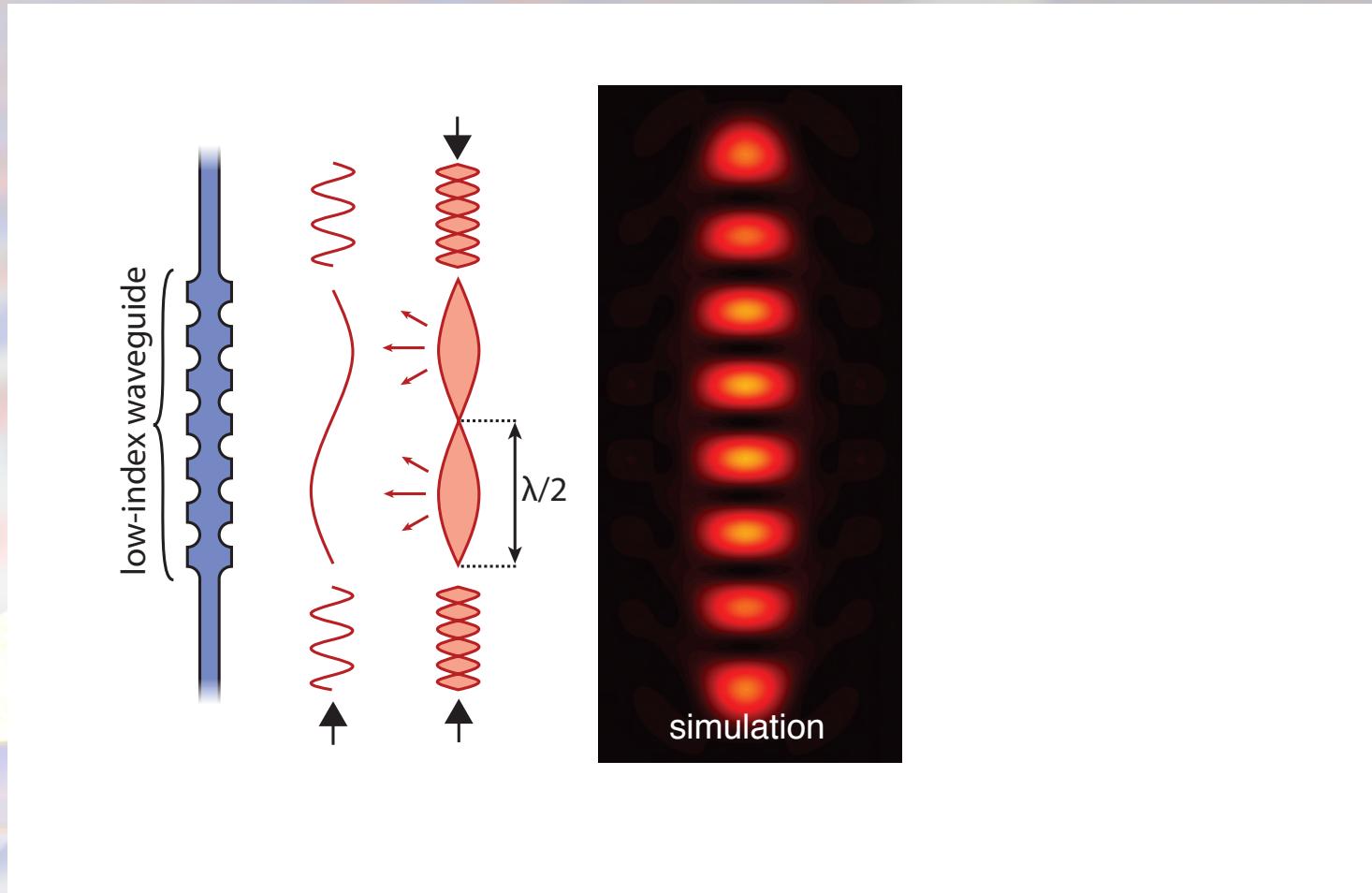
look at standing waves



1 index

2 zero index

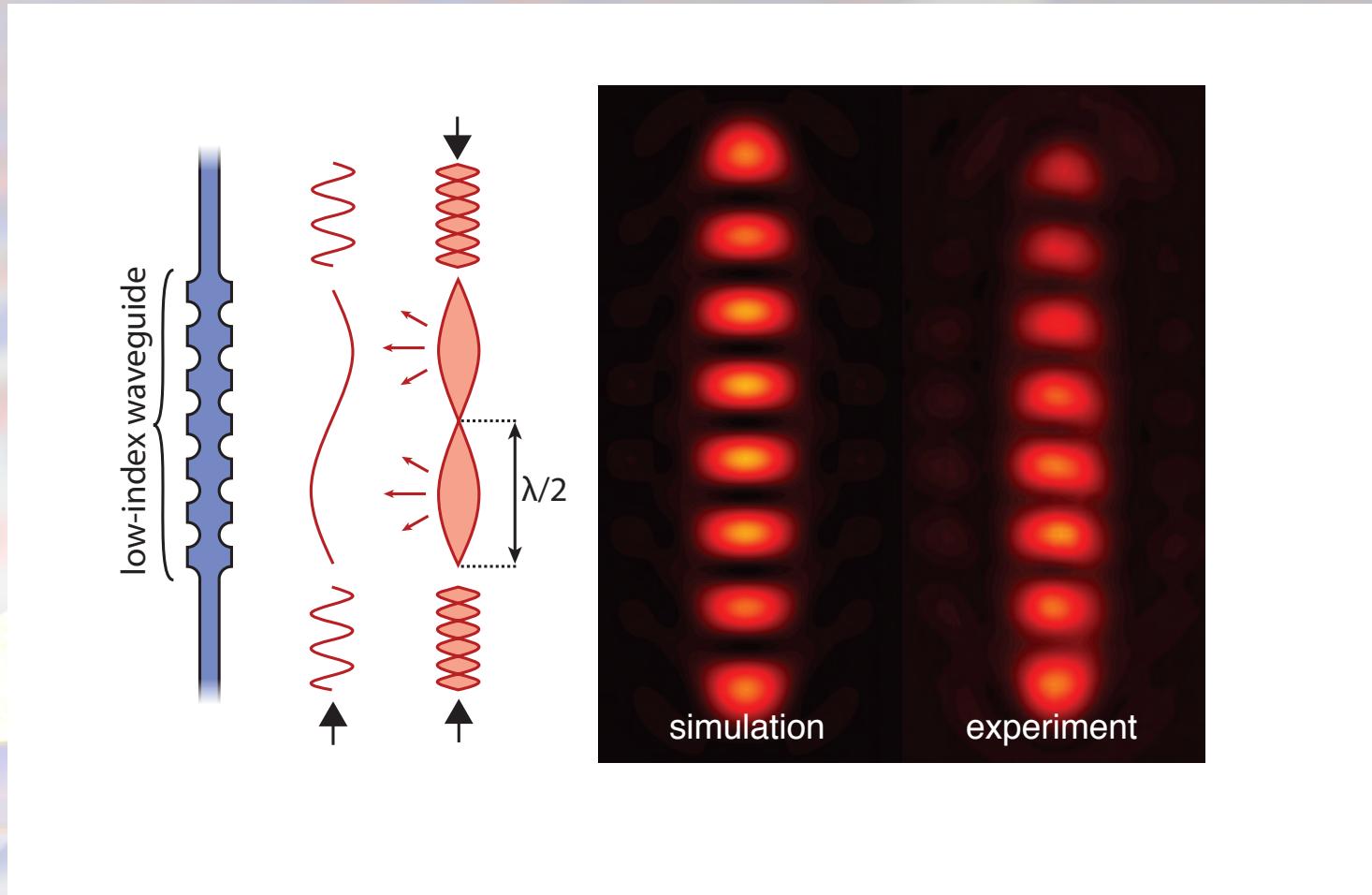
look at standing waves



1 index

2 zero index

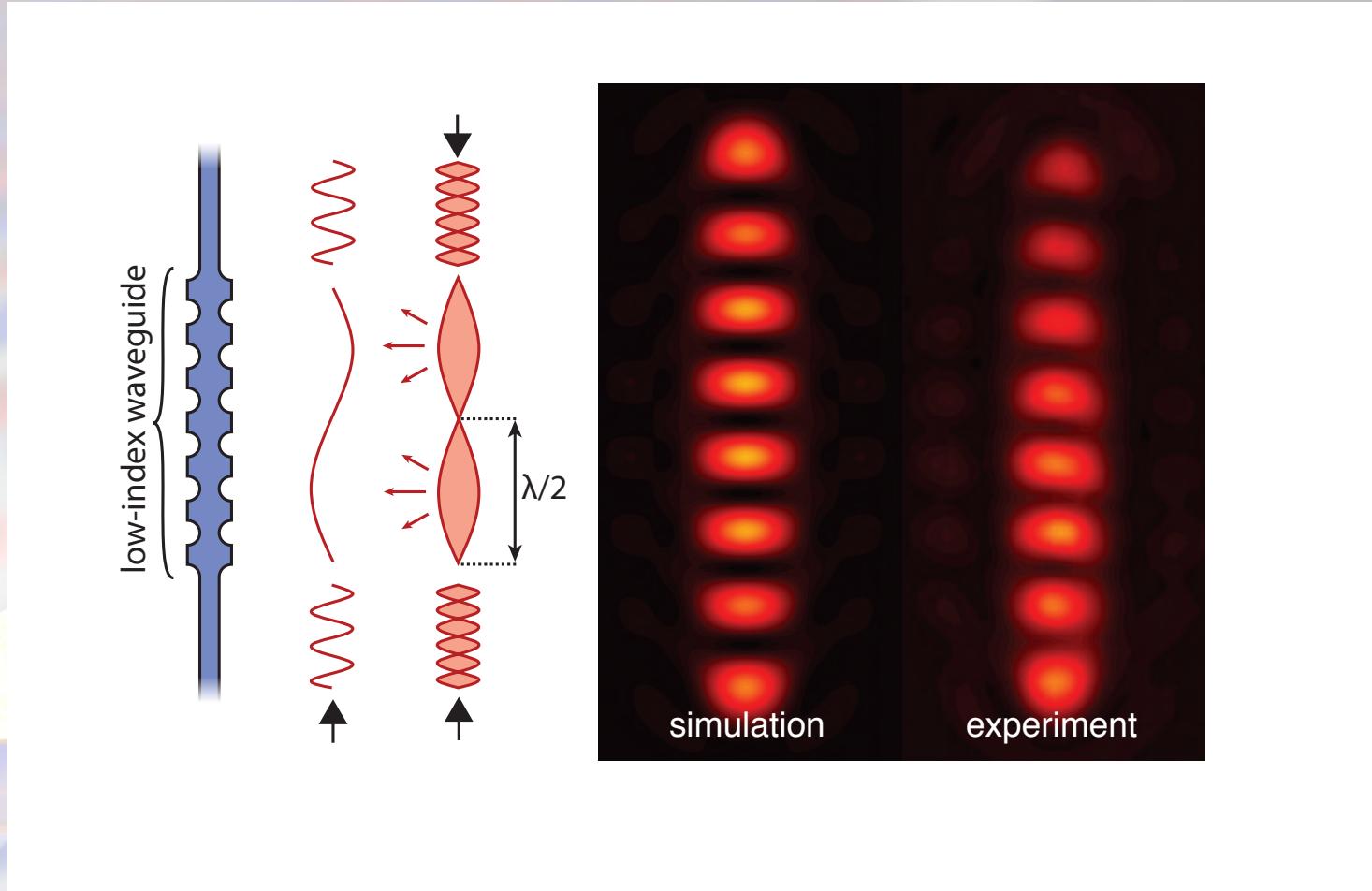
look at standing waves



1 index

2 zero index

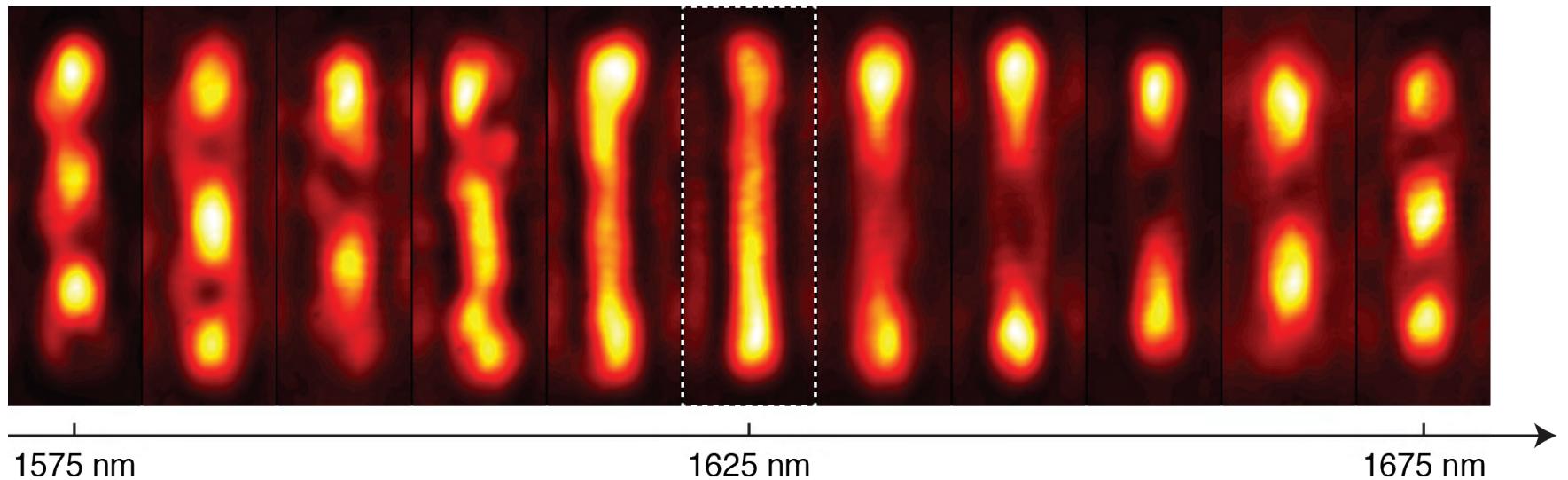
direct observation of effective wavelength!!



1 index

2 zero index

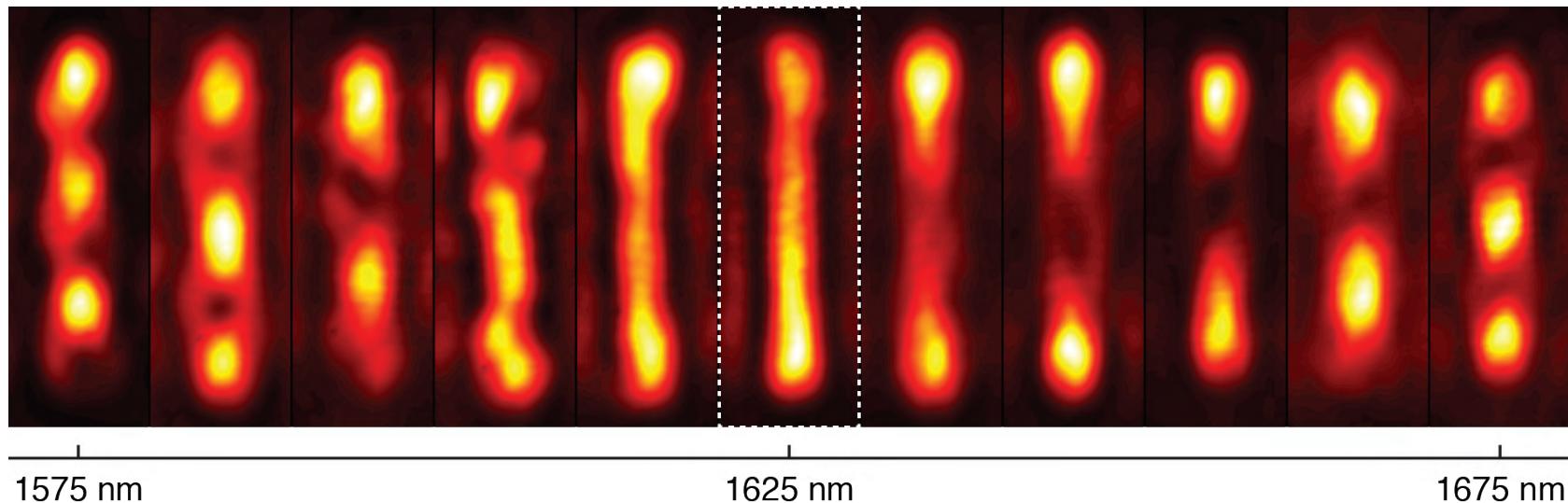
look at standing waves



1 index

2 zero index

look at standing waves

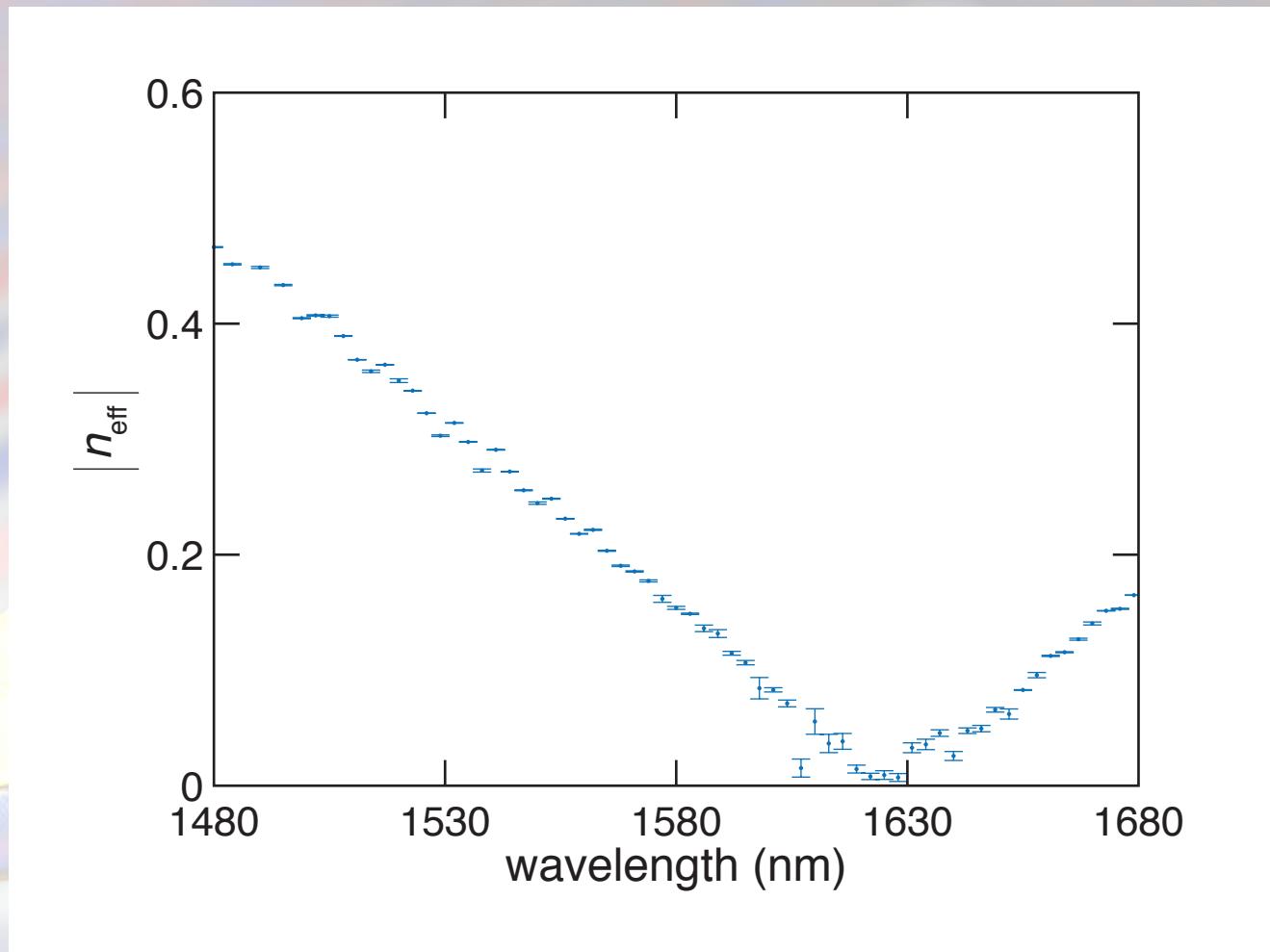


$$| n_{\text{eff}} | = \frac{\lambda_0}{\lambda_{\text{eff}}}$$

1 index

2 zero index

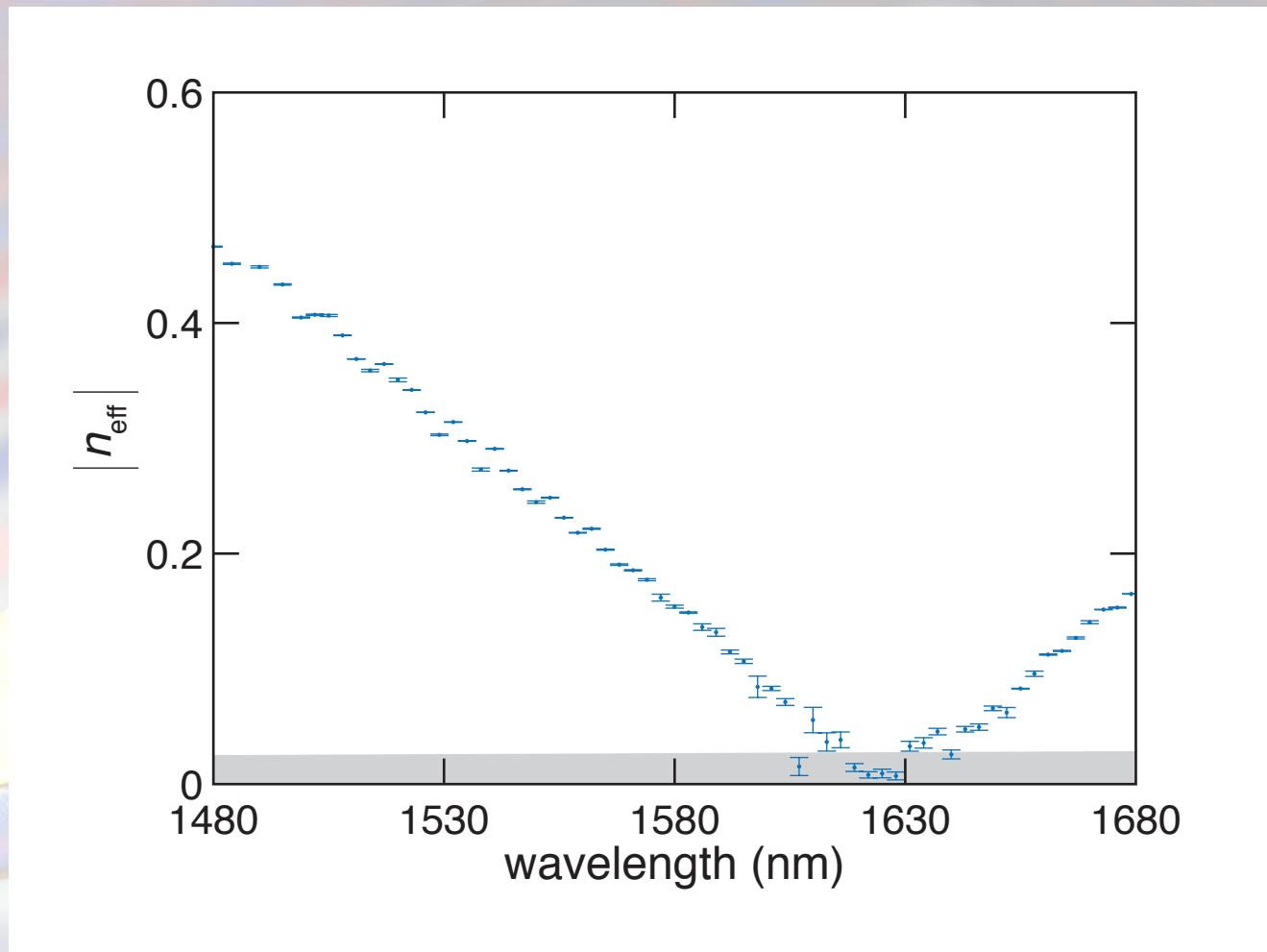
comparison of experiment and simulation



1 index

2 zero index

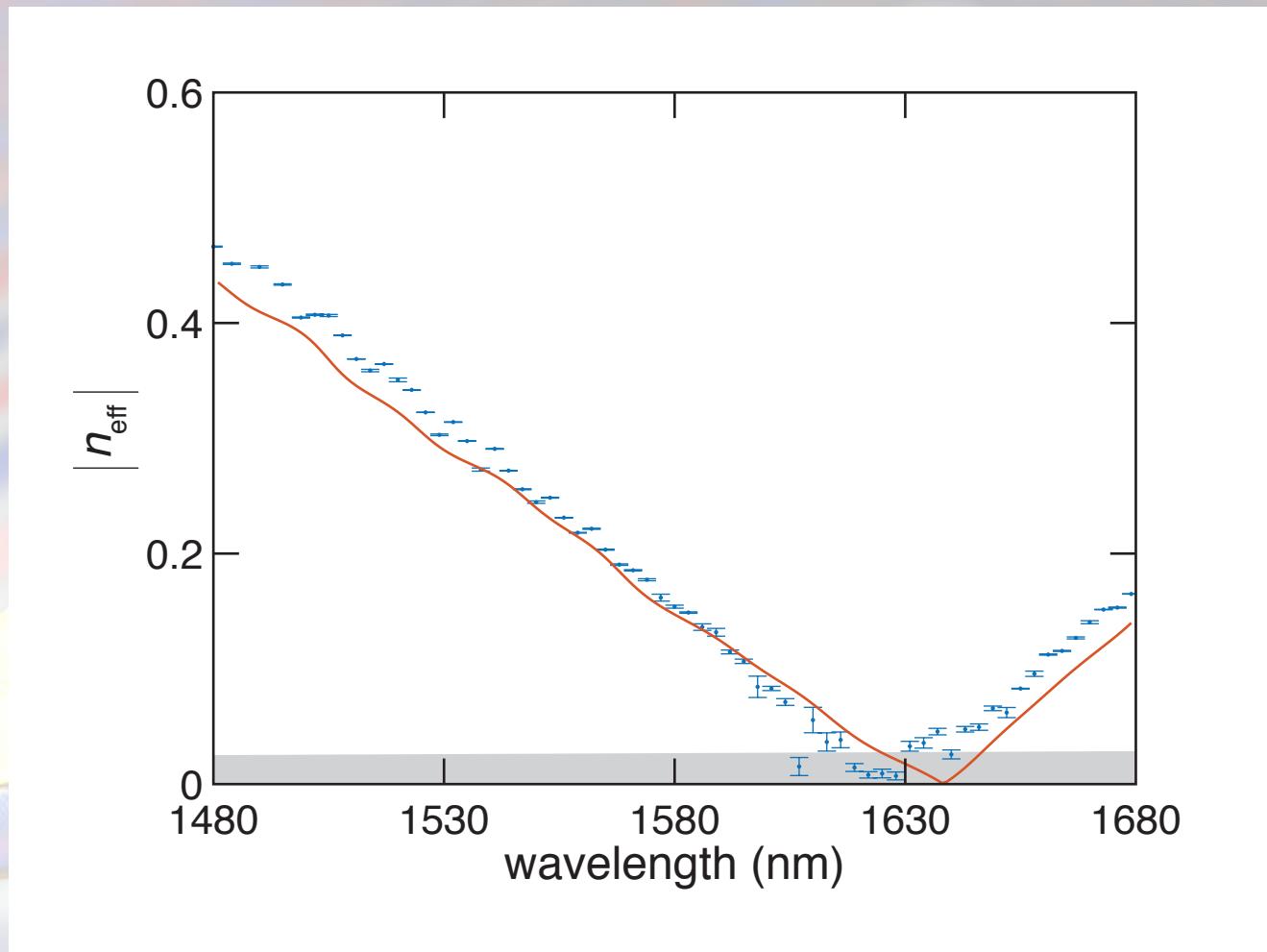
comparison of experiment and simulation



1 index

2 zero index

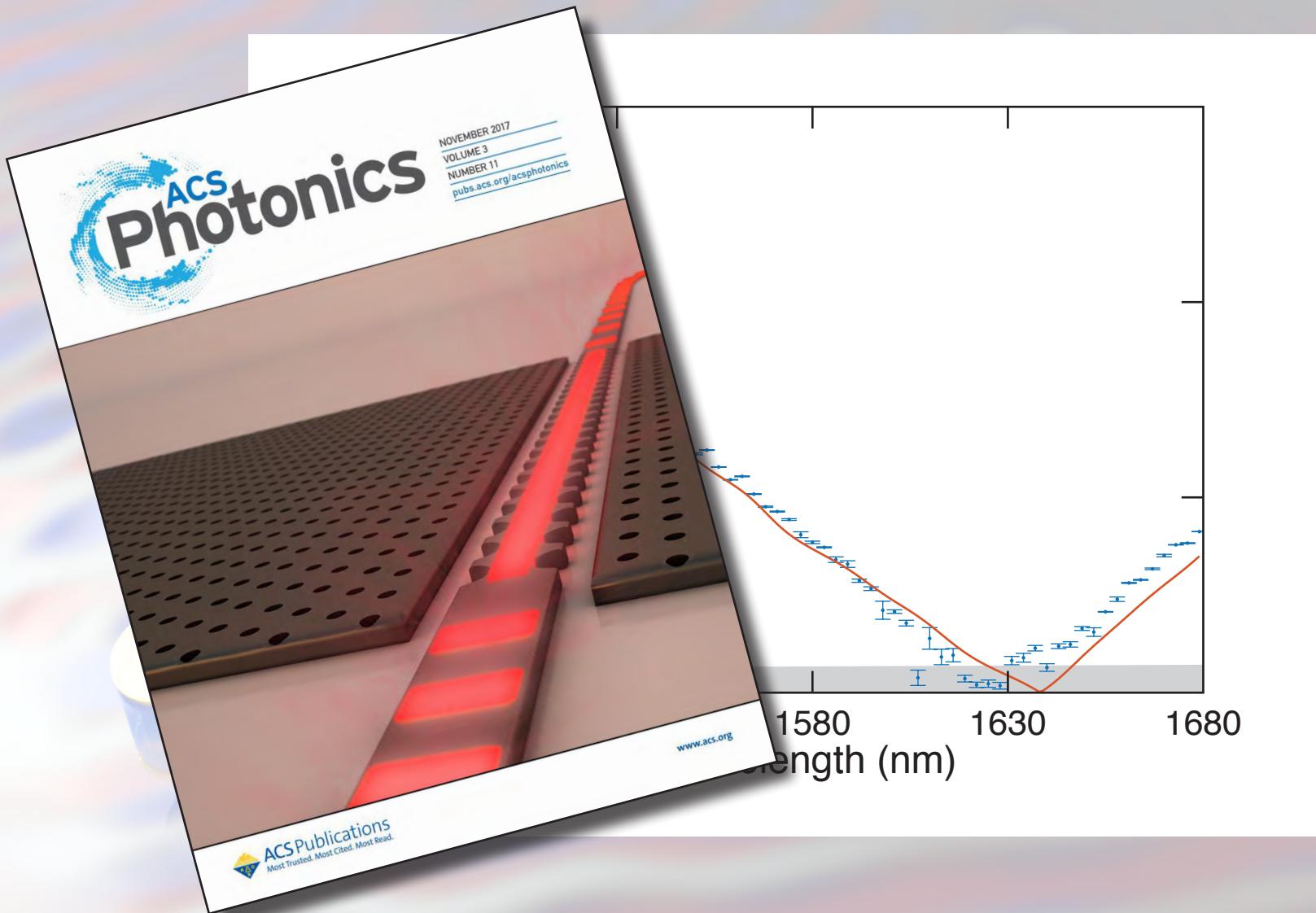
comparison of experiment and simulation



1 index

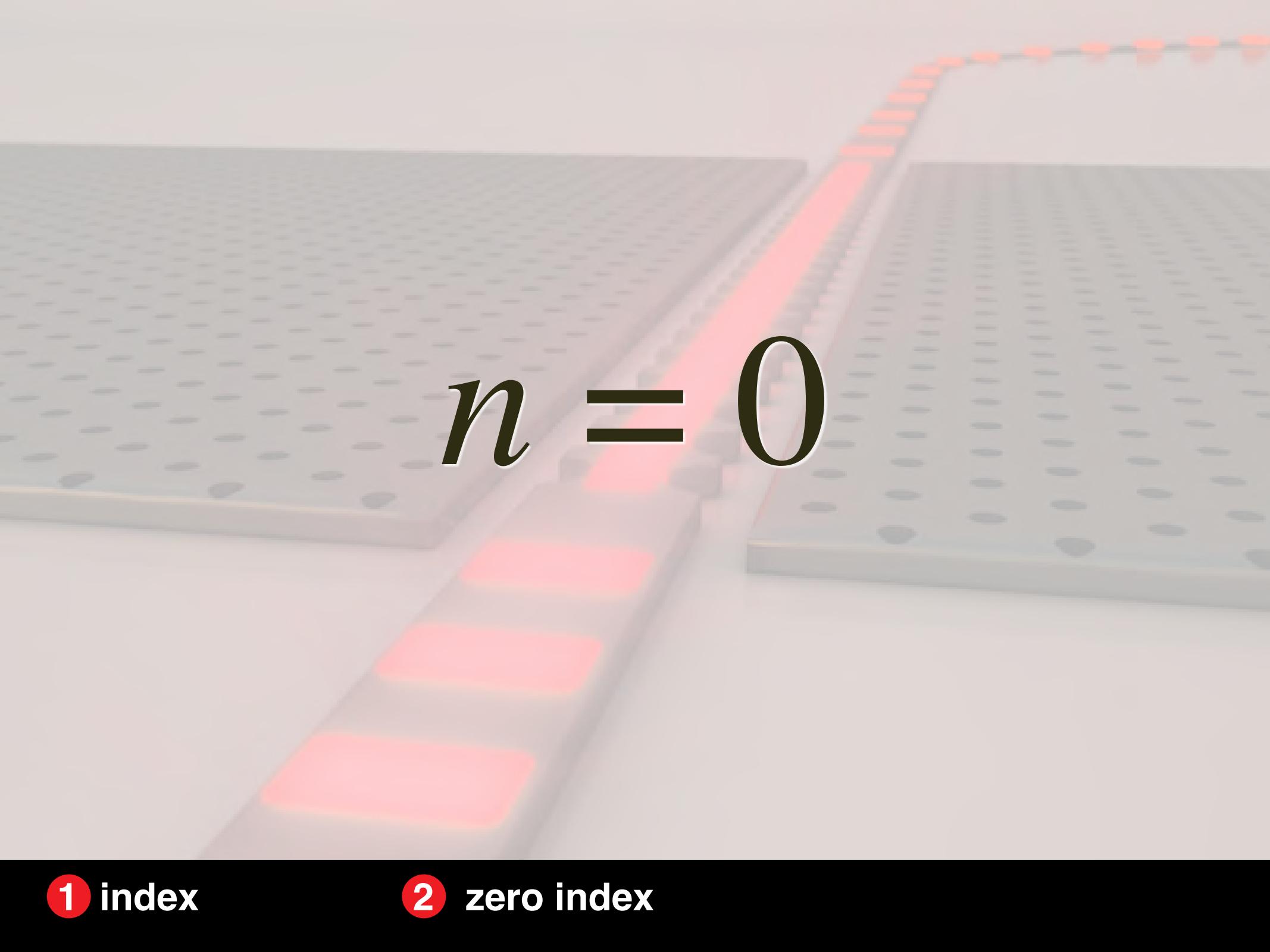
2 zero index

comparison of experiment and simulation



1 index

2 zero index



$n = 0$

1 index

2 zero index

(extreme) opportunities

relaxed phase matching constraints as $k \rightarrow 0$

1 index

2 zero index

(extreme) opportunities

PHYSICAL REVIEW LETTERS 128, 203902 (2022)

Editors' Suggestion

Relaxed Phase-Matching Constraints in Zero-Index Waveguides

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The utility of all parametric nonlinear optical processes is hampered by phase-matching requirements. Quasi-phase-matching, birefringent phase matching, and higher-order-mode phase matching have all been developed to address this constraint, but the methods demonstrated to date suffer from the inconvenience of only being phase matched for a single, specific arrangement of beams, typically copropagating, resulting in cumbersome experimental configurations and large footprints for integrated devices. Here, we experimentally demonstrate that these phase-matching requirements may be satisfied in a parametric nonlinear waveguide using two counterpropagating input and output beams when using low-index

$$v_g = \frac{d\omega}{dk}$$

1 index

2 zero index

3 zero group velocity

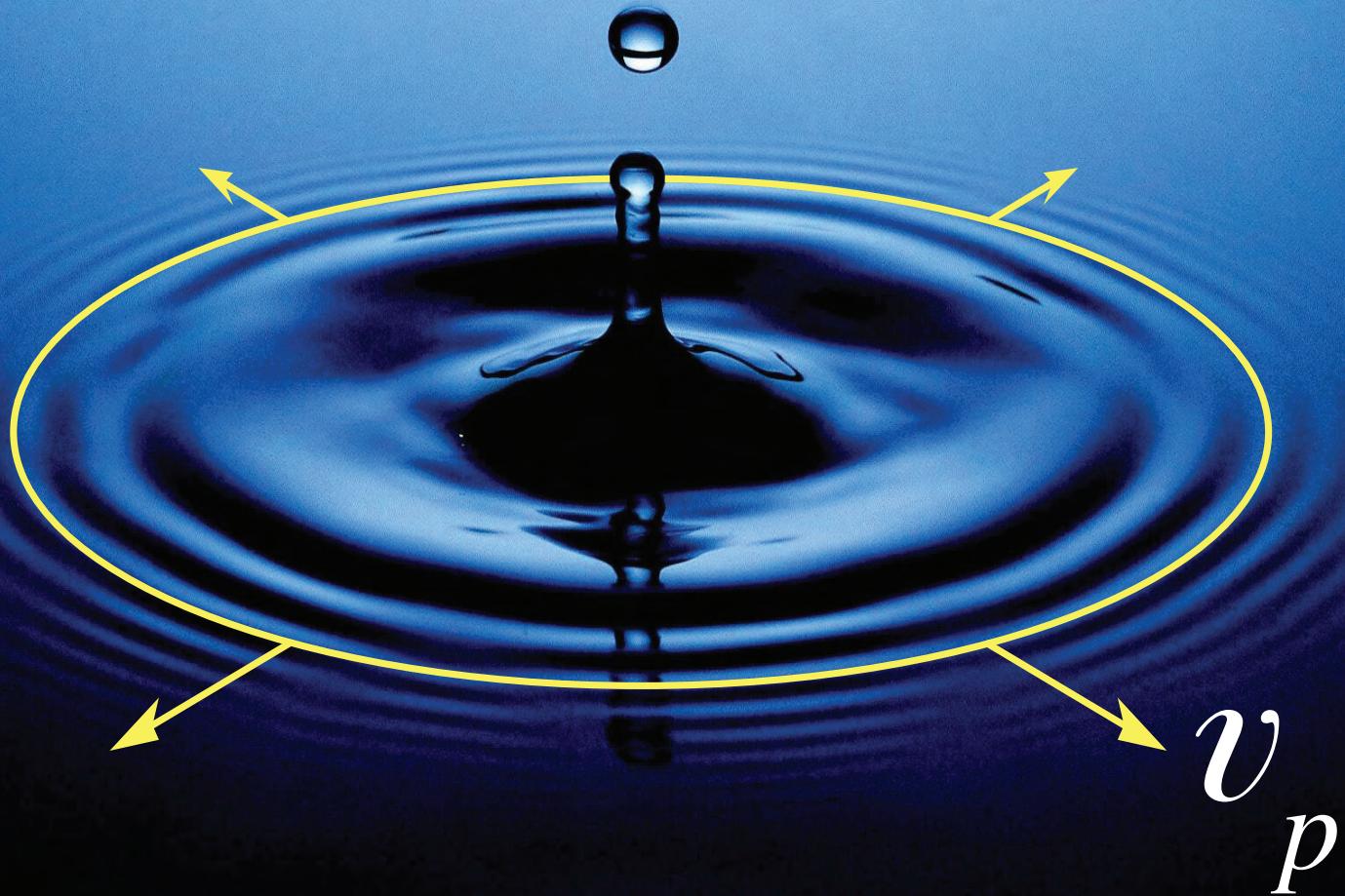


1 index

2 zero index

3 zero group velocity

phase velocity



1 index

2 zero index

3 zero group velocity

group velocity



1 index

2 zero index

3 zero group velocity

$$v_g = \frac{1}{2} v_p$$



1 index

2 zero index

3 zero group velocity

$$v_g = 0$$



1 index

2 zero index

3 zero group velocity

$$v_g = 0$$



localization

1 index

2 zero index

3 zero group velocity

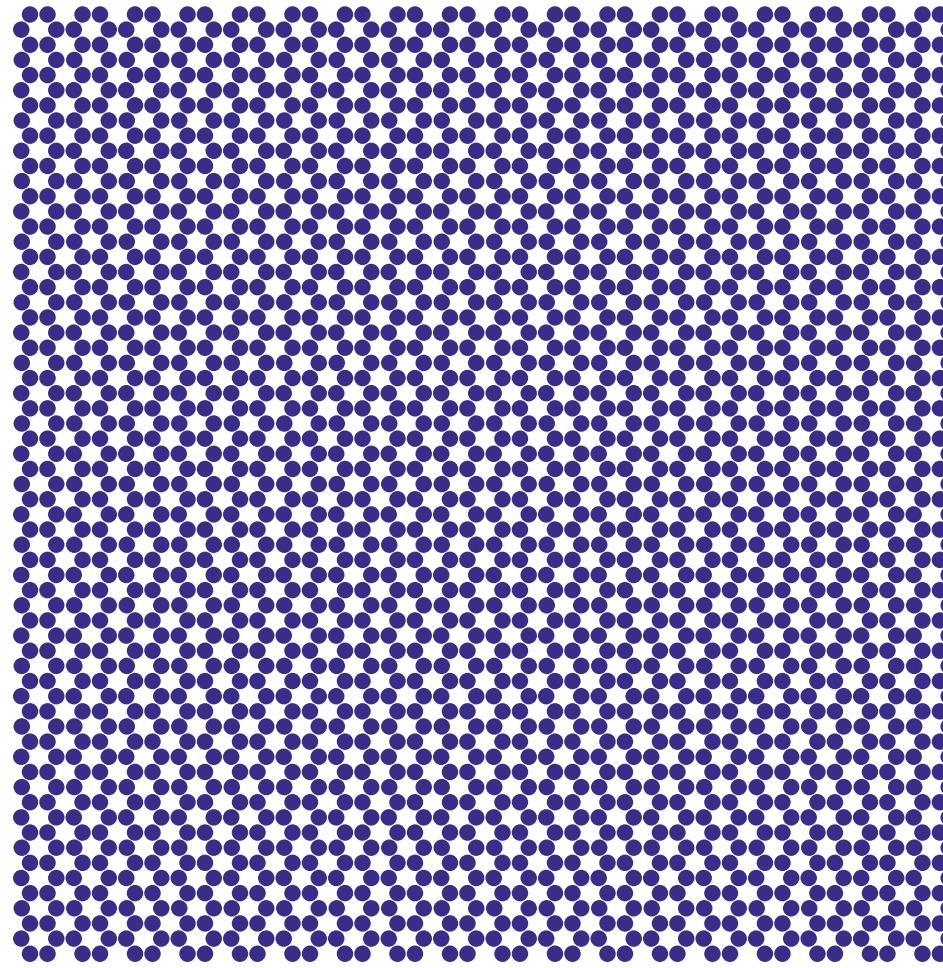


how can we localize light?

1 index

2 zero index

3 zero group velocity

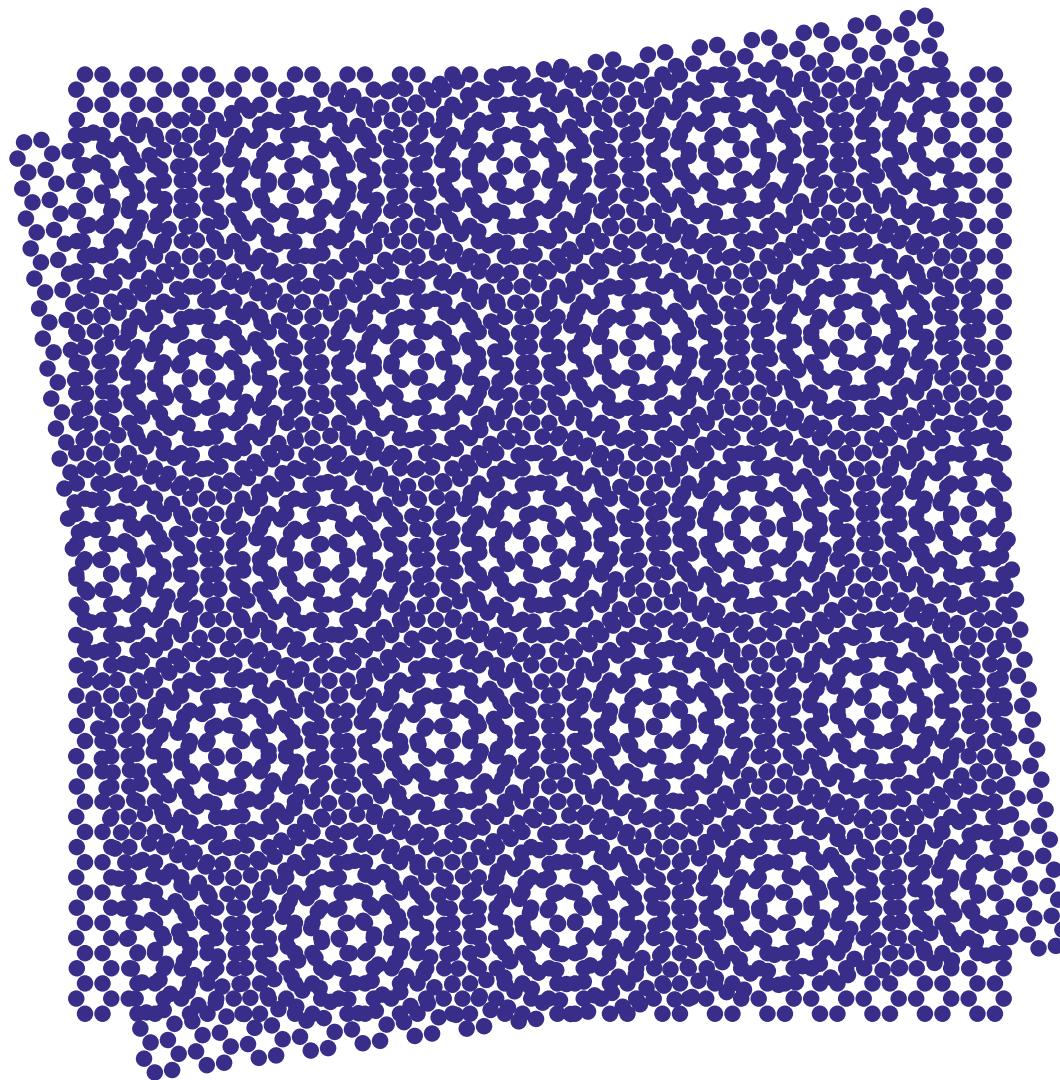


1 index

2 zero index

3 zero group velocity

8°

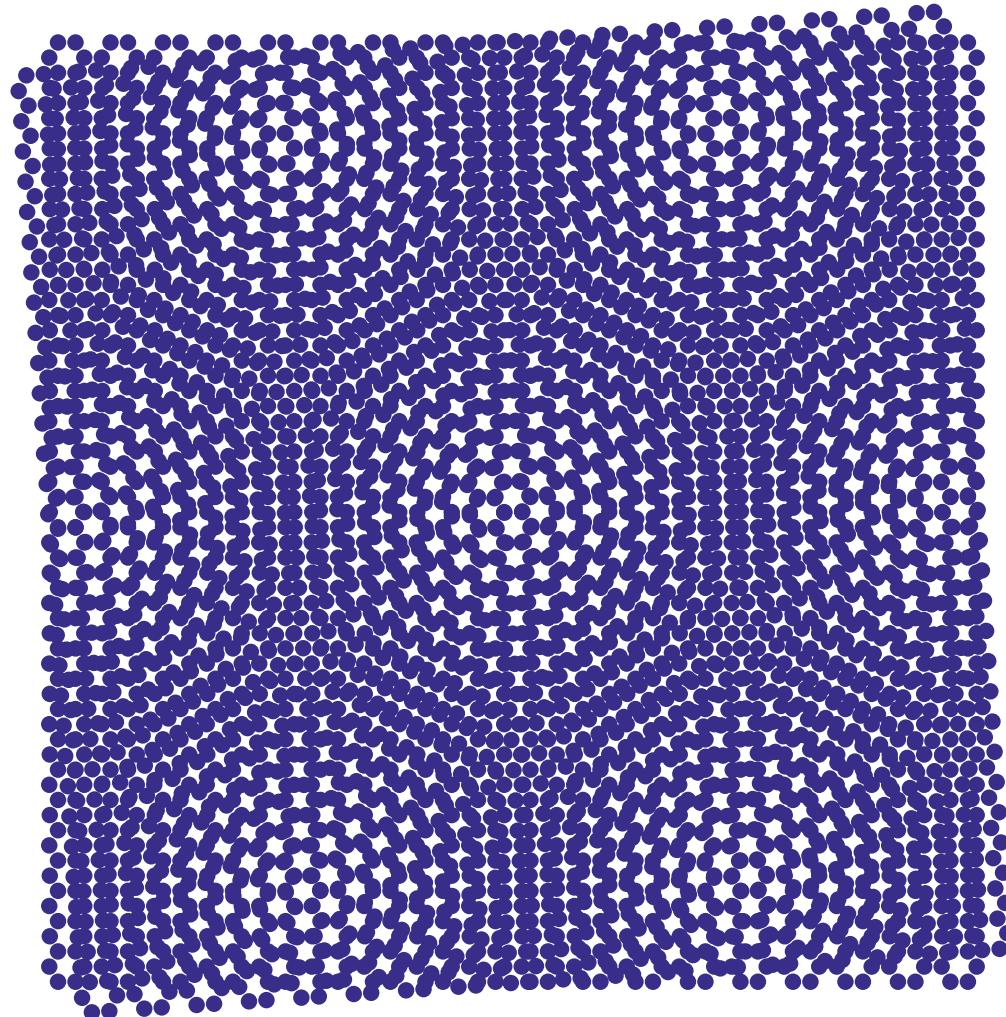


1 index

2 zero index

3 zero group velocity

4°

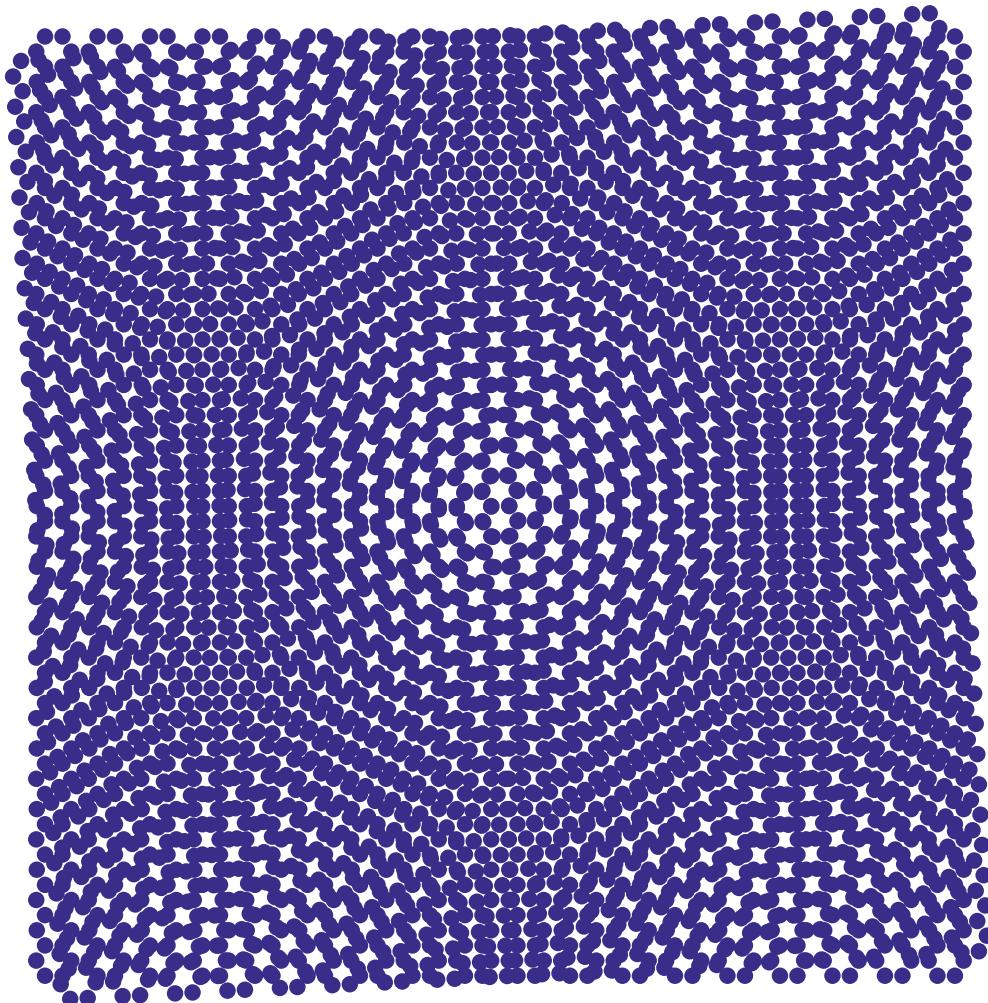


1 index

2 zero index

3 zero group velocity

3°

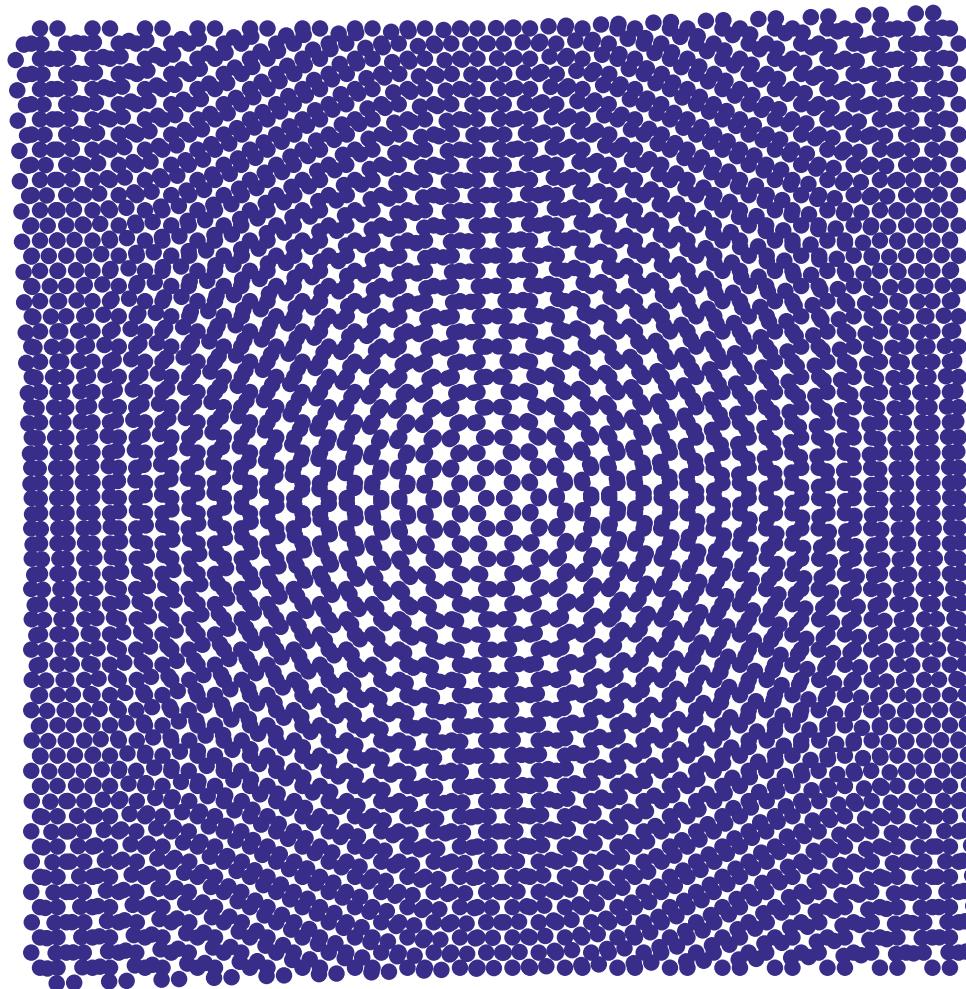


1 index

2 zero index

3 zero group velocity

2°

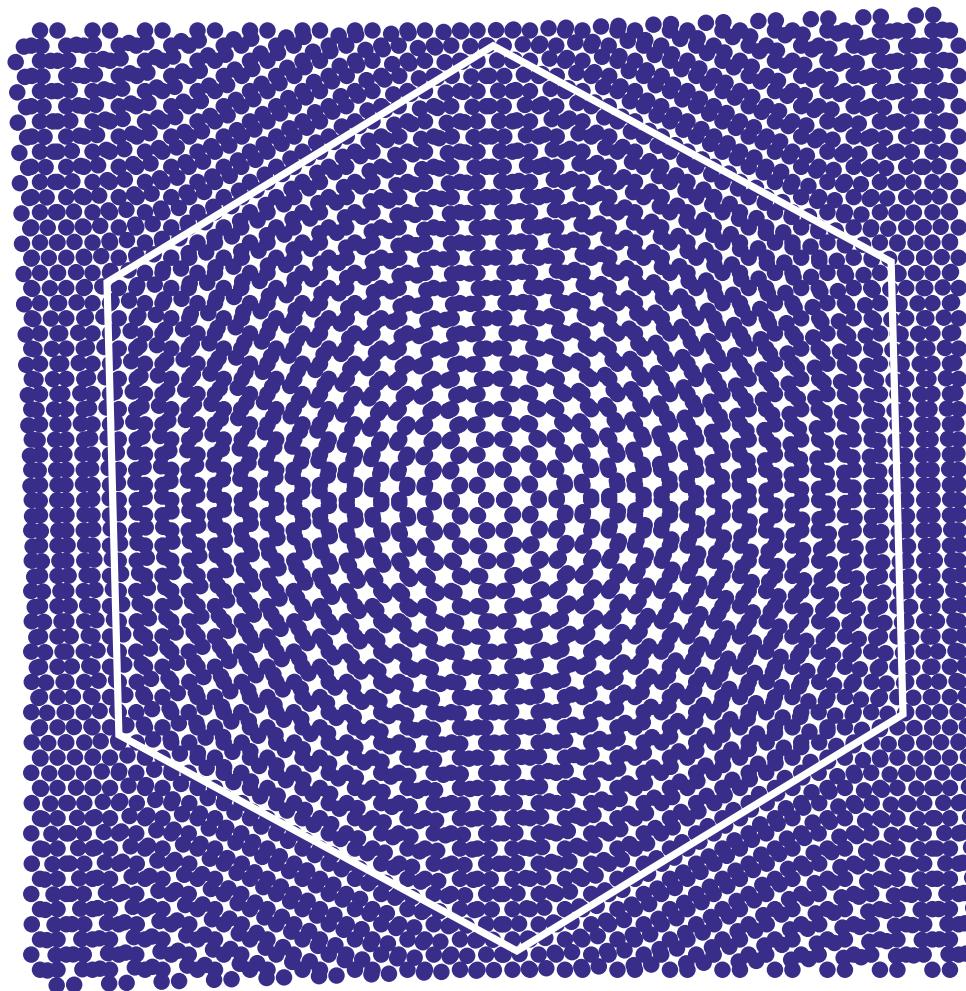


1 index

2 zero index

3 zero group velocity

2°

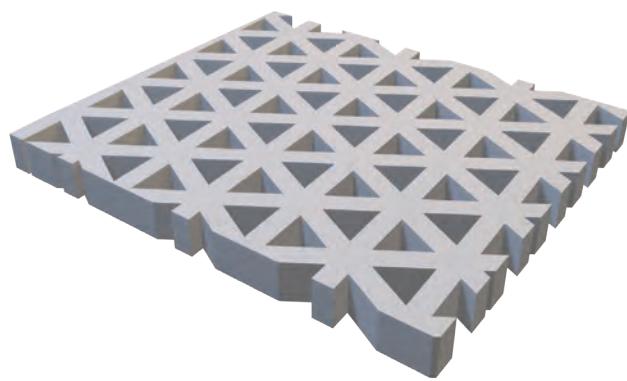


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

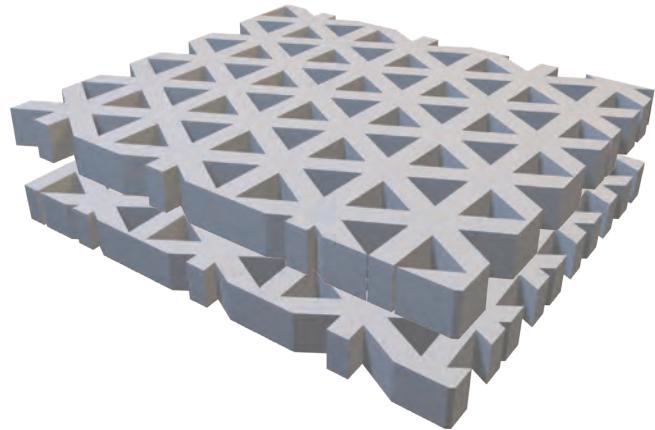


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

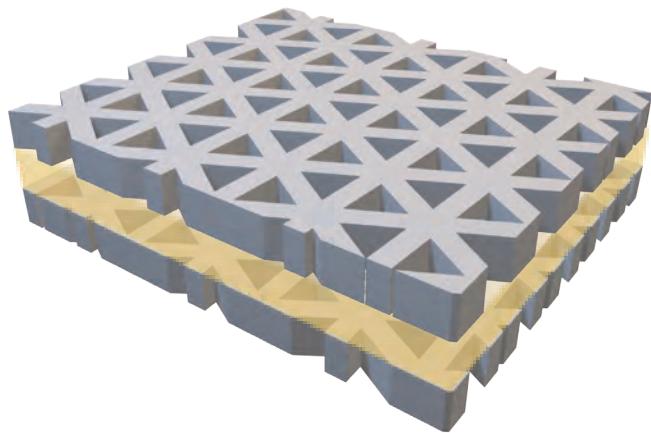


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

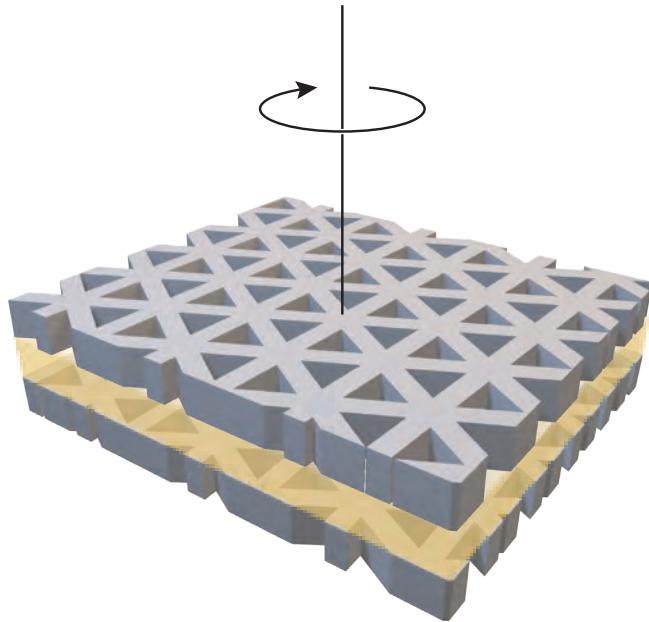


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

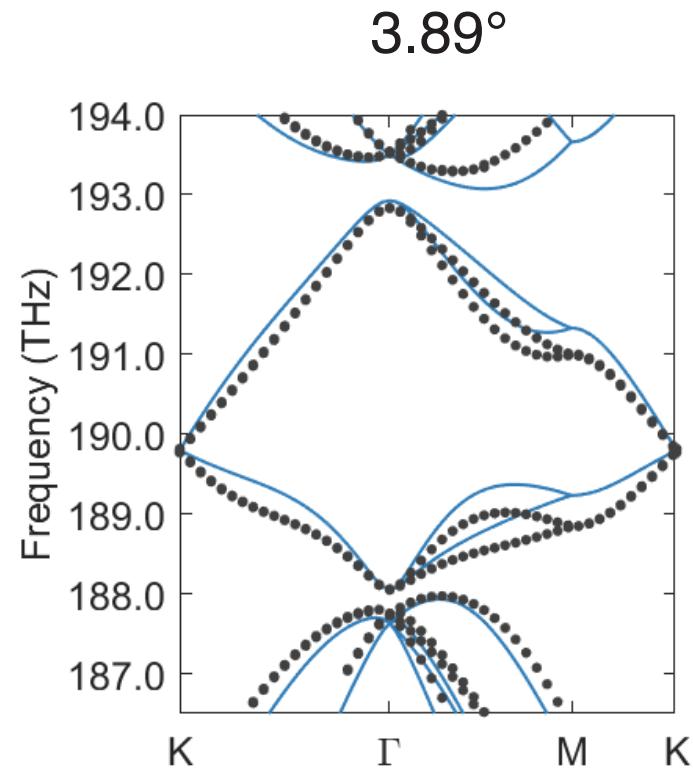
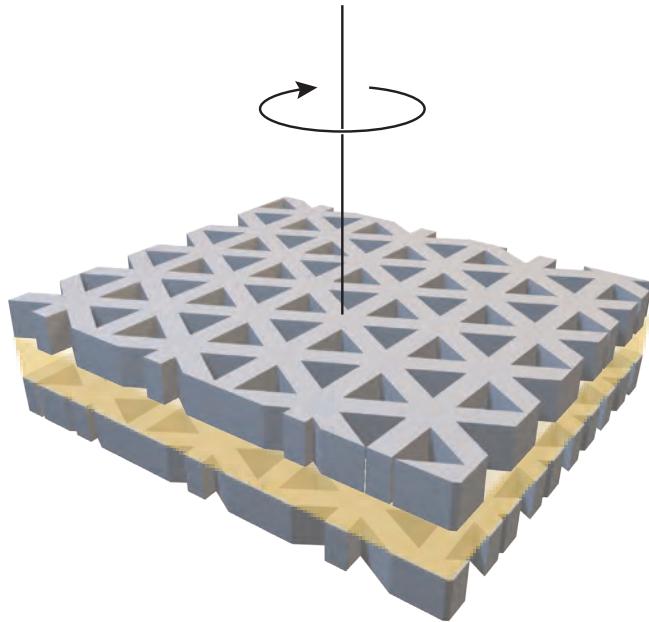


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

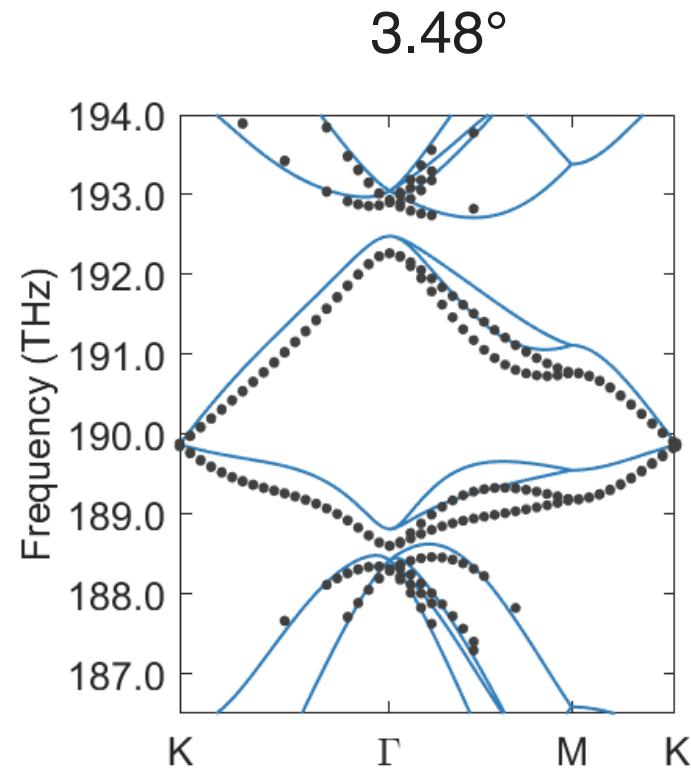
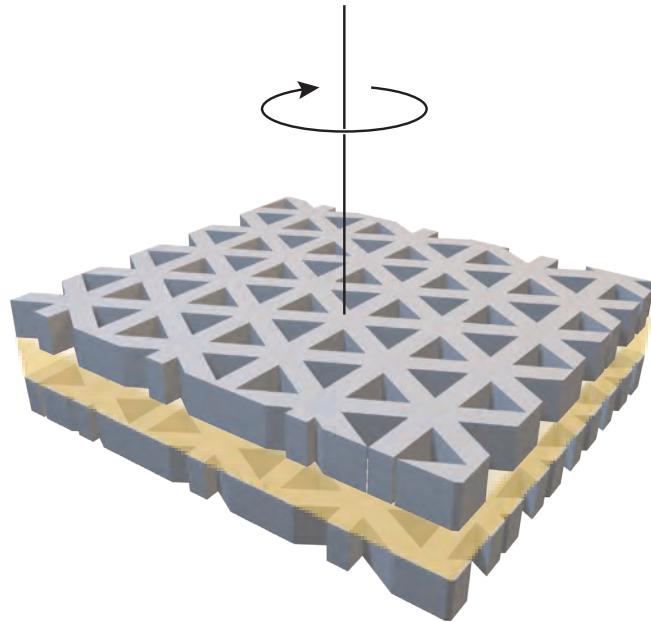


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

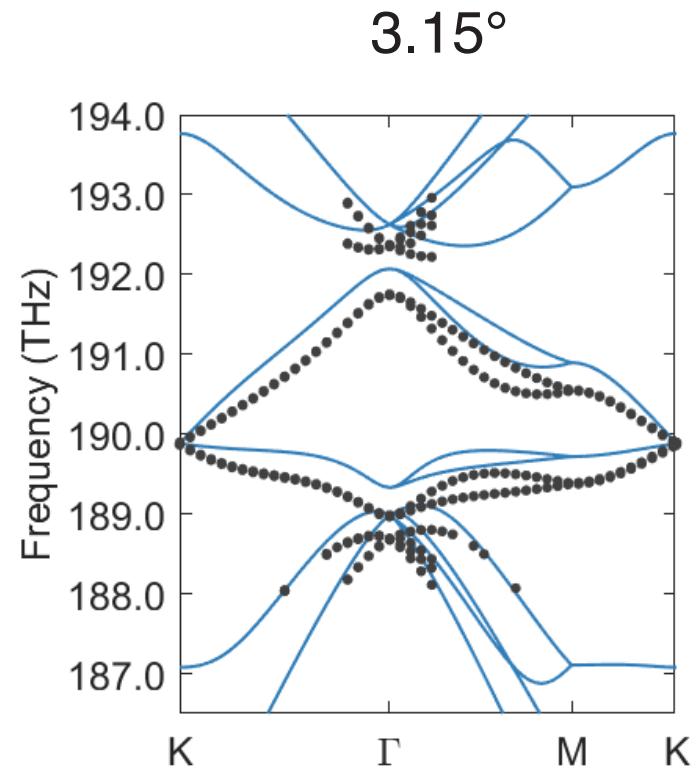
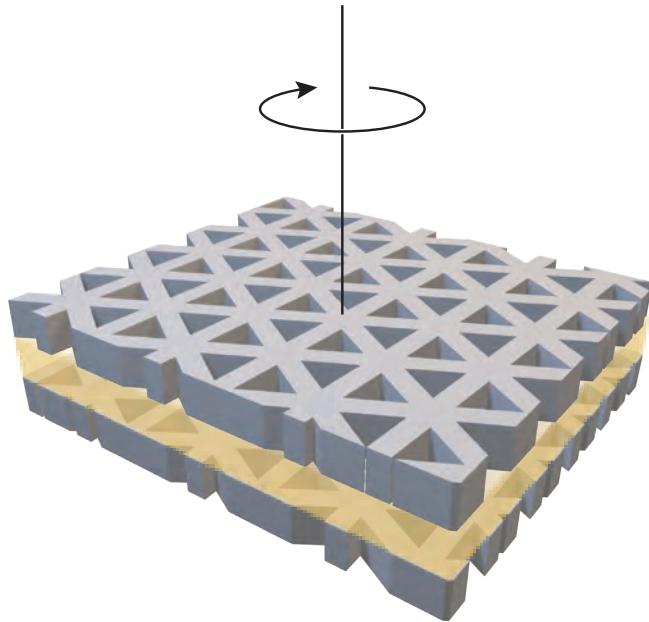


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

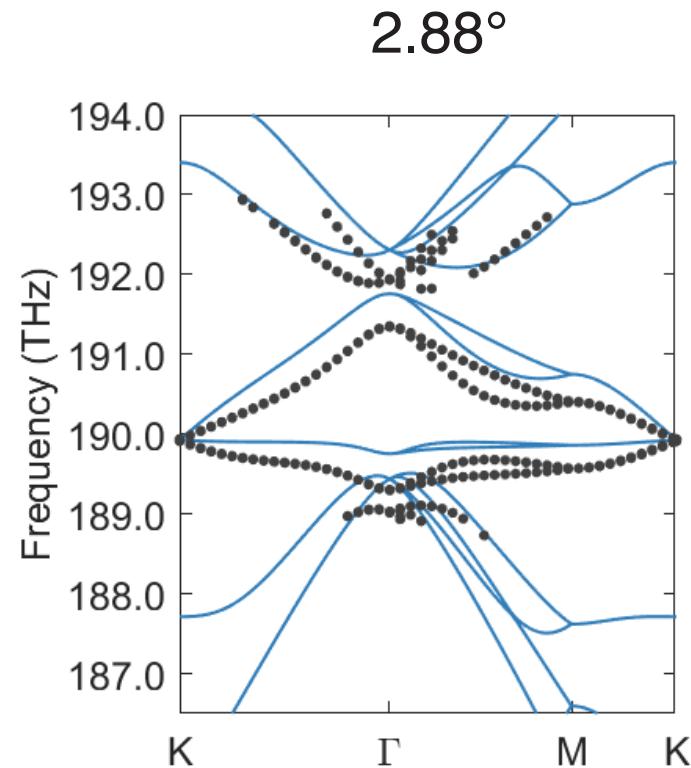
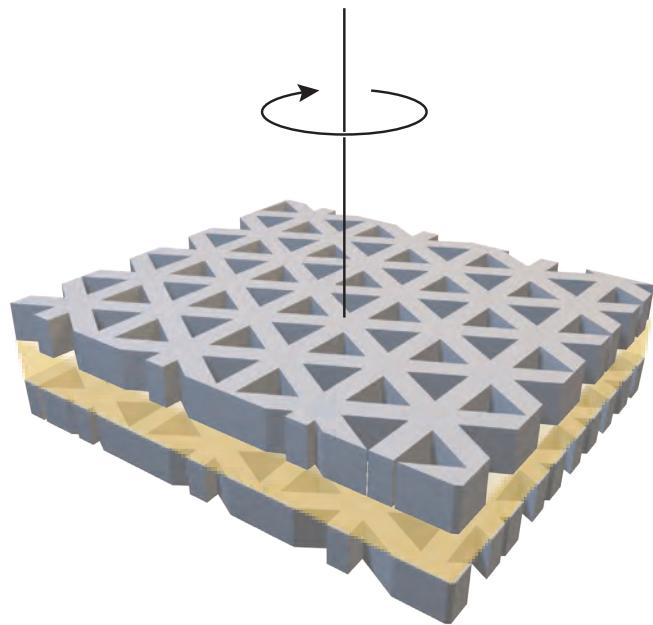


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

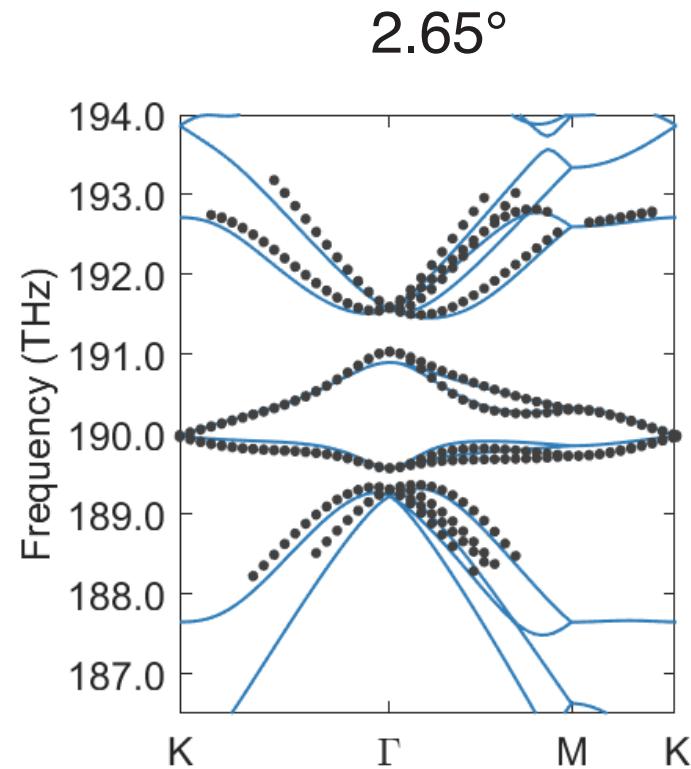
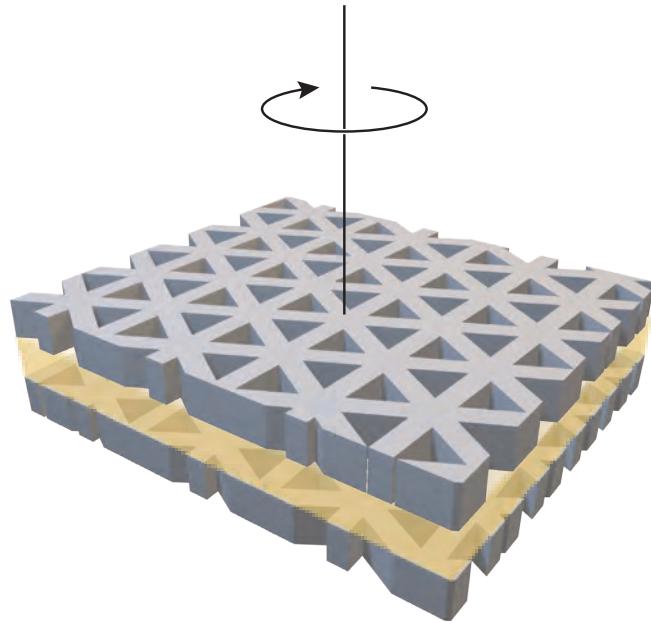


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

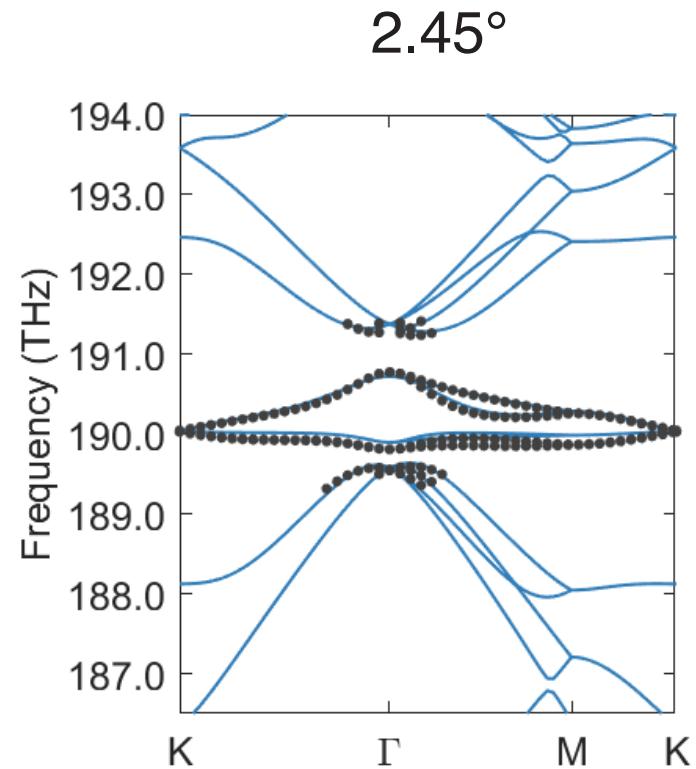
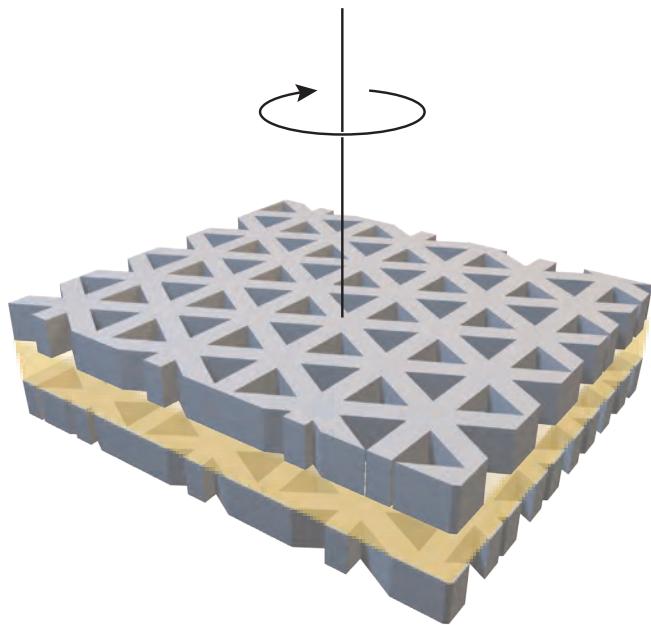


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

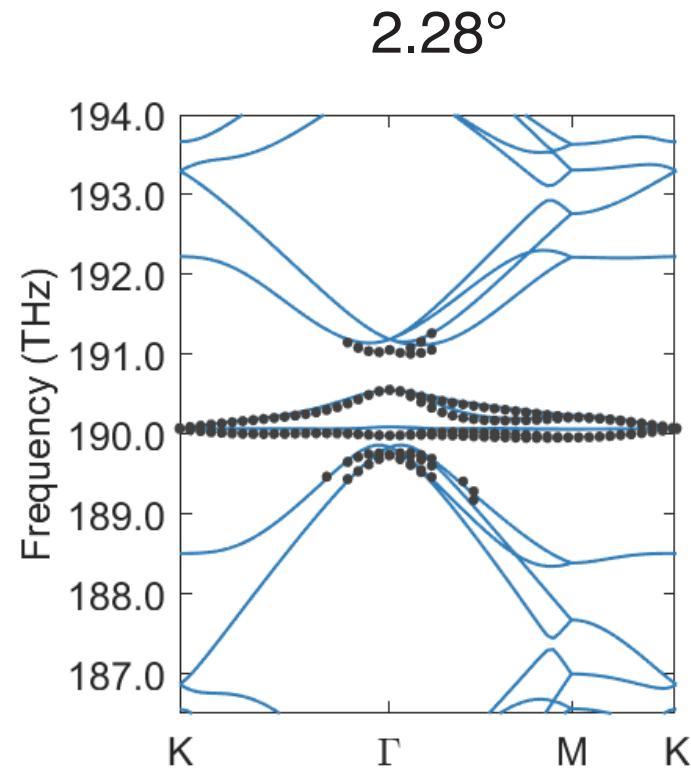
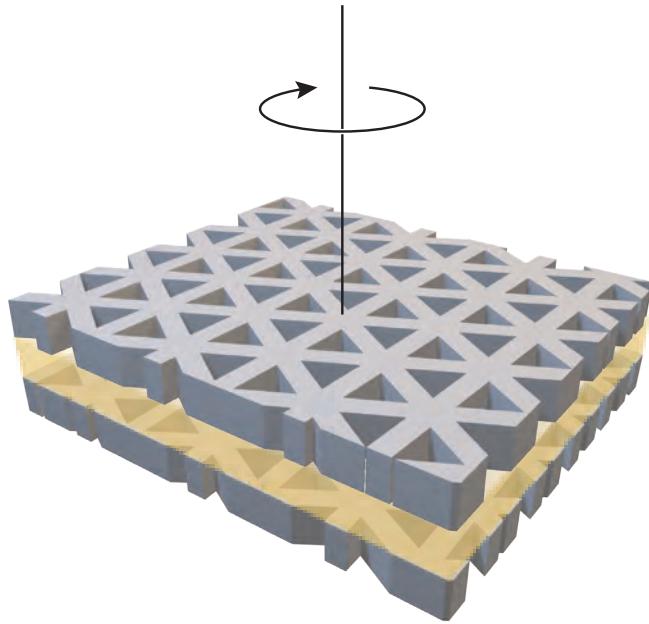


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

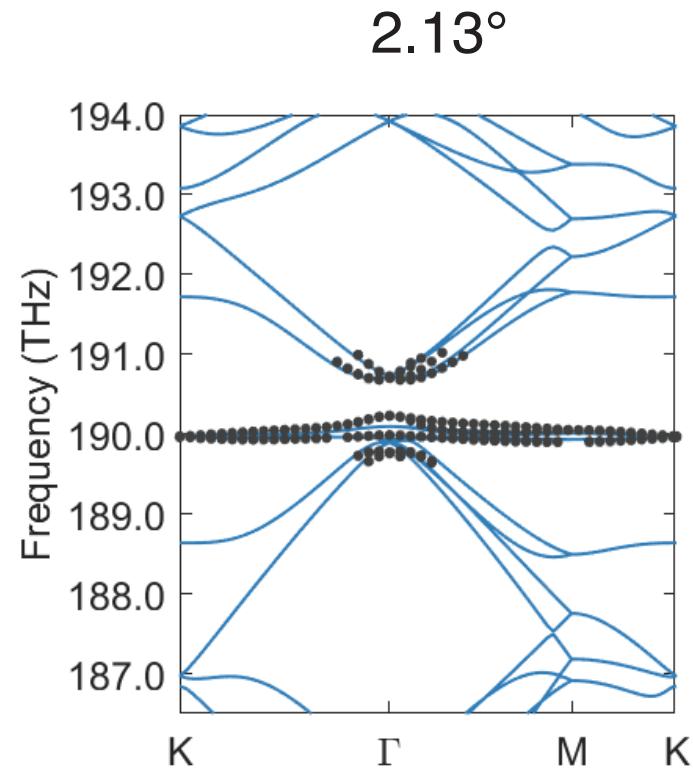
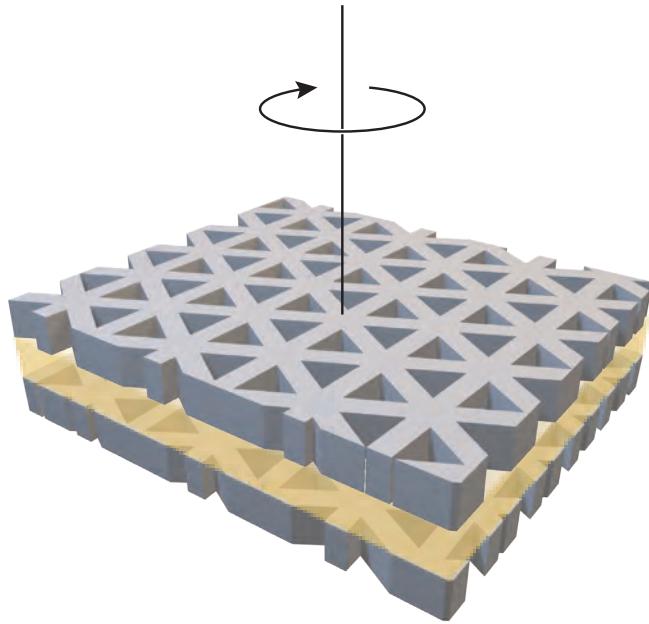


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

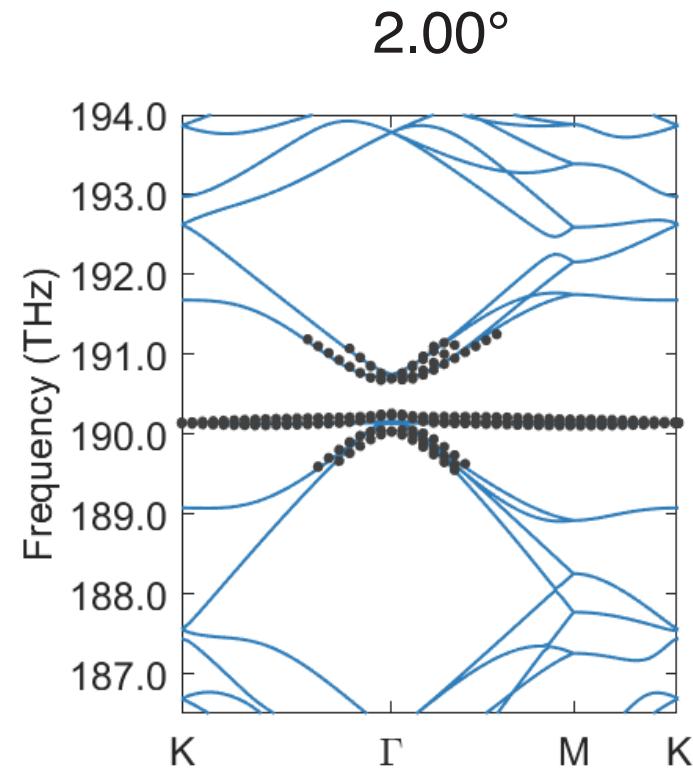
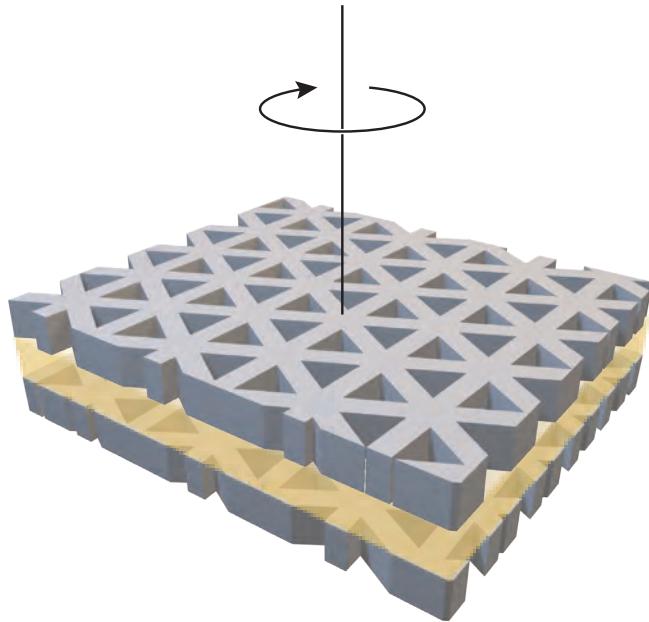


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

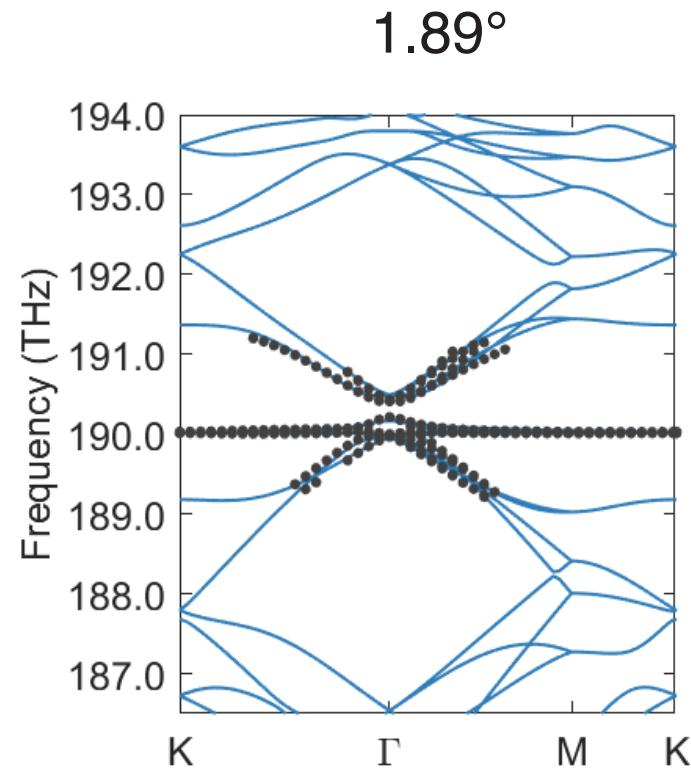
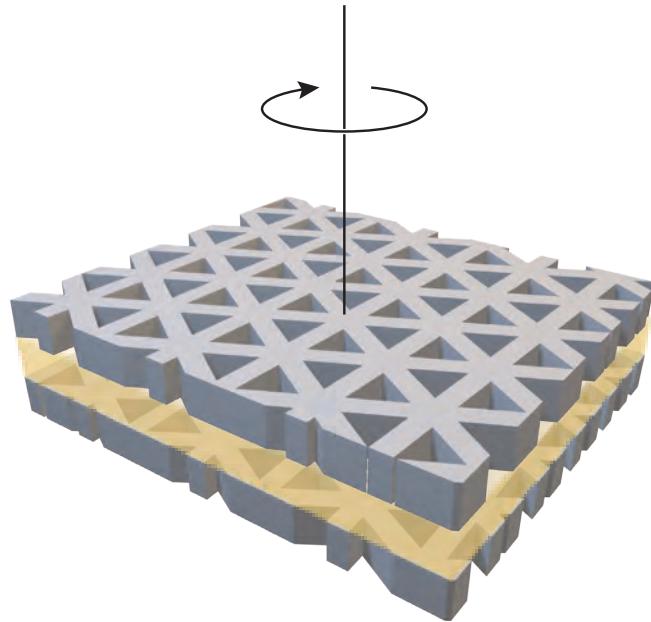


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

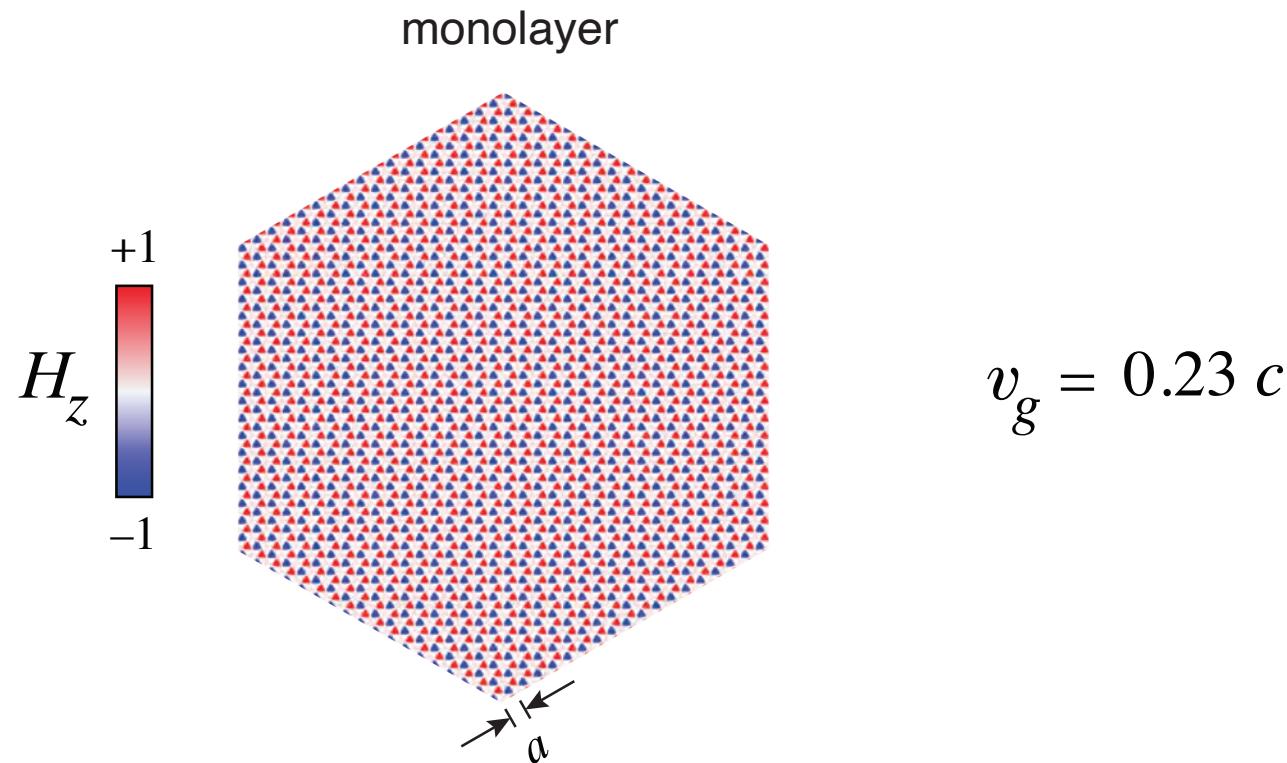


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

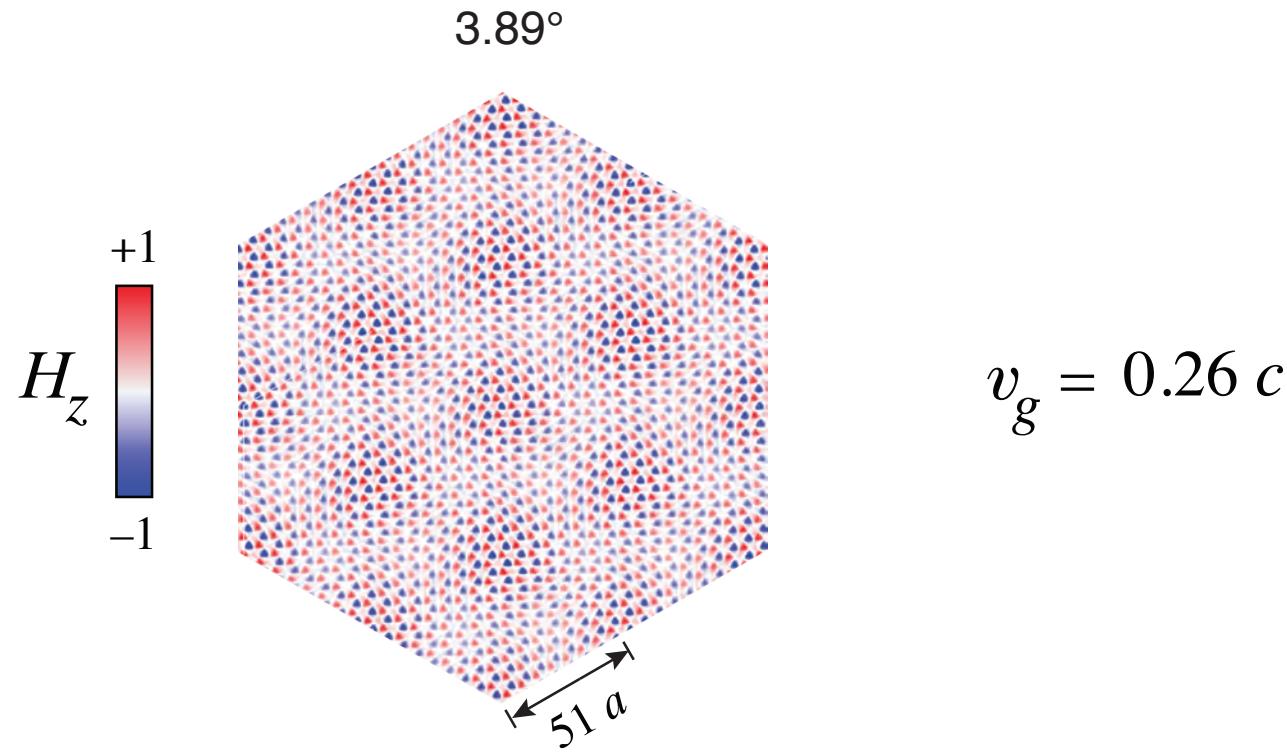


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

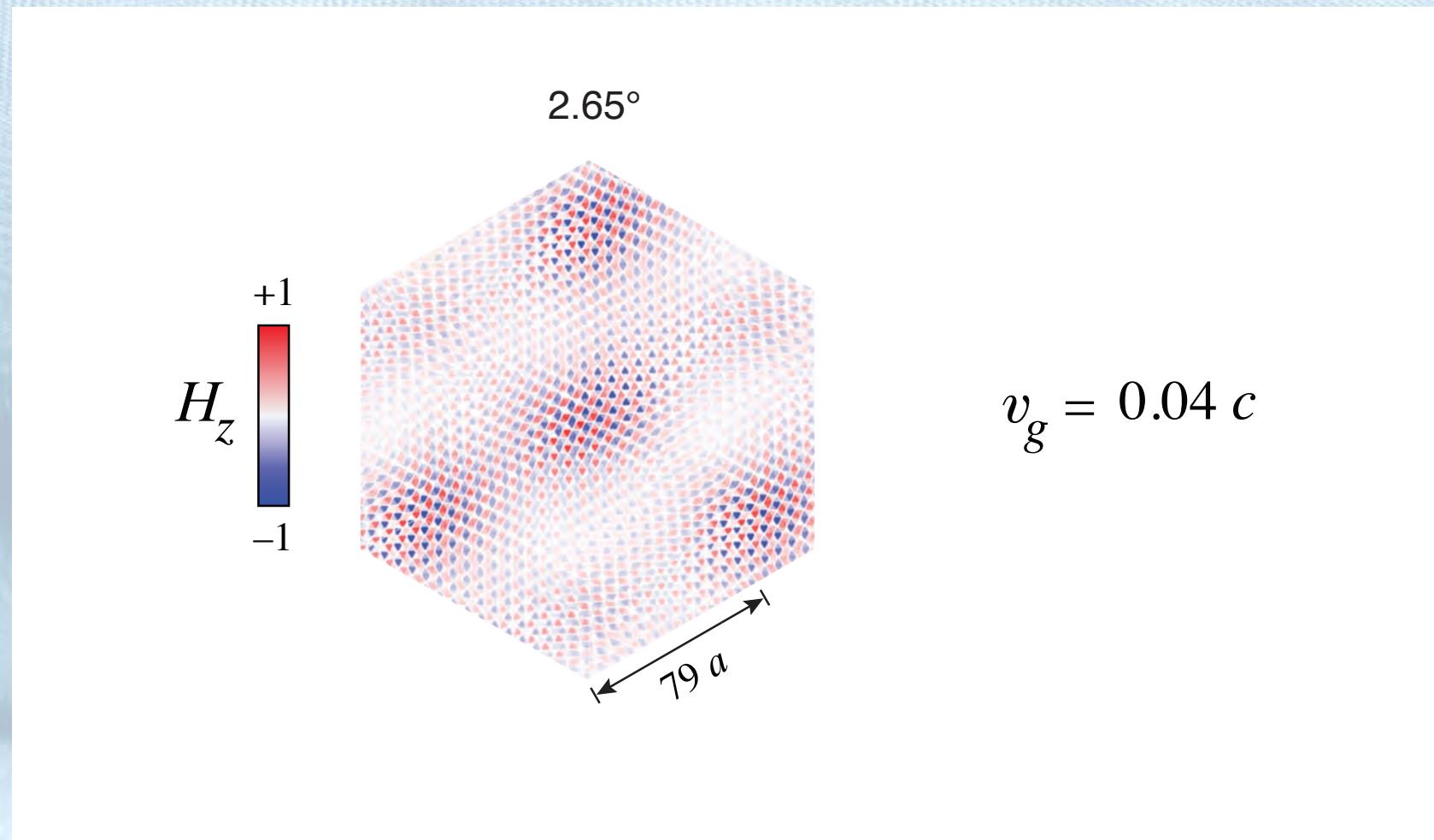


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

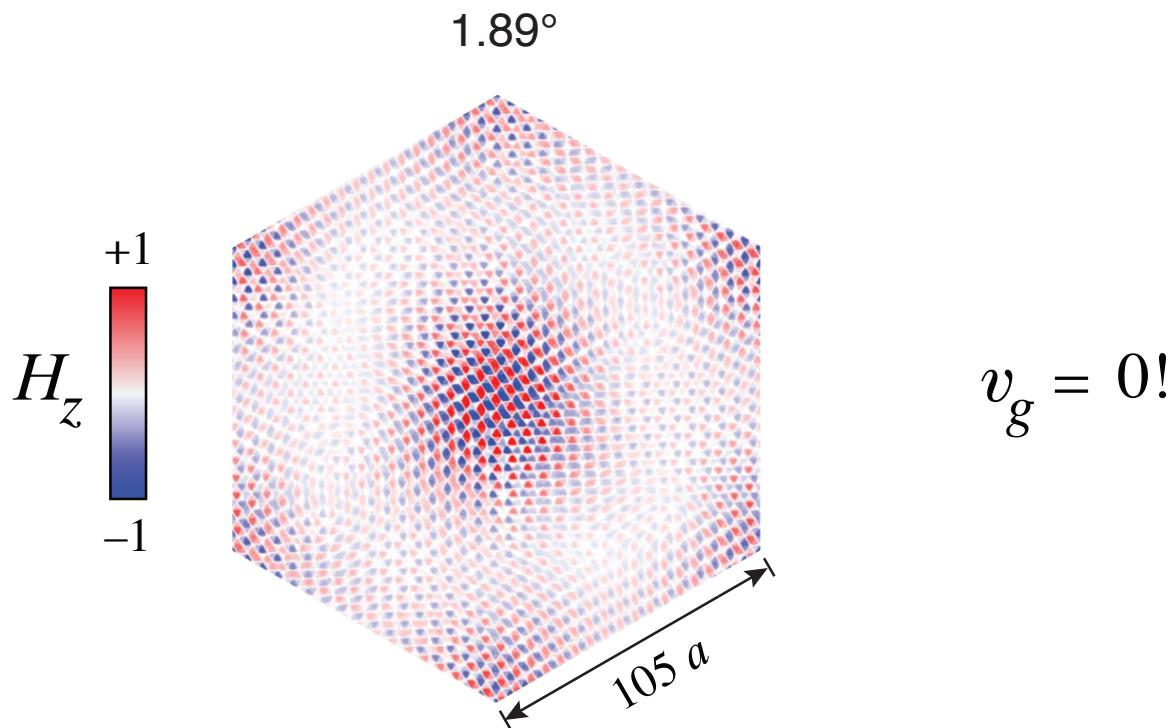


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals

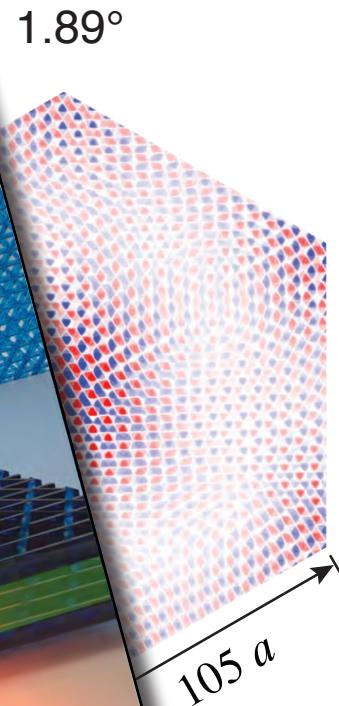
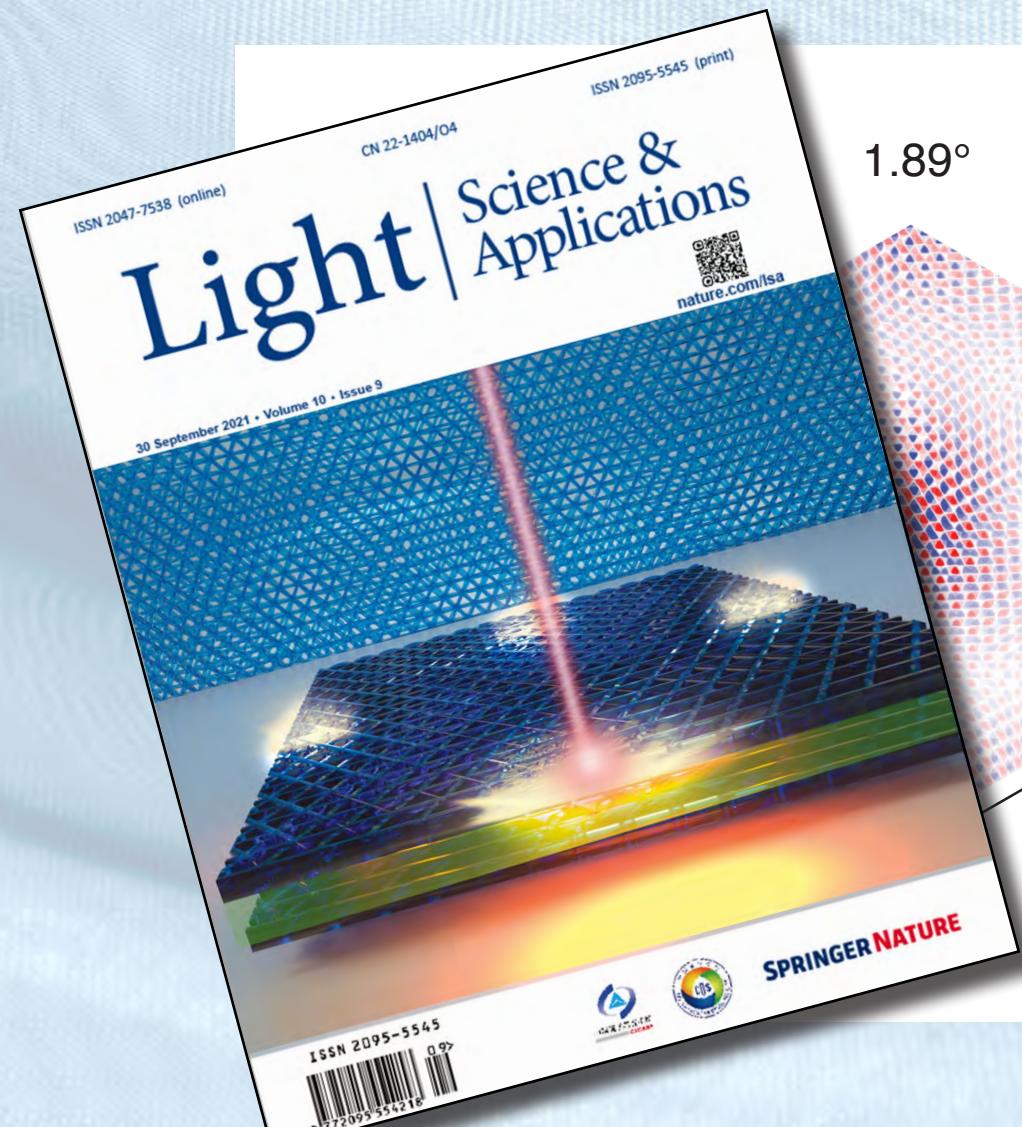


1 index

2 zero index

3 zero group velocity

twisted bilayer photonic crystals



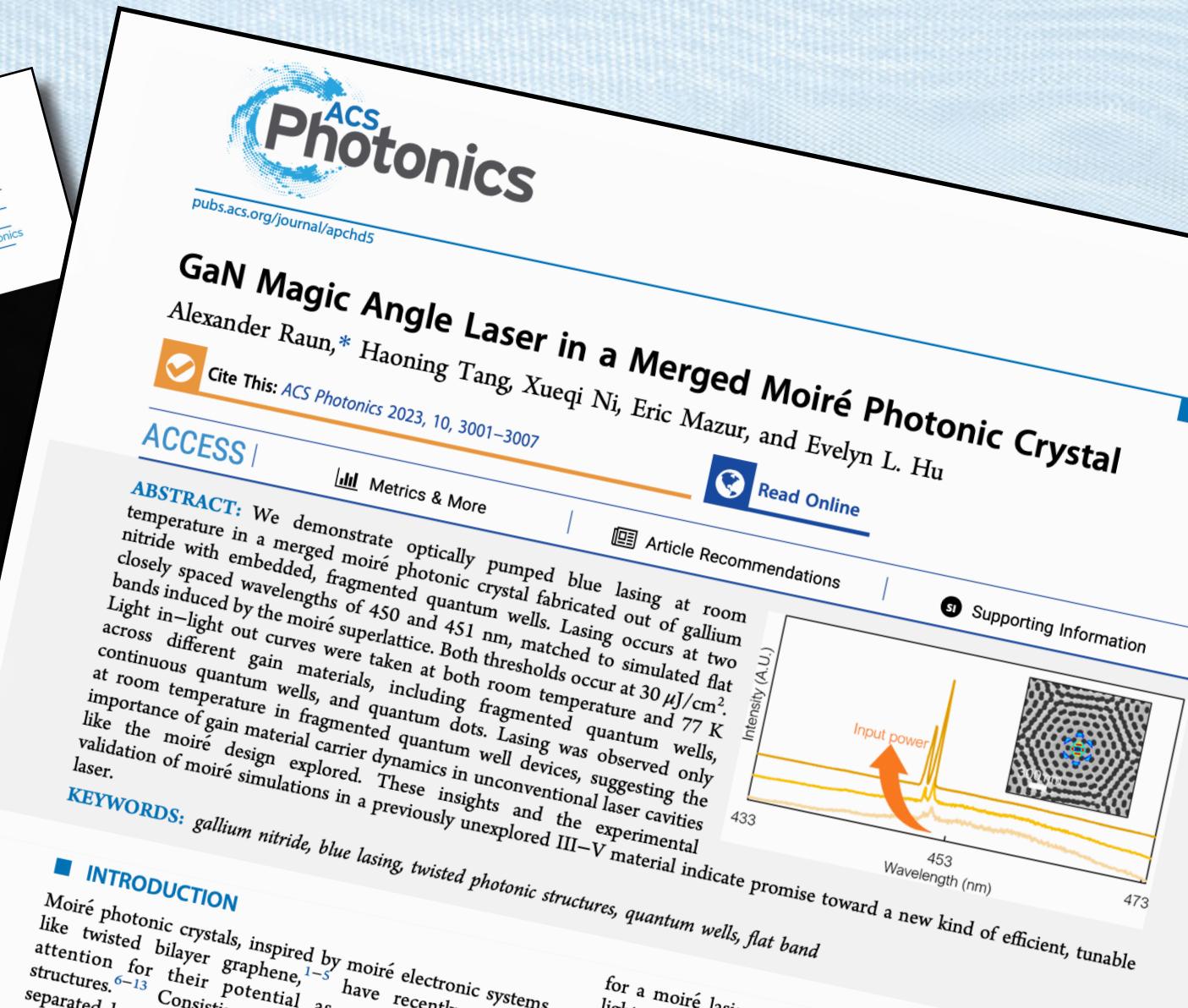
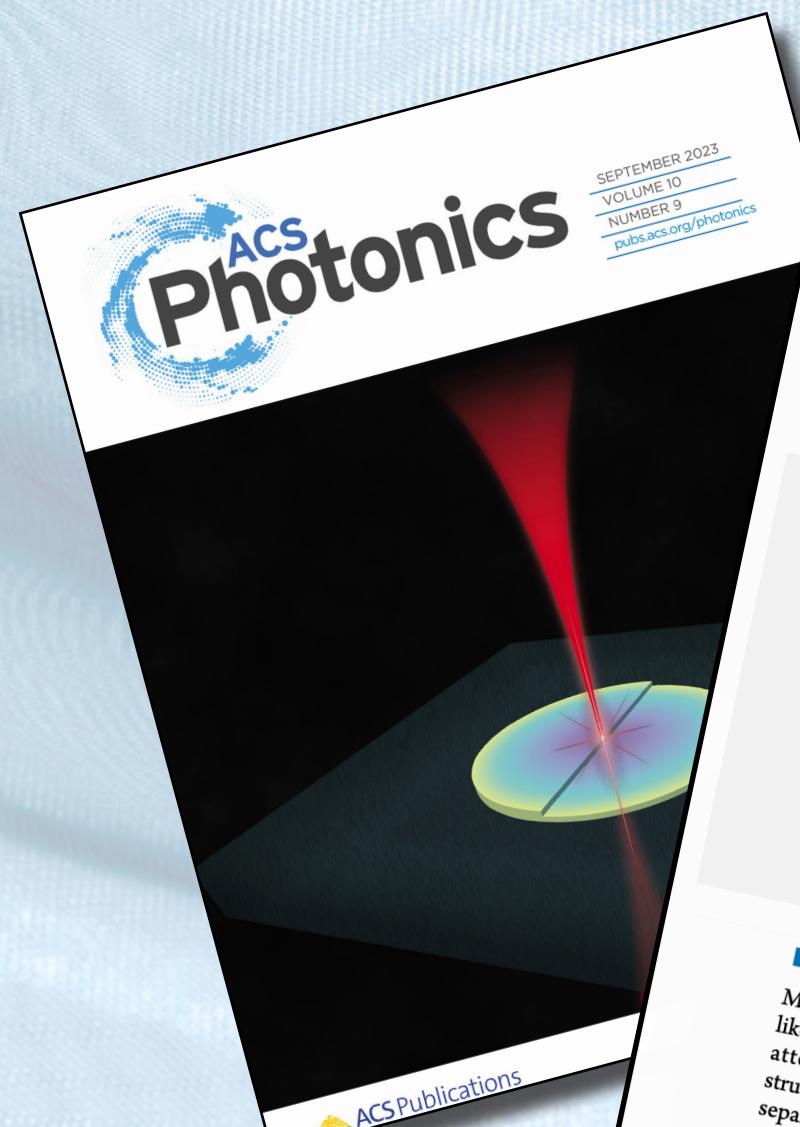
$$v_g = 0!$$

1 index

2 zero index

3 zero group velocity

use localization to enhance on-chip lasing

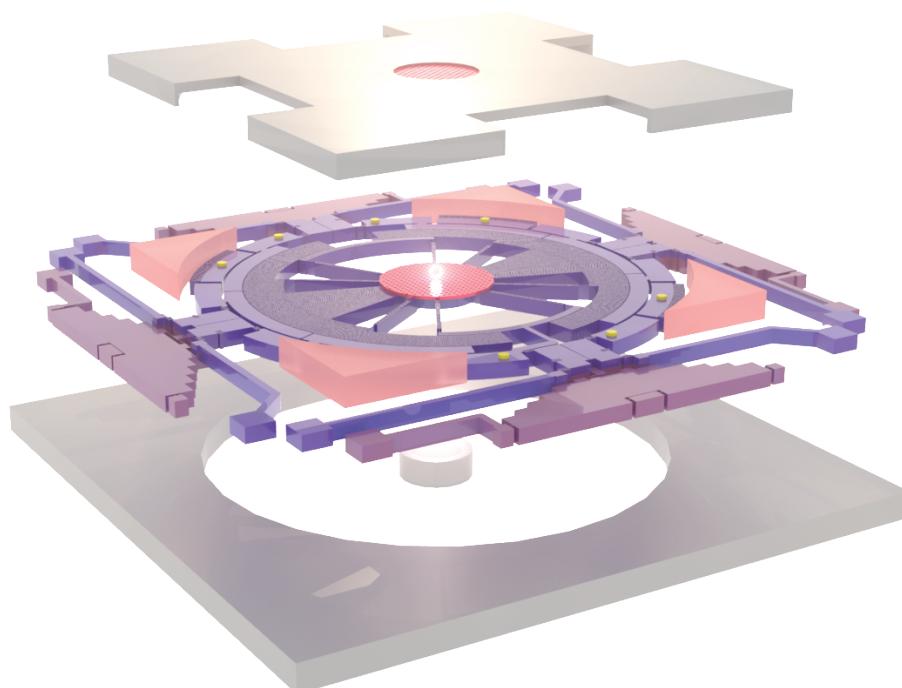


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

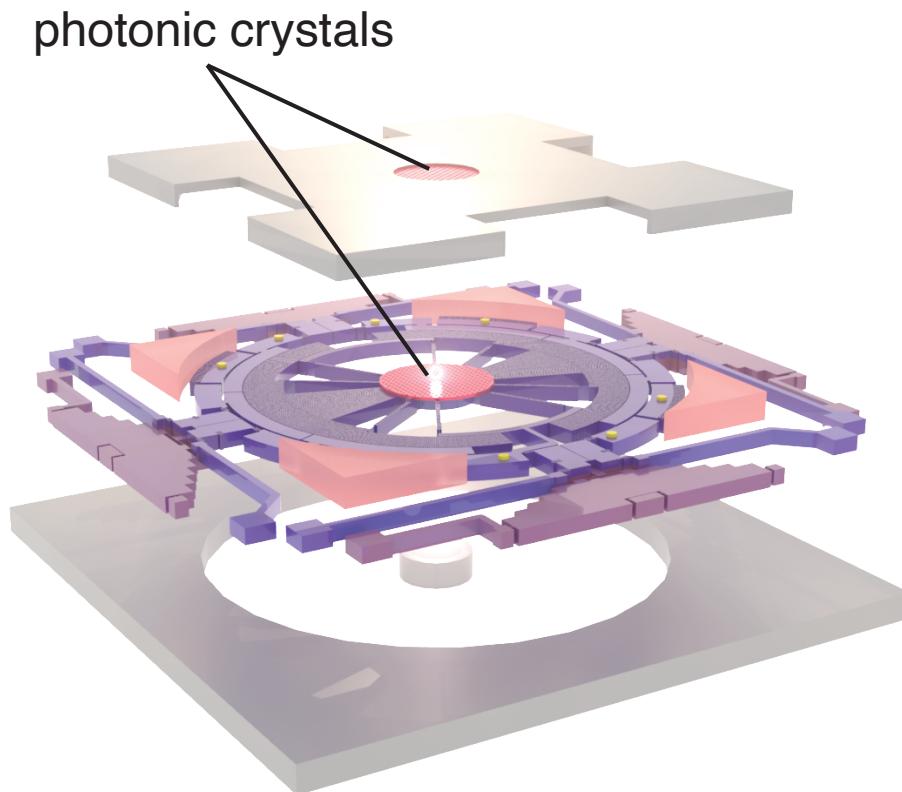


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

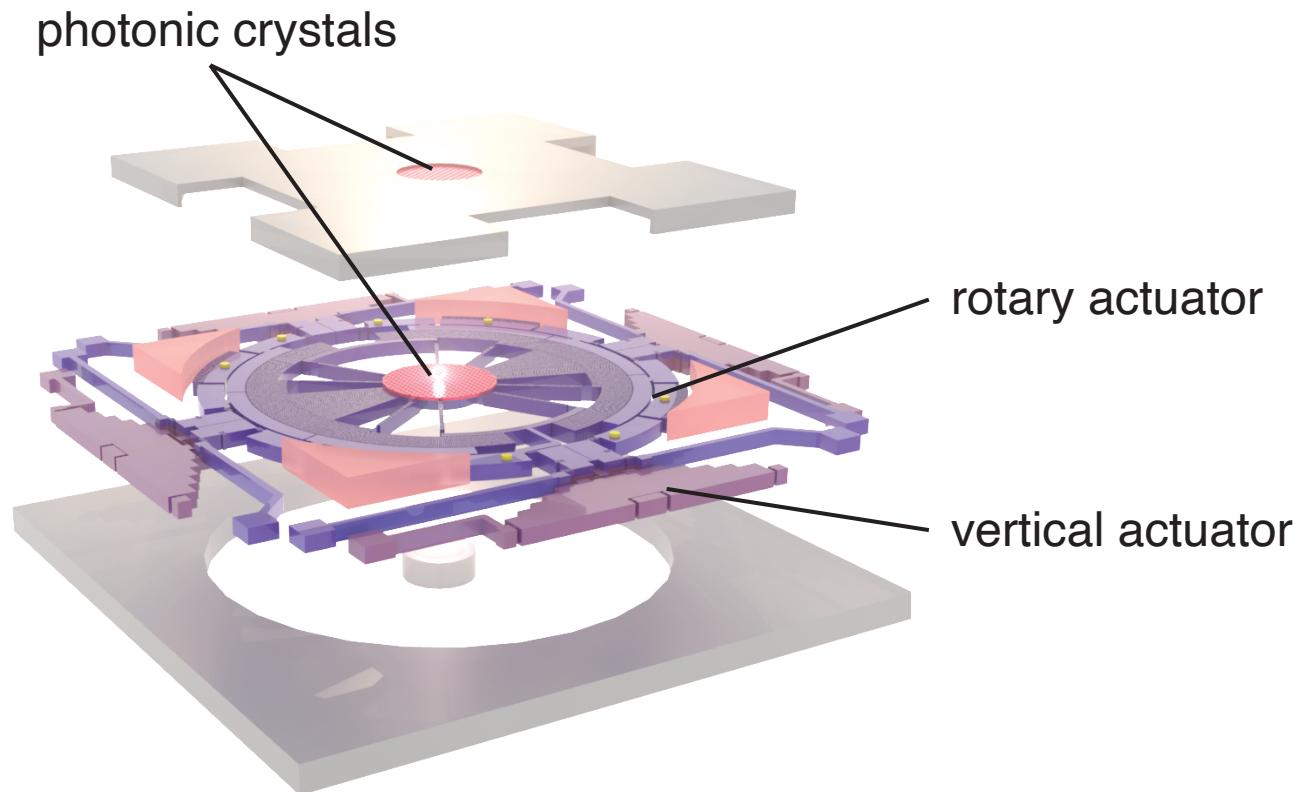


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

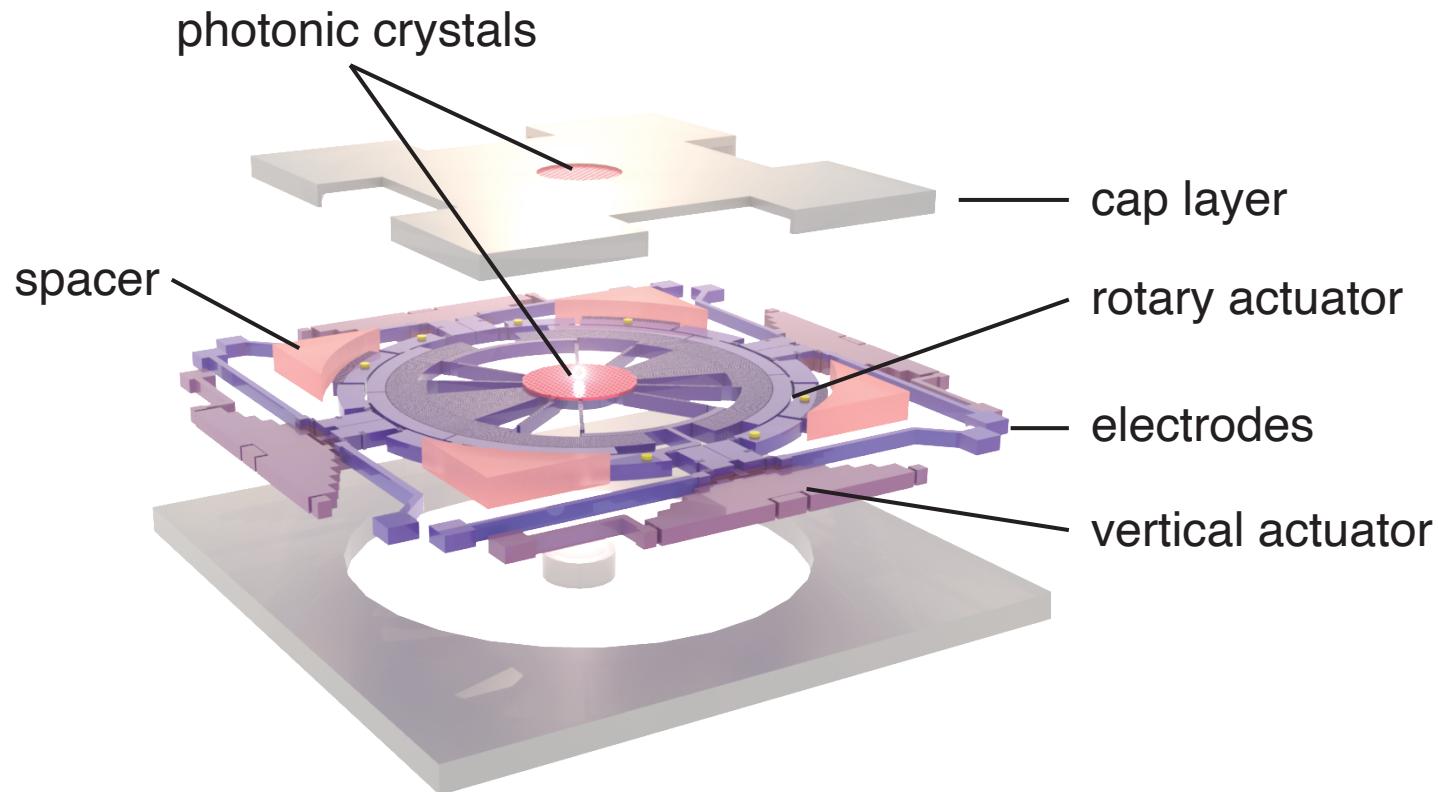


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

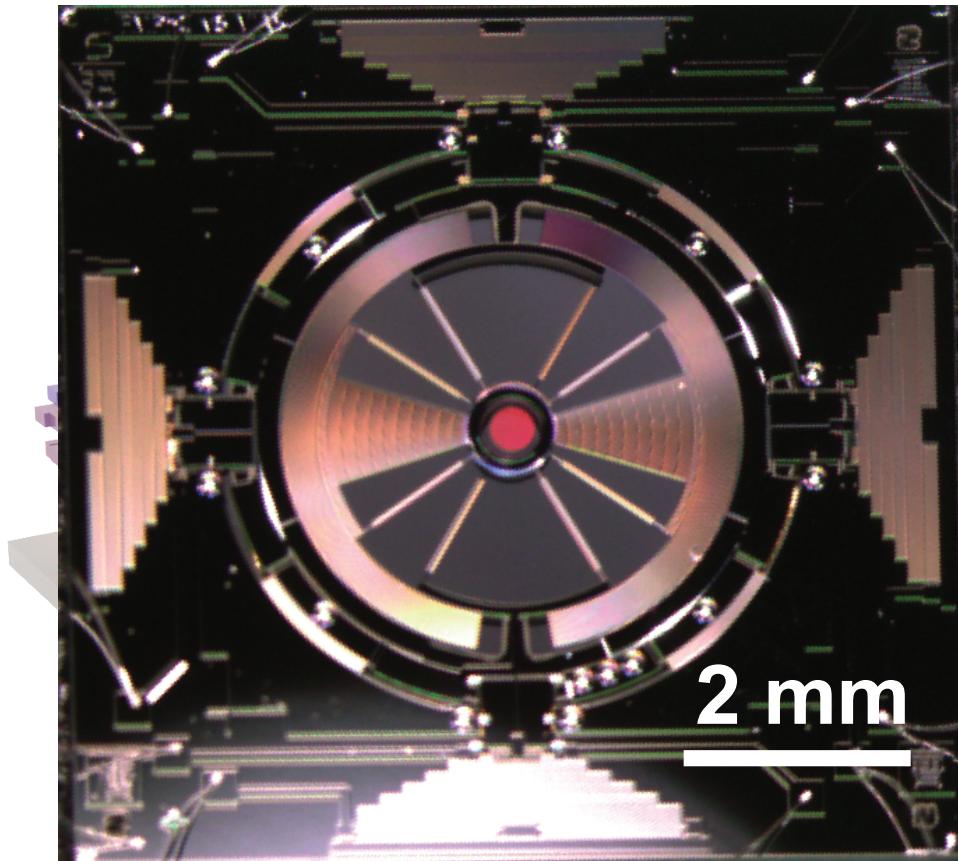


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

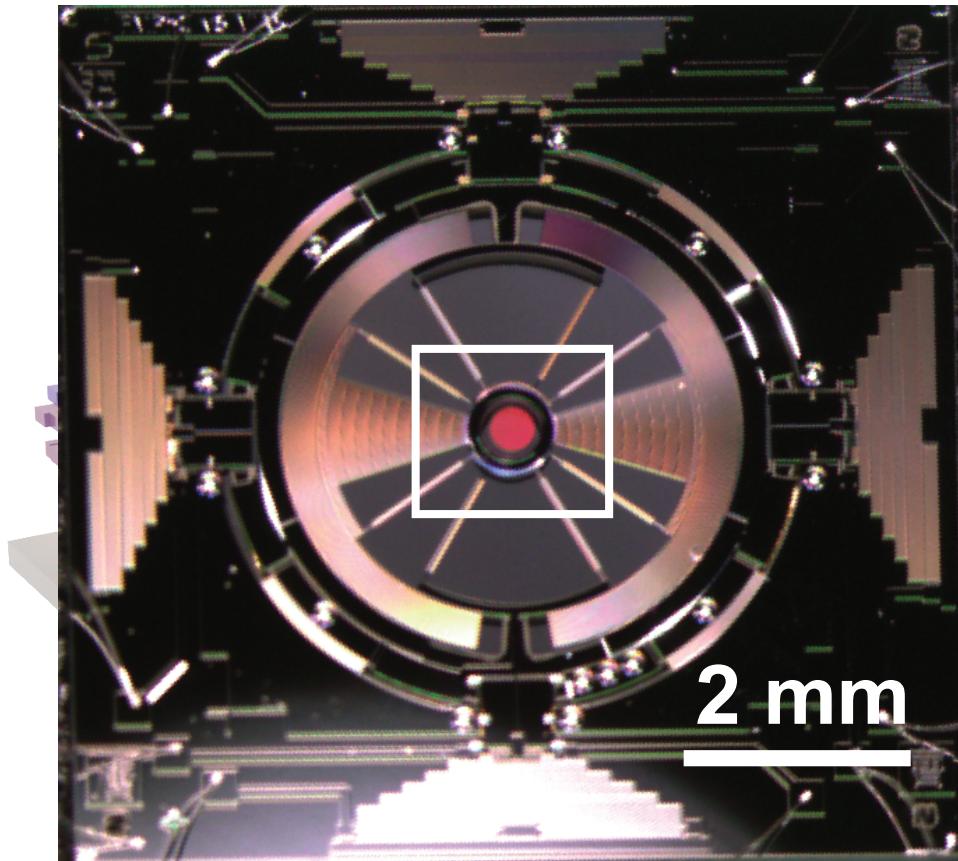


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

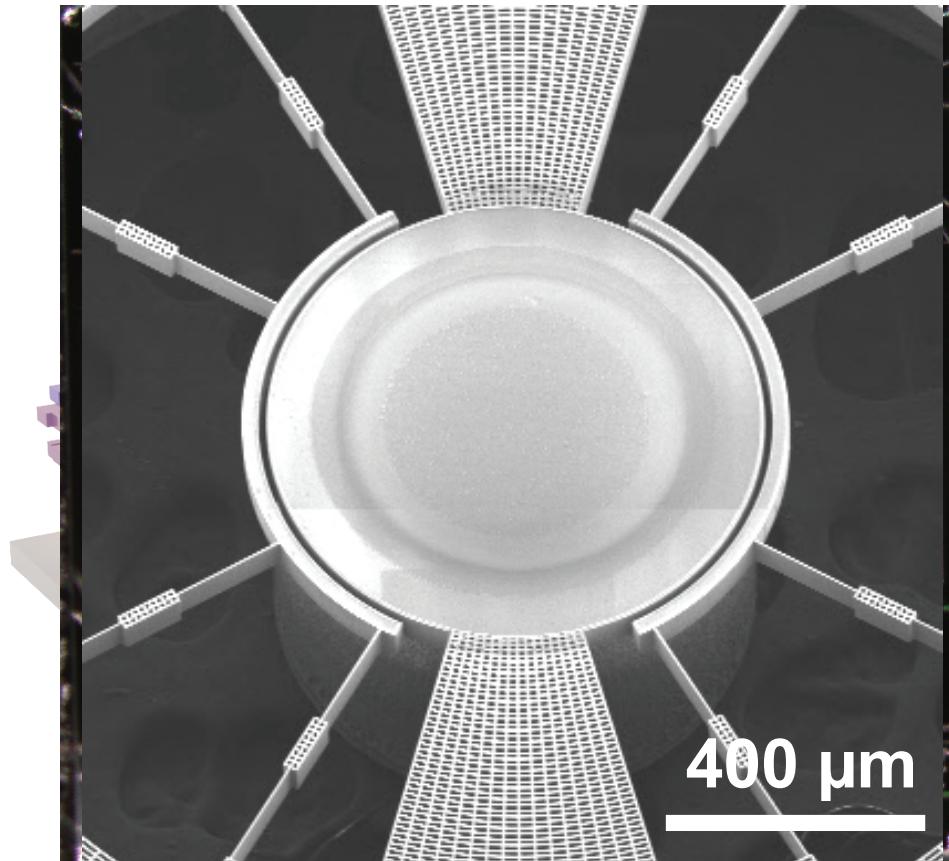


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

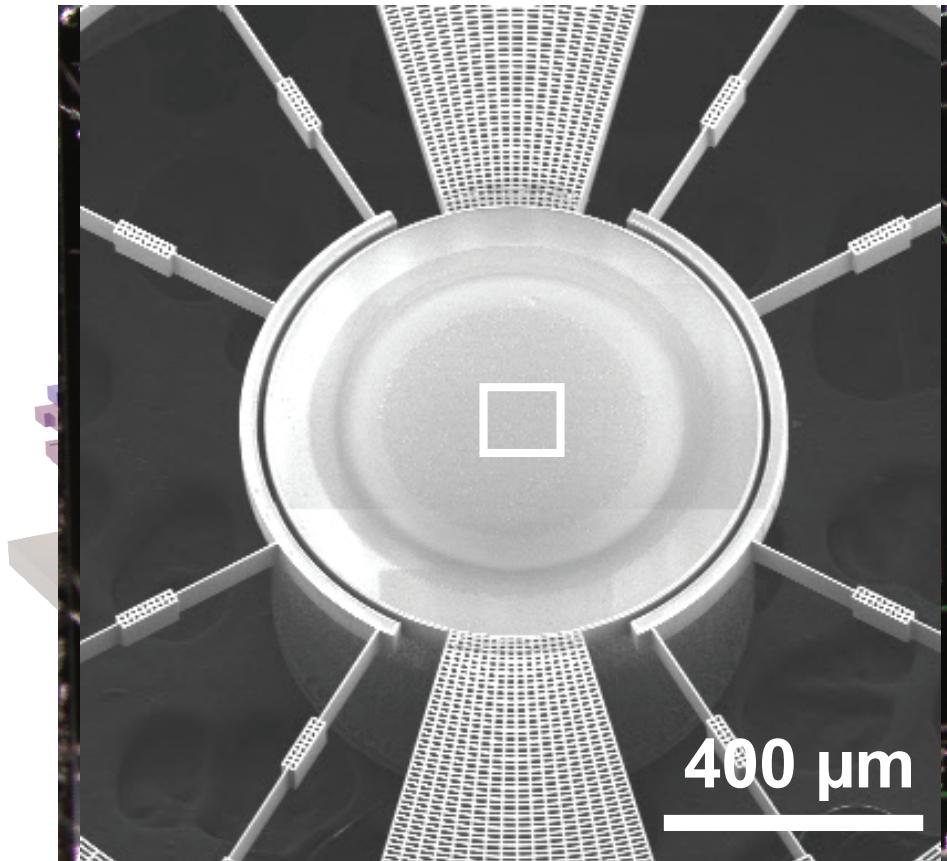


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability

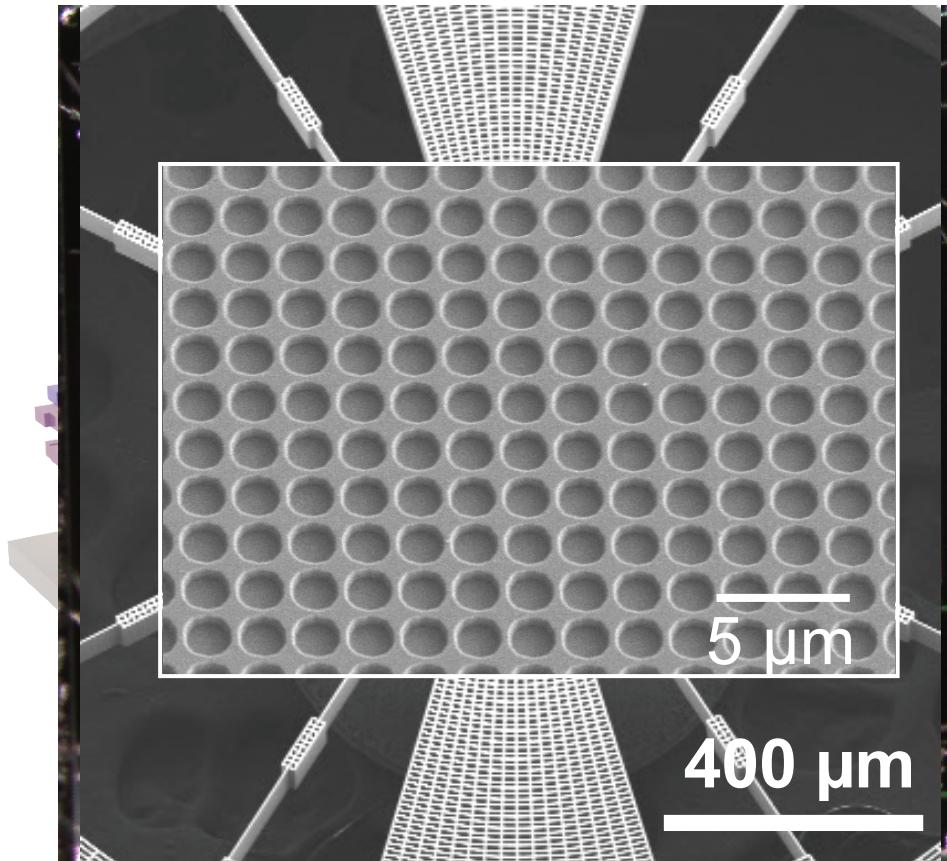


1 index

2 zero index

3 zero group velocity

use MEMS technology for tunability



1 index

2 zero index

3 zero group velocity

use localization to enhance on-chip lasing



SCIENCE ADVANCES | RESEARCH ARTICLE
APPLIED SCIENCES AND ENGINEERING
Experi-

SCIENCES AND ENGINEERING

Control of twist angle-dependent band structure in on-chip optical bilayer photonic crystal

INTRODUCTION

INTRODUCTION There are emerging interests in using moiré physics to engineer optical dispersion. For example, moiré-patterned single-layer (1–15) and twisted-bilayer (16–35) photonic structures exhibit ultraflat bands with no dispersion. The moiré pattern created by twisting two photonic structures relative to each other gives rise to distinctive optical properties, including nonlinear enhancement (36) and anisotropic dispersion (37). Using a pair of photonic crystal slabs (38) that are twisted relative to each other provides a large number of degrees of freedom—choice of material, lattice symmetry, feature size, twist angle, and interlayer gap—and permits tailoring the optical properties of the material. In particular, recent theoretical work shows that twisted bilayer photonic crystal (TBPhC) structures exhibit slow light (39), facilitating the study of strong light-matter interactions and Purcell enhancement (40), and frequency filtering (41). To date, however, there has been no demonstration of TBPhC devices.

RESULTS

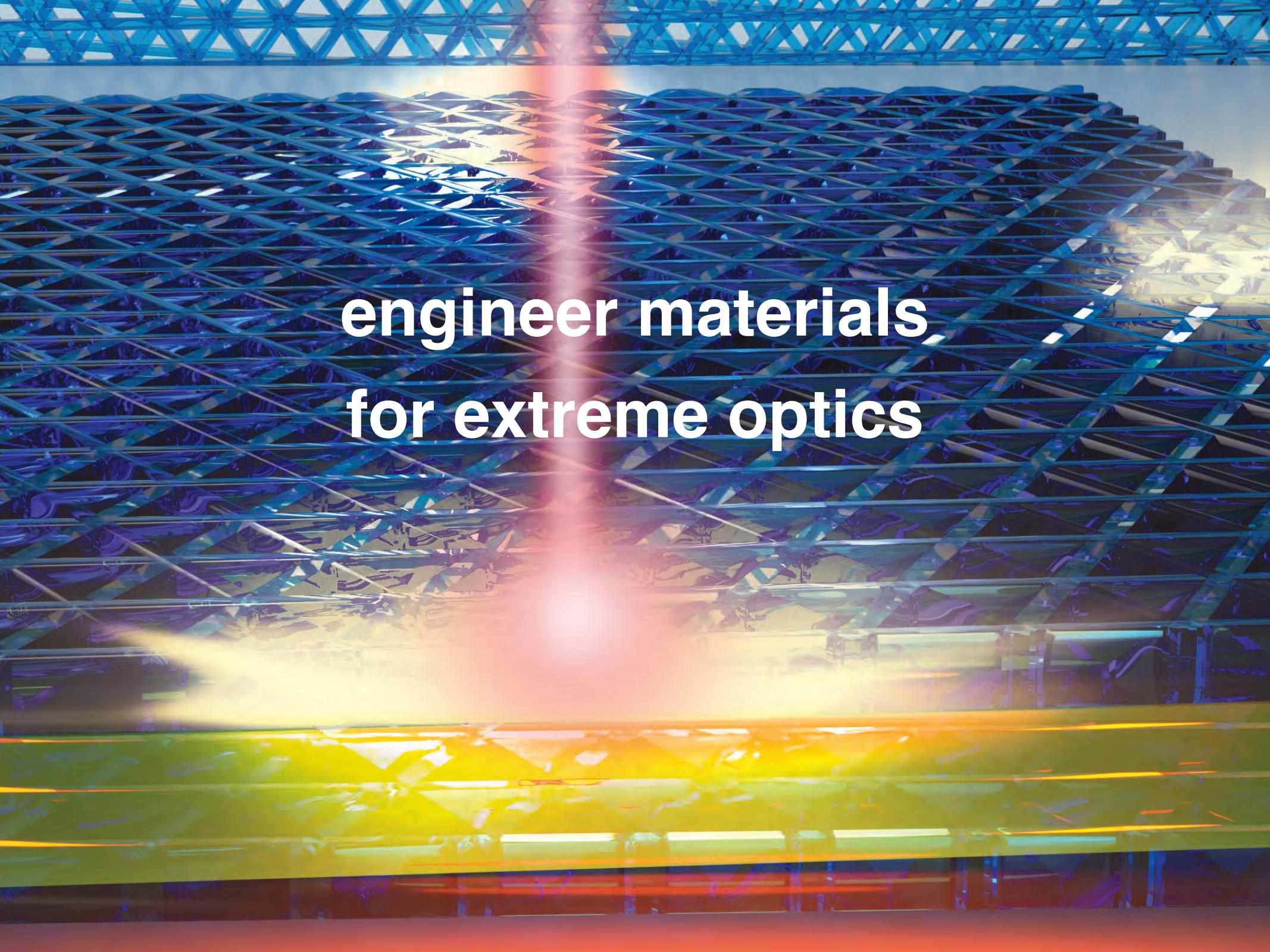
We start by analyzing the optical scattering properties of a single layer photonic crystal slab and of the TBPhC slabs. A photonic crystal slab is a dielectric structure that is finite in the z direction and periodic in xy plane. The periodicity can be represented by a lattice, either in real space or in reciprocal space, as a set of points $\mathcal{G}_1 \equiv \{(i\hat{x} + j\hat{y})2\pi/a | i, j \in \mathbb{Z}\}$, where \hat{x}, \hat{y} are the unit vectors in the xy plane, and a is its period in real space. When two identical square lattices are twisted against each other (Fig. 1A), the moiré lattices in real space (Fig. 1B). The reciprocal space involves a large number of wavevectors, and the periodic structure is characterized by a large number of bands.

Here, we report that

1 index

2 zero index

3 zero group velocity



engineer materials
for extreme optics

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