

Less is more: Extreme optics with zero refractive index

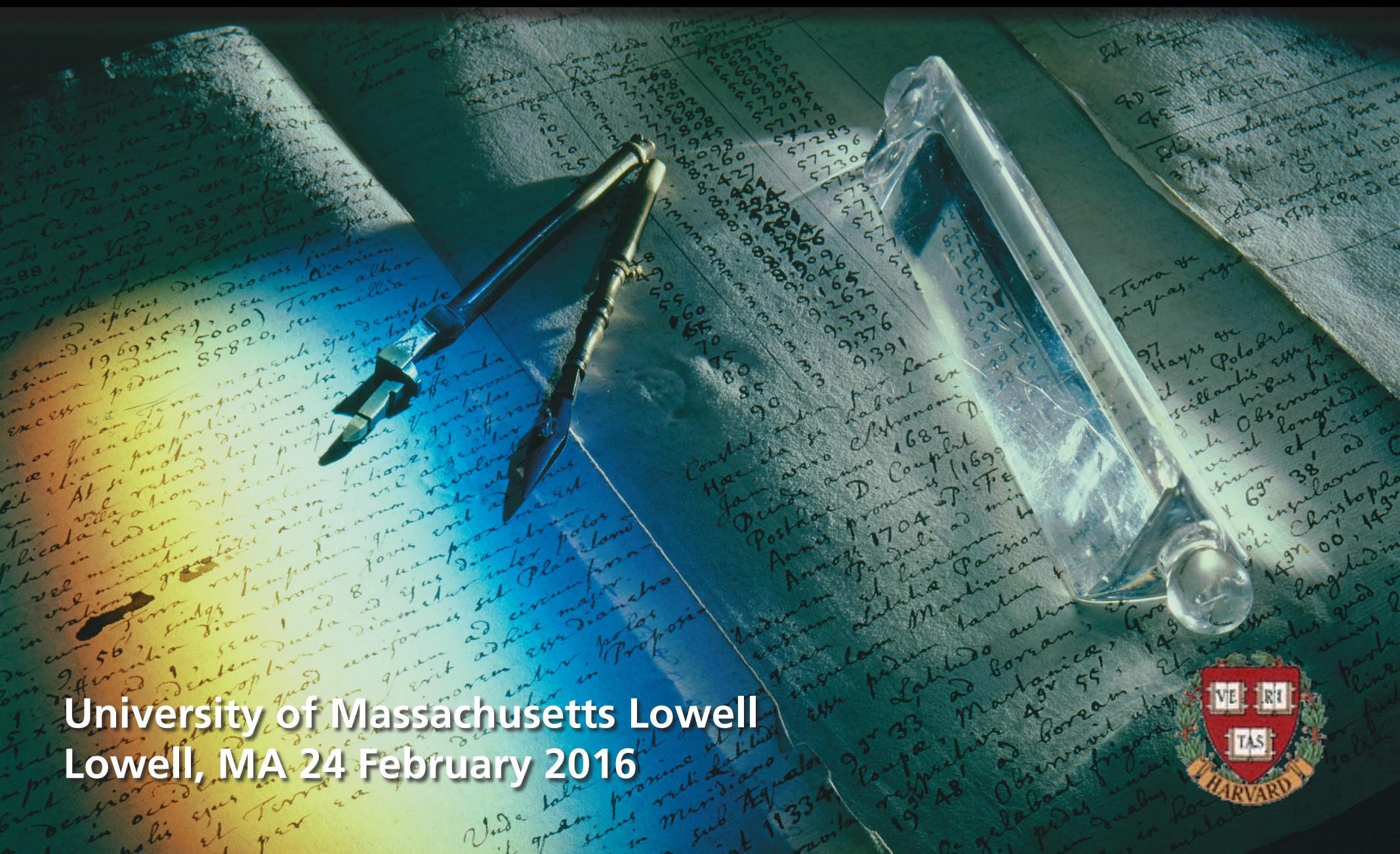


@eric_mazur

University of Massachusetts Lowell
Lowell, MA 24 February 2016



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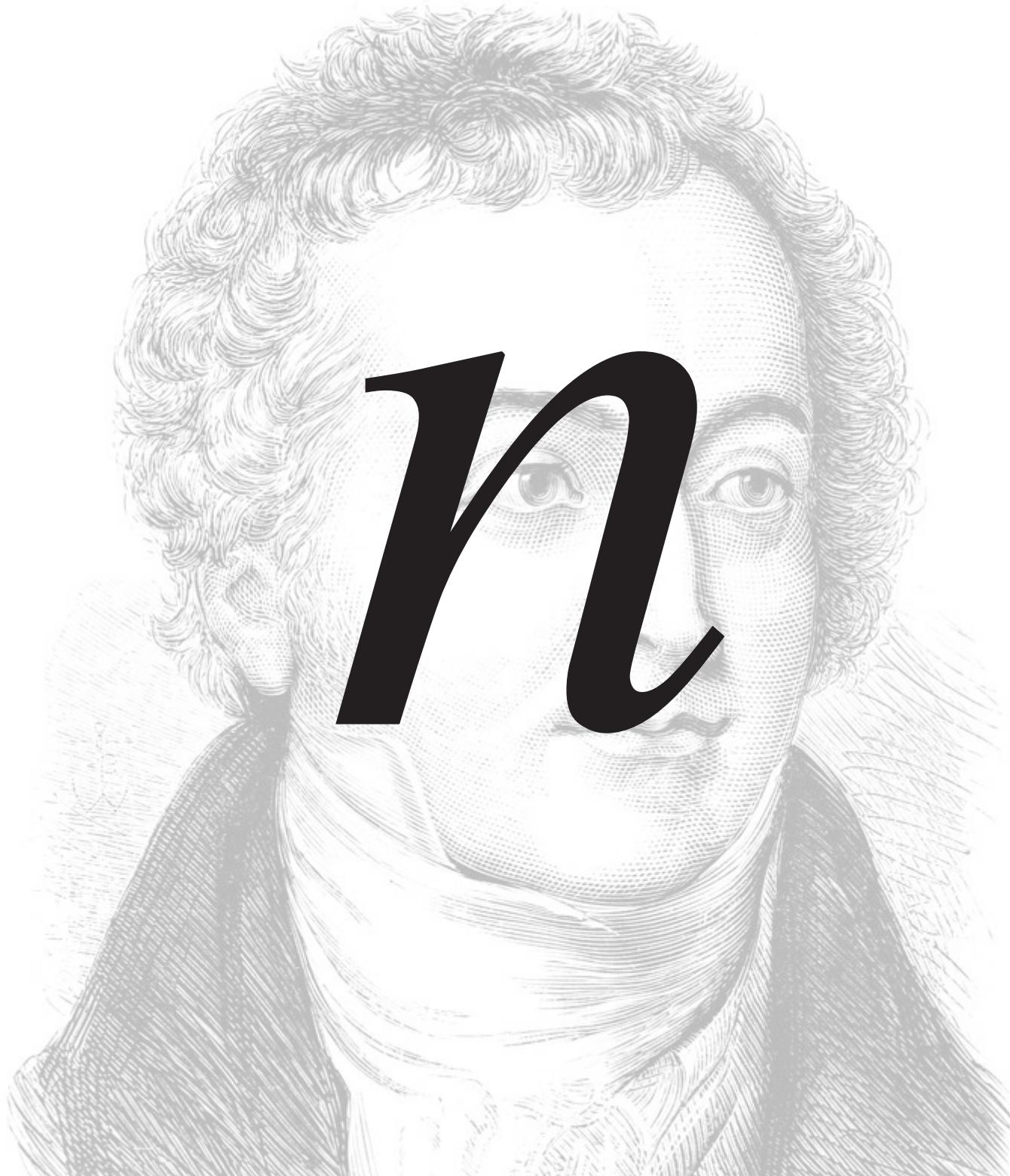




Reflecting a Century of Innovation



n



n



n

1 index

2 zero index



n

1 index

2 zero index

3 experiments

Propagation of EM wave

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governed by wave equation

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

Index of refraction

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

Index of refraction

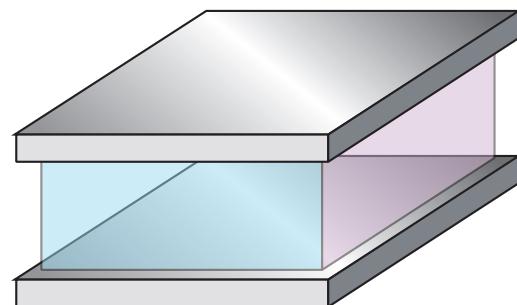
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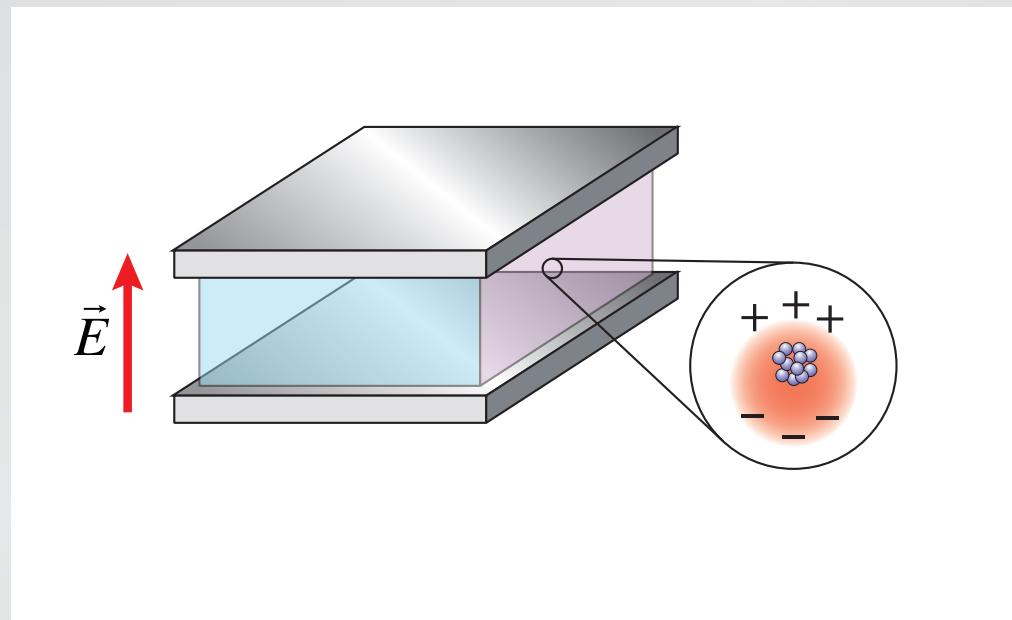
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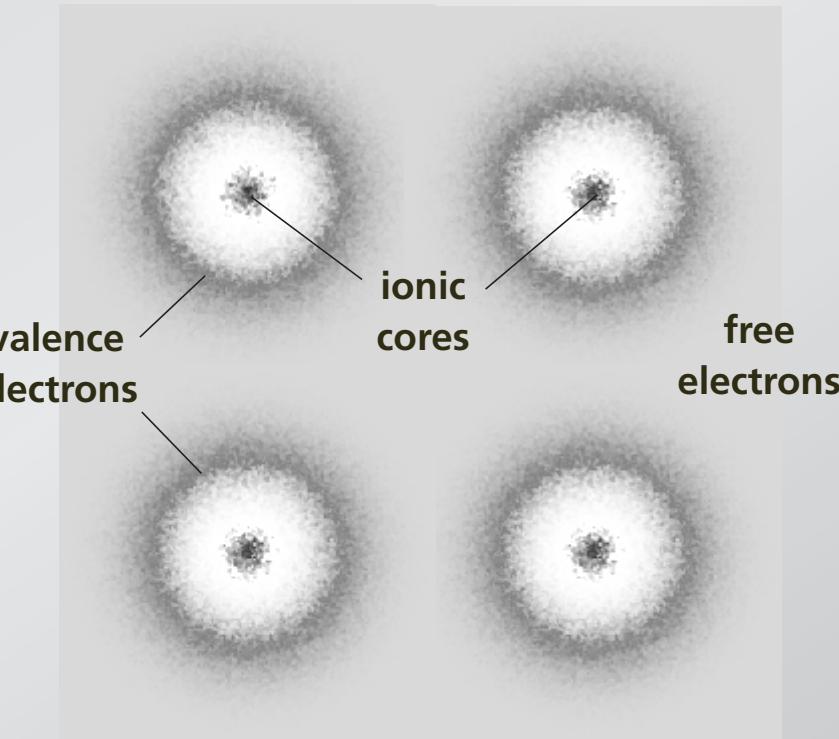


$\epsilon(\omega)$ measure of attenuation of electric field

Index of refraction

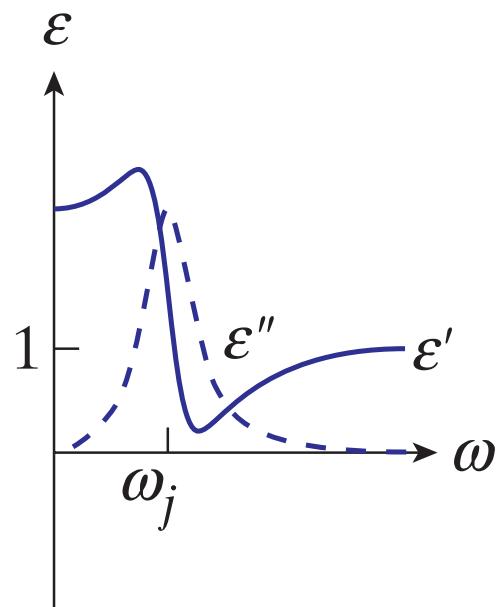
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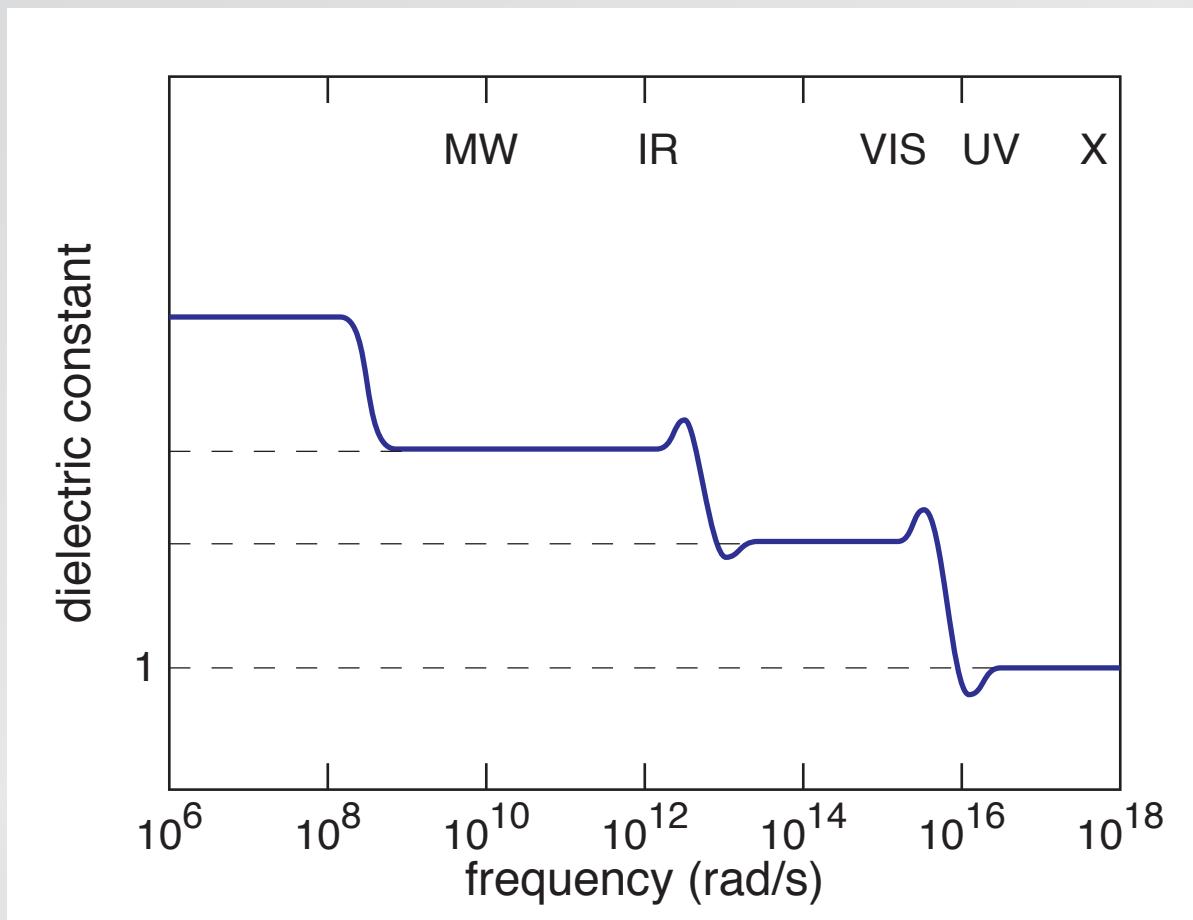


Dielectric constant

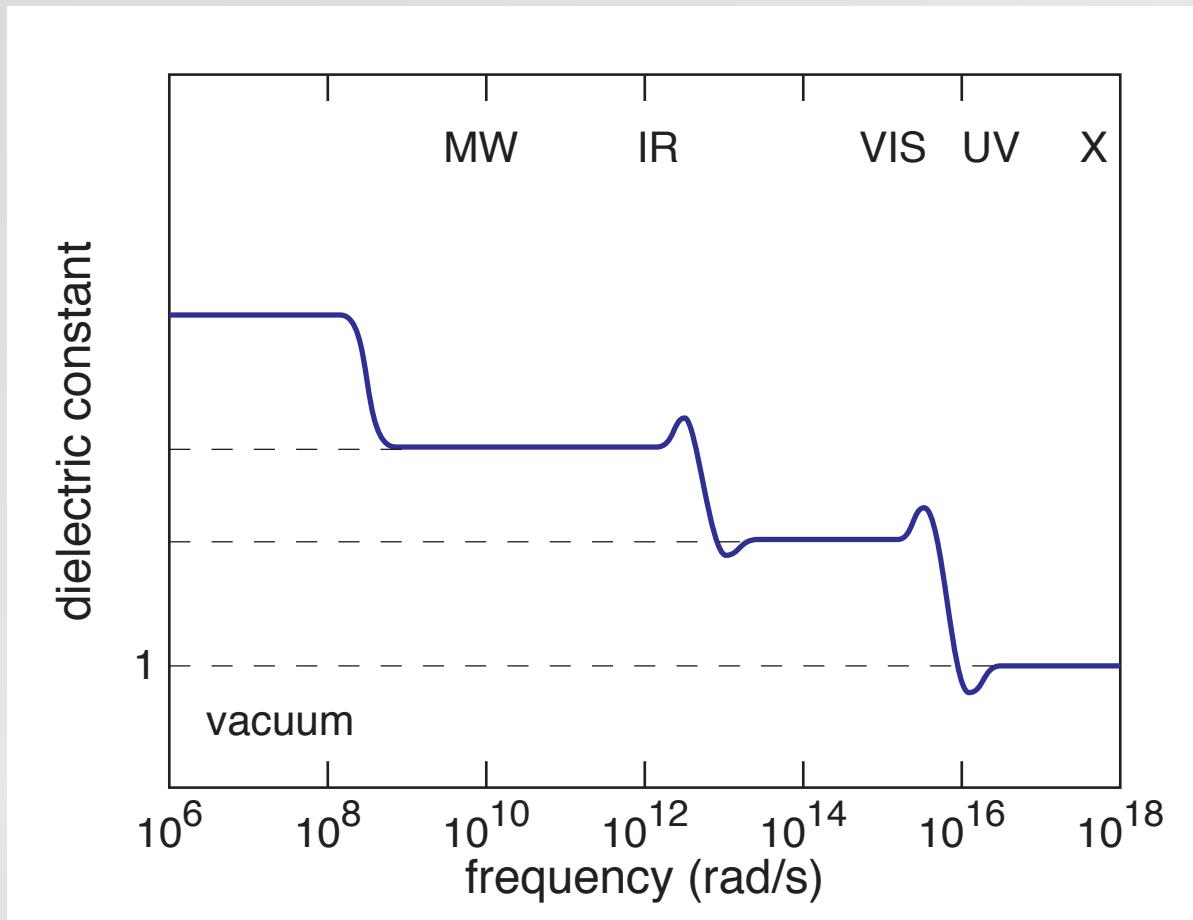
Lorentz oscillator



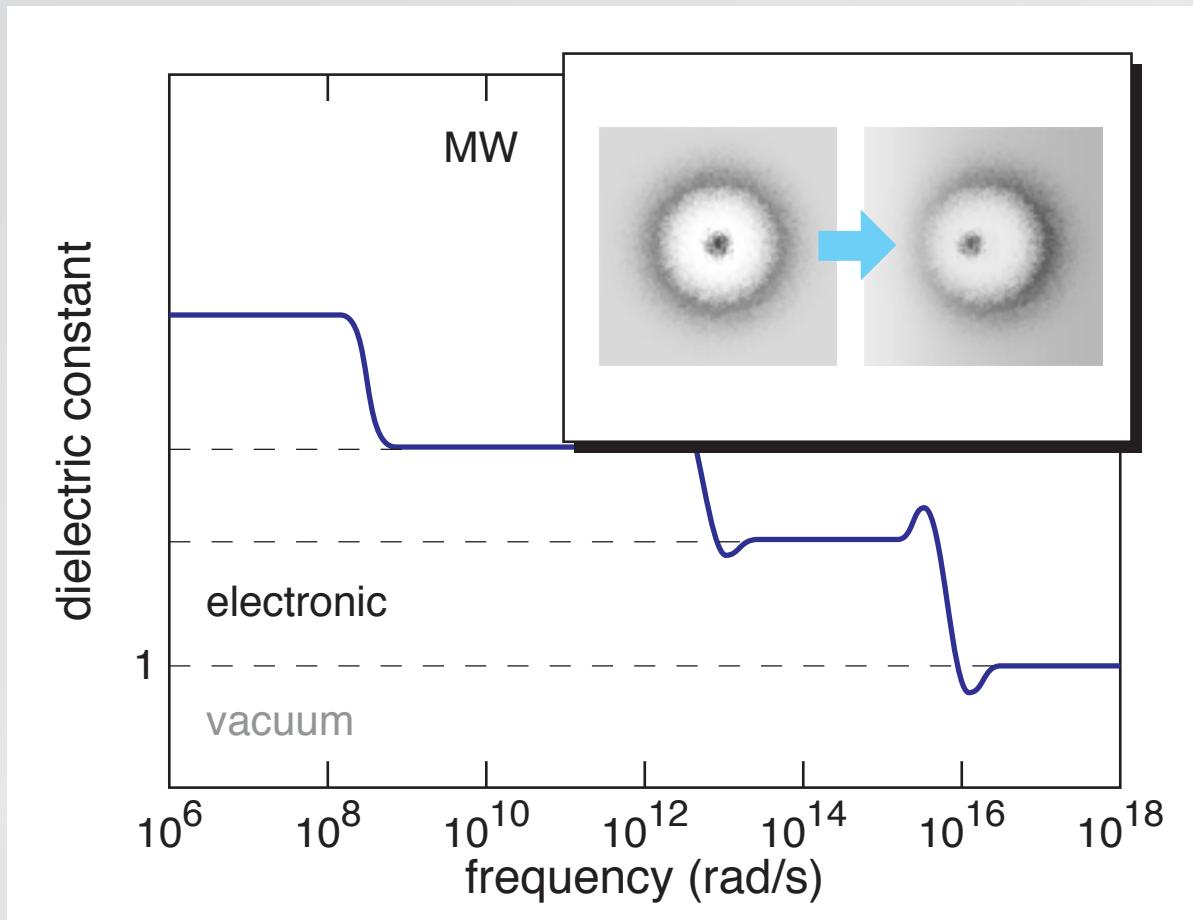
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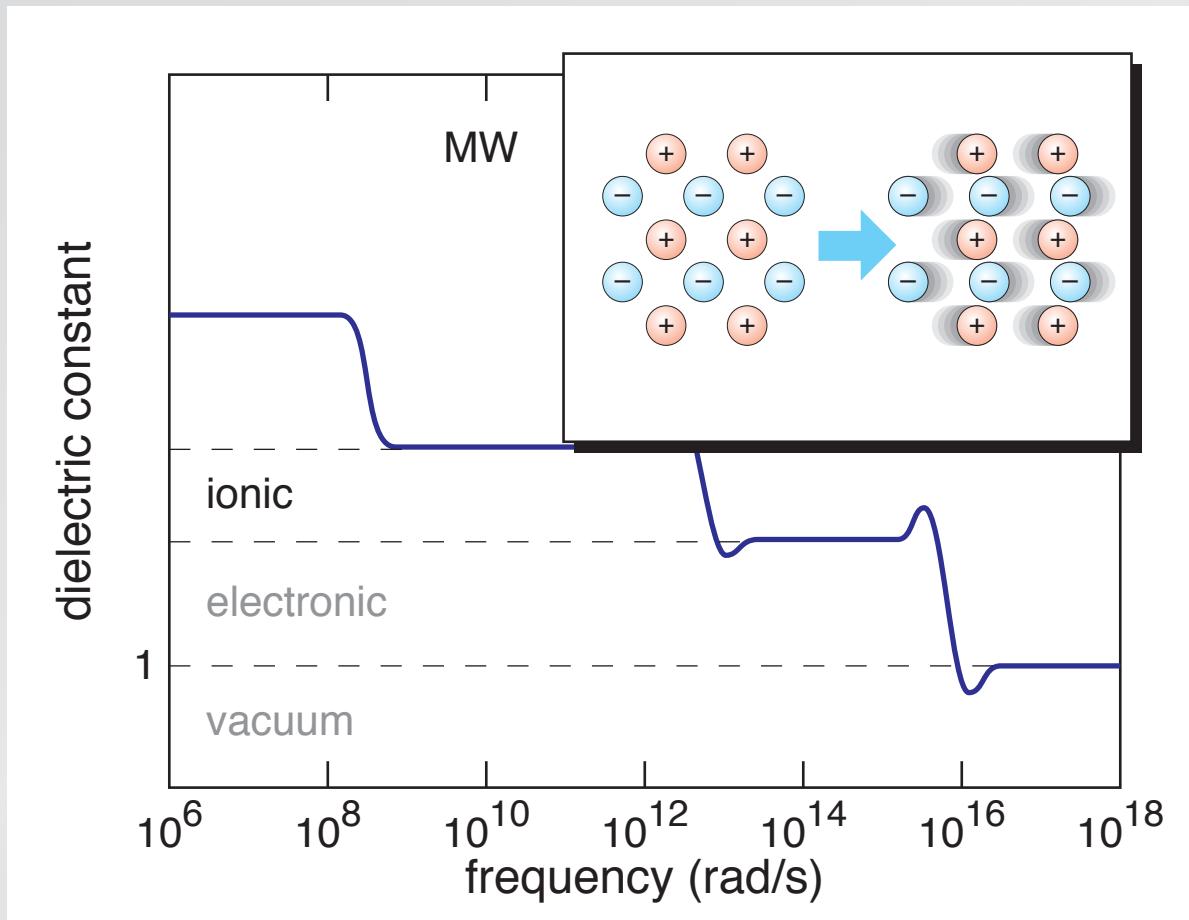
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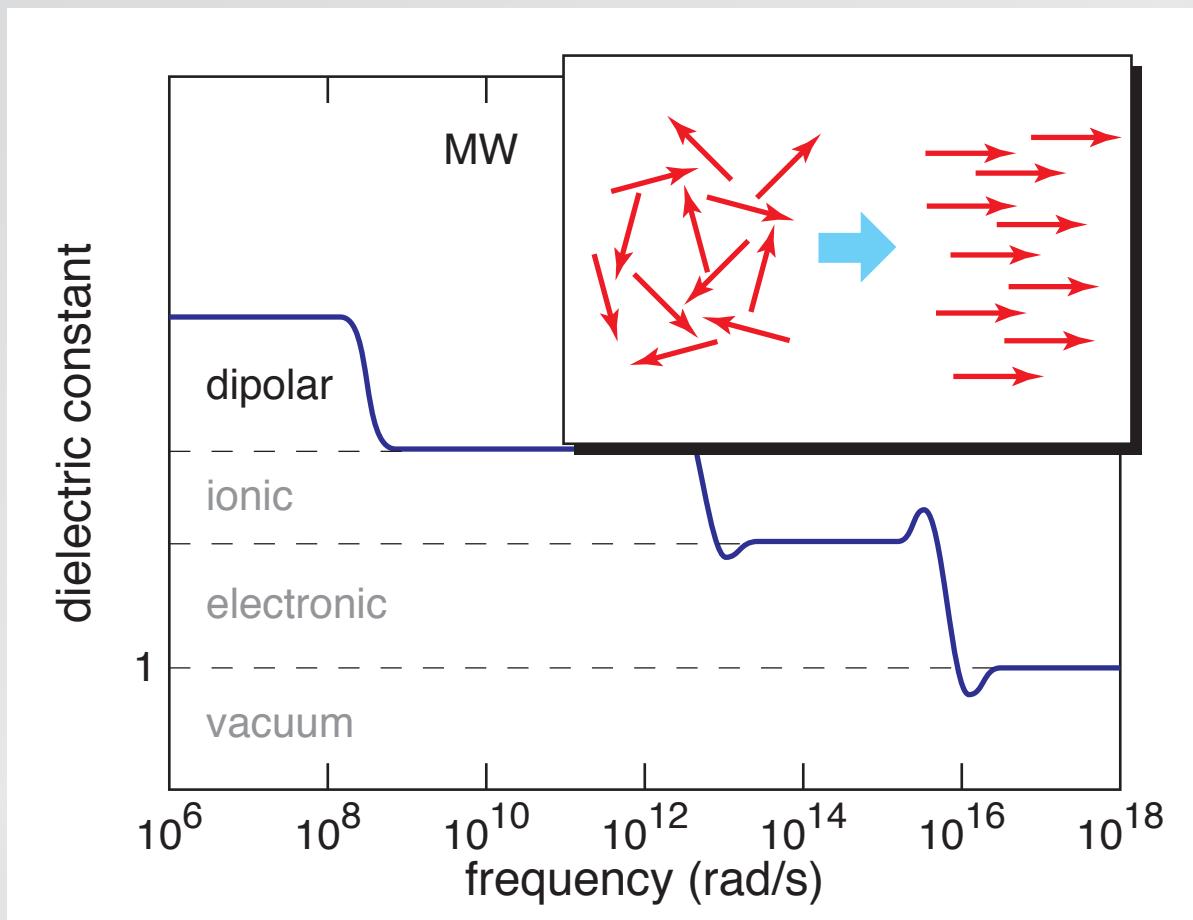
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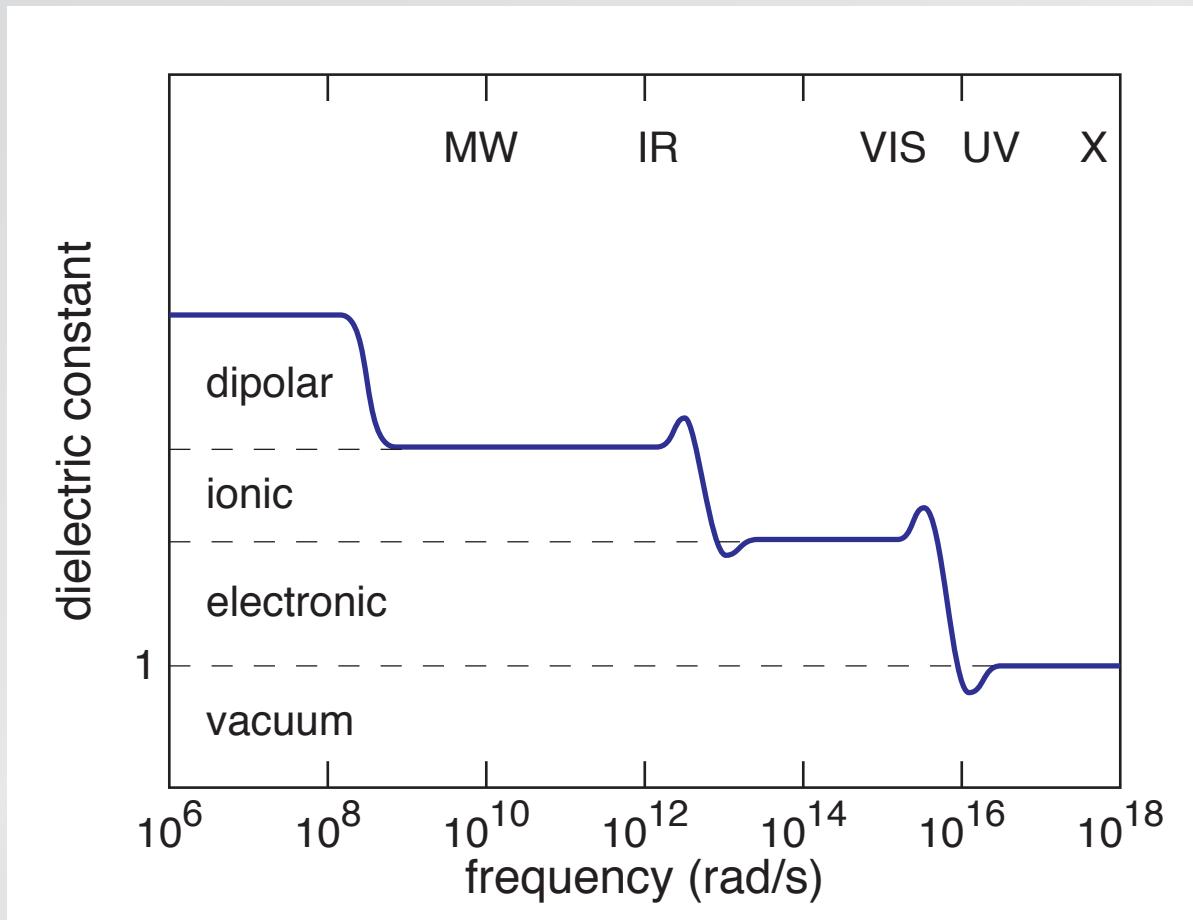
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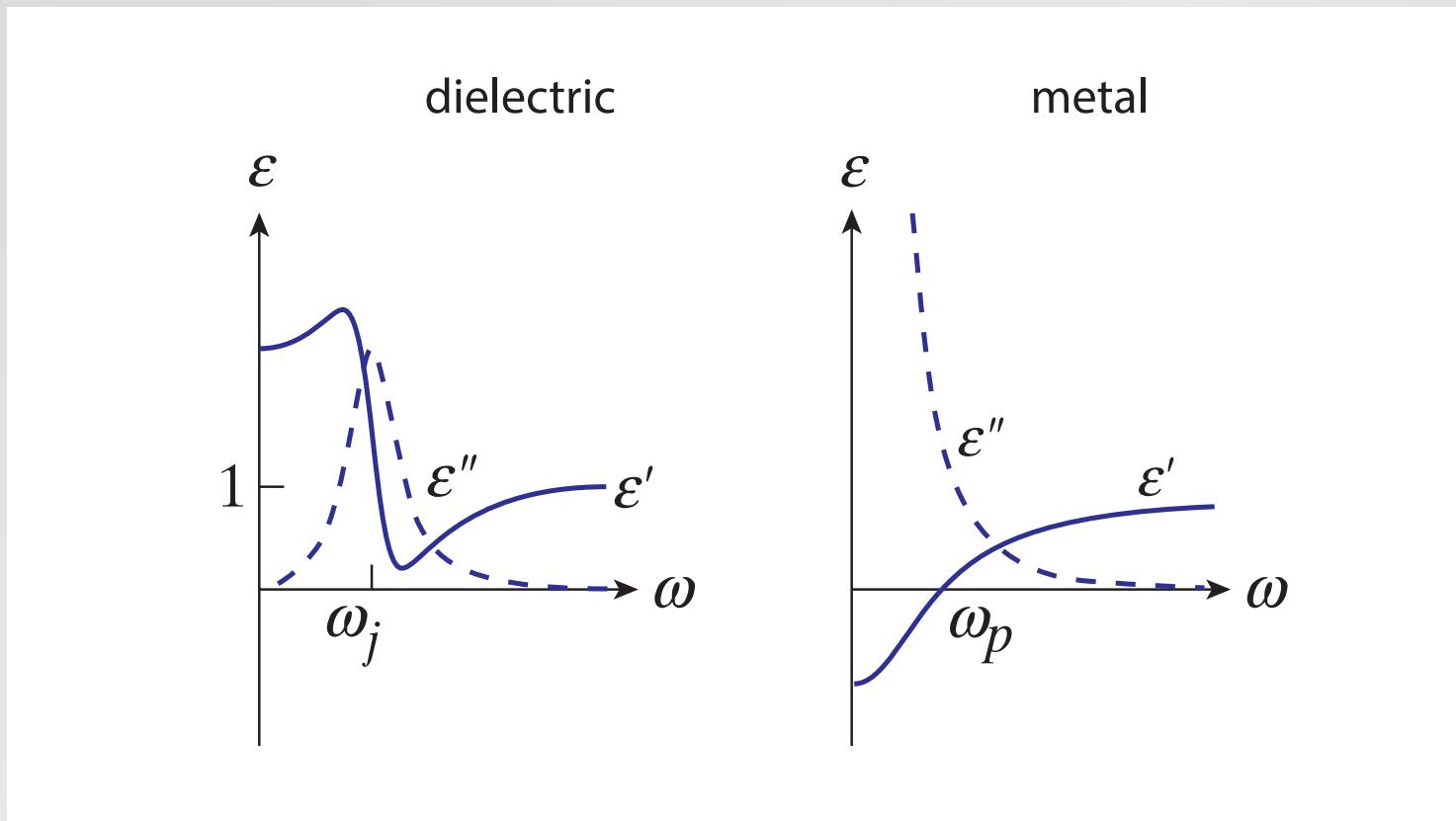
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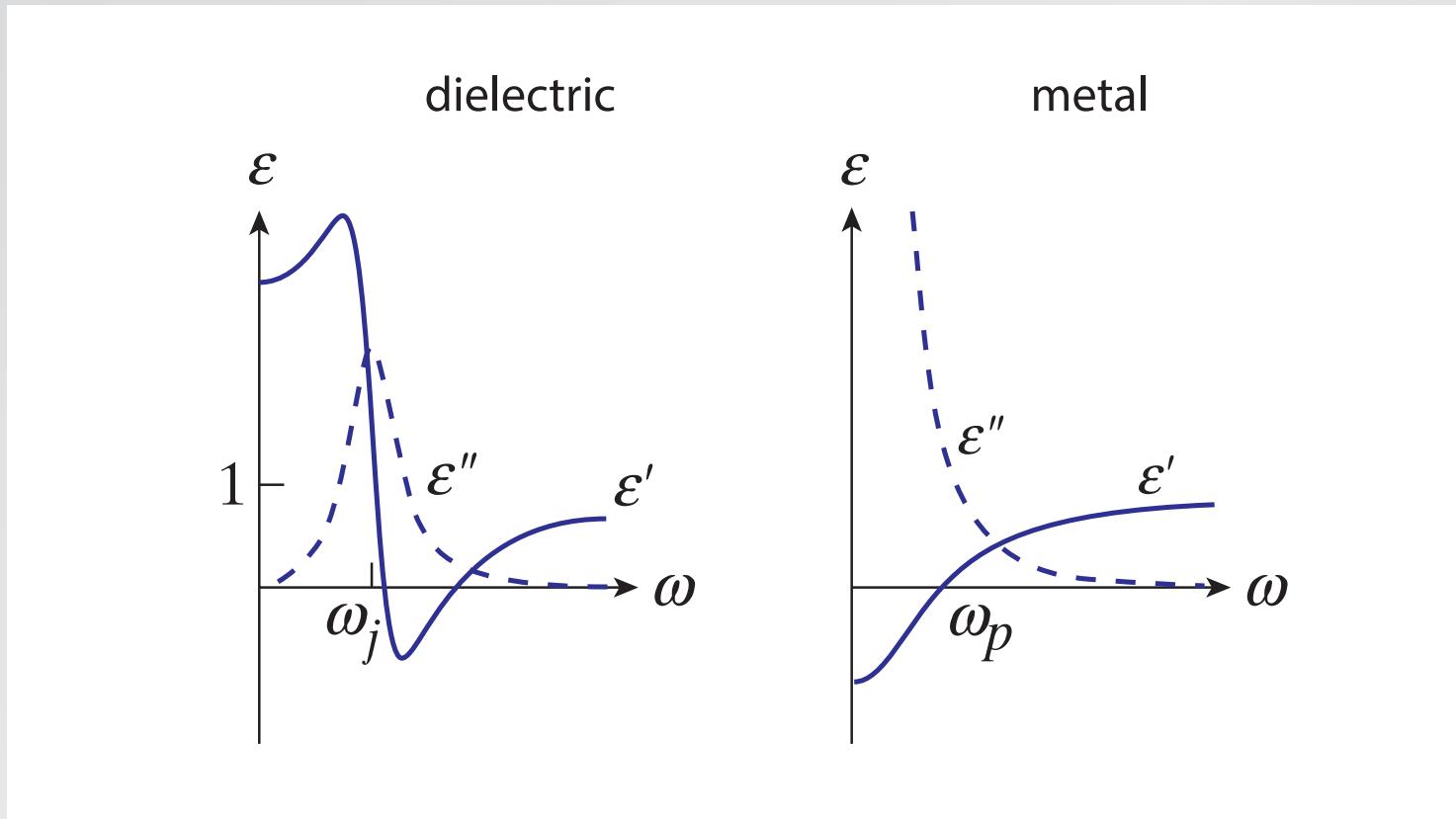


Lorentz and Drude models



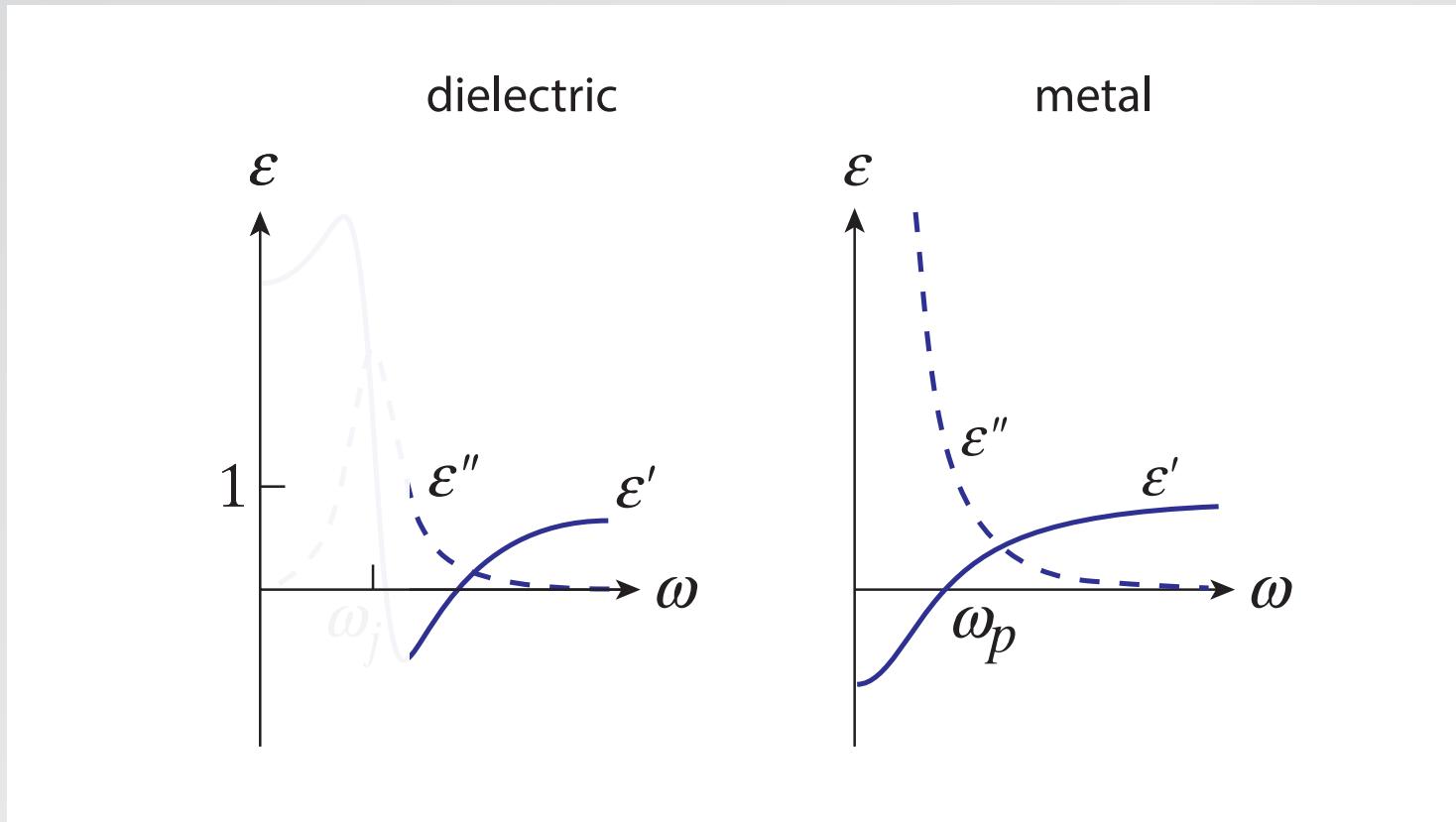
Lorentz and Drude models

for a strong (dielectric) resonance ϵ can become negative



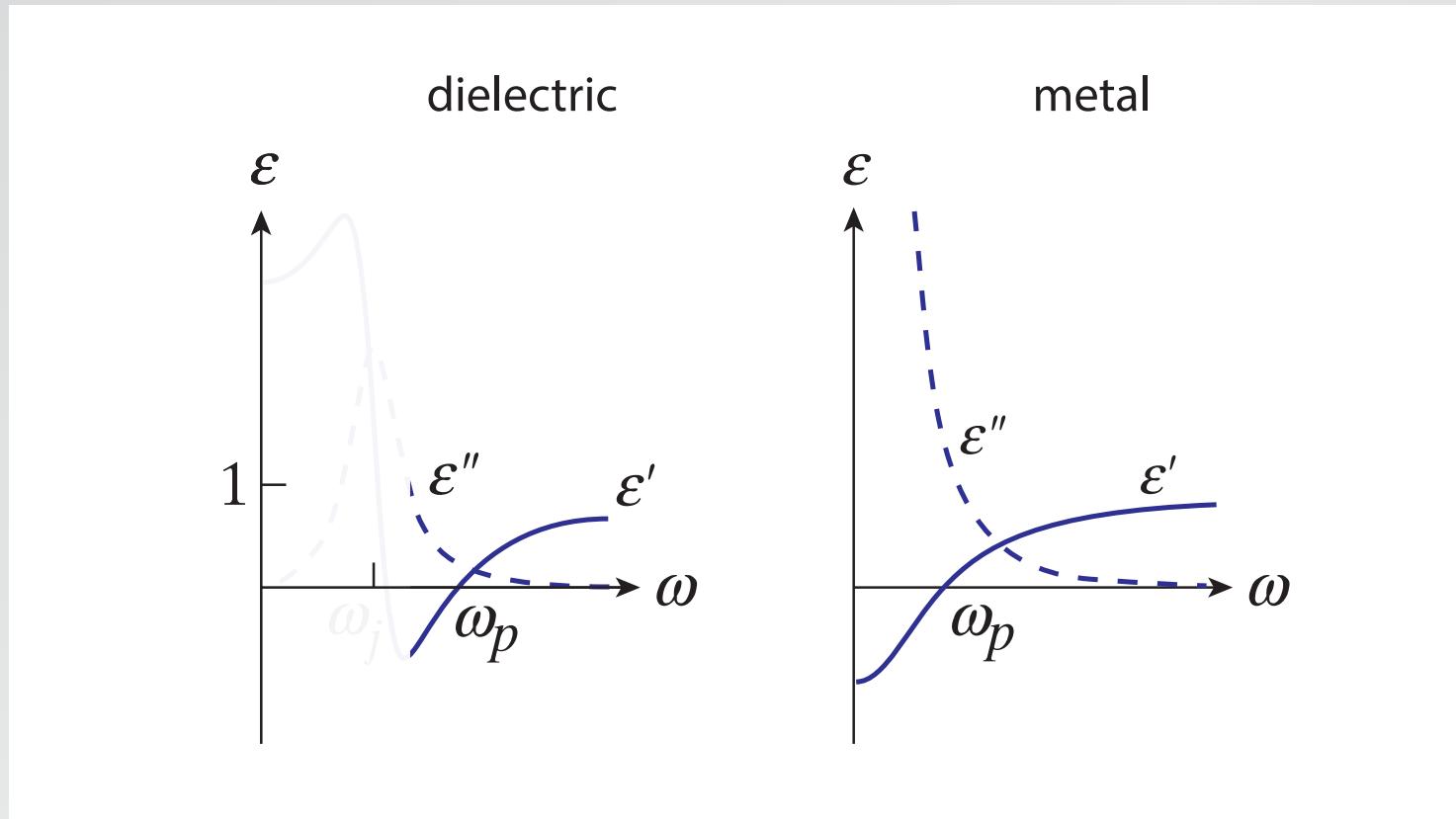
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valence electrons in dielectric then behave like a plasma



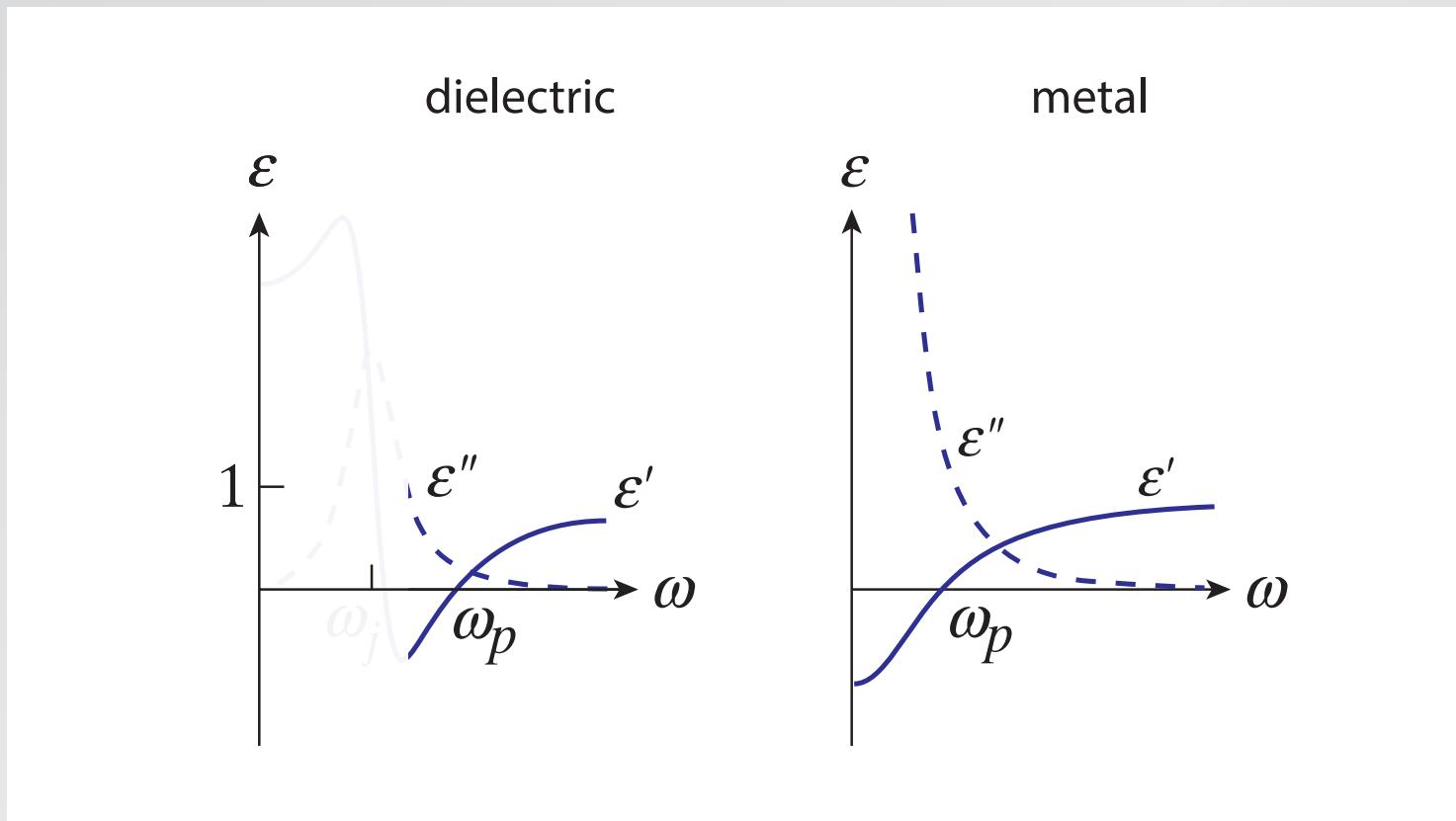
Lorentz and Drude models

with plasma frequency above the resonance



Lorentz and Drude models

(and far below the UV region)



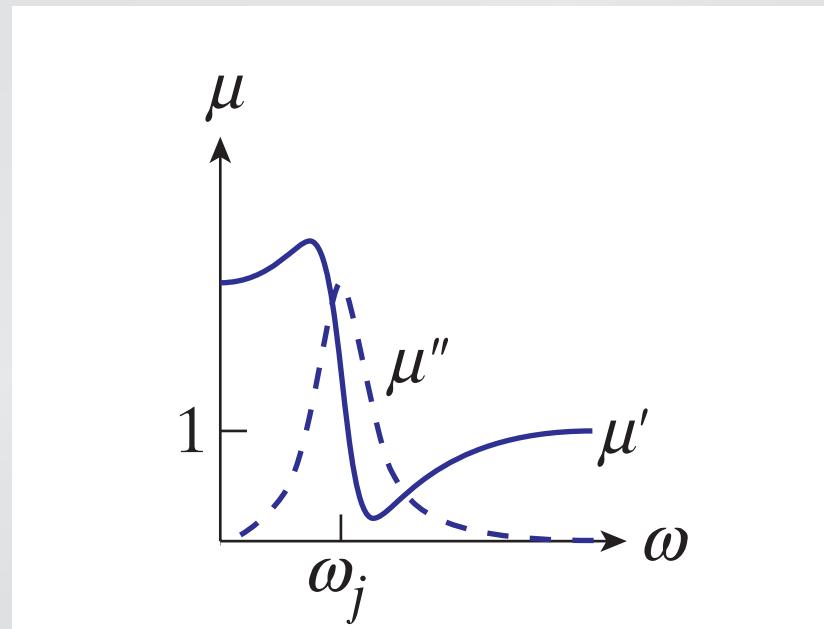
Index also determined by magnetic response

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

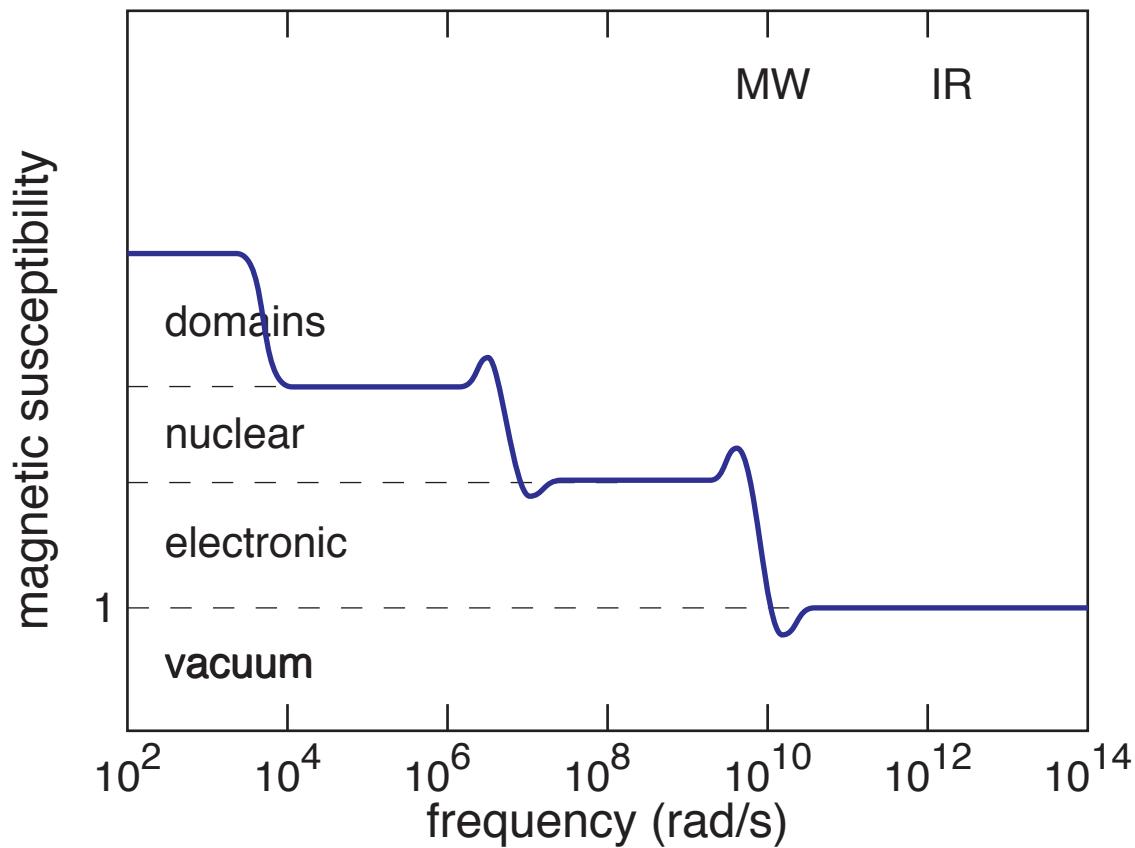
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and magnetic response shows similar resonances

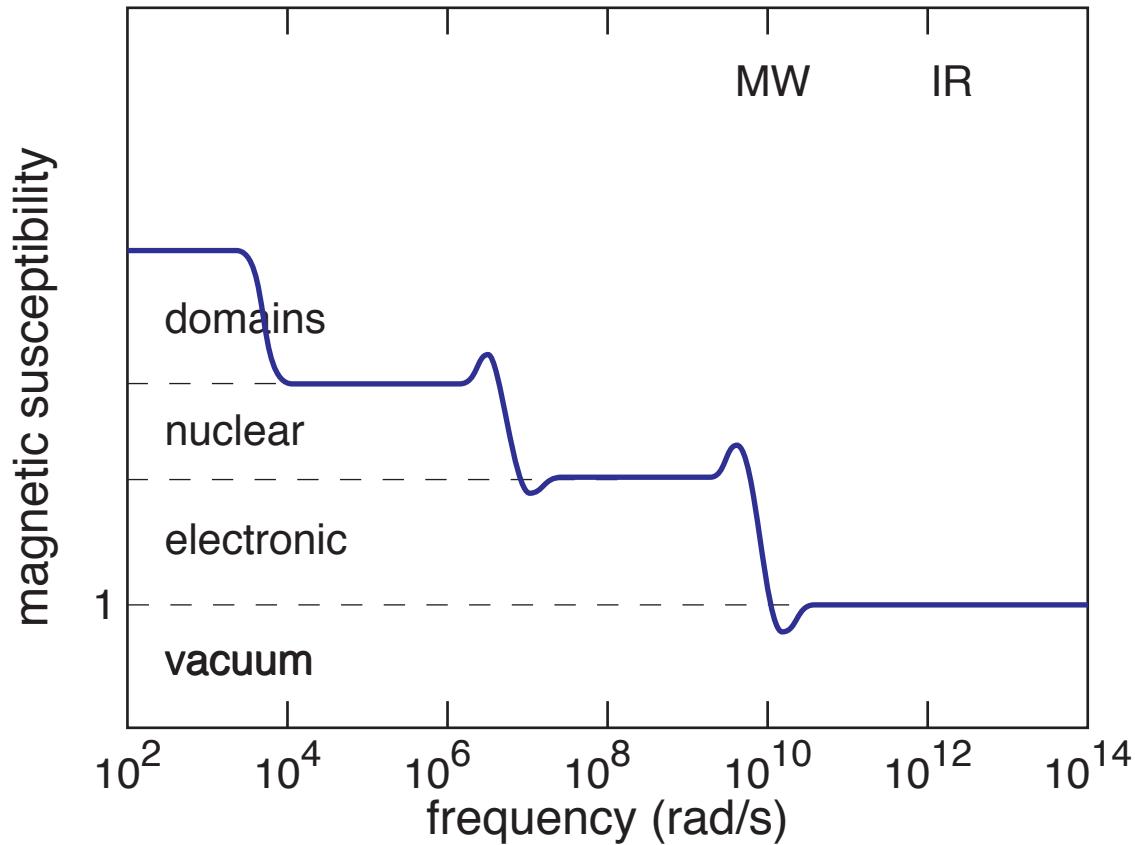


Magnetic response



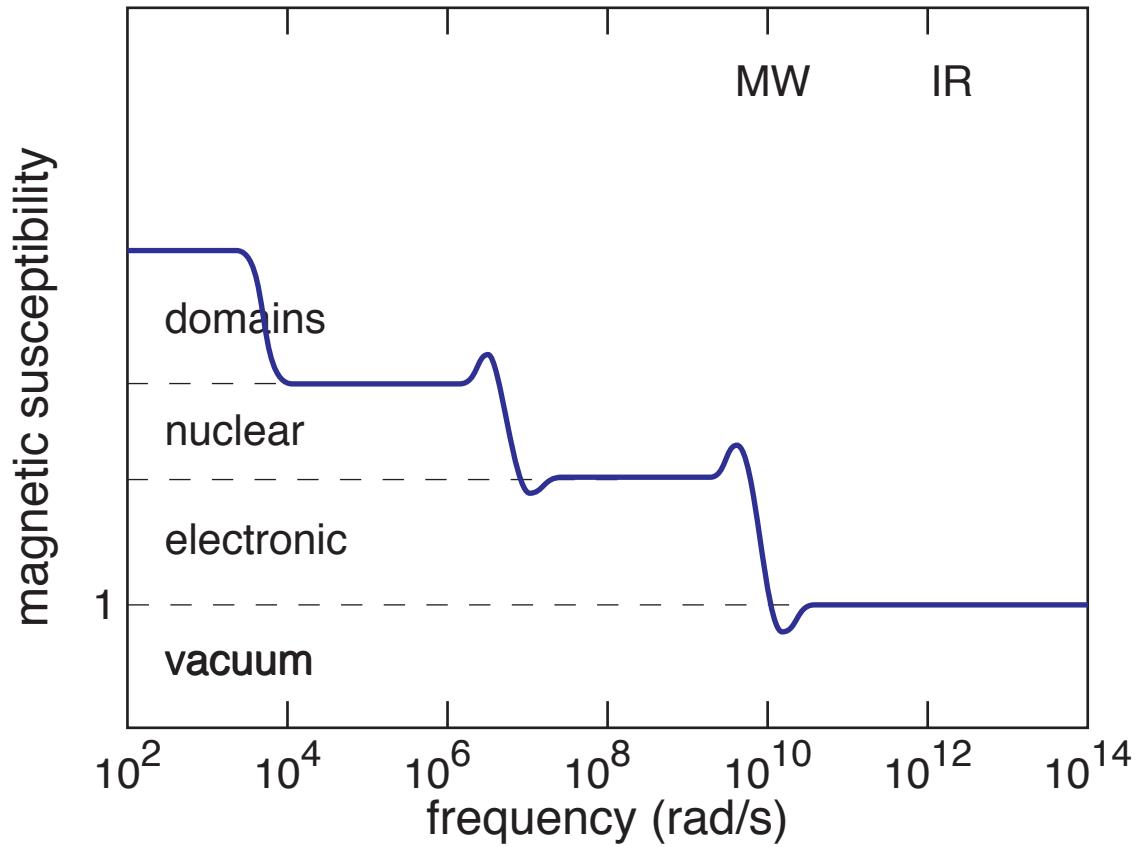
Magnetic response

but magnetic resonances occur below optical frequencies



Magnetic response

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



Index of refraction

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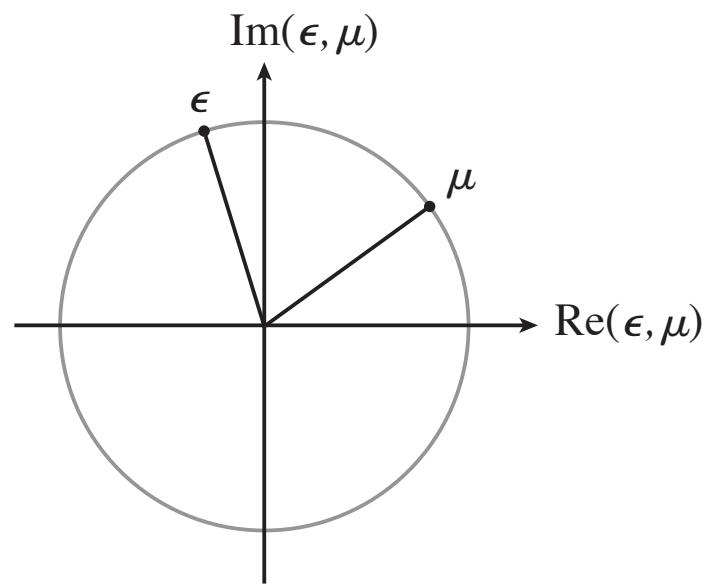
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Write complex quantities as

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

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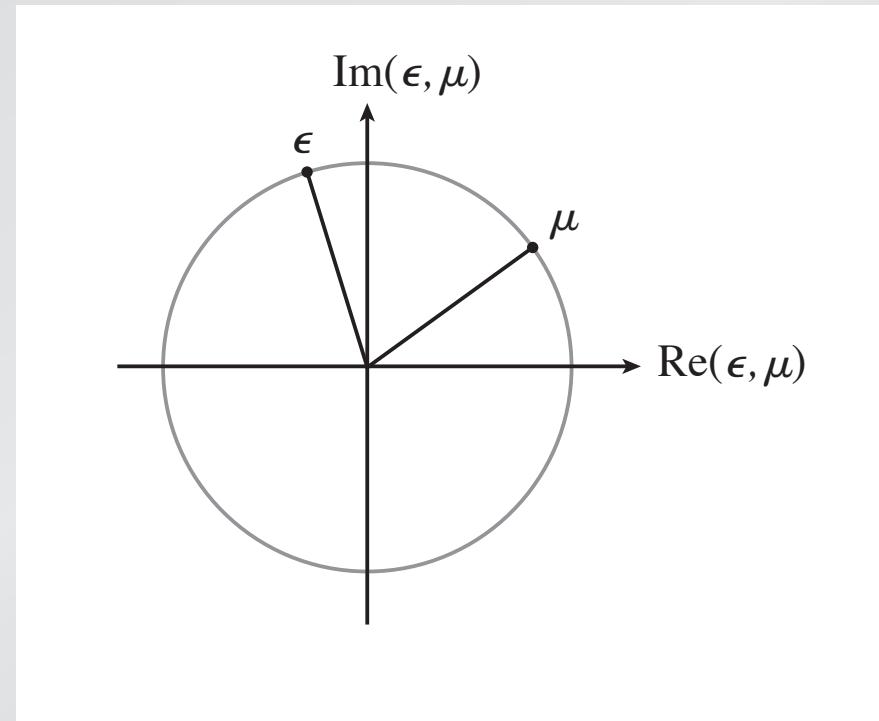


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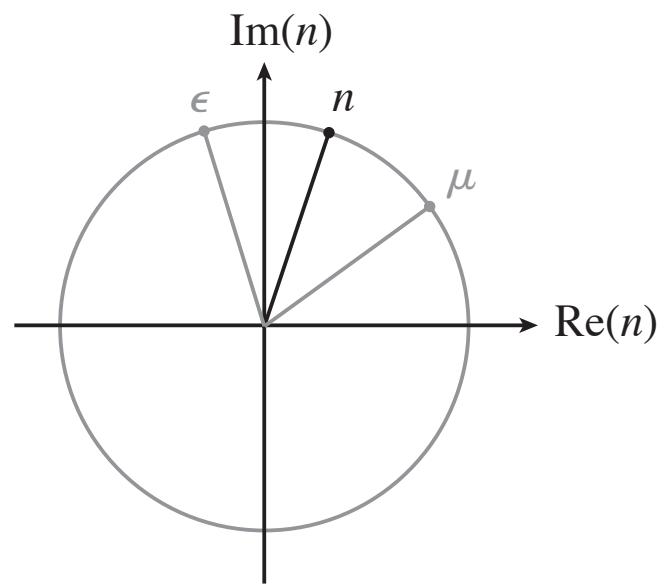


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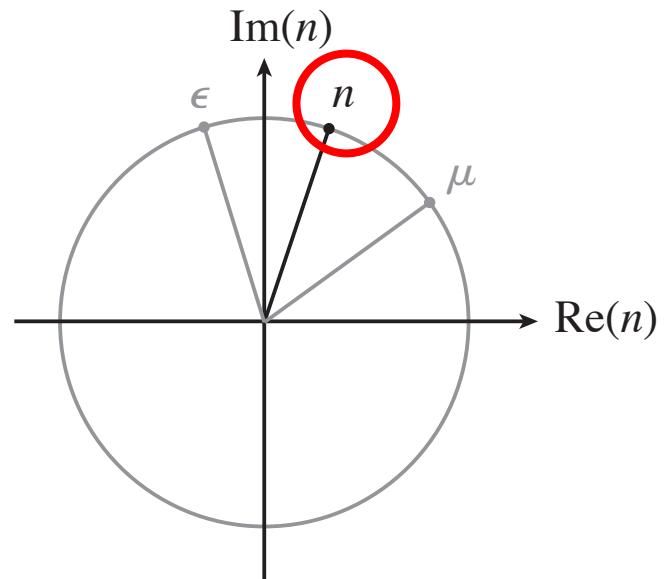
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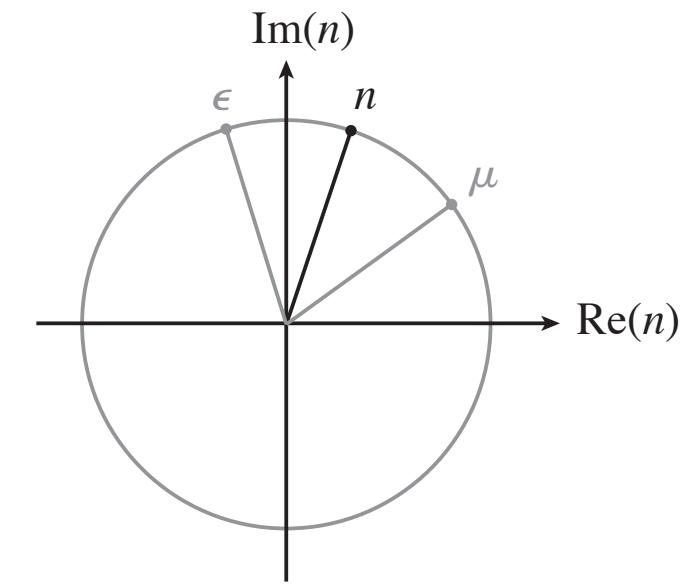
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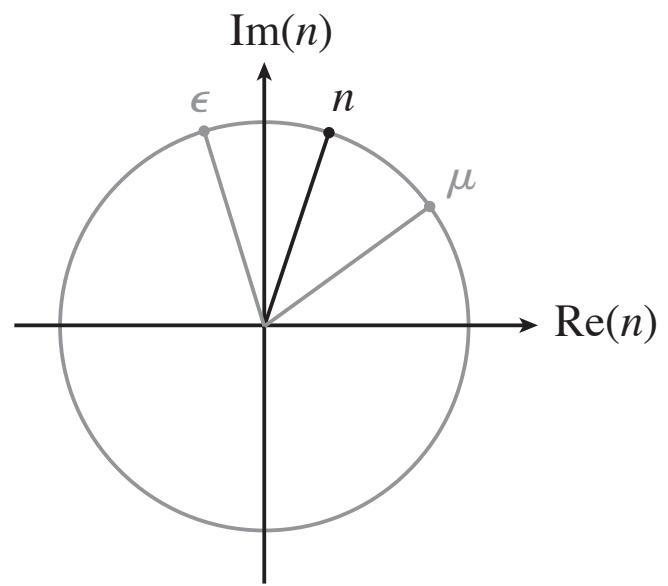
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Can add 2π to exponent

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



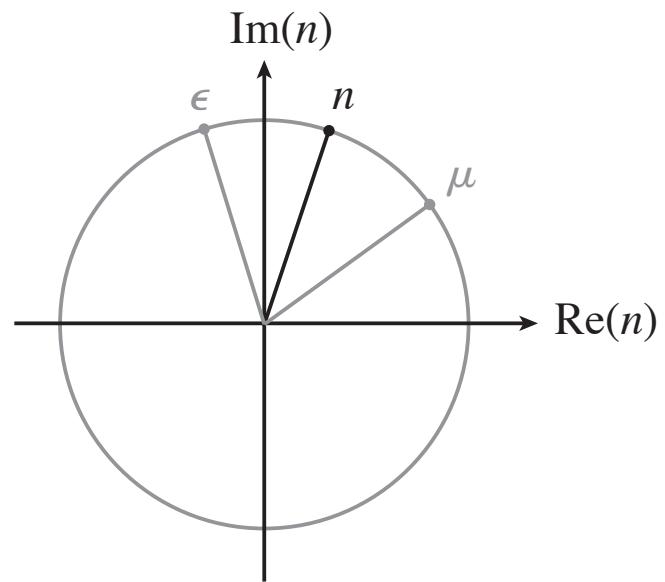
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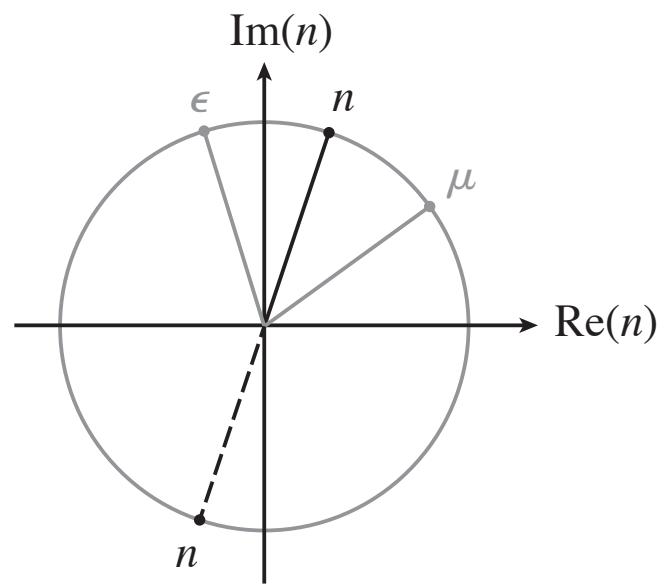
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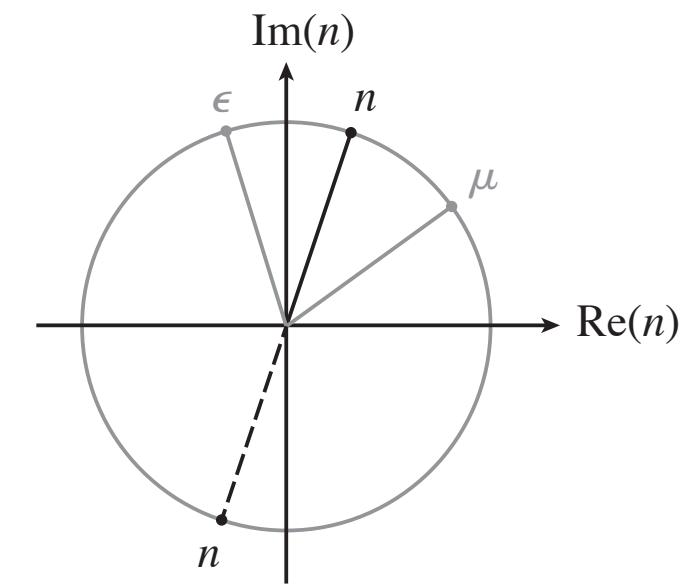
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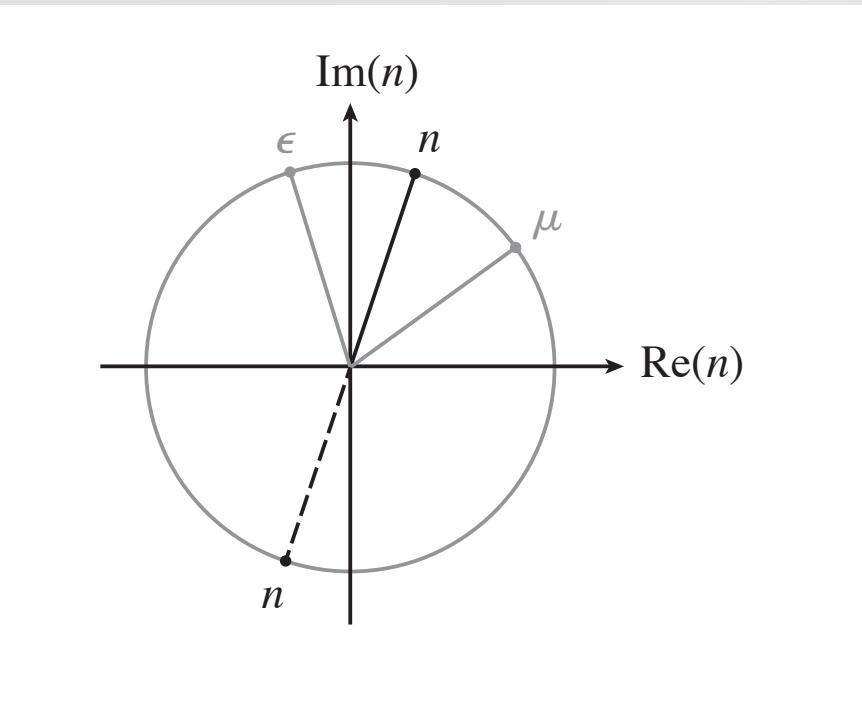
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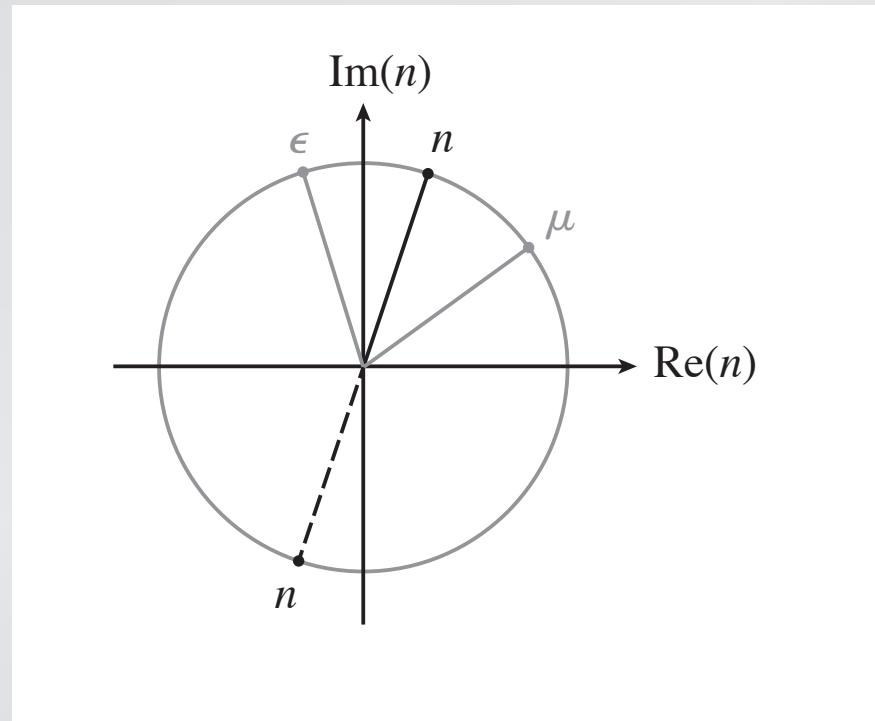
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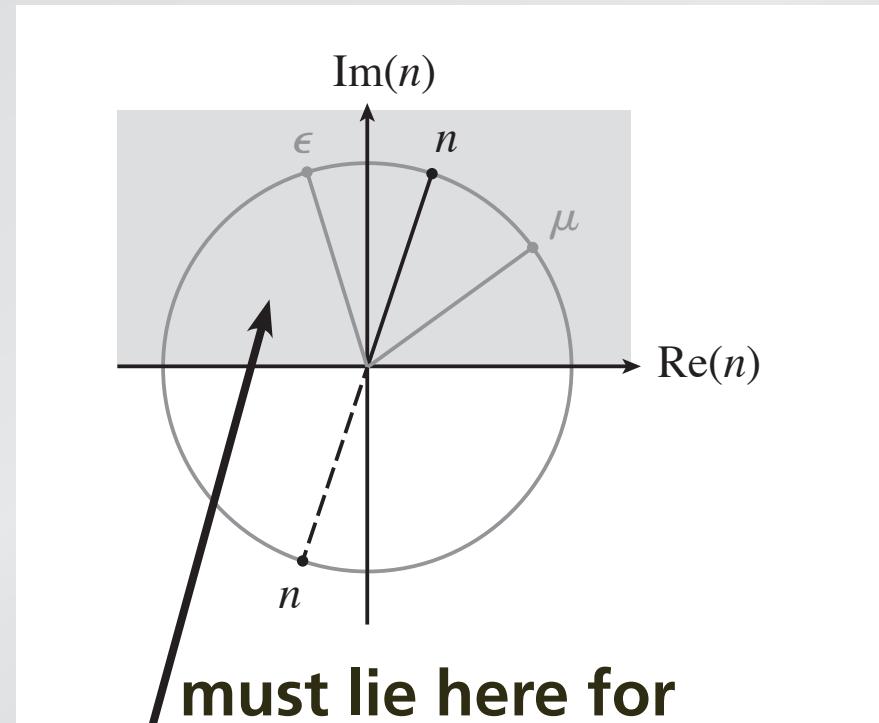
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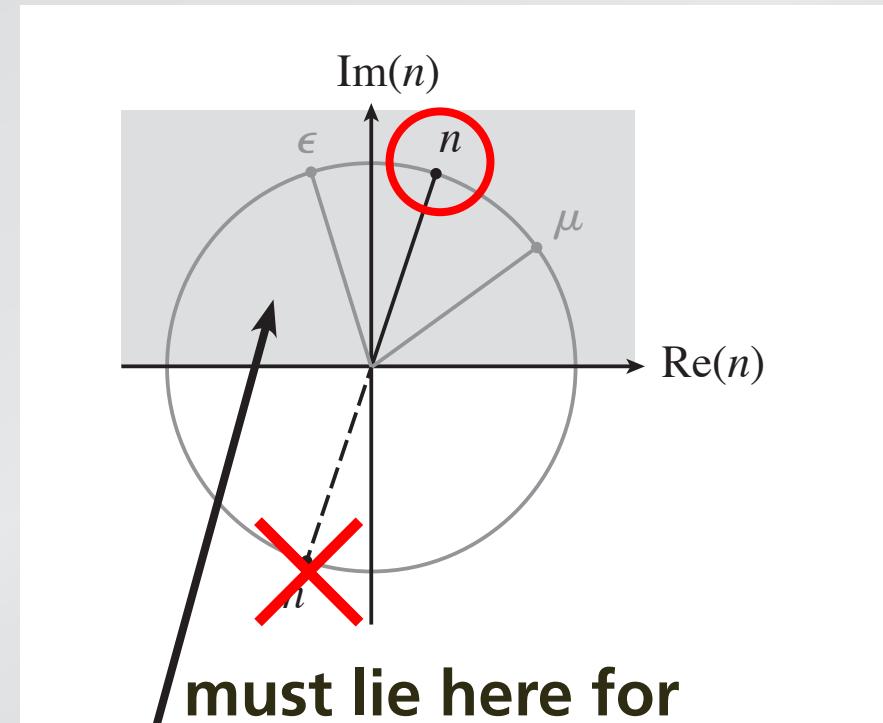
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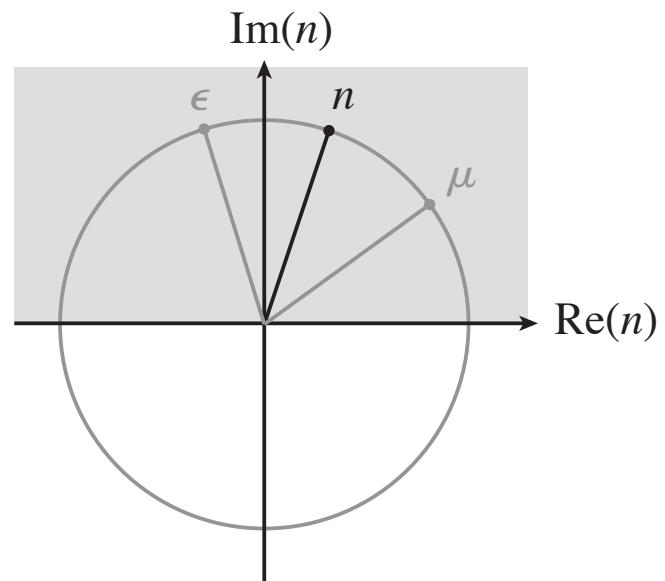
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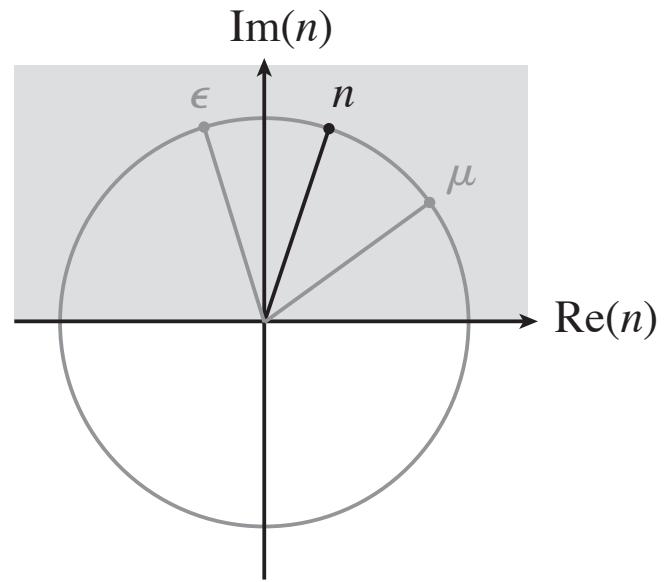
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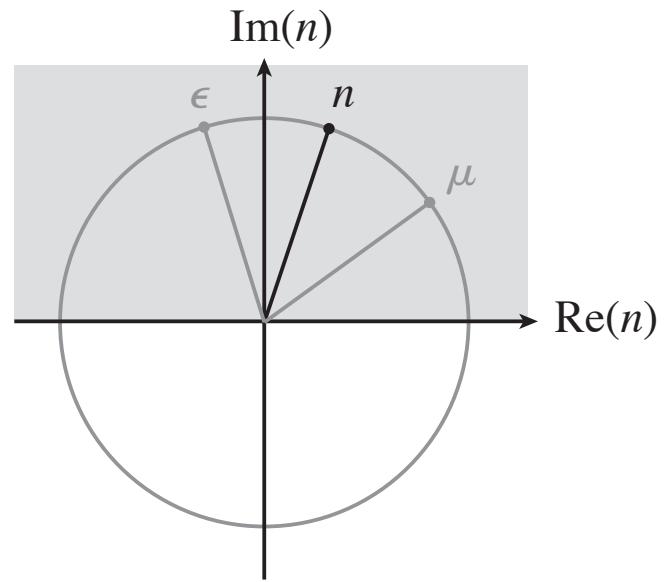
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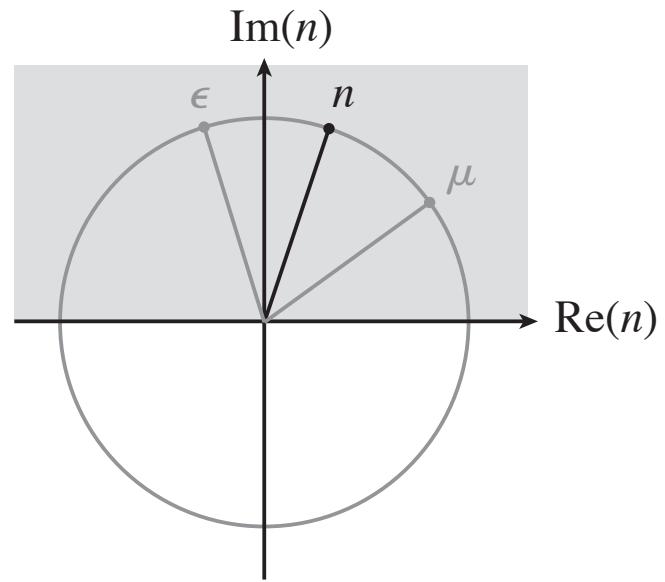
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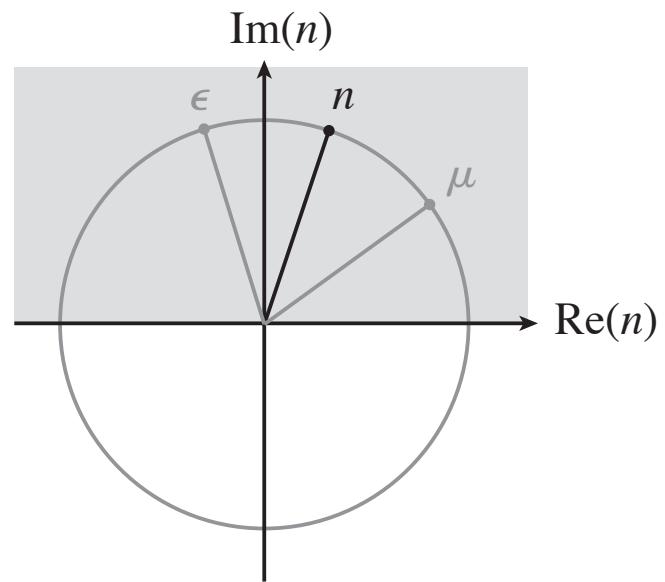
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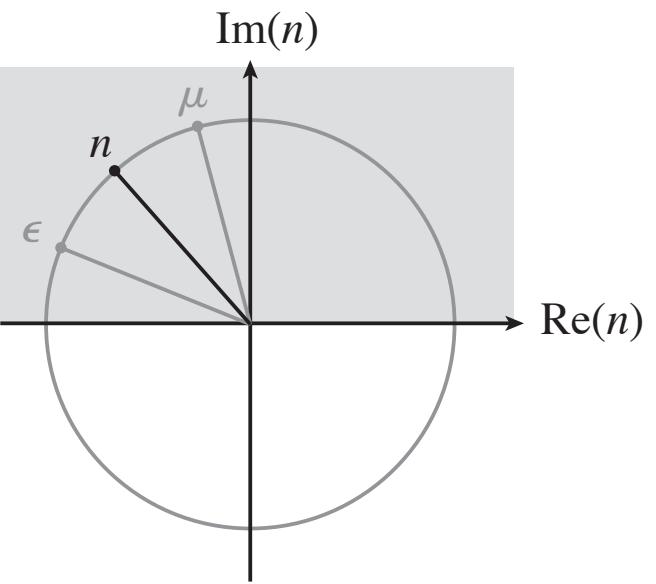
To find n (passive materials):

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



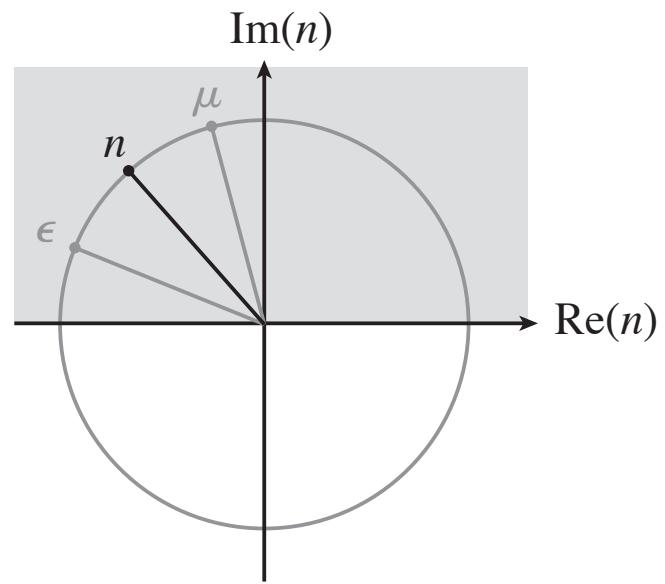
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**For certain values of ϵ and μ
we can get a *negative* $\text{Re}(n)$!**



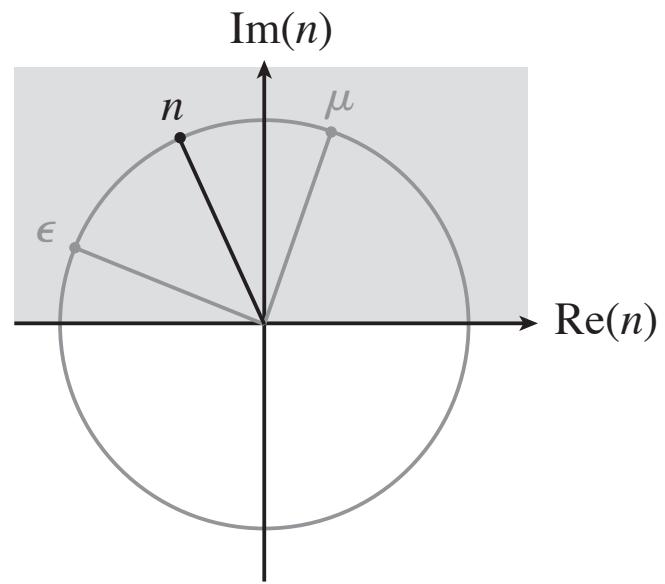
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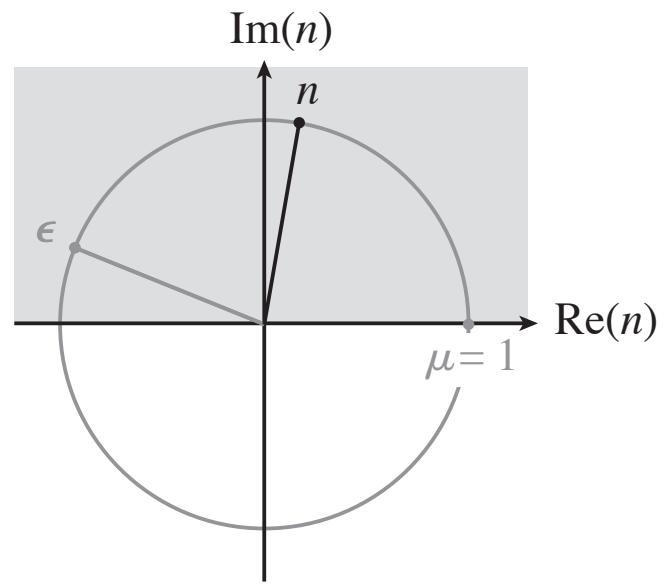


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**However, need magnetic response
to achieve $\text{Re}(n) \leq 0$!**



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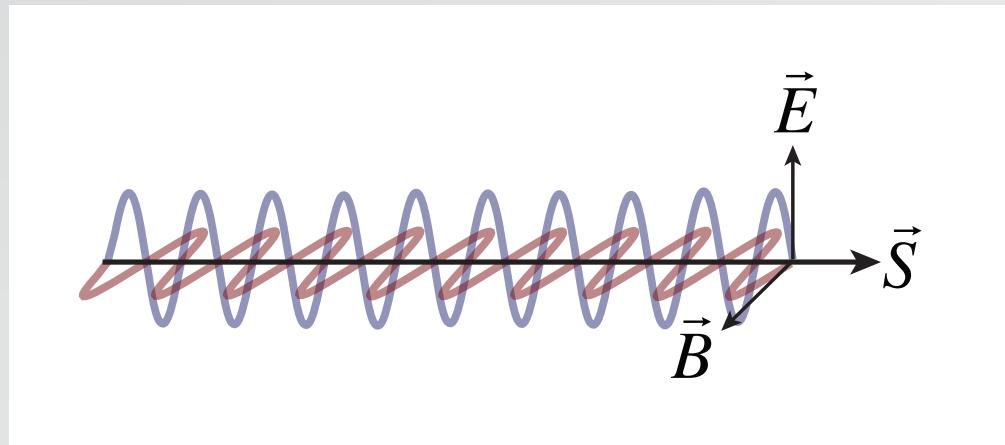
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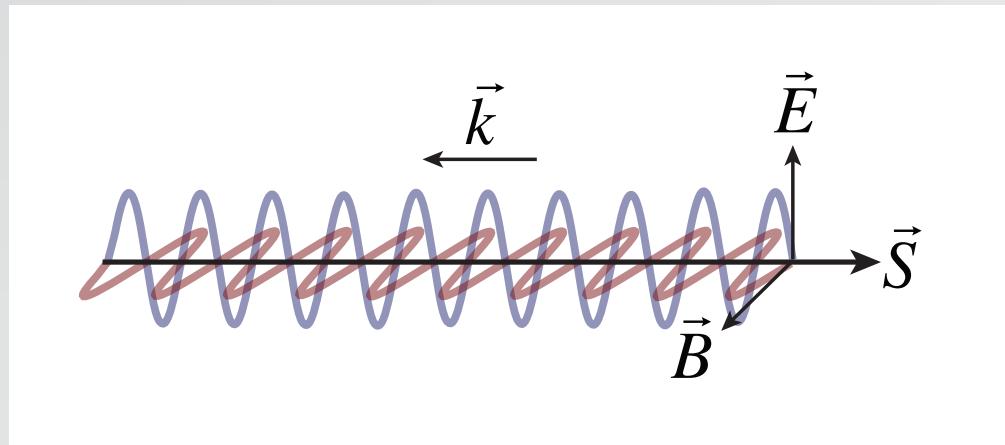
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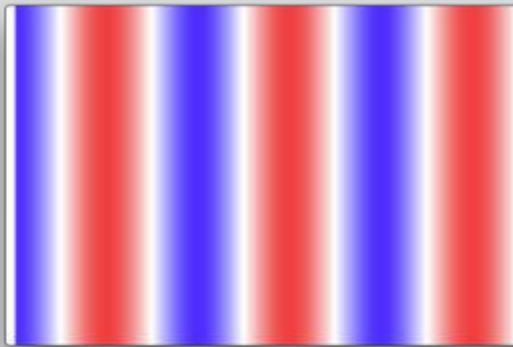
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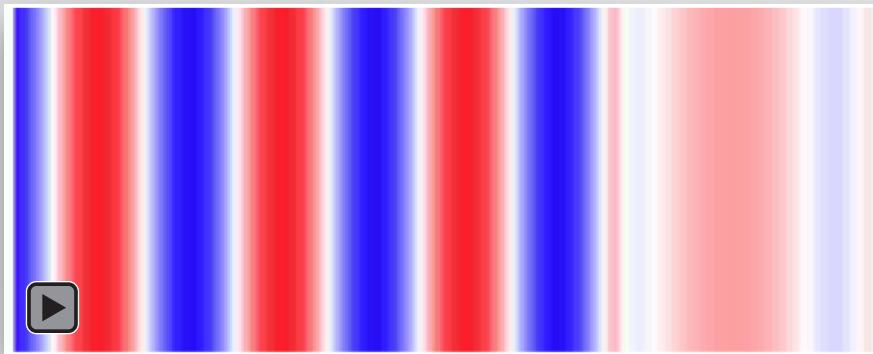


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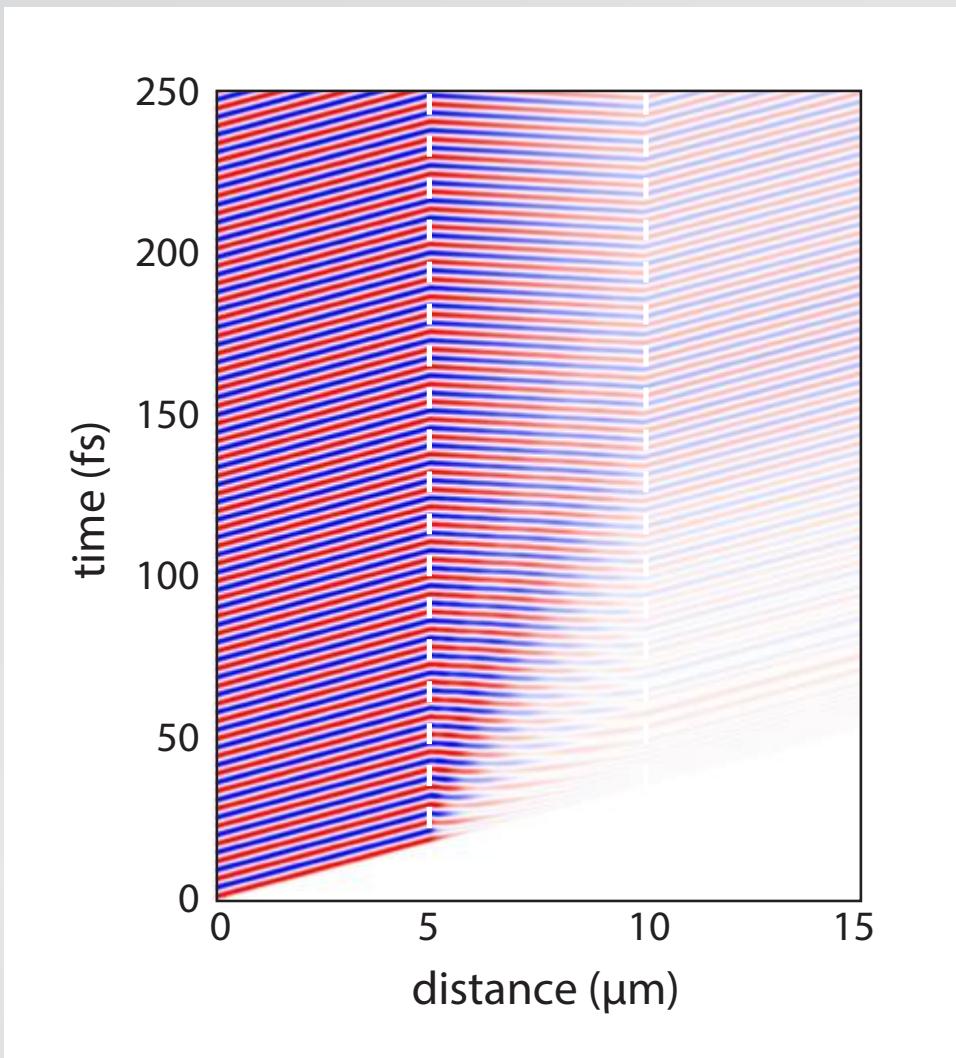
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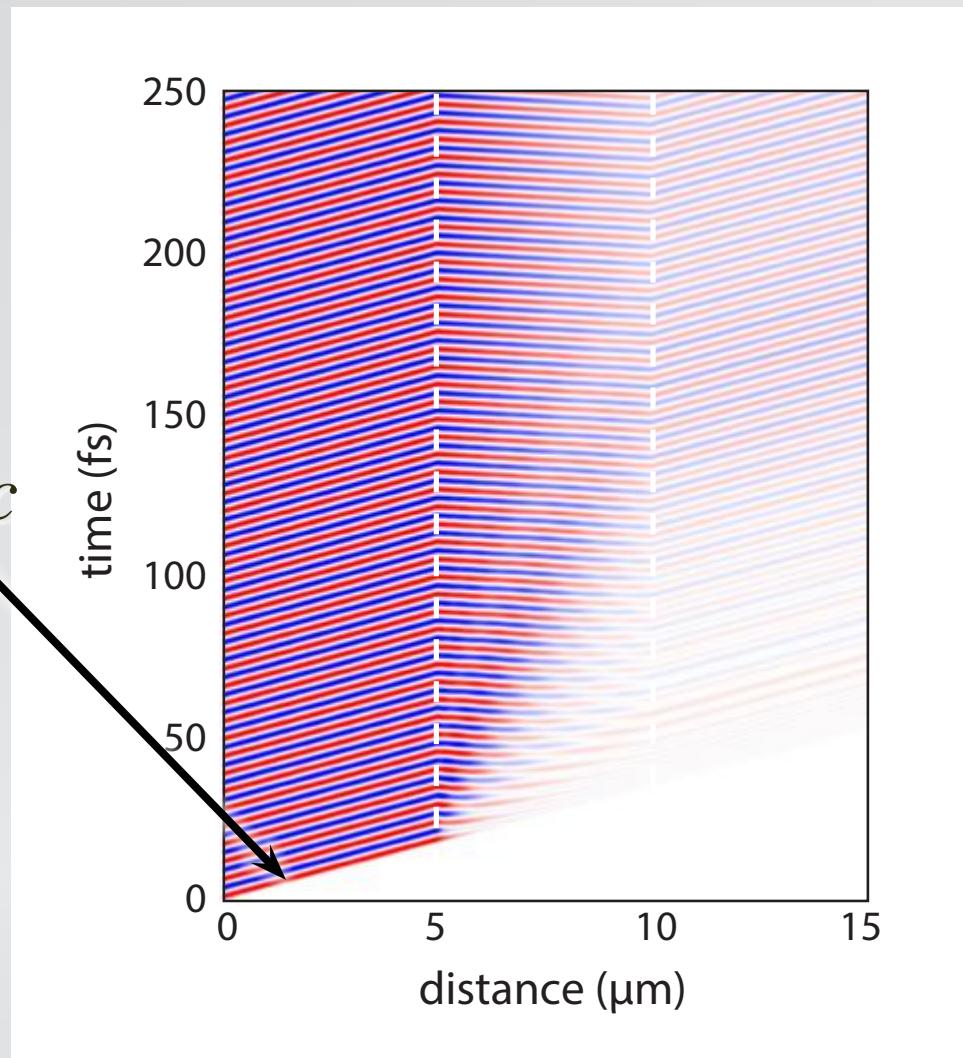


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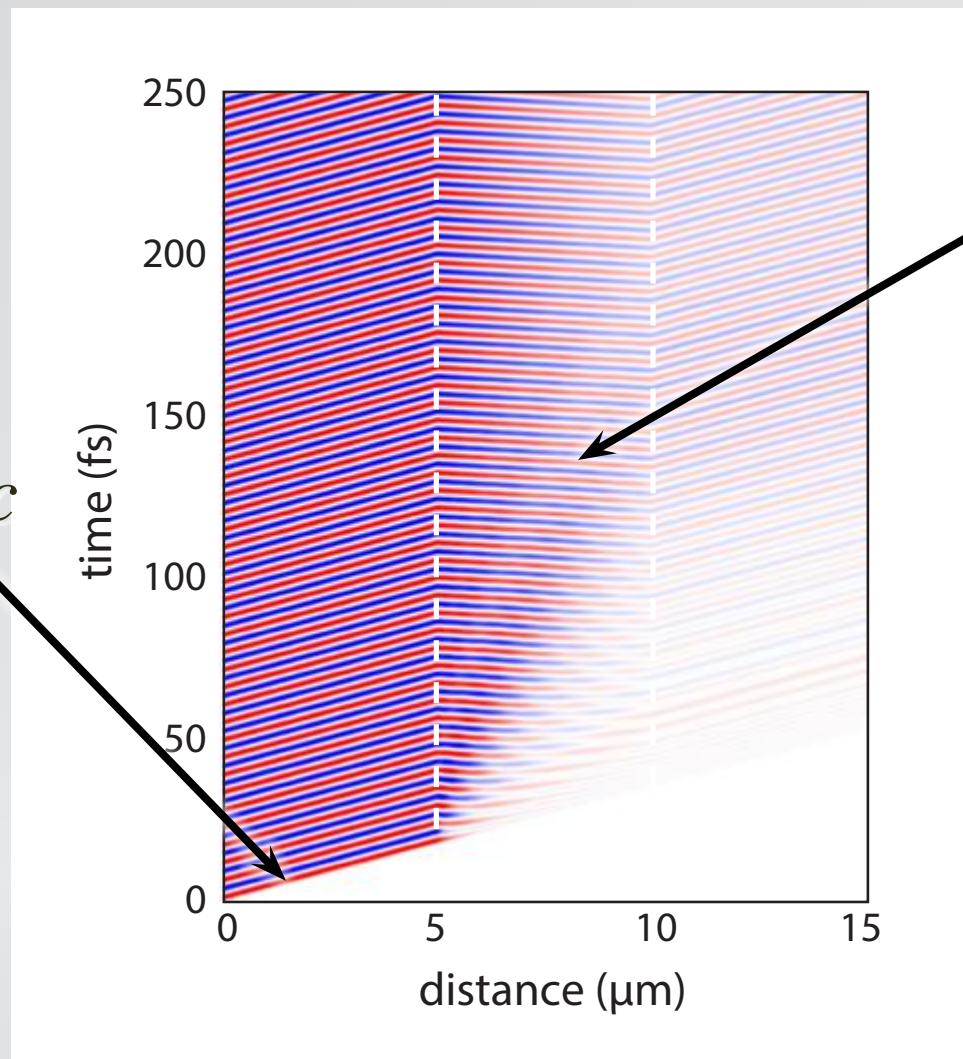
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speed of light c



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reverse phase
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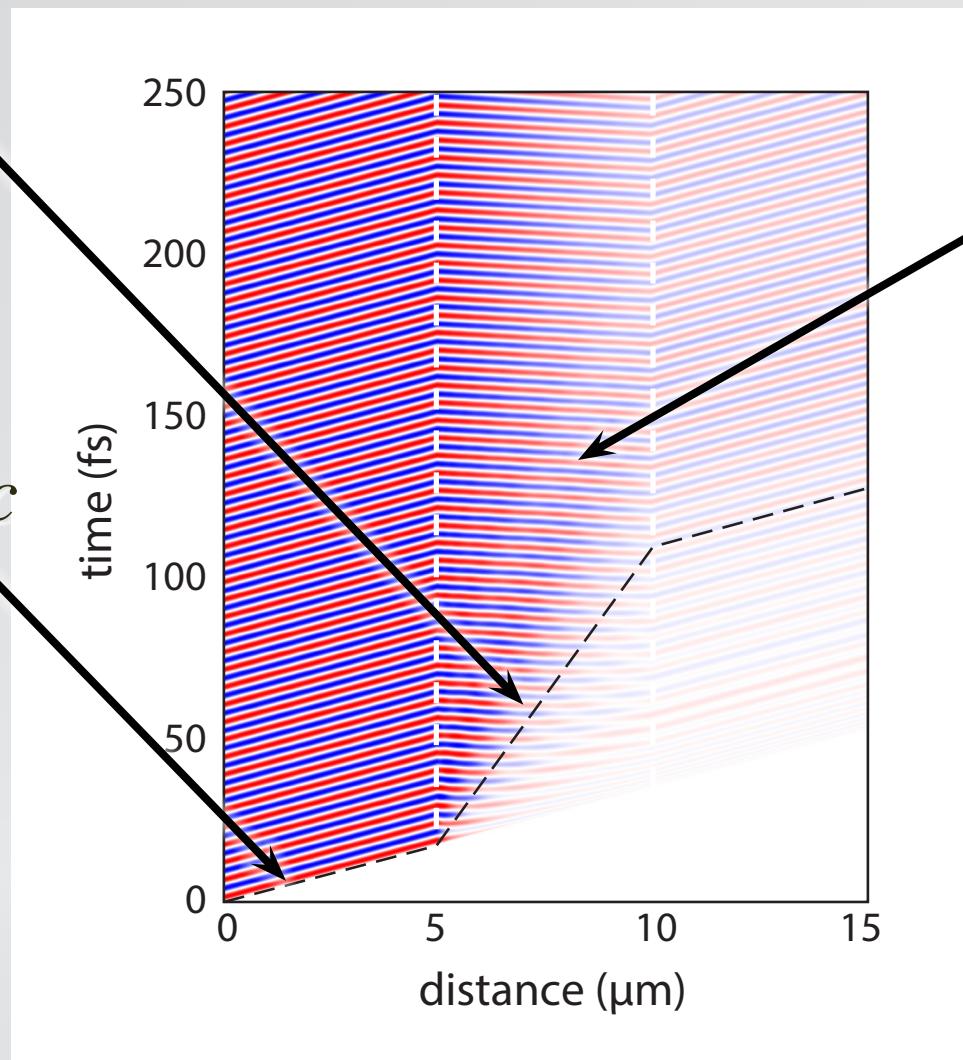
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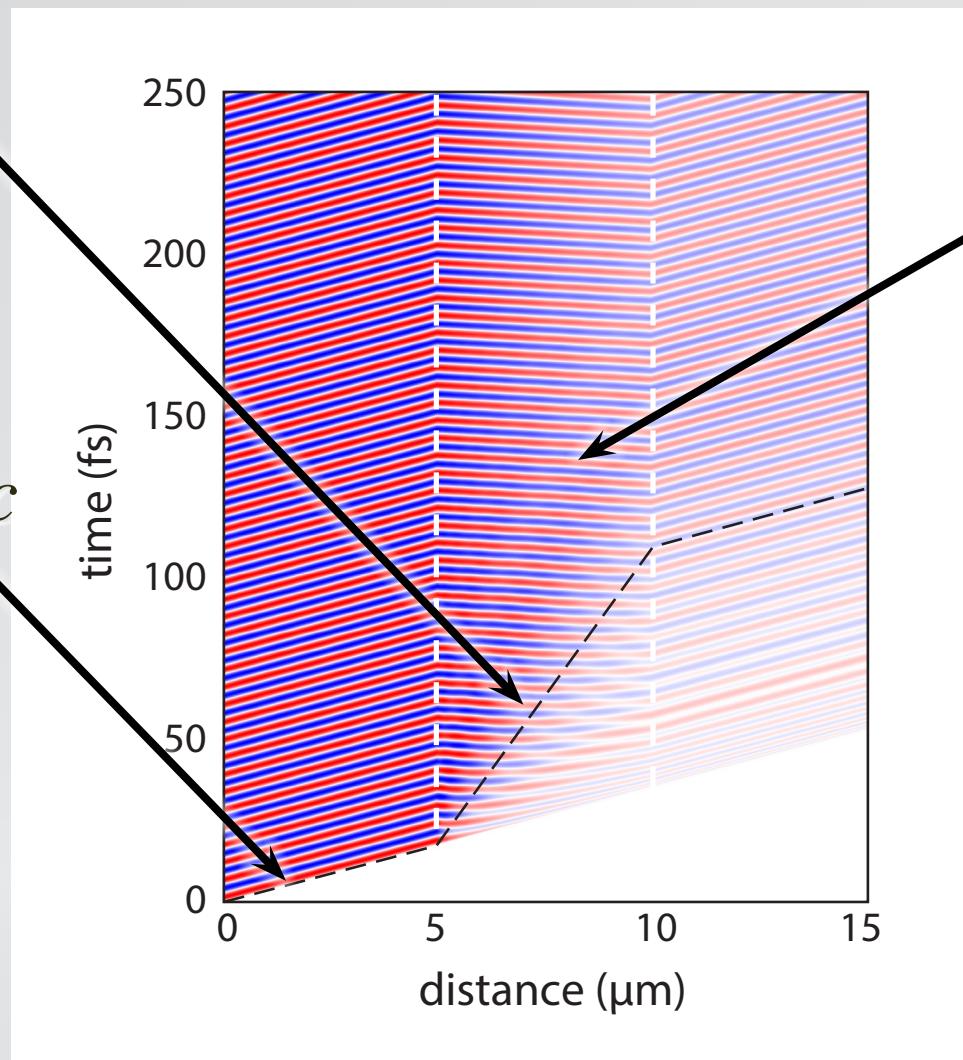
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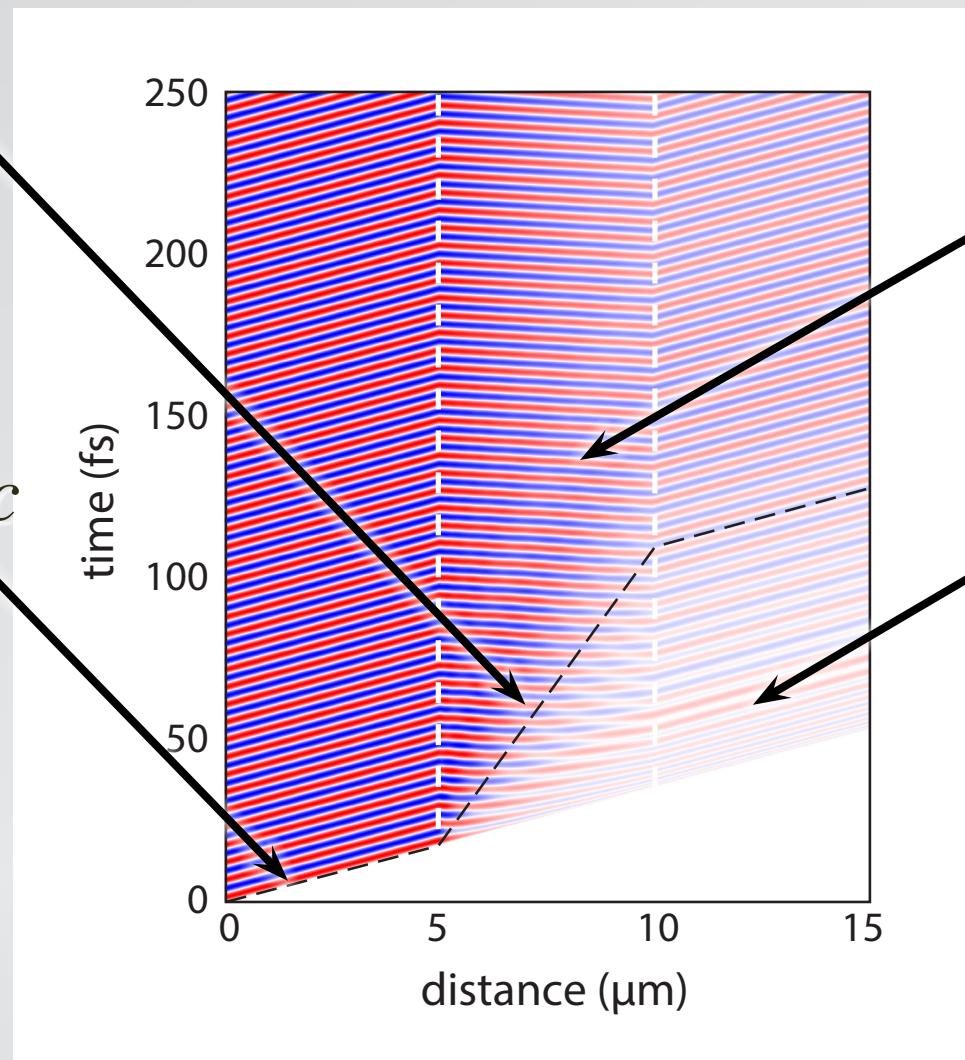


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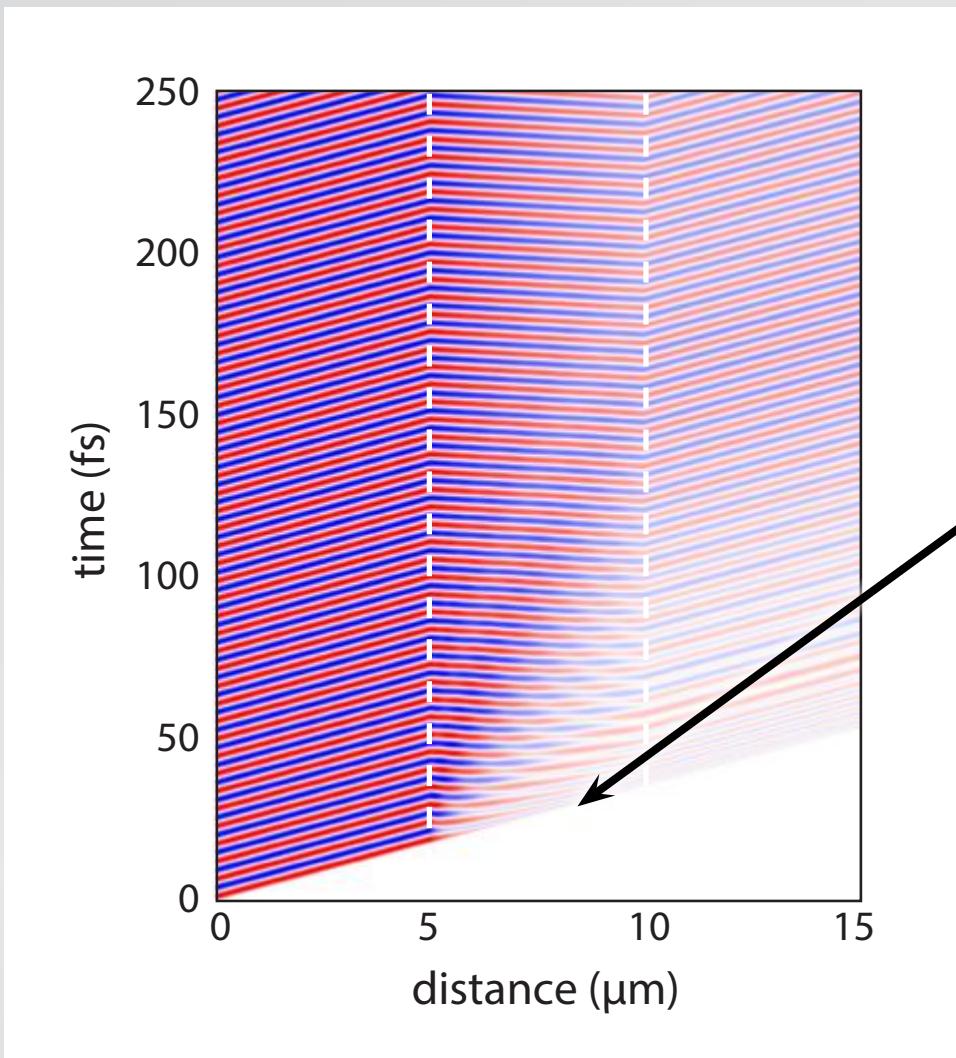
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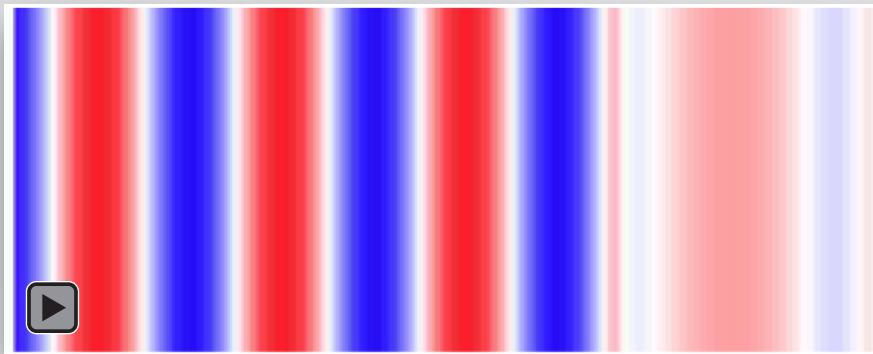
high-frequency
precursors

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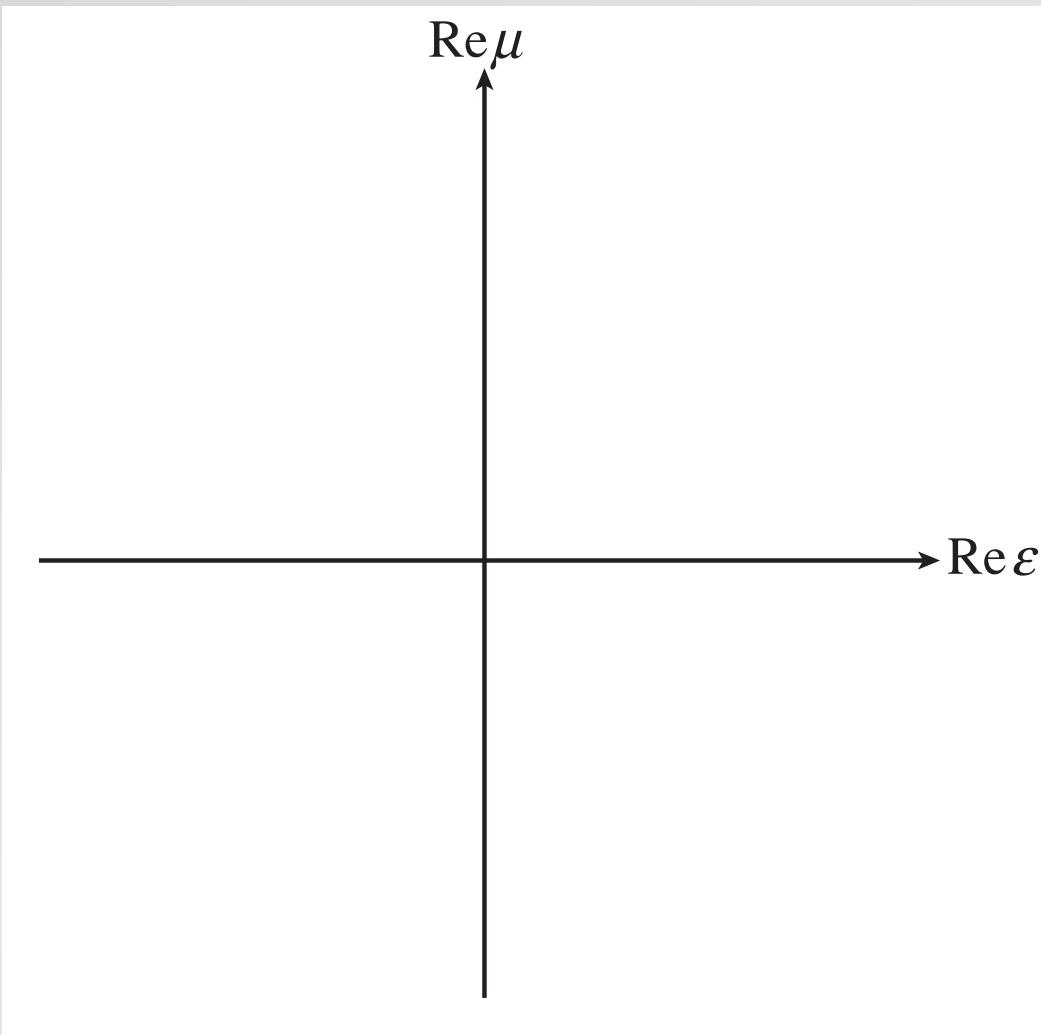


**signal *always*
travels at speed c !**

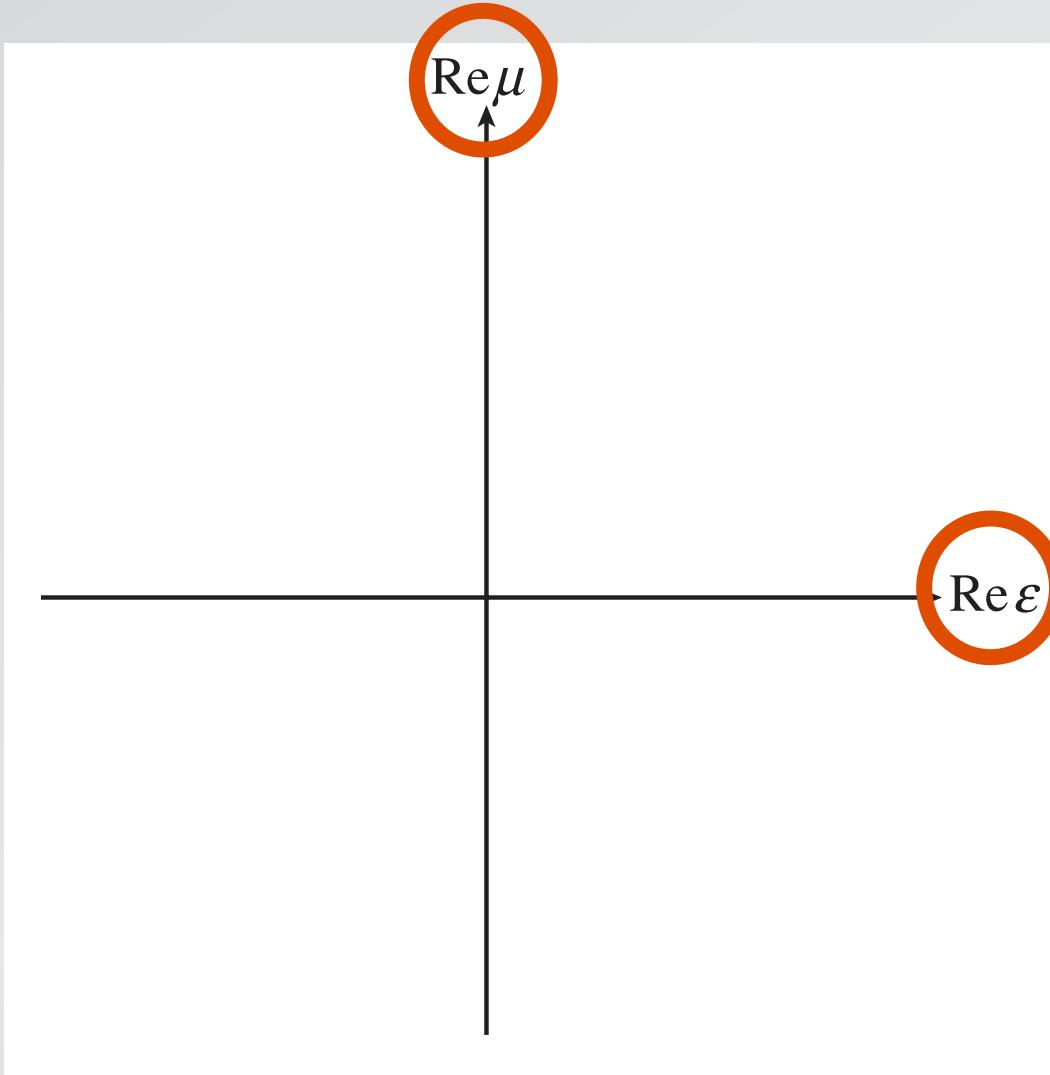
What about causality?



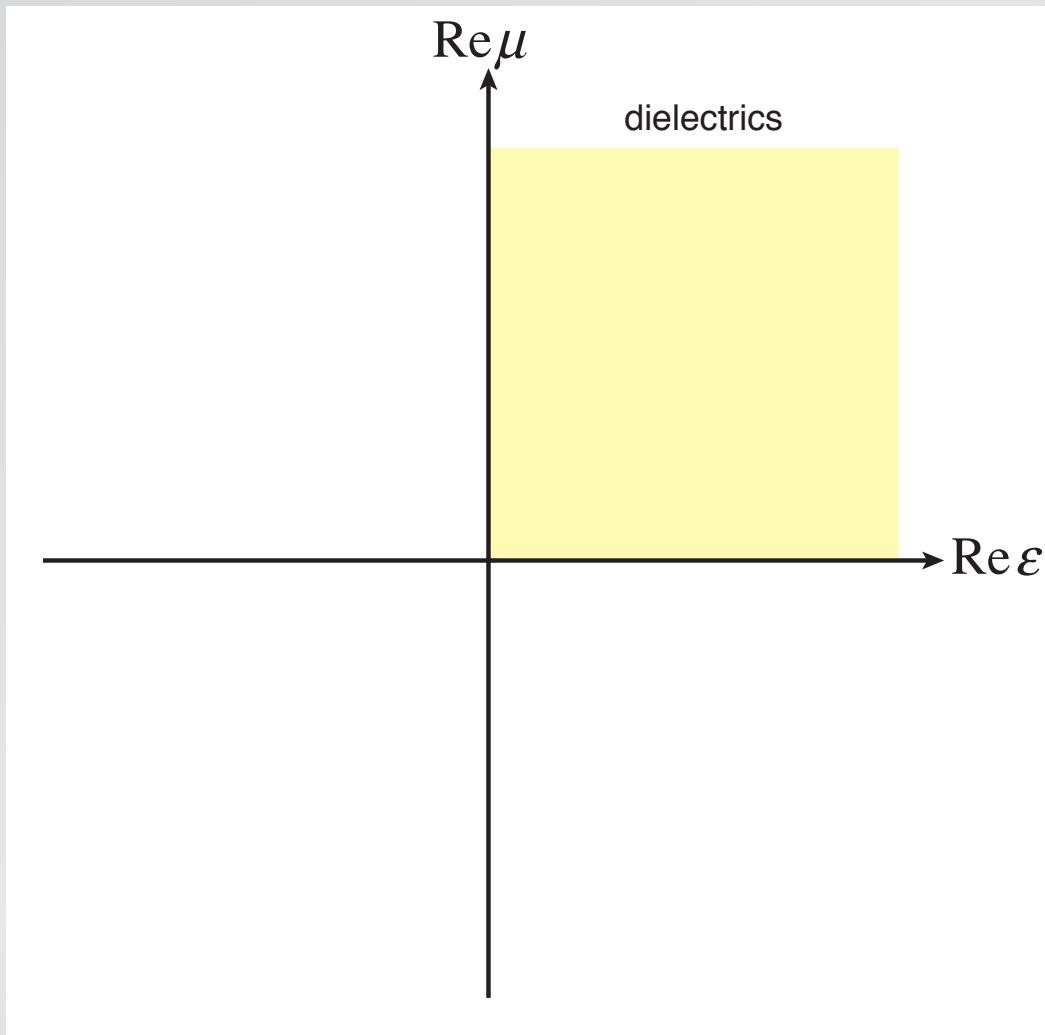
classification of (non-lossy) materials



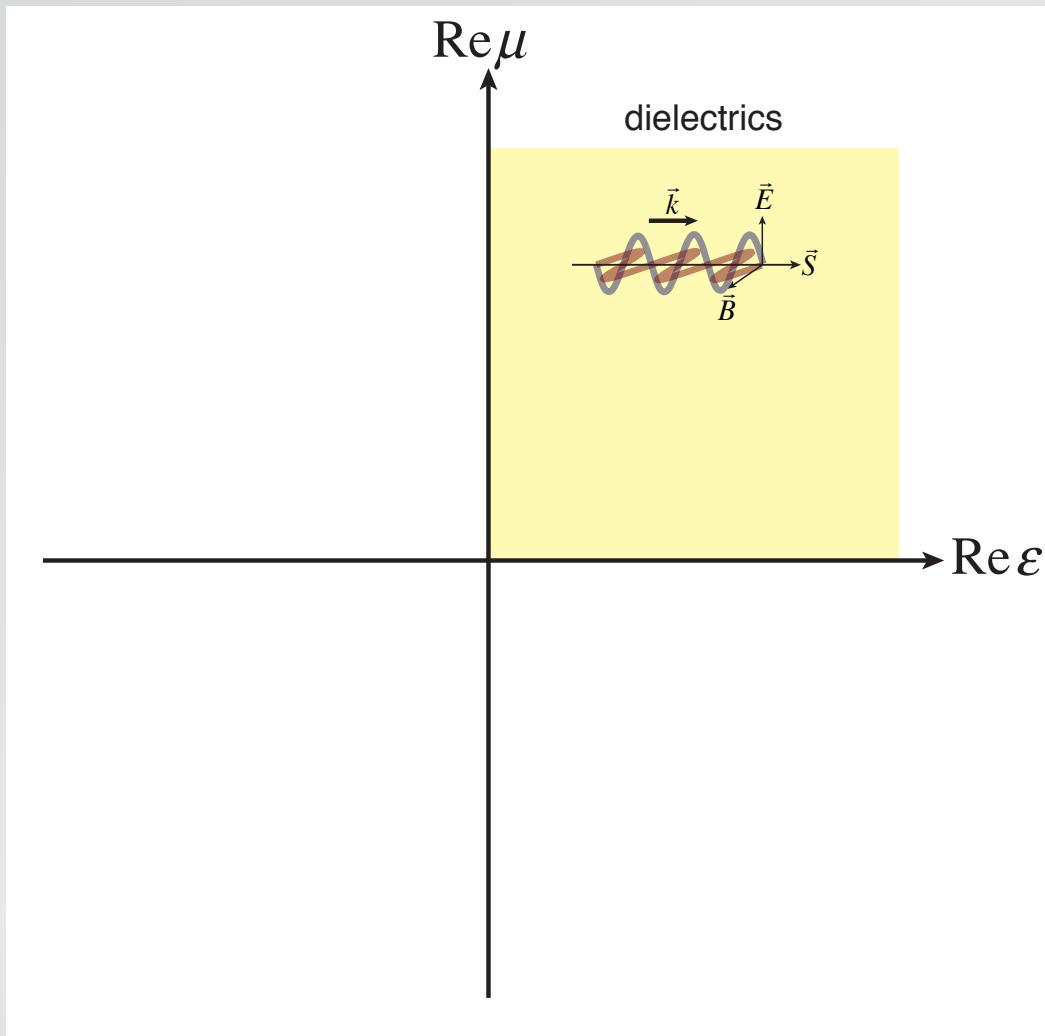
classification of (non-lossy) materials



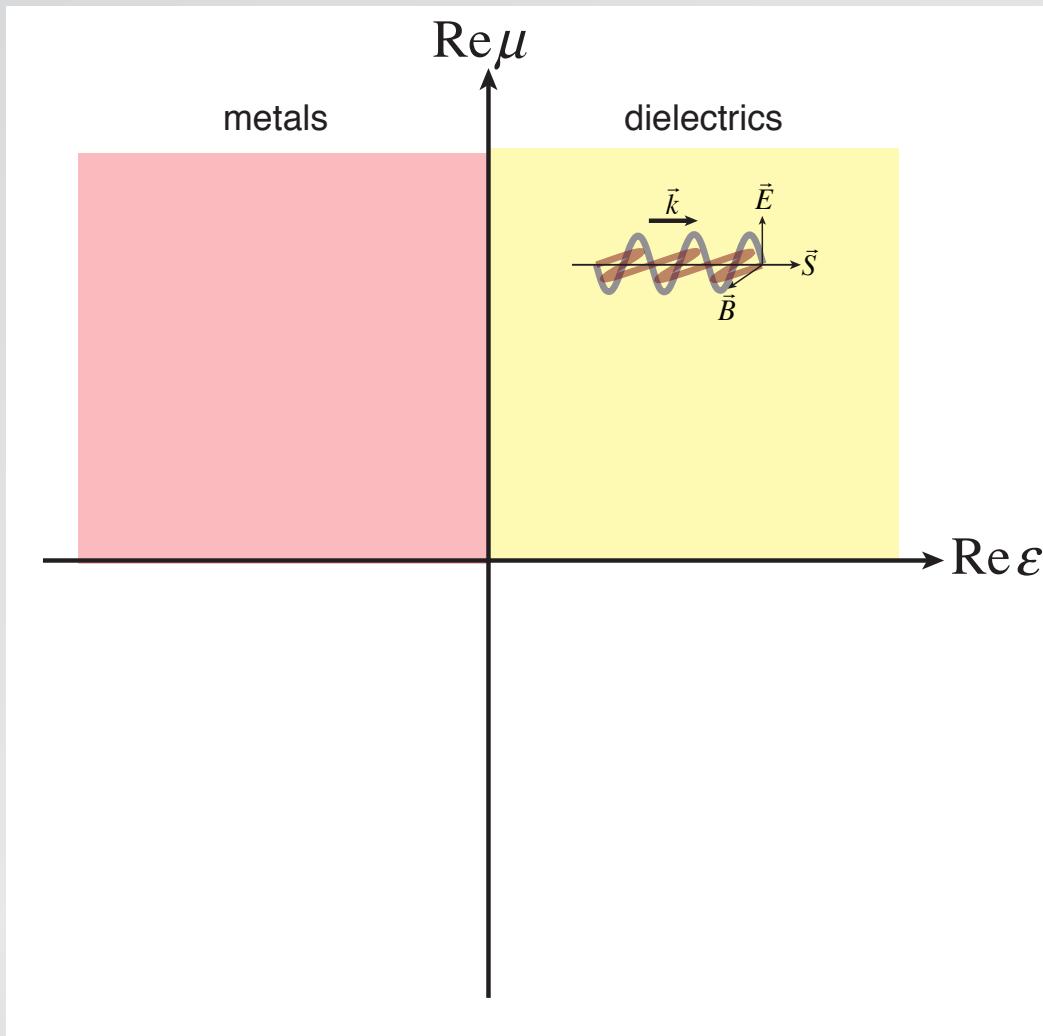
classification of (non-lossy) materials



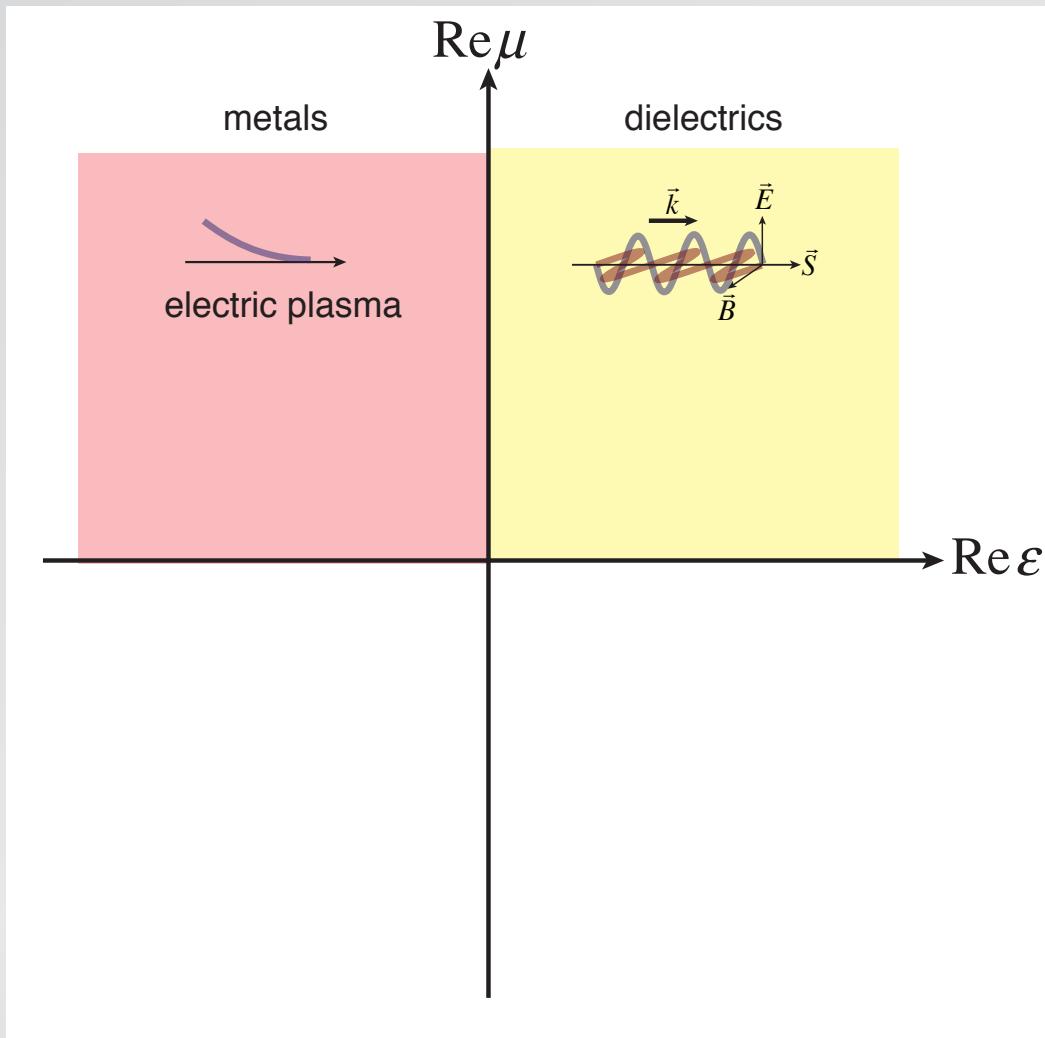
classification of (non-lossy) materials



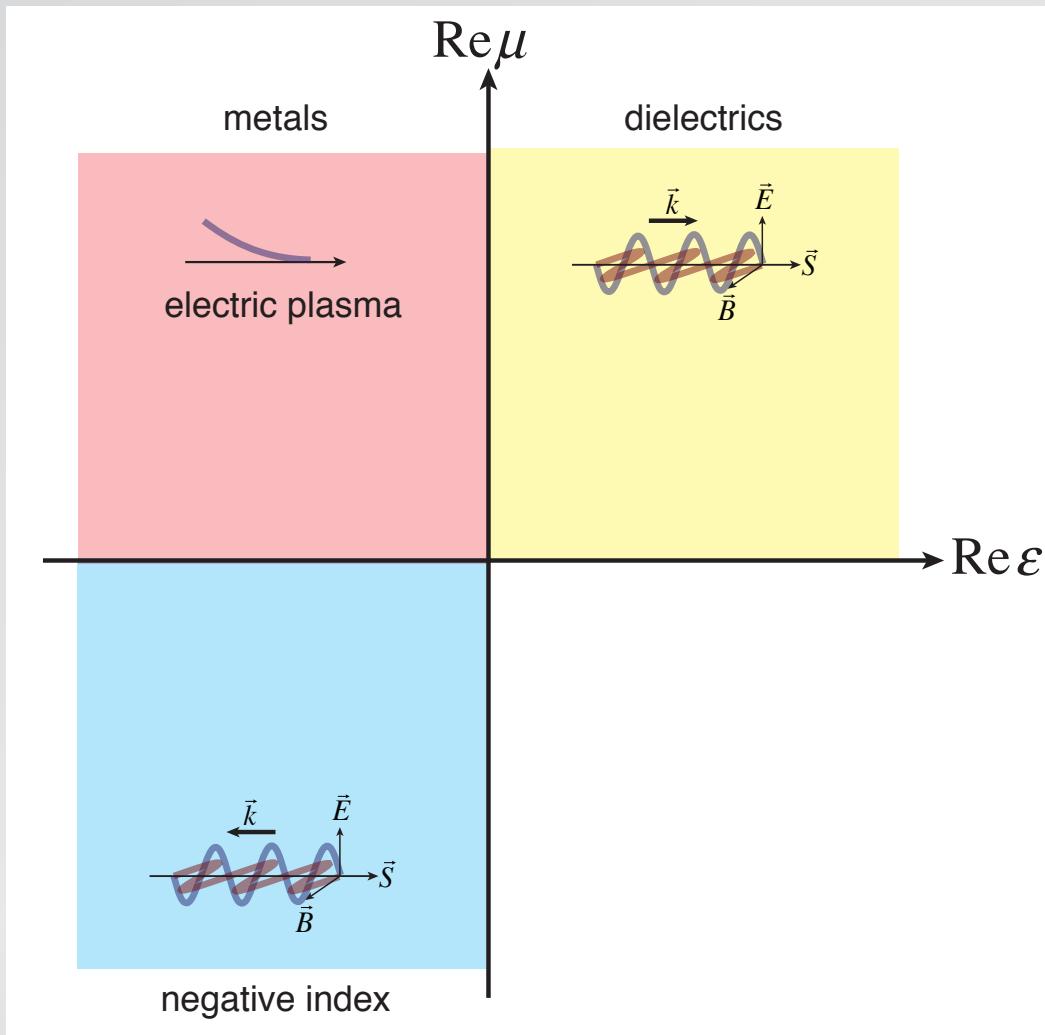
classification of (non-lossy) materials



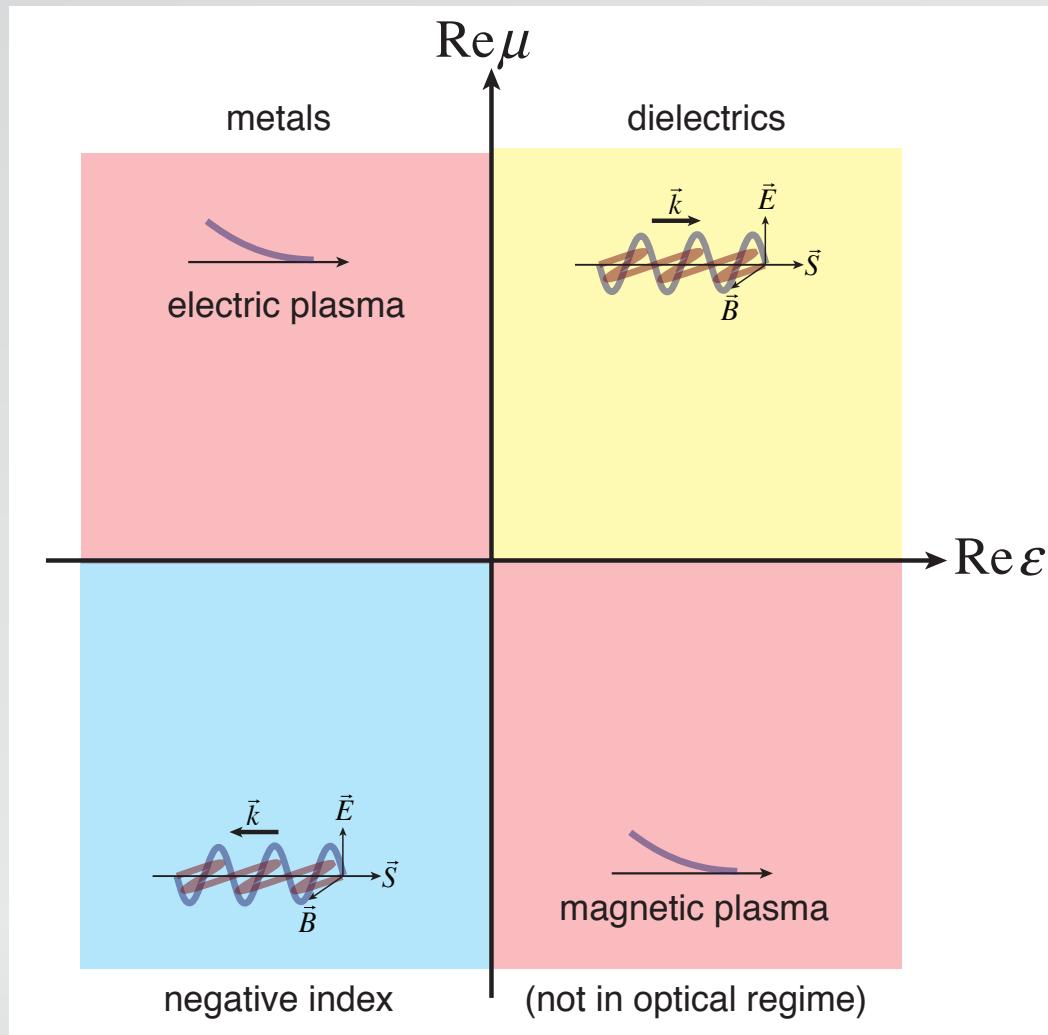
classification of (non-lossy) materials



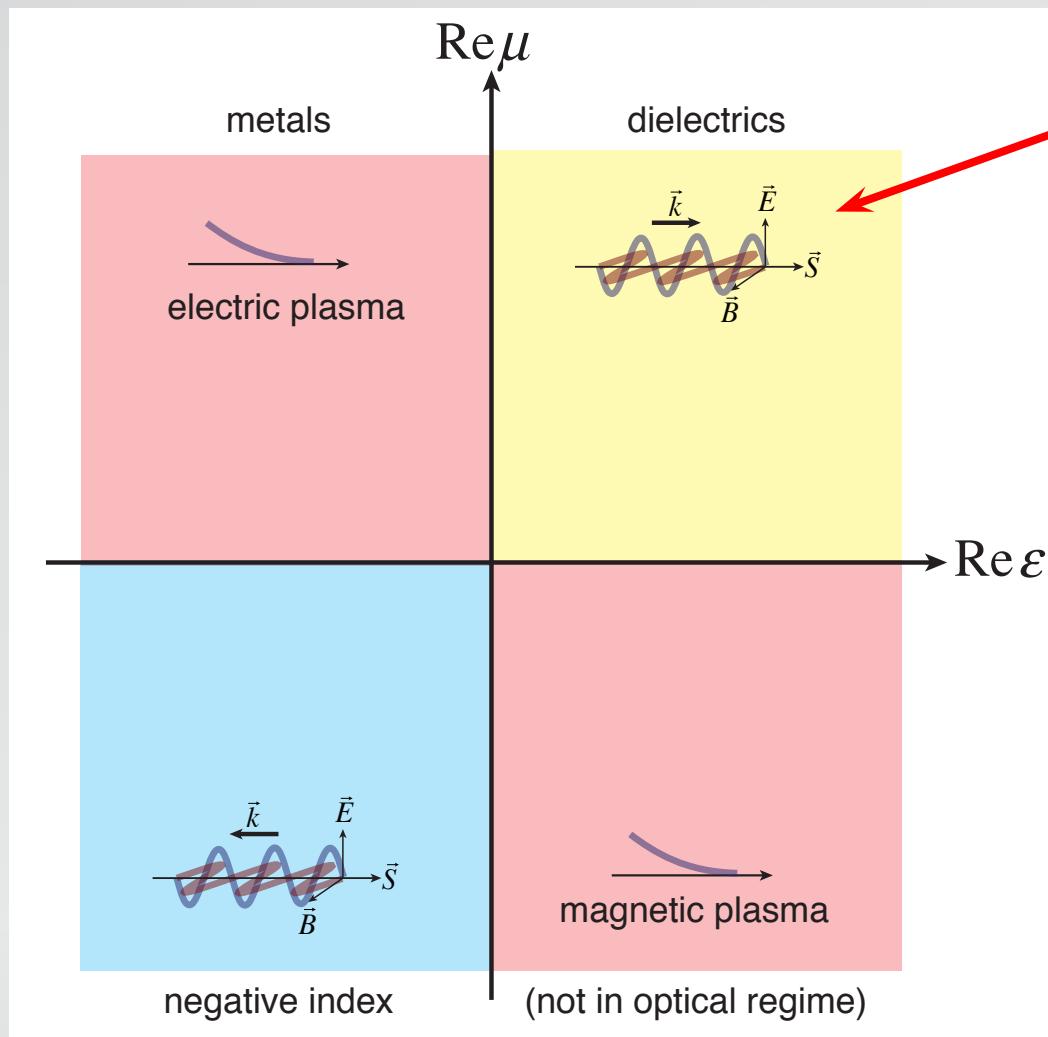
classification of (non-lossy) materials



classification of (non-lossy) materials



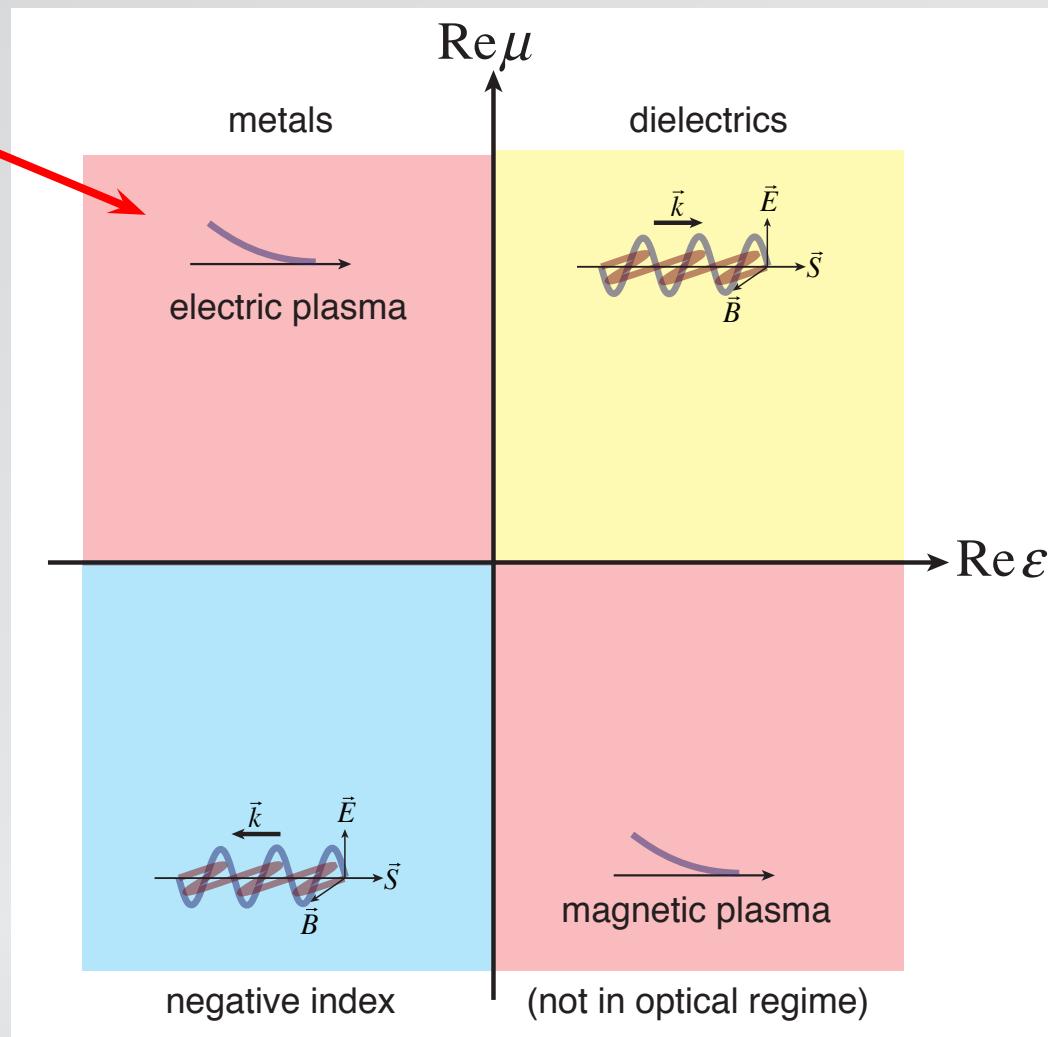
classification of (non-lossy) materials



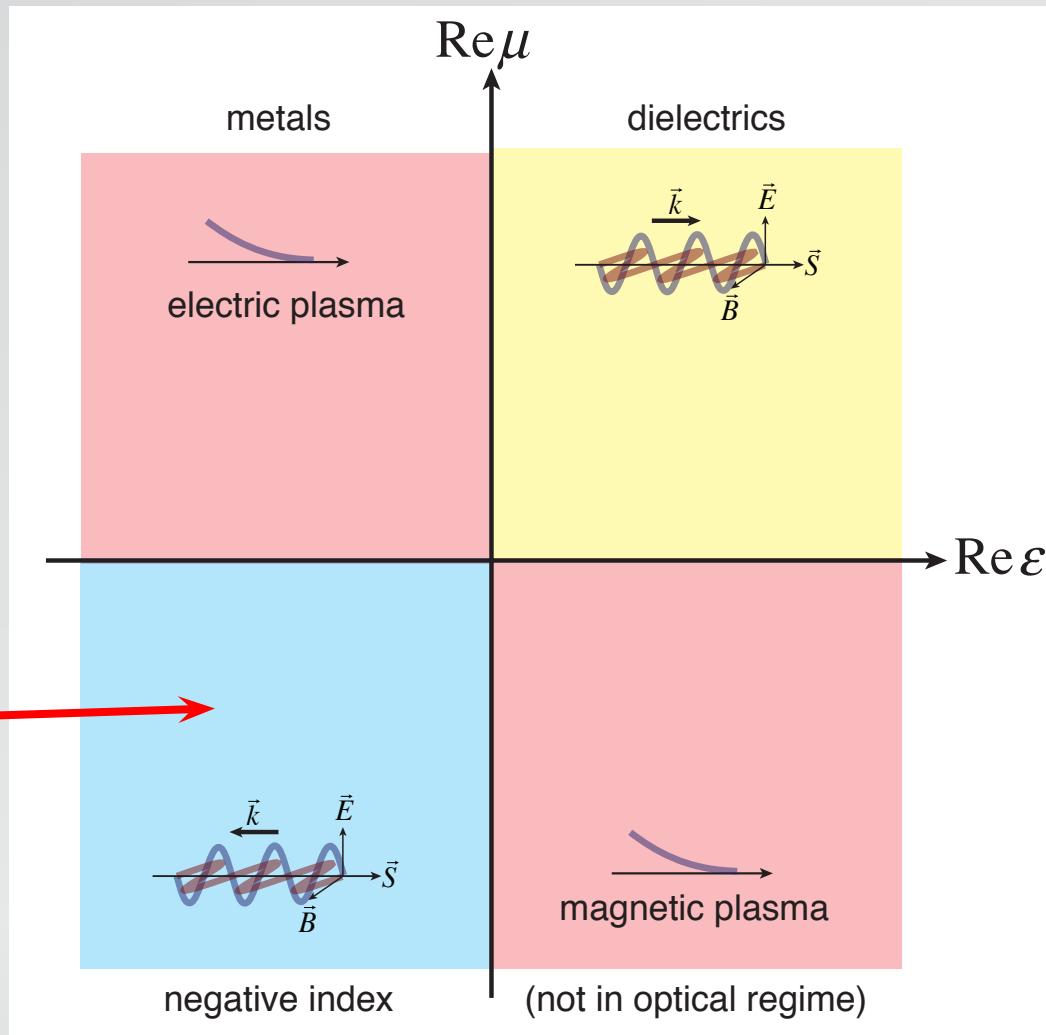
limited by
diffraction

classification of (non-lossy) materials

no propagation

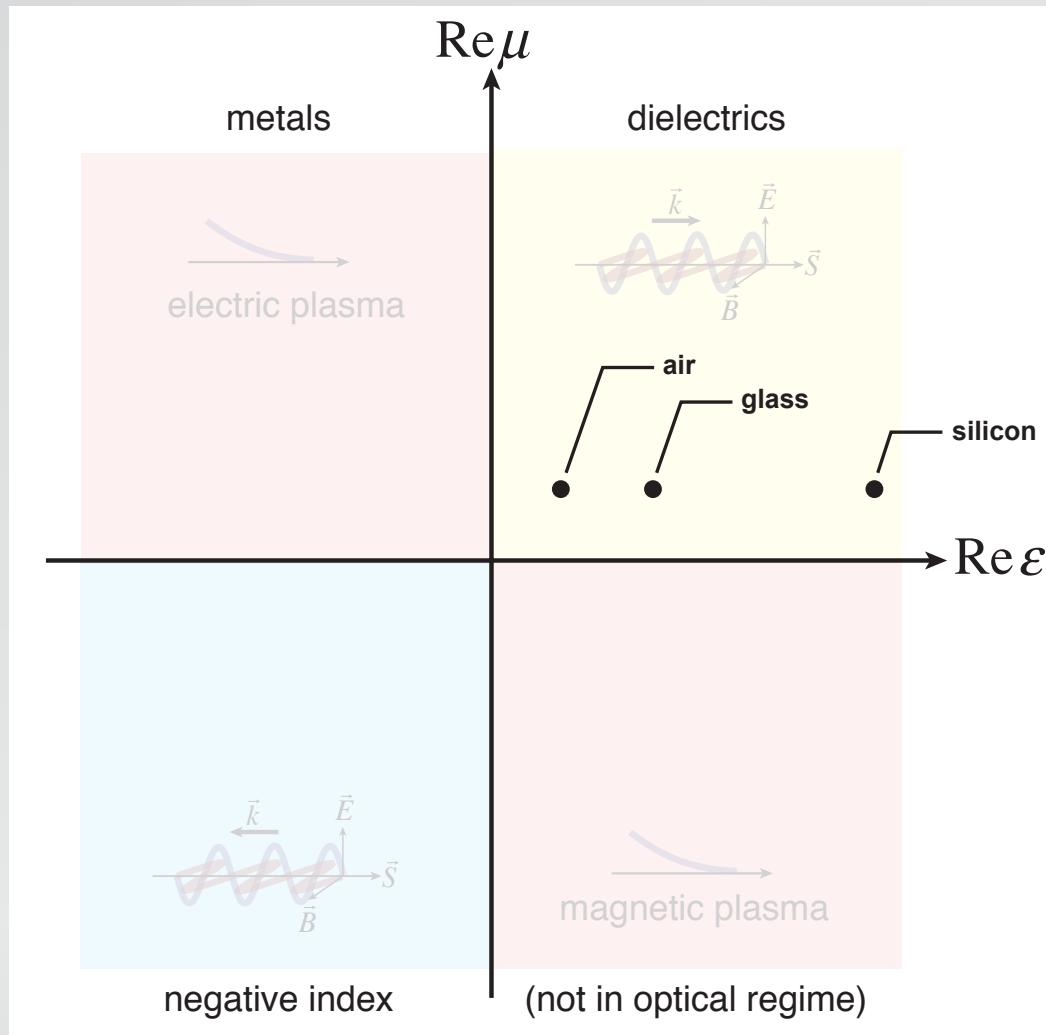


classification of (non-lossy) materials

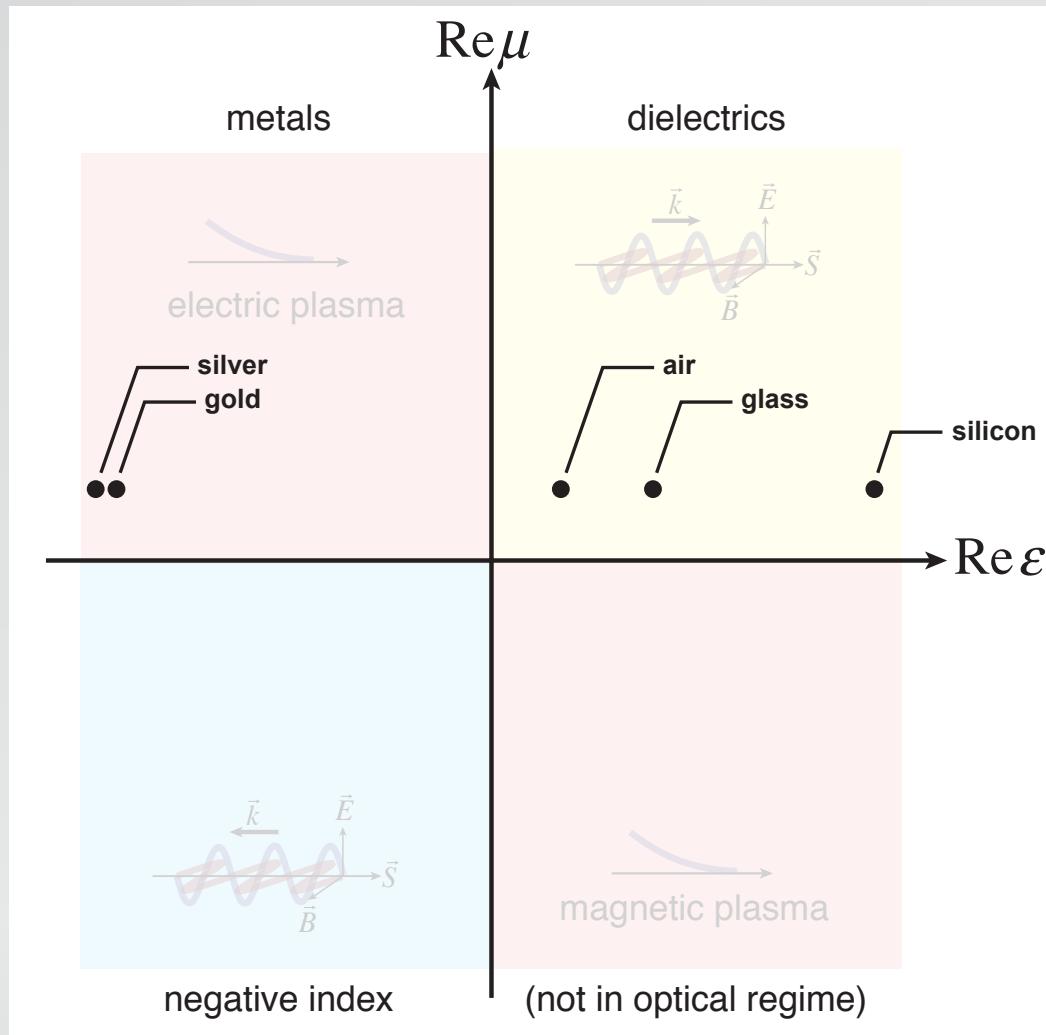


1 index

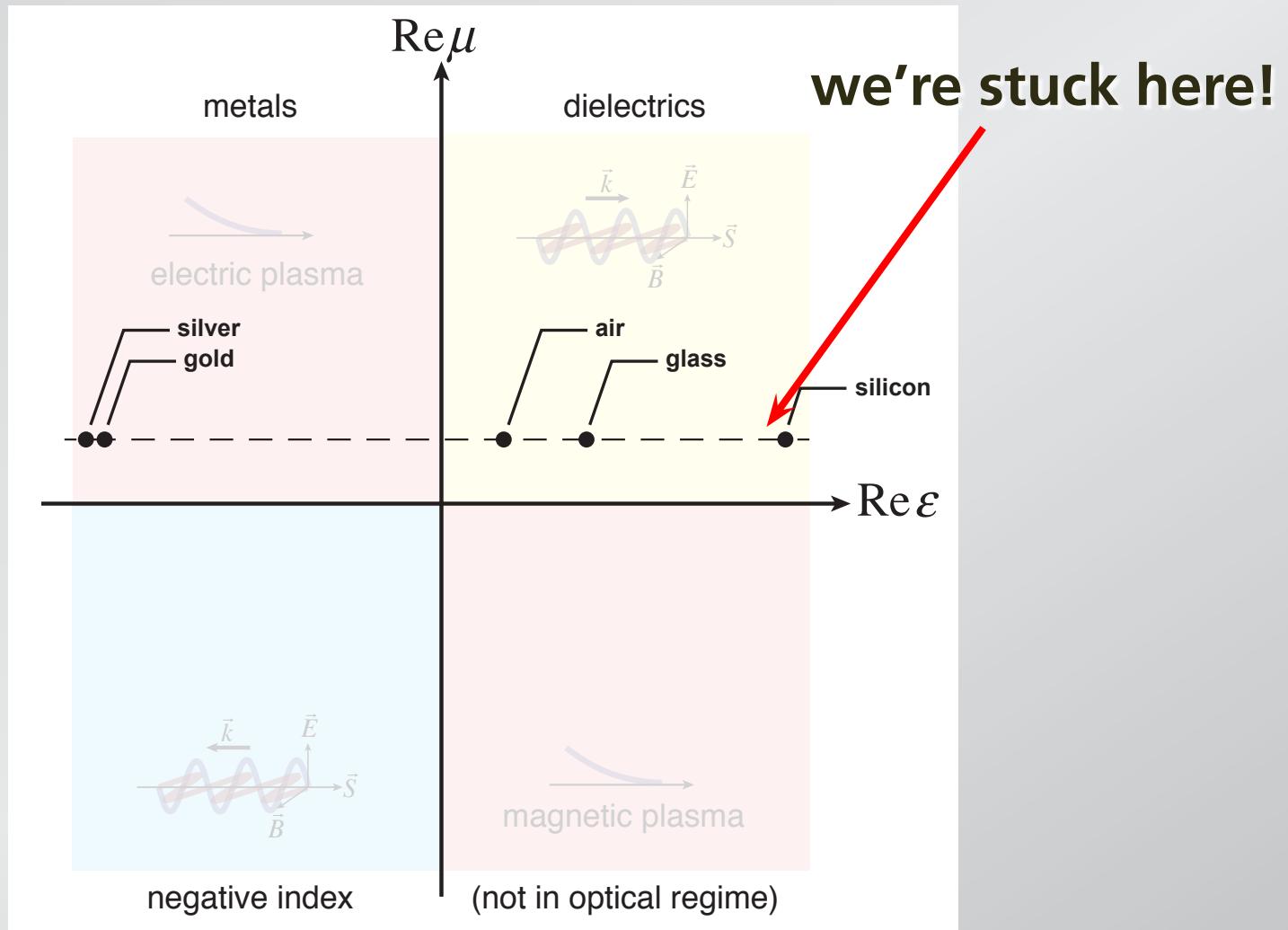
common materials very limited



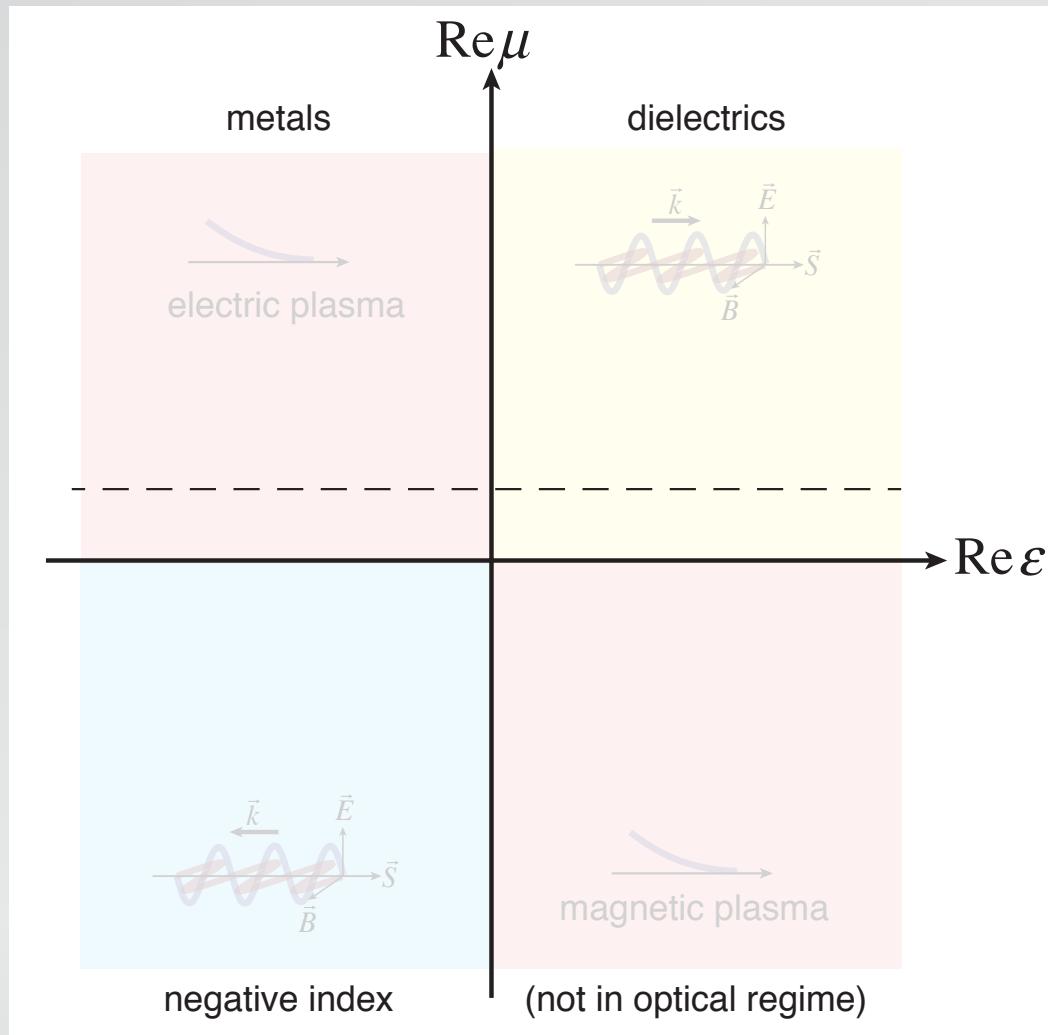
common materials very limited



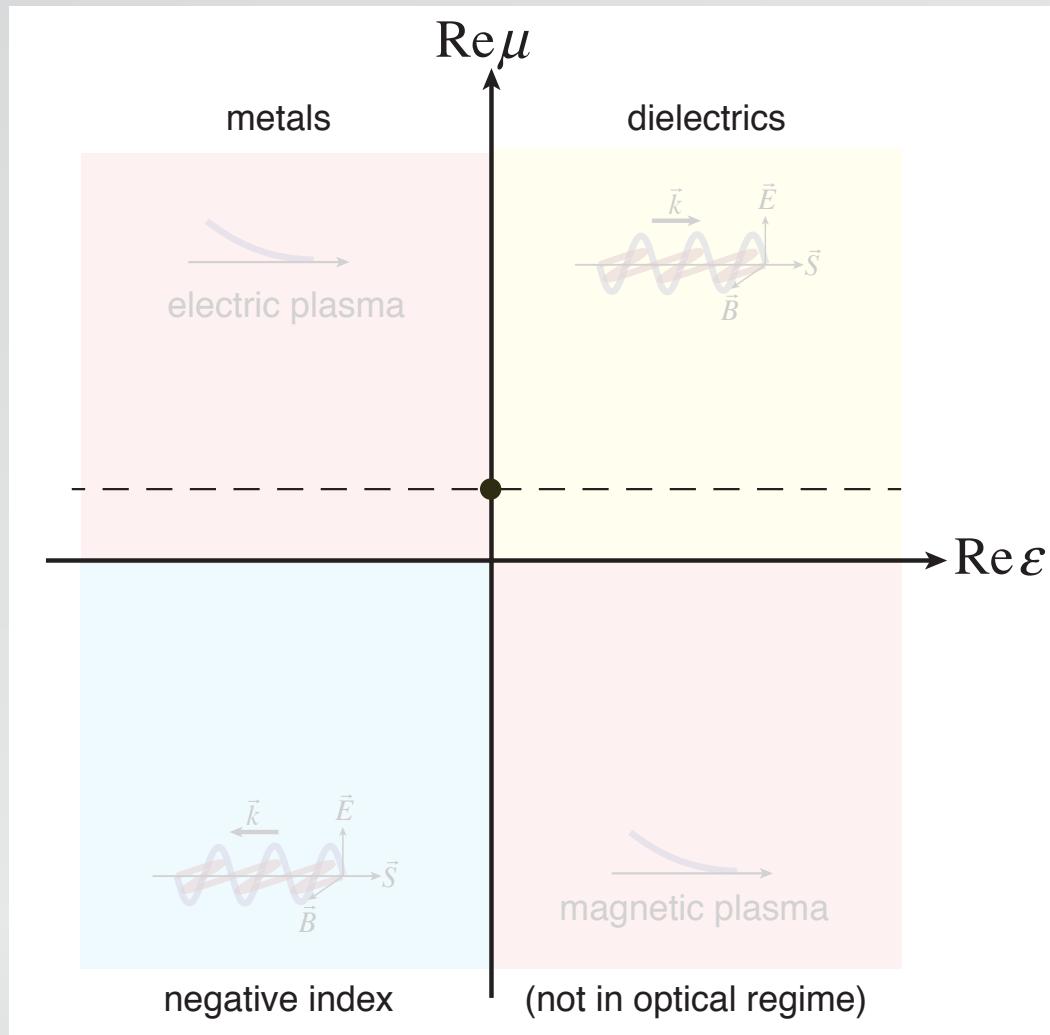
common materials very limited



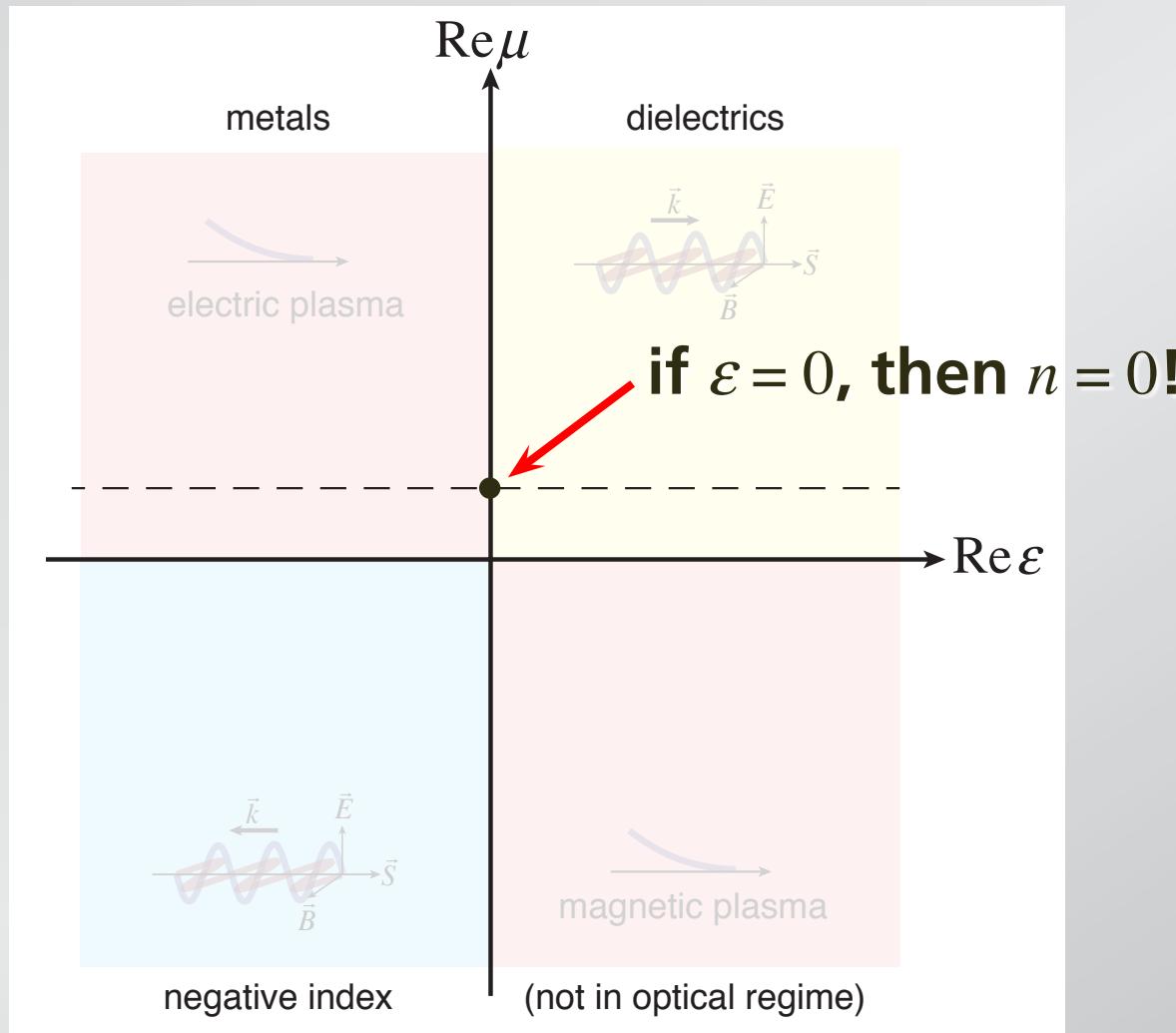
What happens on the axes?



what if we let $\varepsilon = 0$?



what if we let $\varepsilon = 0$?



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

$$\nabla^2 \vec{E} - \frac{\mu \epsilon_0}{c^2} \vec{E} = 0$$

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

$$\nabla^2 \vec{E} - \frac{\mu \epsilon_0}{c^2} \vec{E} = 0$$

solution

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

where

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

1 index

2 zero index

wave equation

$$\nabla^2 \vec{E} - \frac{\mu \epsilon_0}{c^2} \vec{E} = 0$$

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

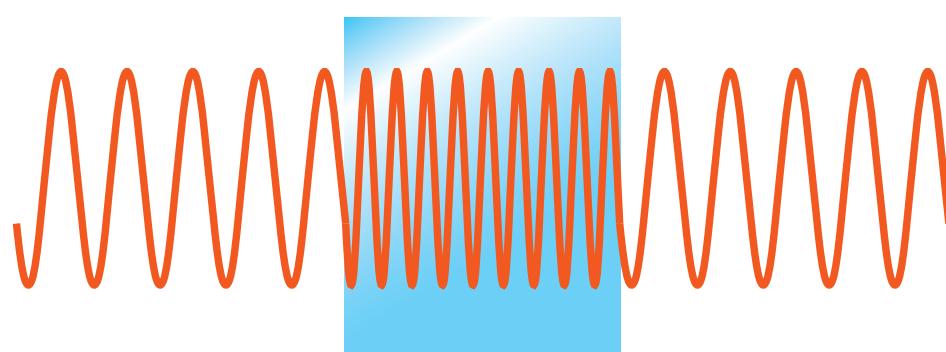
Q: If $n = 0$, which of the following is true?

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

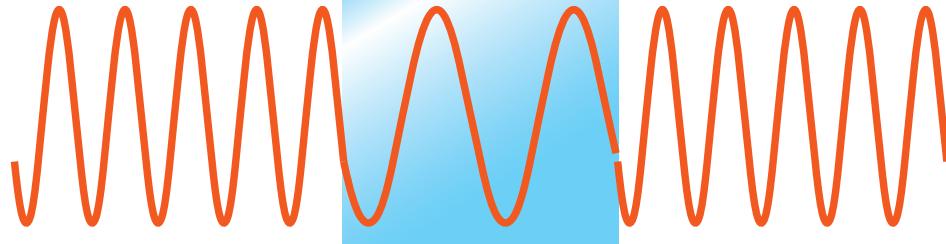
$n > 1$



1 index

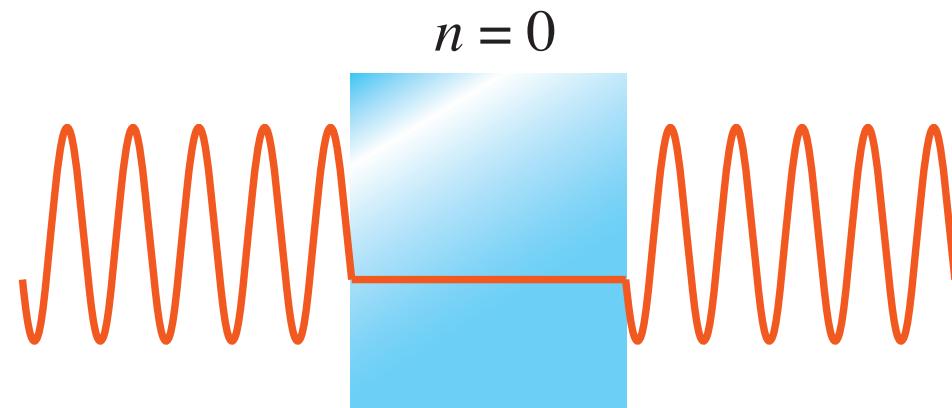
2 zero index

$$0 < n < 1$$



1 index

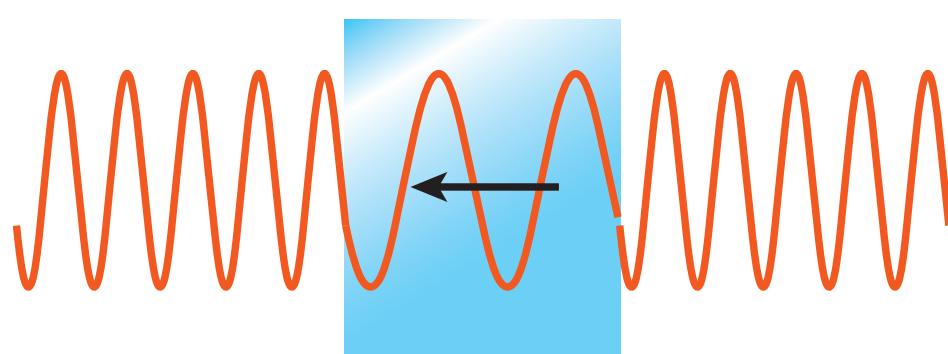
2 zero index



1 index

2 zero index

$n < 0$



1 index

2 zero index



1 index

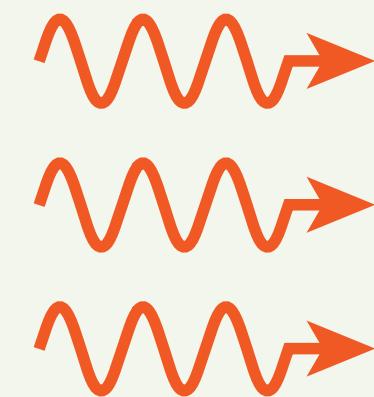
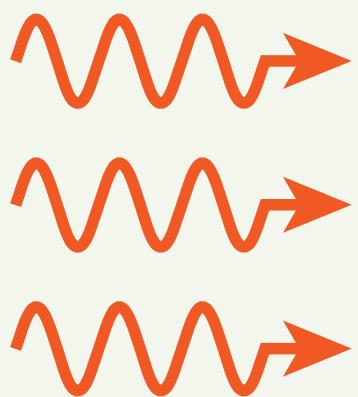
2 zero index

What can we do with uniform phase?

1 index

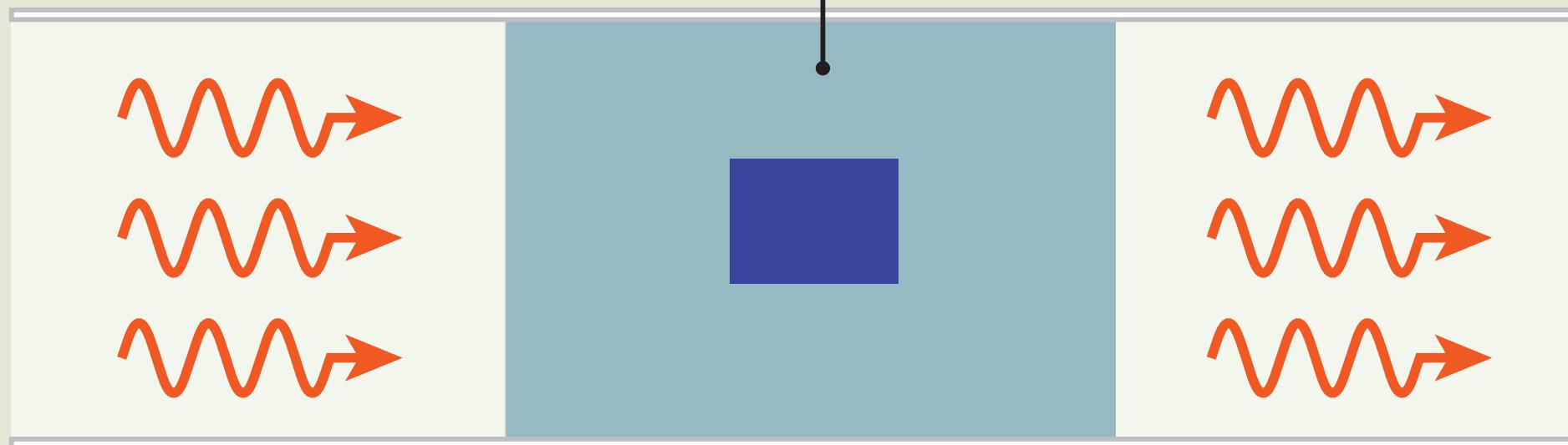
2 zero index

$n = 0$



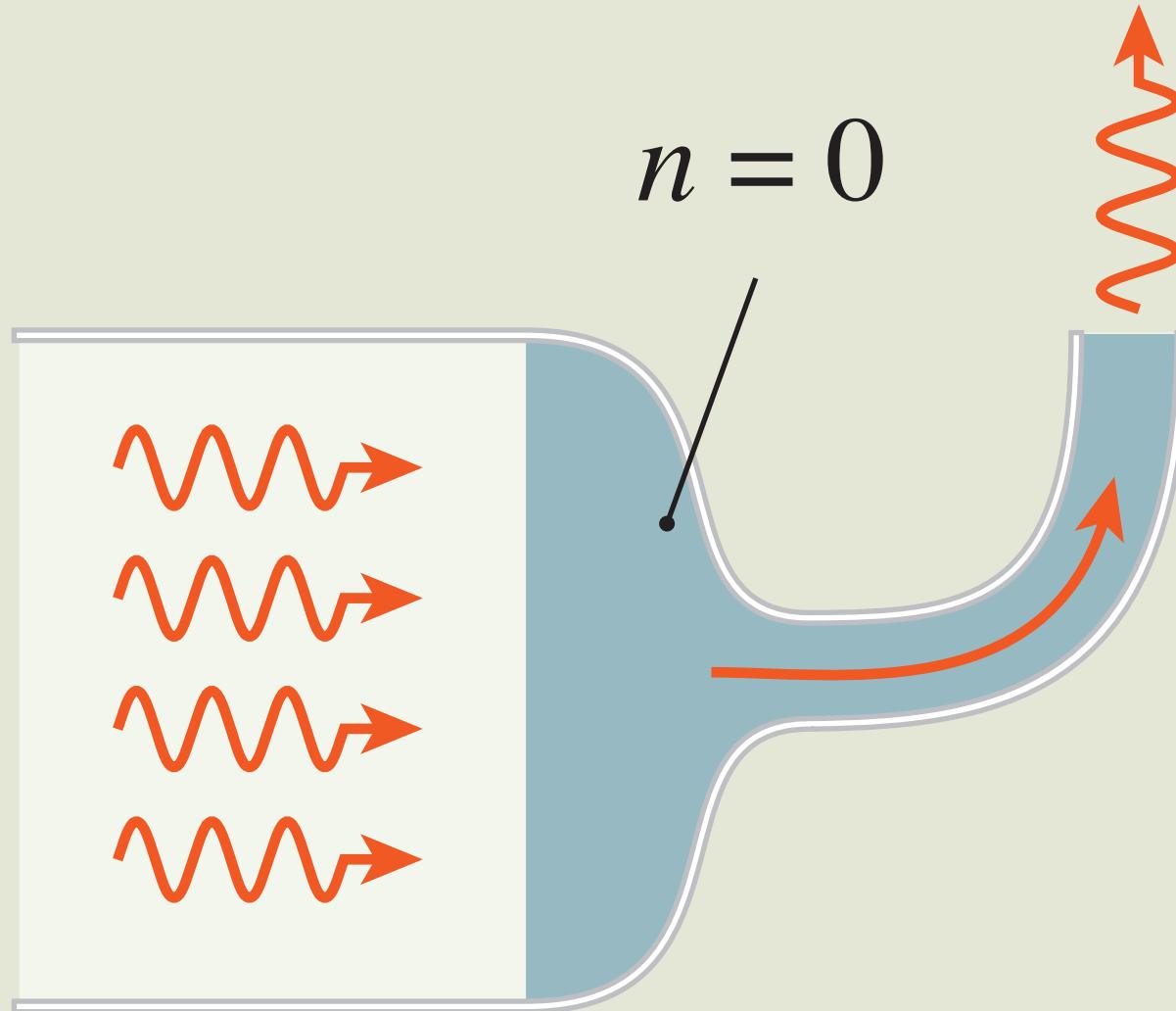
1 index

2 zero index

$n = 0$ 

1 index

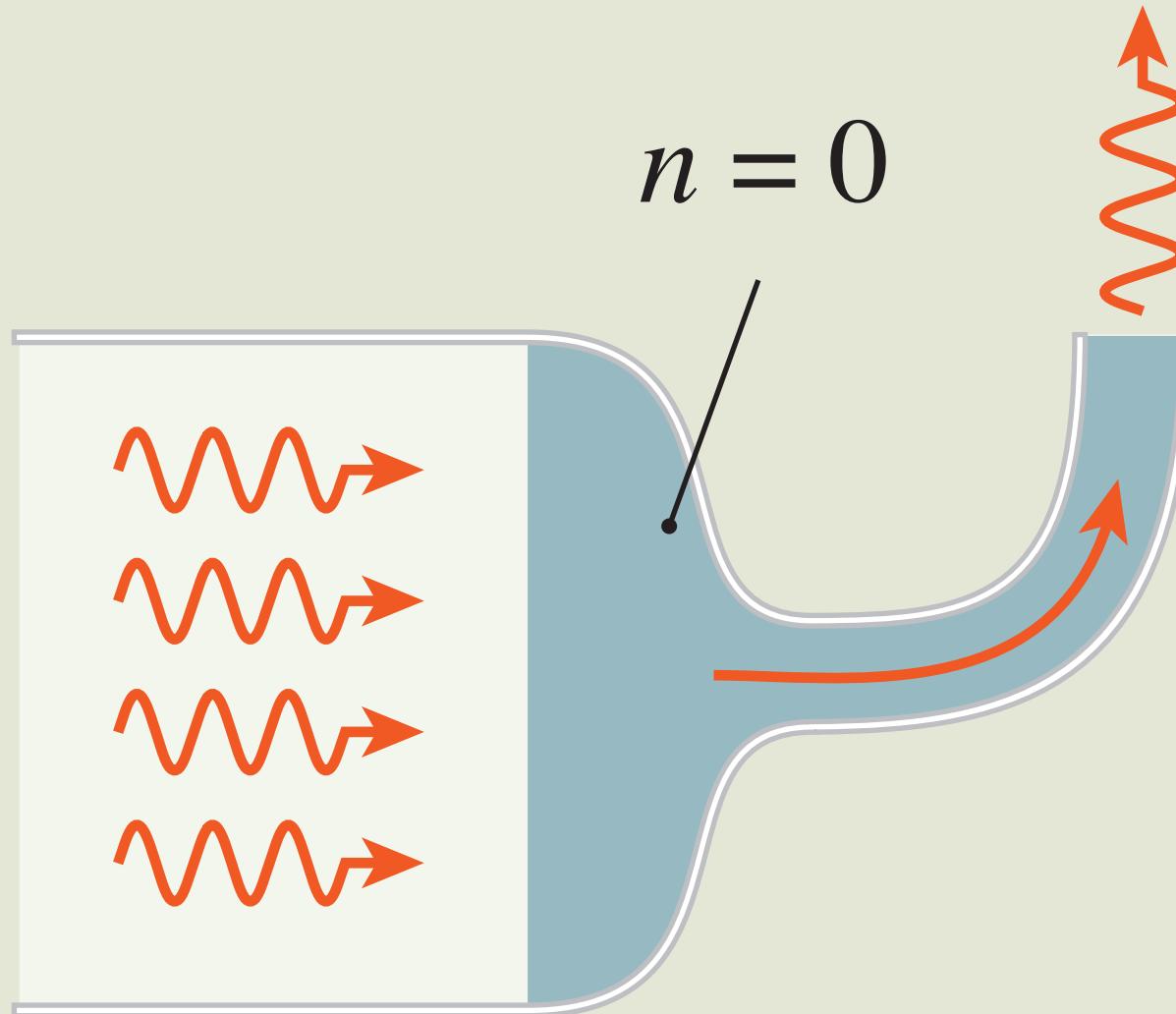
2 zero index



1 index

2 zero index

“tunneling with infinite decay length”



1 index

2 zero index

how?

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

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?

$$\varepsilon \rightarrow 0$$

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

but ϵ and μ also determine reflectivity

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

where

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

1 index

2 zero index

how?

$$\varepsilon \rightarrow 0$$

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

but ϵ and μ also determine reflectivity

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

where

$$Z = \sqrt{\frac{\mu}{\varepsilon}} \rightarrow \infty$$

1 index

2 zero index

how?

$$\varepsilon \rightarrow 0$$

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

but ϵ and μ also determine reflectivity

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

where

$$Z = \sqrt{\frac{\mu}{\varepsilon}} \rightarrow \infty$$

1 index

2 zero index

how?

$$\mu \rightarrow 0$$

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

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?

$$\mu \rightarrow 0$$

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

but ϵ and μ also determine reflectivity

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

where

$$Z = \sqrt{\frac{\mu}{\epsilon}} \rightarrow 0$$

1 index

2 zero index

how?

$$\mu \rightarrow 0$$

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

but ϵ and μ also determine reflectivity

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

where

$$Z = \sqrt{\frac{\mu}{\epsilon}} \rightarrow 0$$

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

but $\mu \neq 1$ requires a magnetic response!

1 index

2 zero index

3 experiments

Engineering a magnetic response

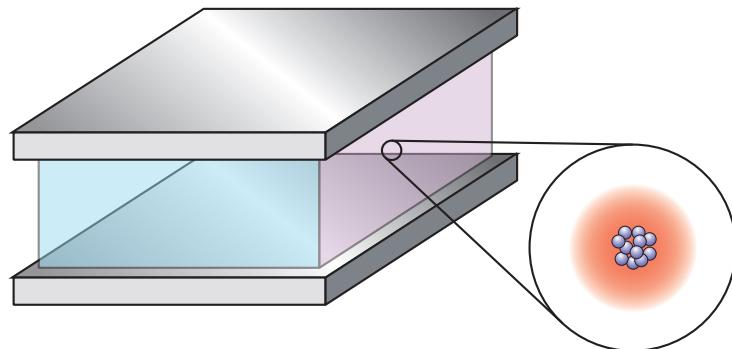
1 index

2 zero index

3 experiments

Engineering a magnetic response

bulk material



properties derive from
constituent atoms

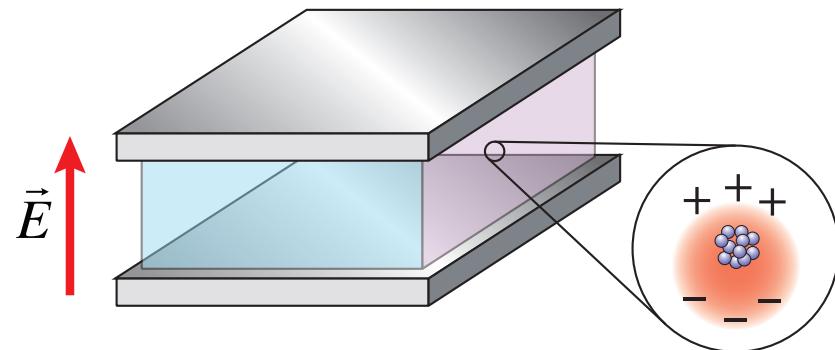
1 index

2 zero index

3 experiments

Engineering a magnetic response

bulk material



properties derive from
constituent atoms

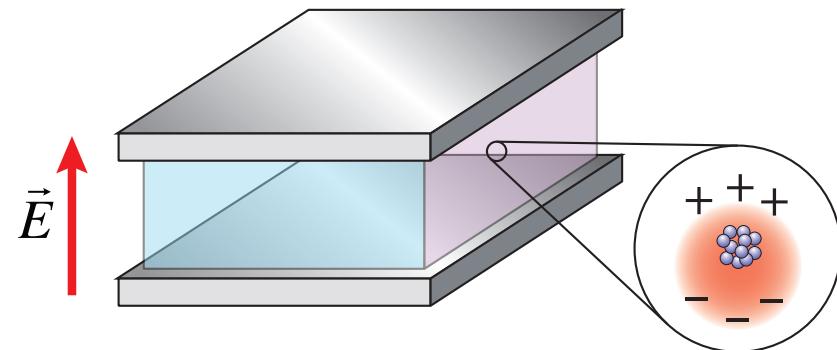
1 index

2 zero index

3 experiments

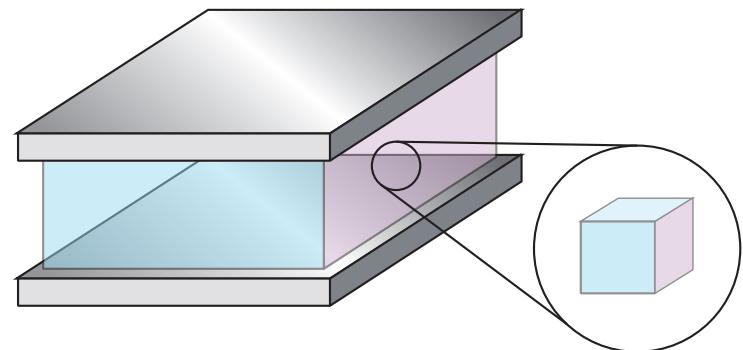
Engineering a magnetic response

bulk material



properties derive from
constituent atoms

composite material



properties derive from
constituent units

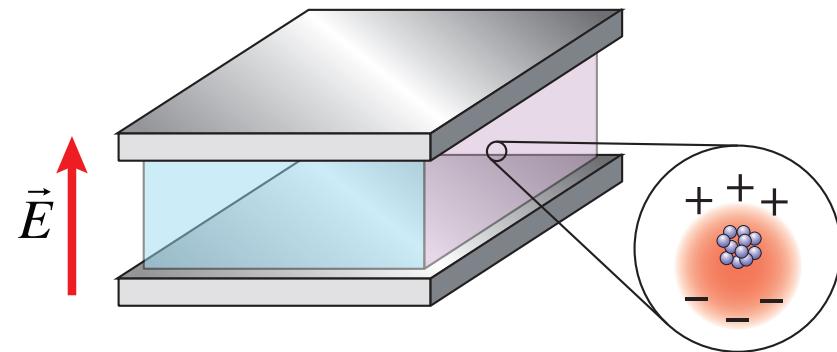
1 index

2 zero index

3 experiments

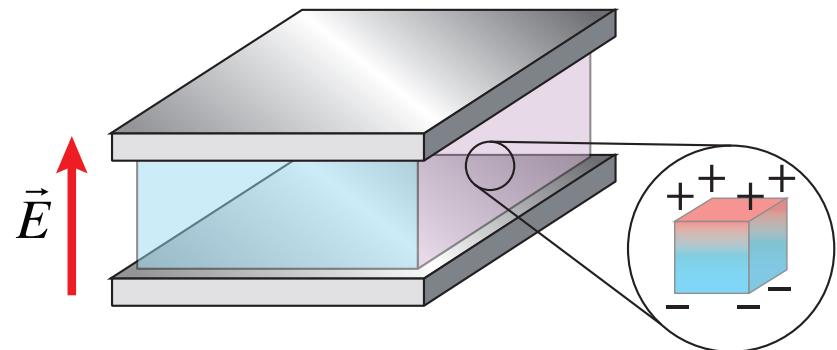
Engineering a magnetic response

bulk material



properties derive from
constituent atoms

composite material



properties derive from
constituent units

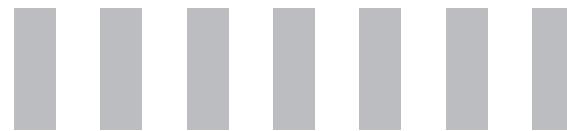
1 index

2 zero index

3 experiments

Engineering a magnetic response

use array of dielectric rods



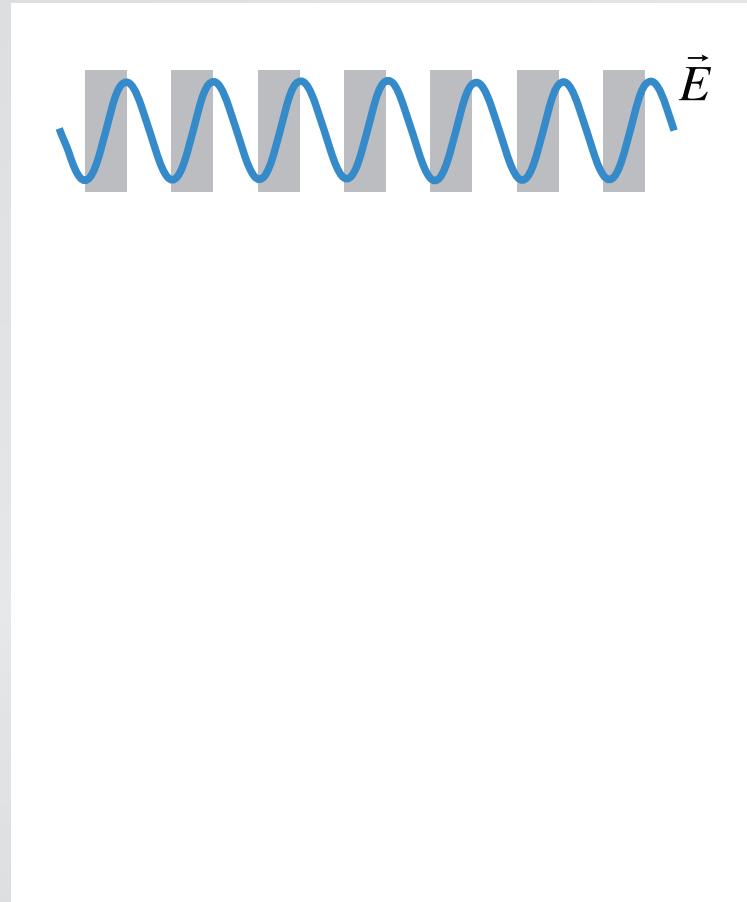
1 index

2 zero index

3 experiments

Engineering a magnetic response

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

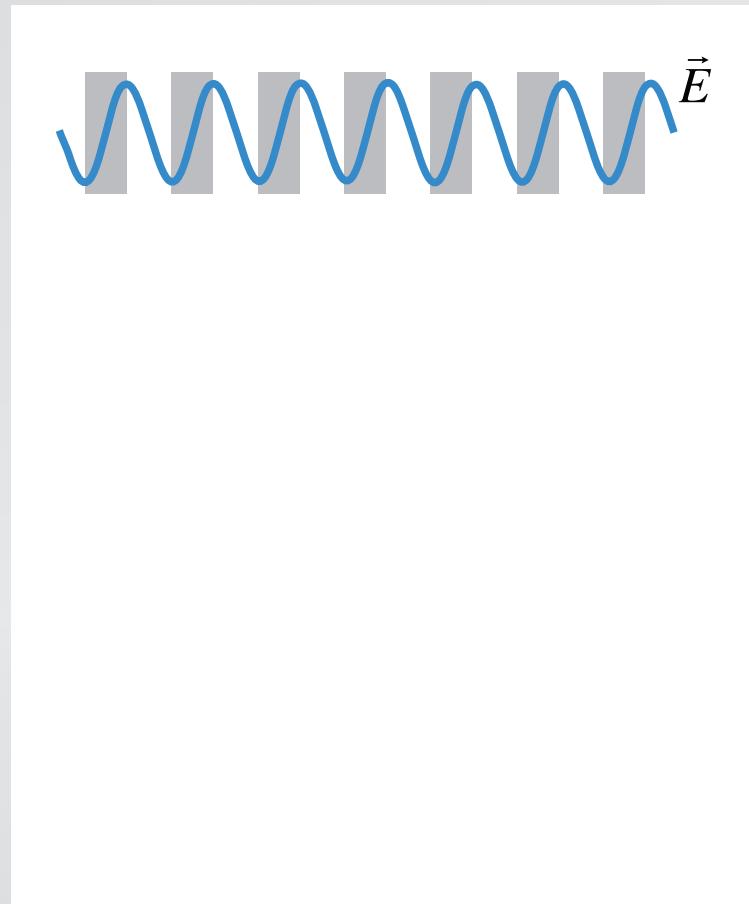


1 index

2 zero index

Engineering a magnetic response

produces an electric response...



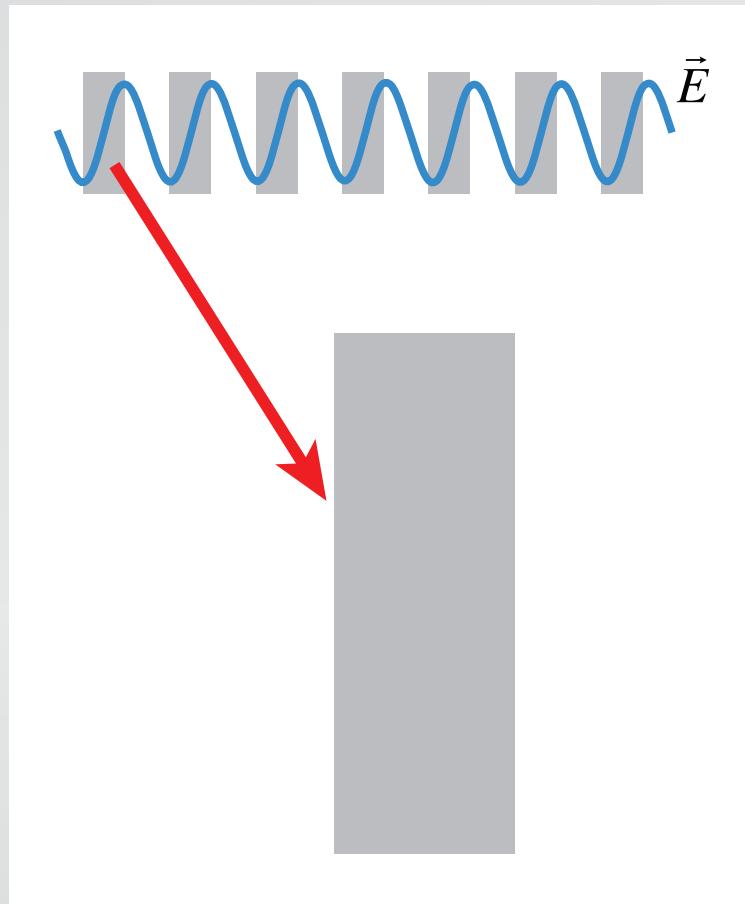
1 index

2 zero index

3 experiments

Engineering a magnetic response

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



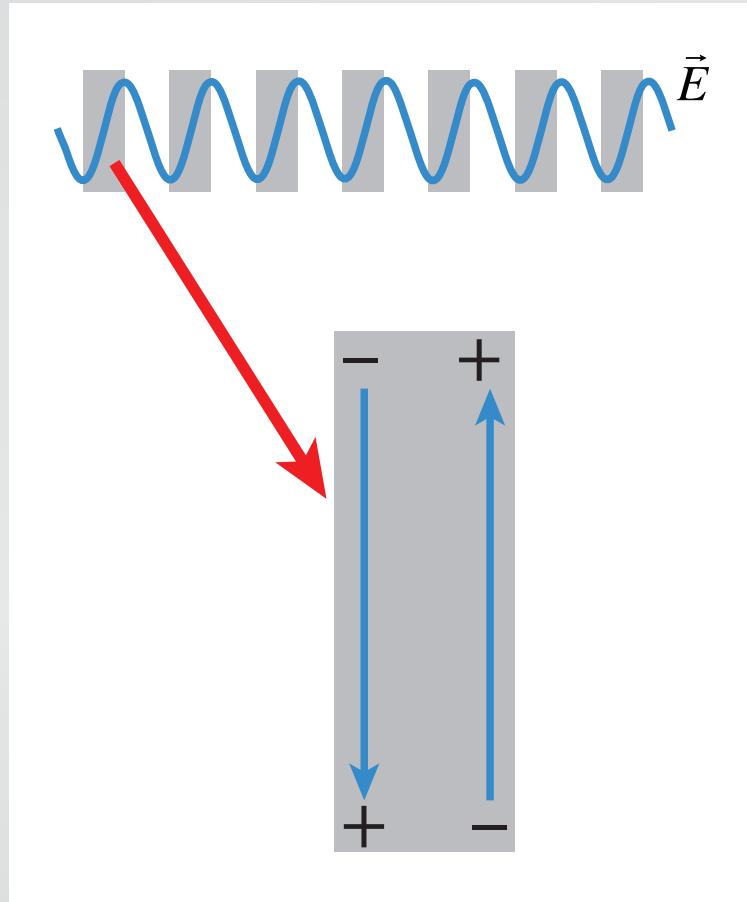
1 index

2 zero index

3 experiments

Engineering a magnetic response

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



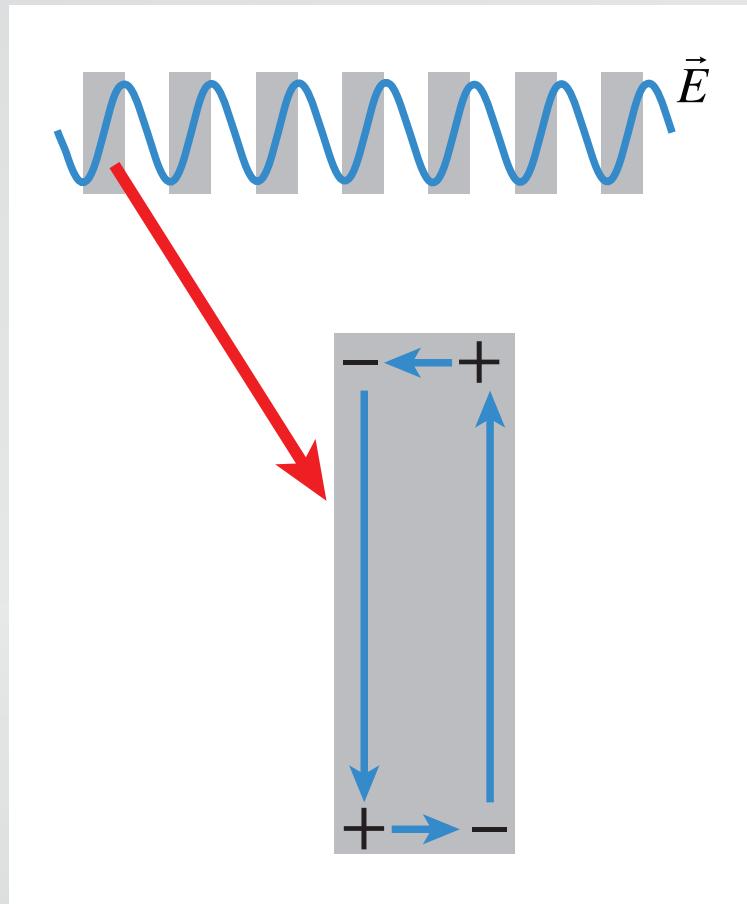
1 index

2 zero index

3 experiments

Engineering a magnetic response

...causing a current loop...



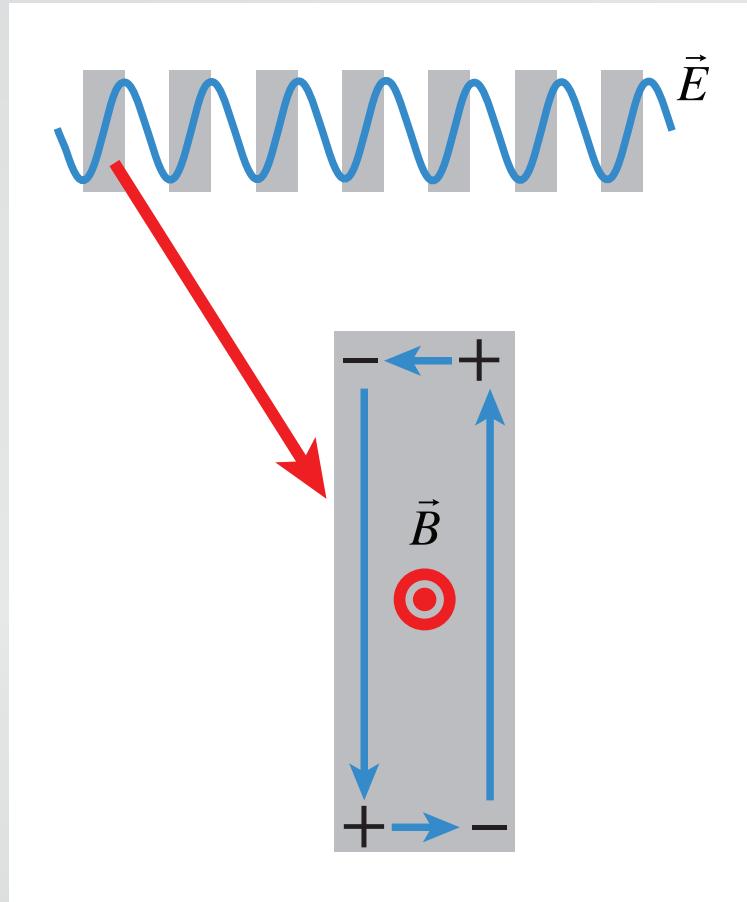
1 index

2 zero index

3 experiments

Engineering a magnetic response

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



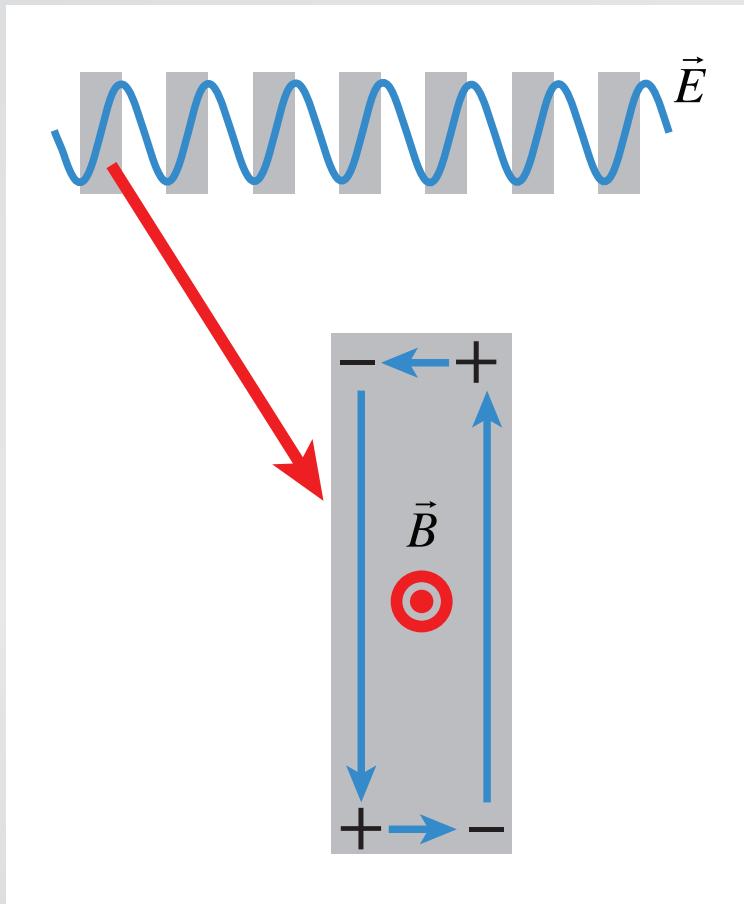
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide



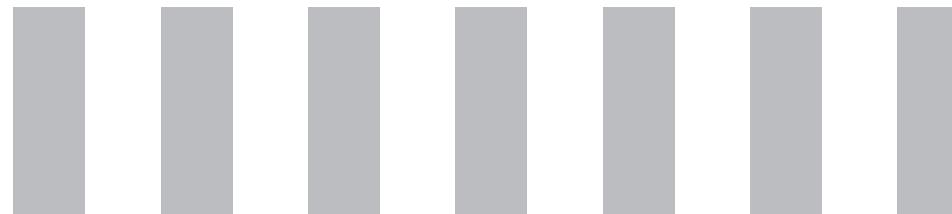
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjustable parameters



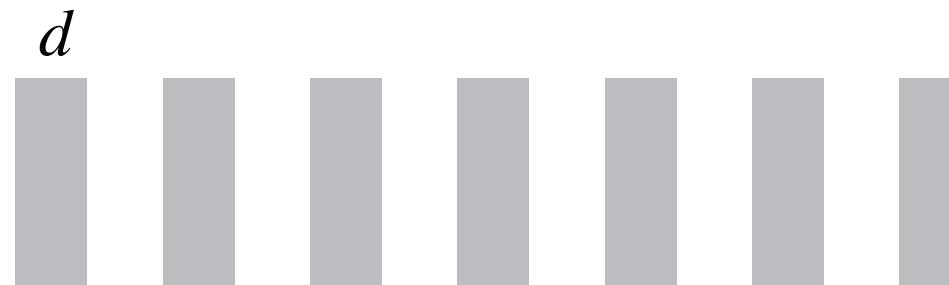
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjustable parameters



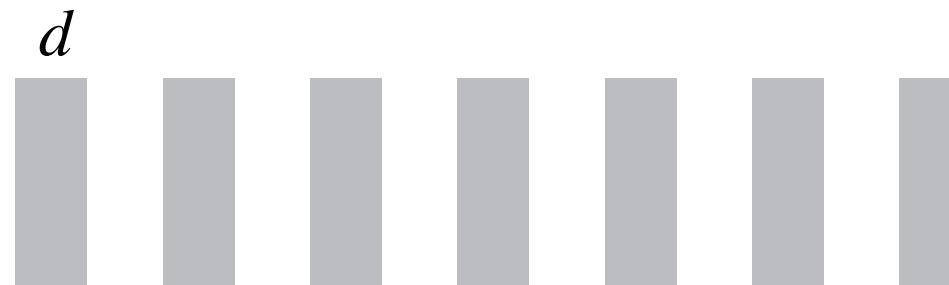
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjustable parameters



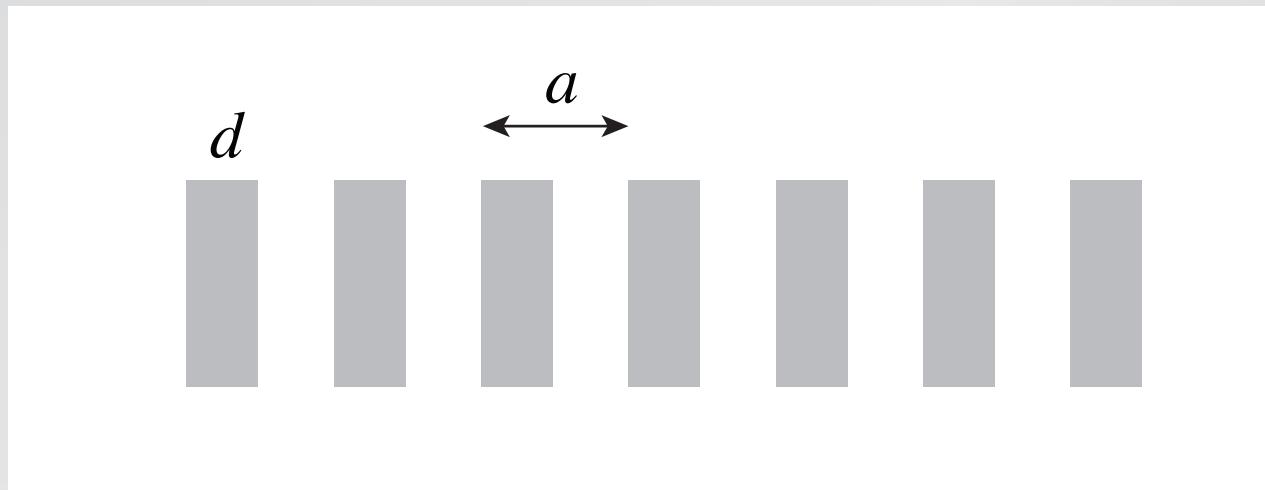
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjustable parameters



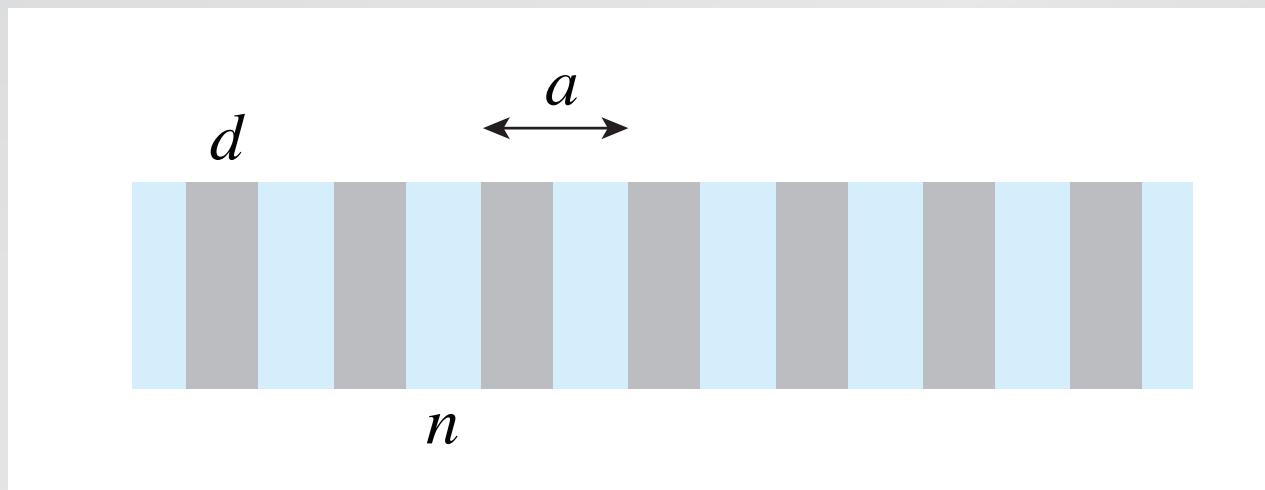
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjustable parameters



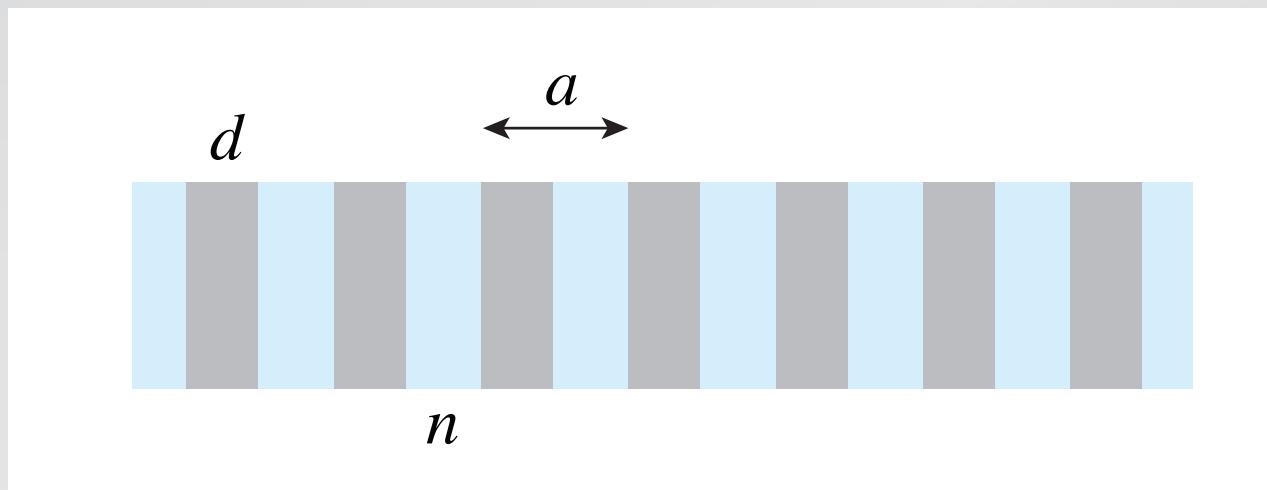
1 index

2 zero index

3 experiments

Engineering a magnetic response

adjustable parameters

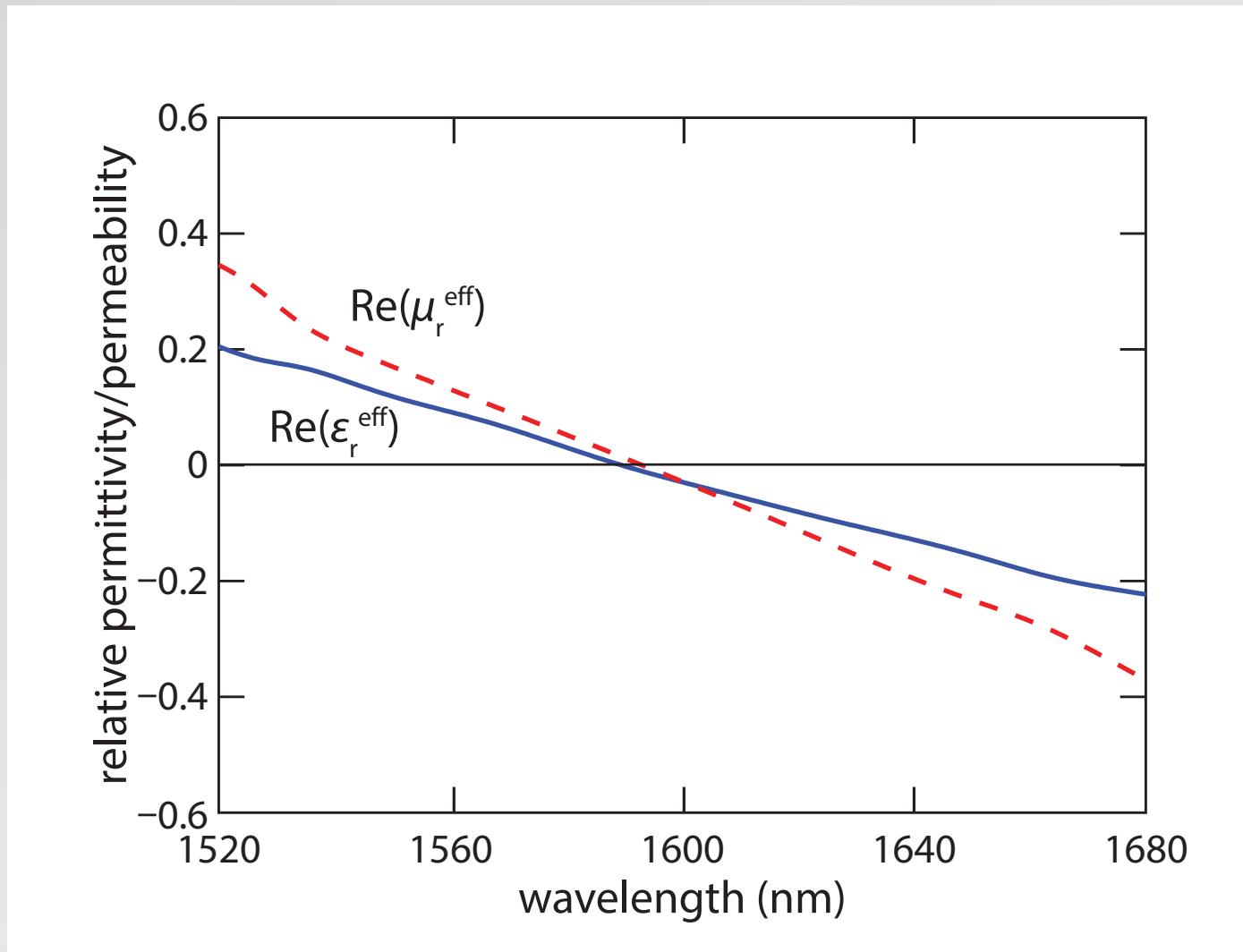


$$d = 422 \text{ nm}, \quad a = 690 \text{ nm}, \quad n = 1.57 \text{ (SU8)}$$

1 index

2 zero index

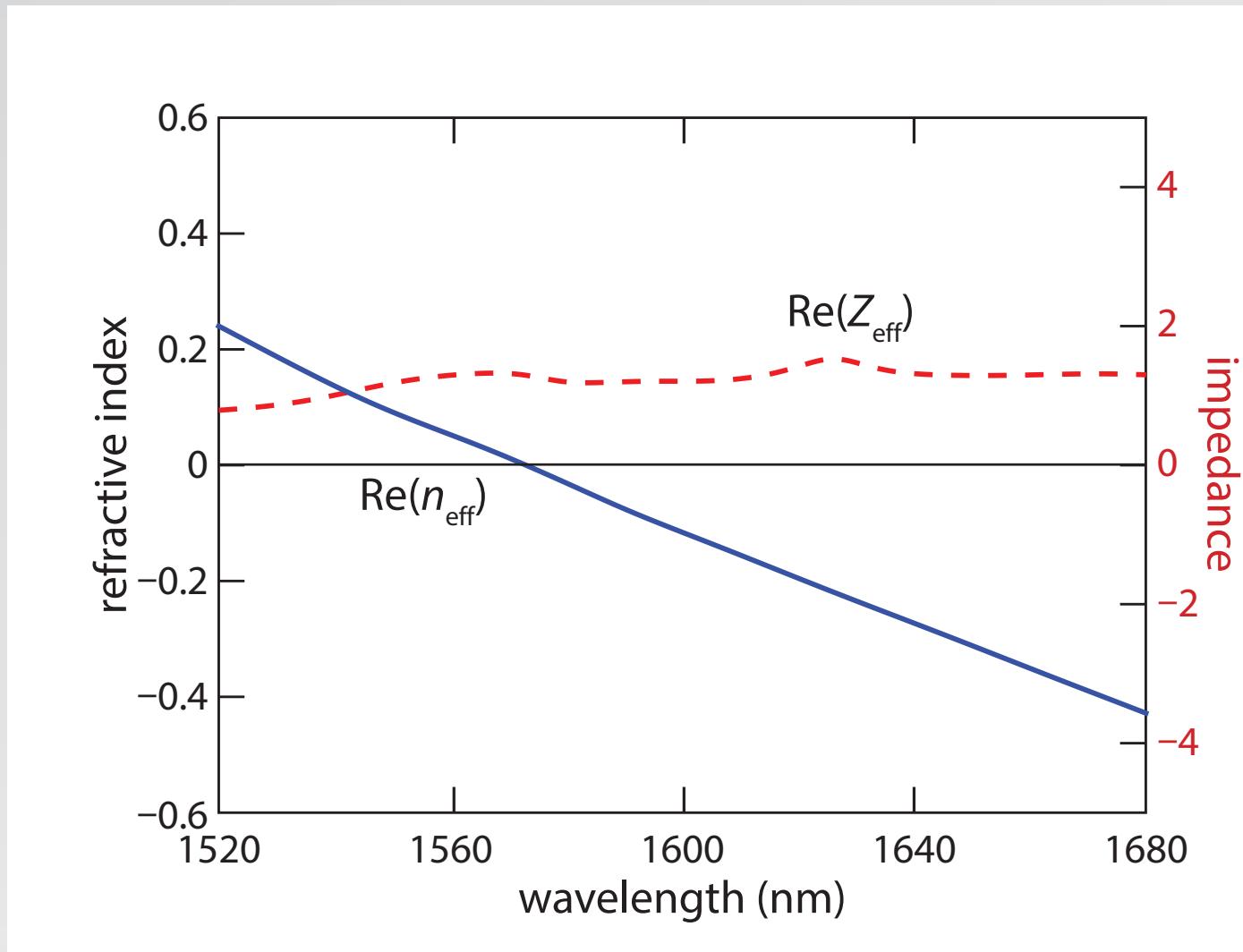
3 experiments



1 index

2 zero index

3 experiments

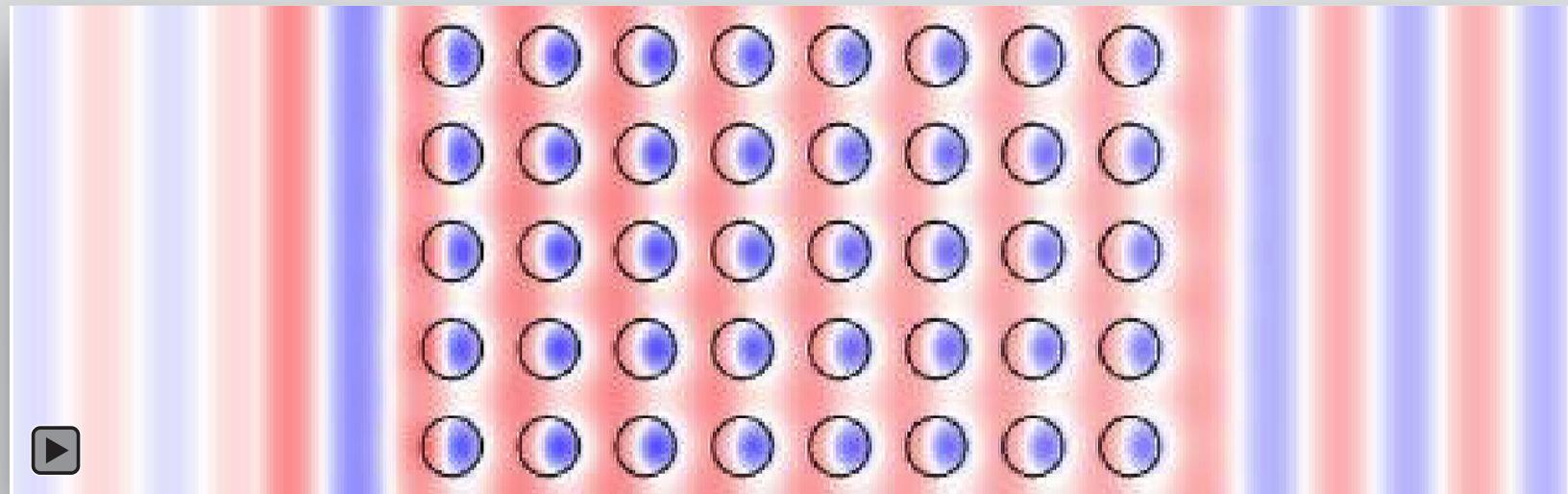


1 index

2 zero index

3 experiments

at design wavelength (1590 nm)

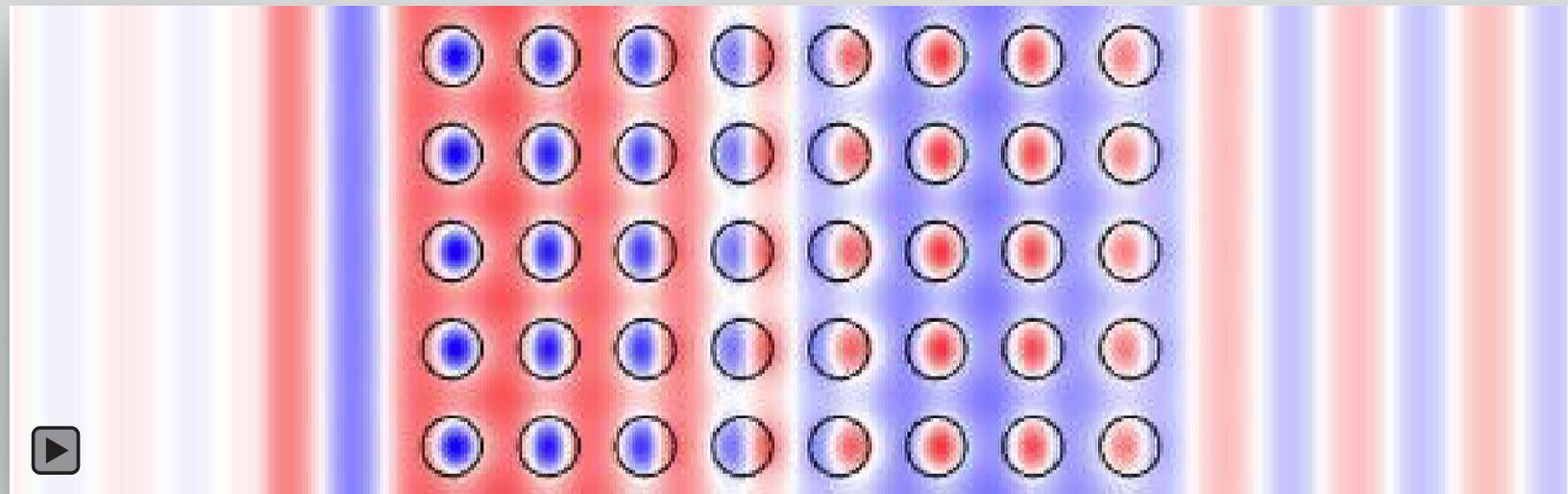


1 index

2 zero index

3 experiments

below design wavelength (1530 nm)

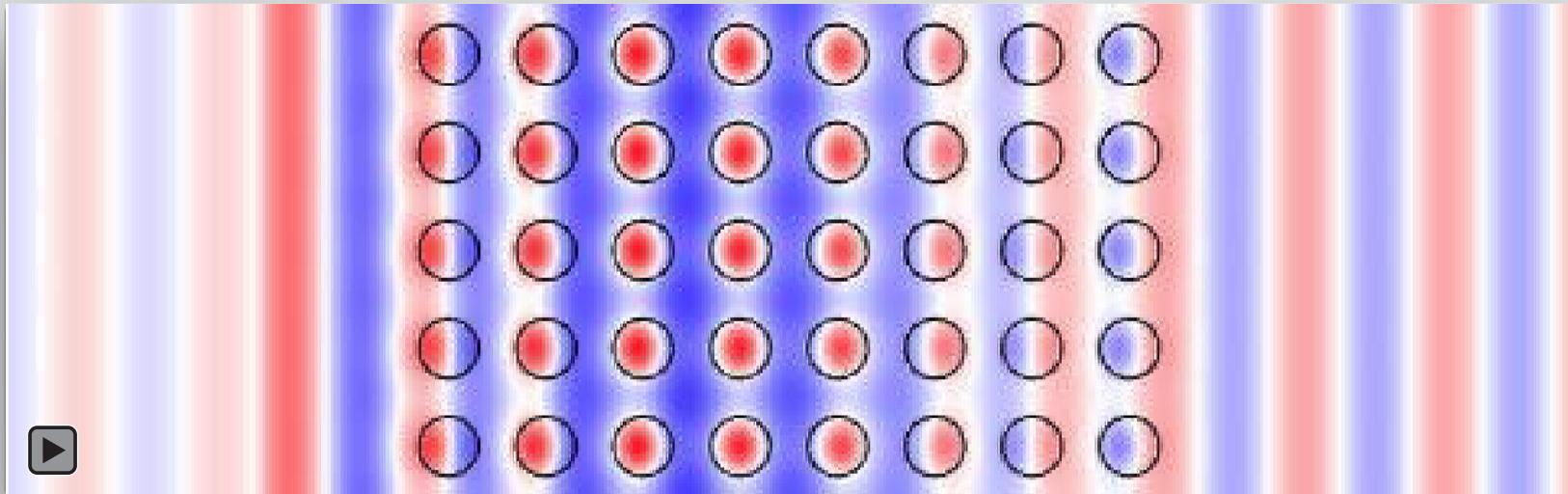


1 index

2 zero index

3 experiments

above design wavelength (1650 nm)

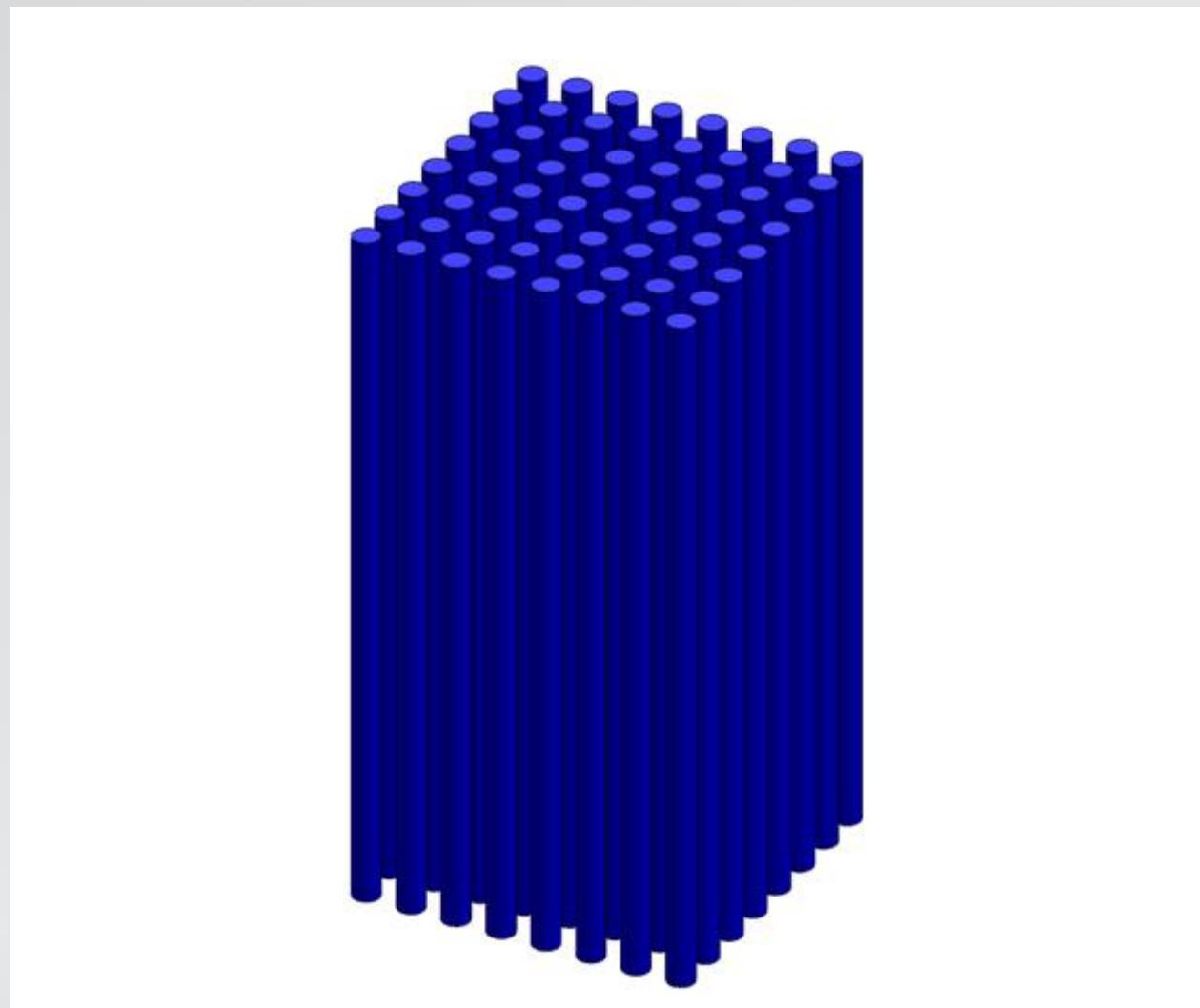


1 index

2 zero index

3 experiments

How to fabricate?



1 index

2 zero index

3 experiments

On-chip zero-index fabrication

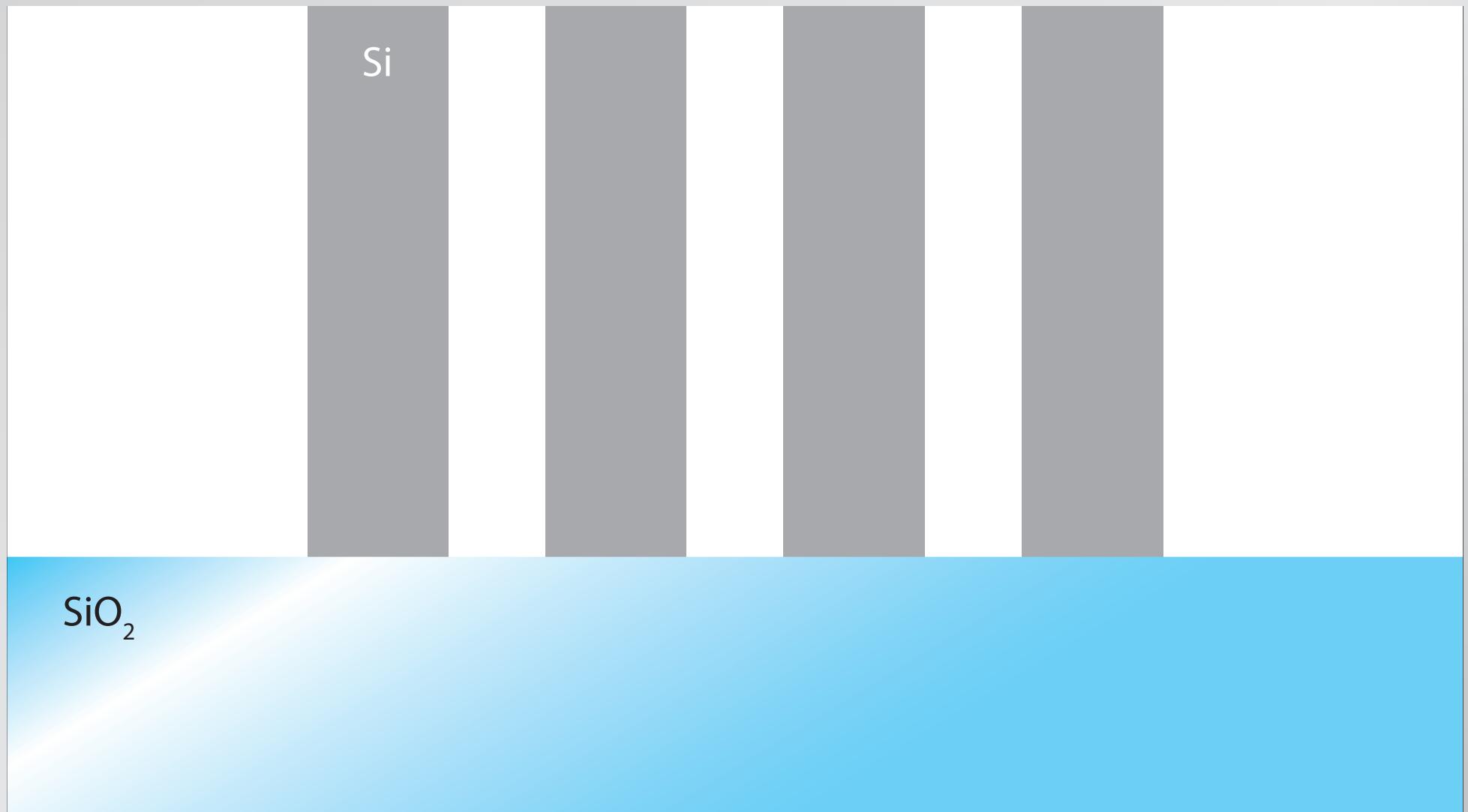


1 index

2 zero index

3 experiments

On-chip zero-index fabrication

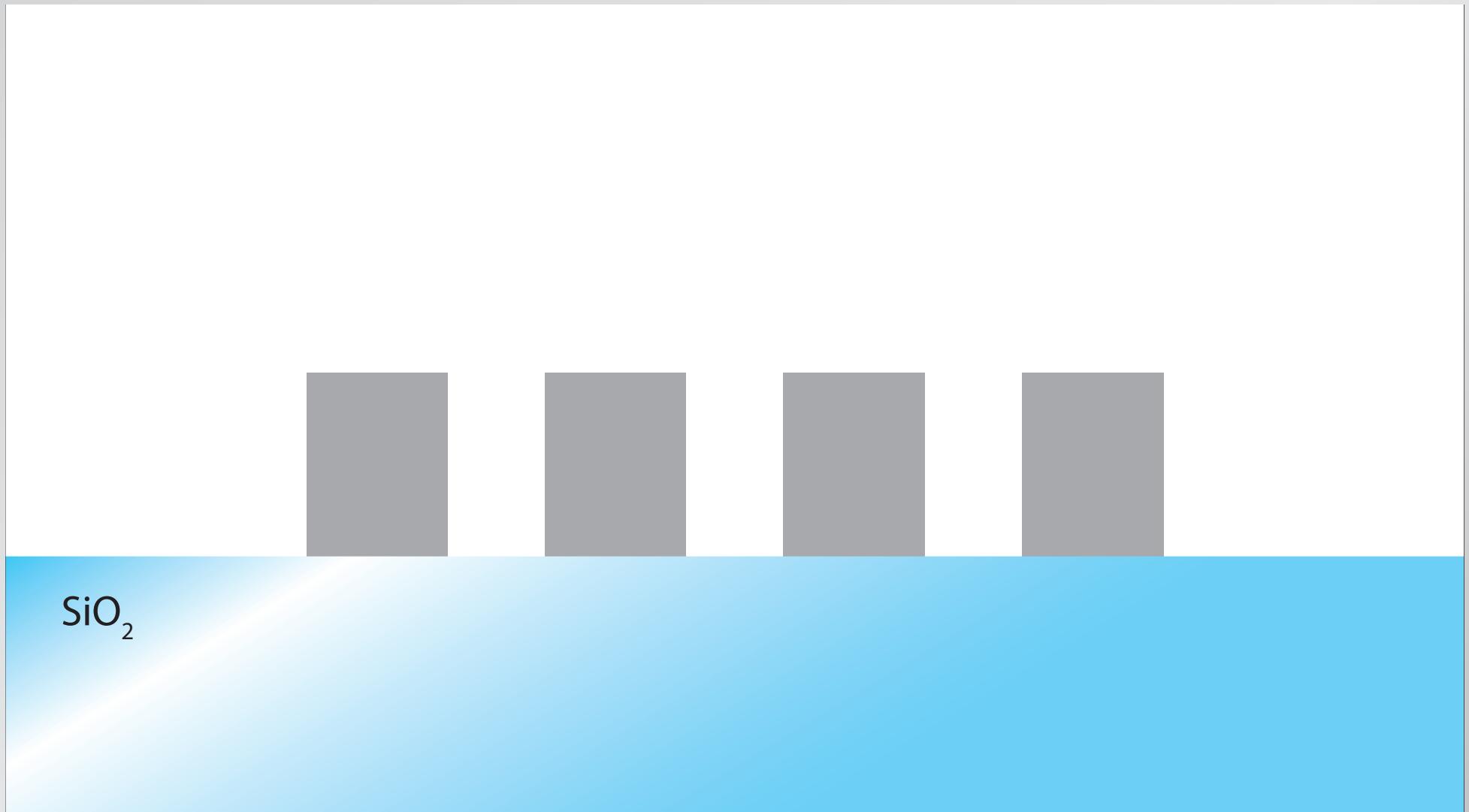


1 index

2 zero index

3 experiments

On-chip zero-index fabrication

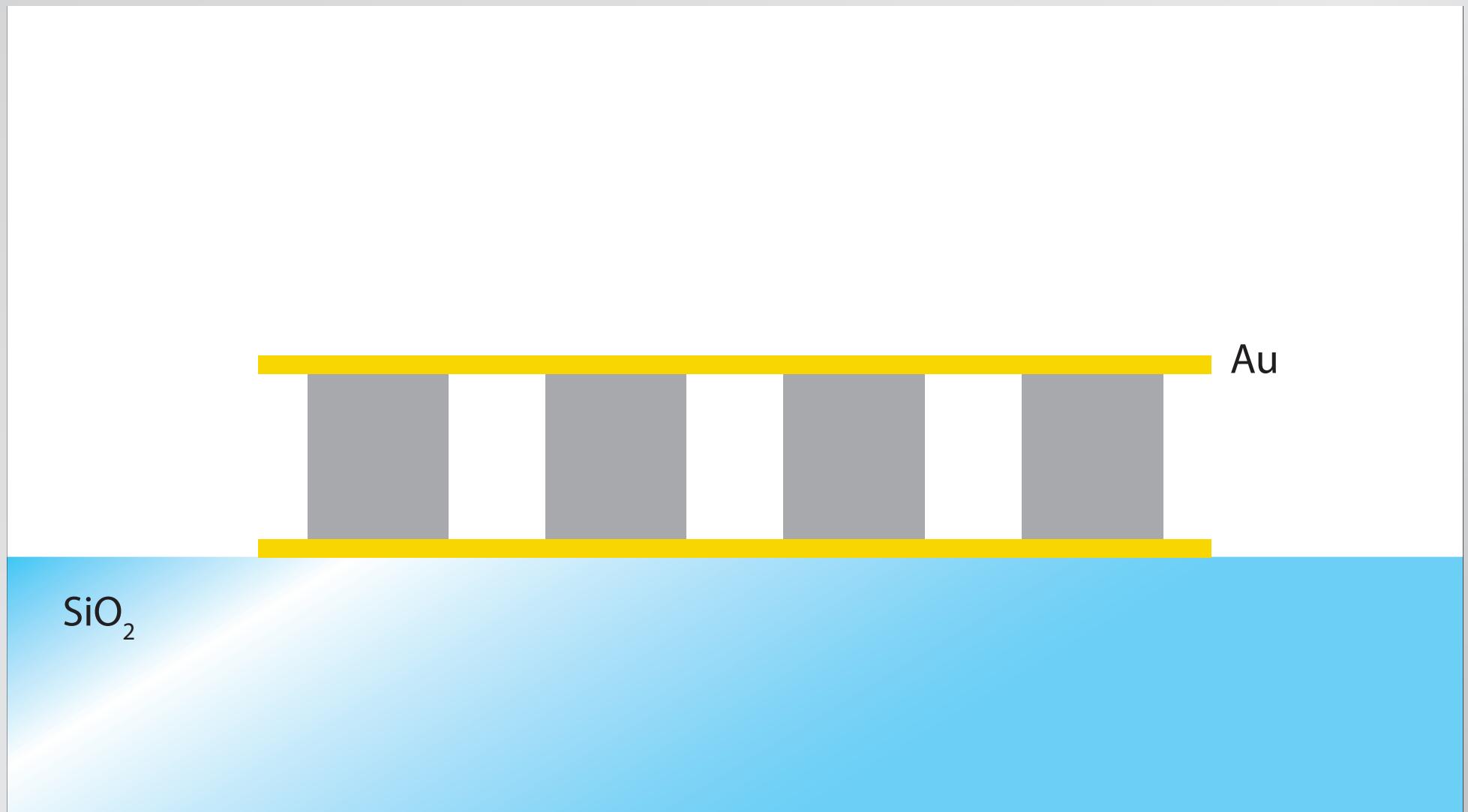


1 index

2 zero index

3 experiments

On-chip zero-index fabrication

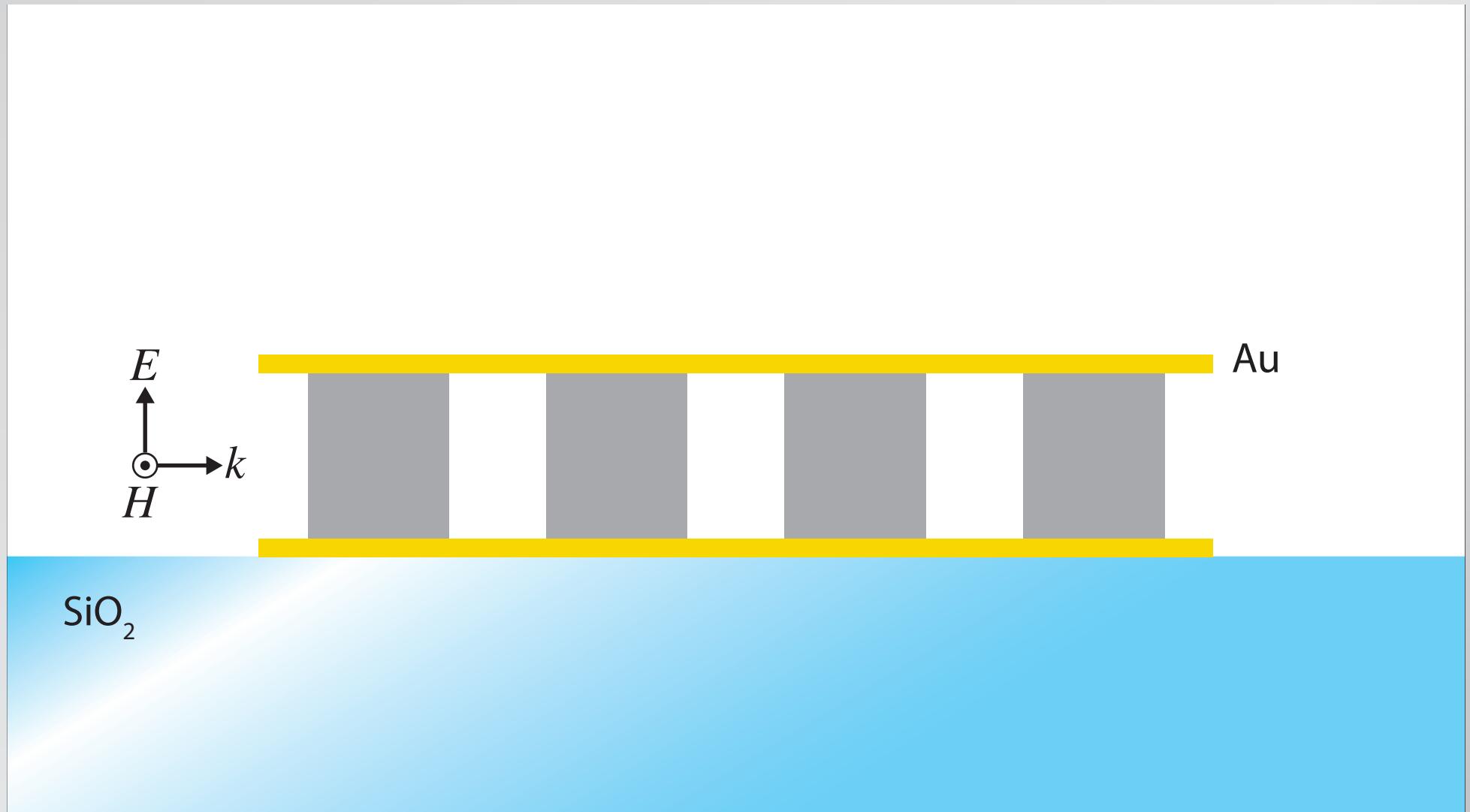


1 index

2 zero index

3 experiments

On-chip zero-index fabrication

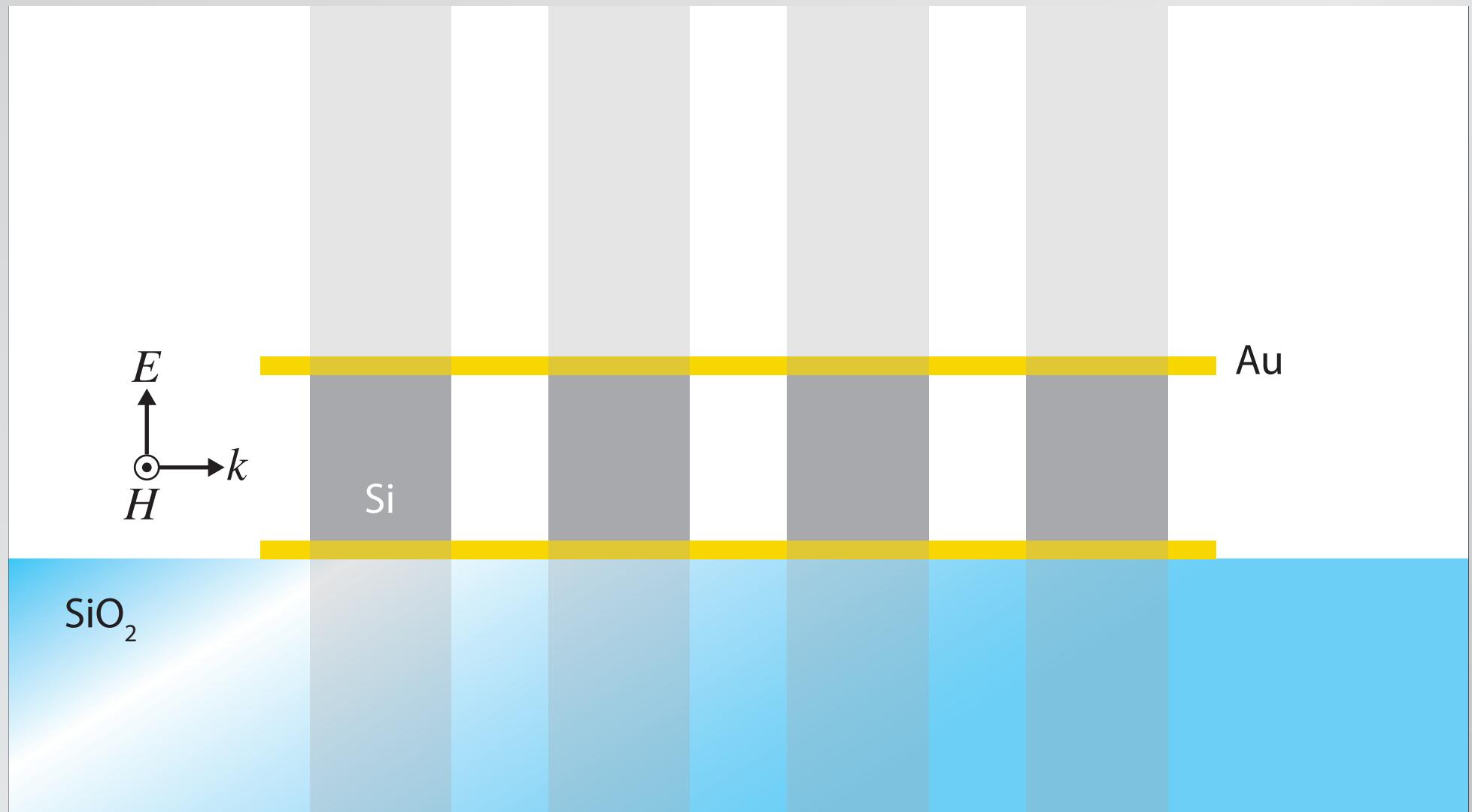


1 index

2 zero index

3 experiments

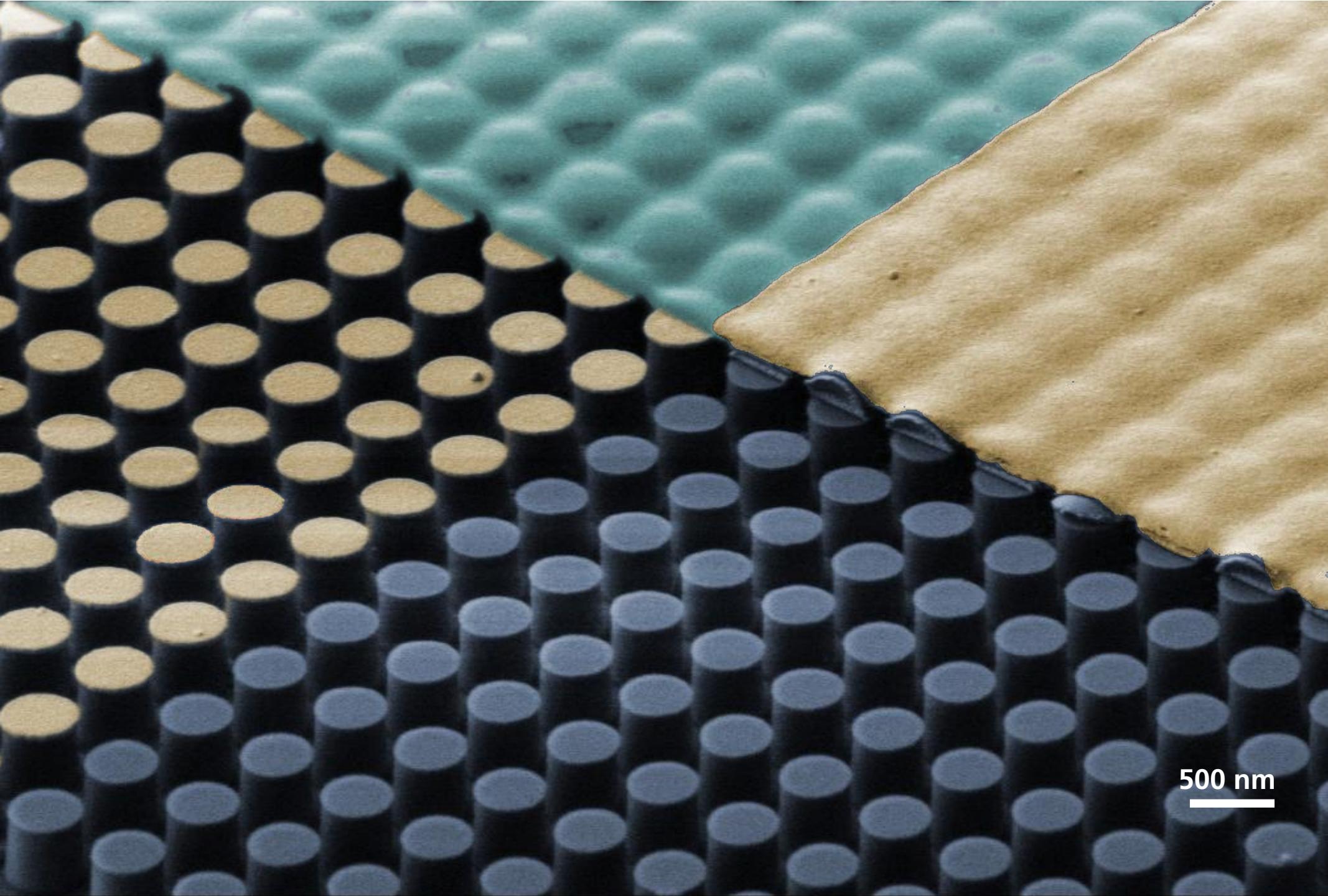
On-chip zero-index fabrication



1 index

2 zero index

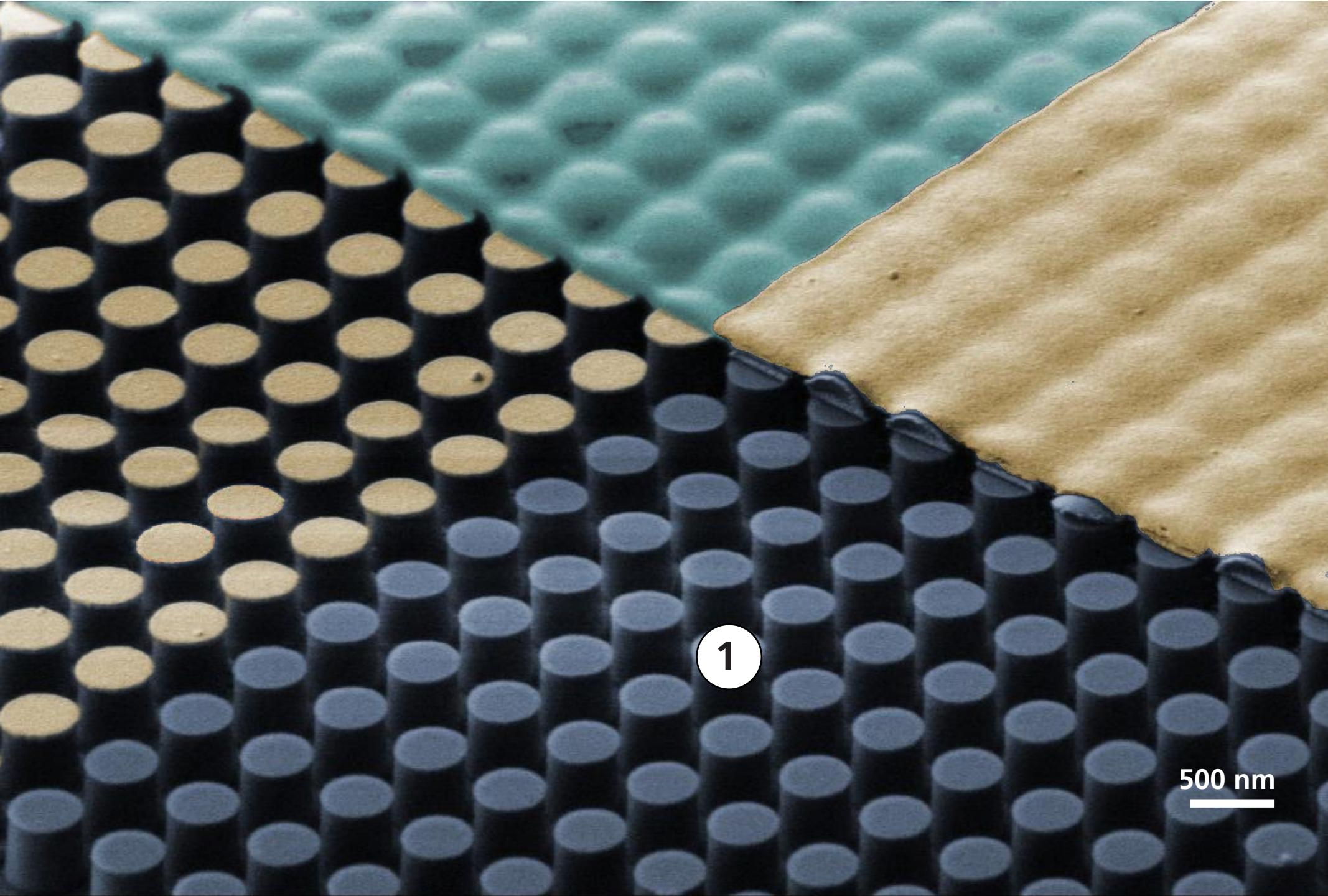
3 experiments



1 index

2 zero index

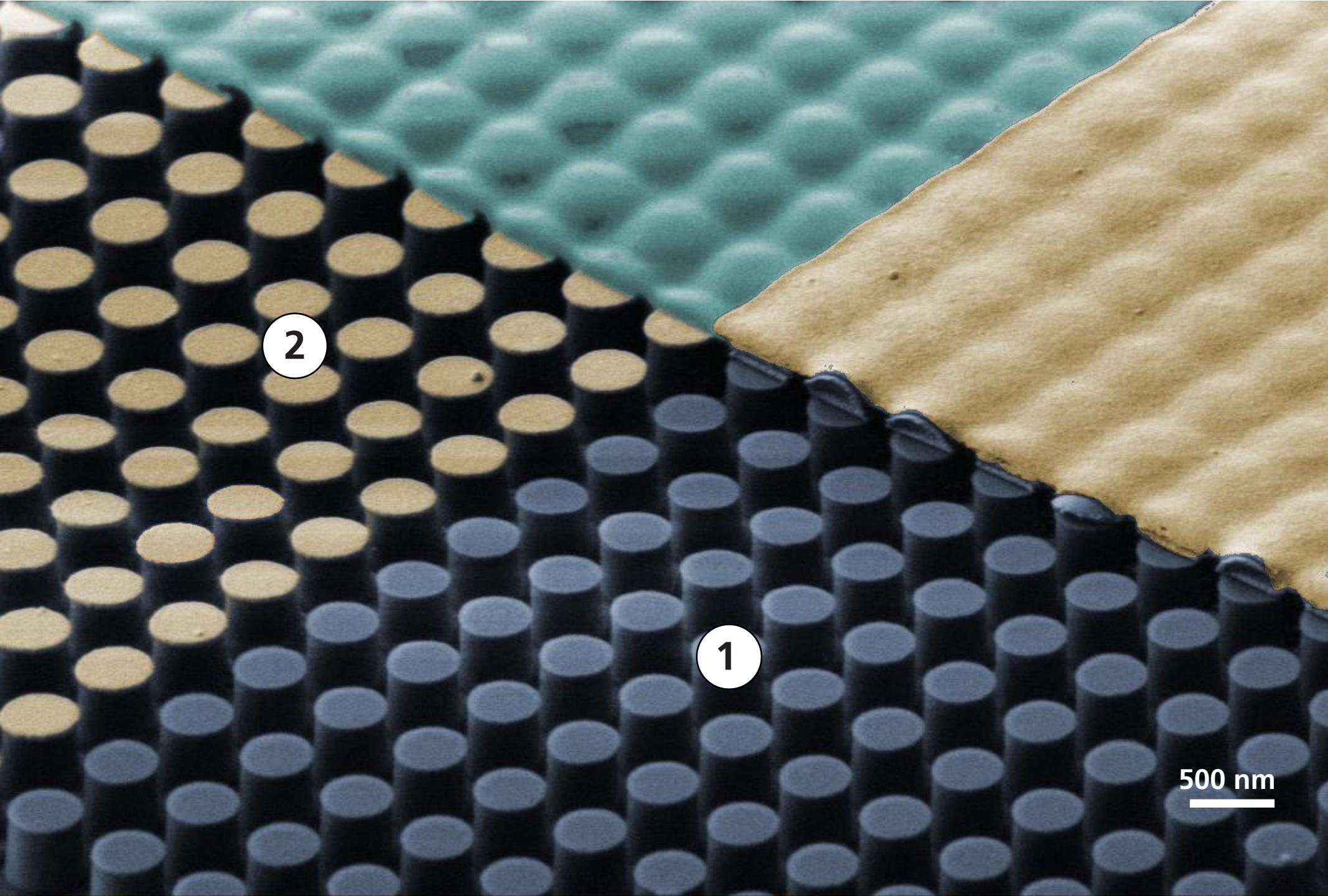
3 experiments



1 index

2 zero index

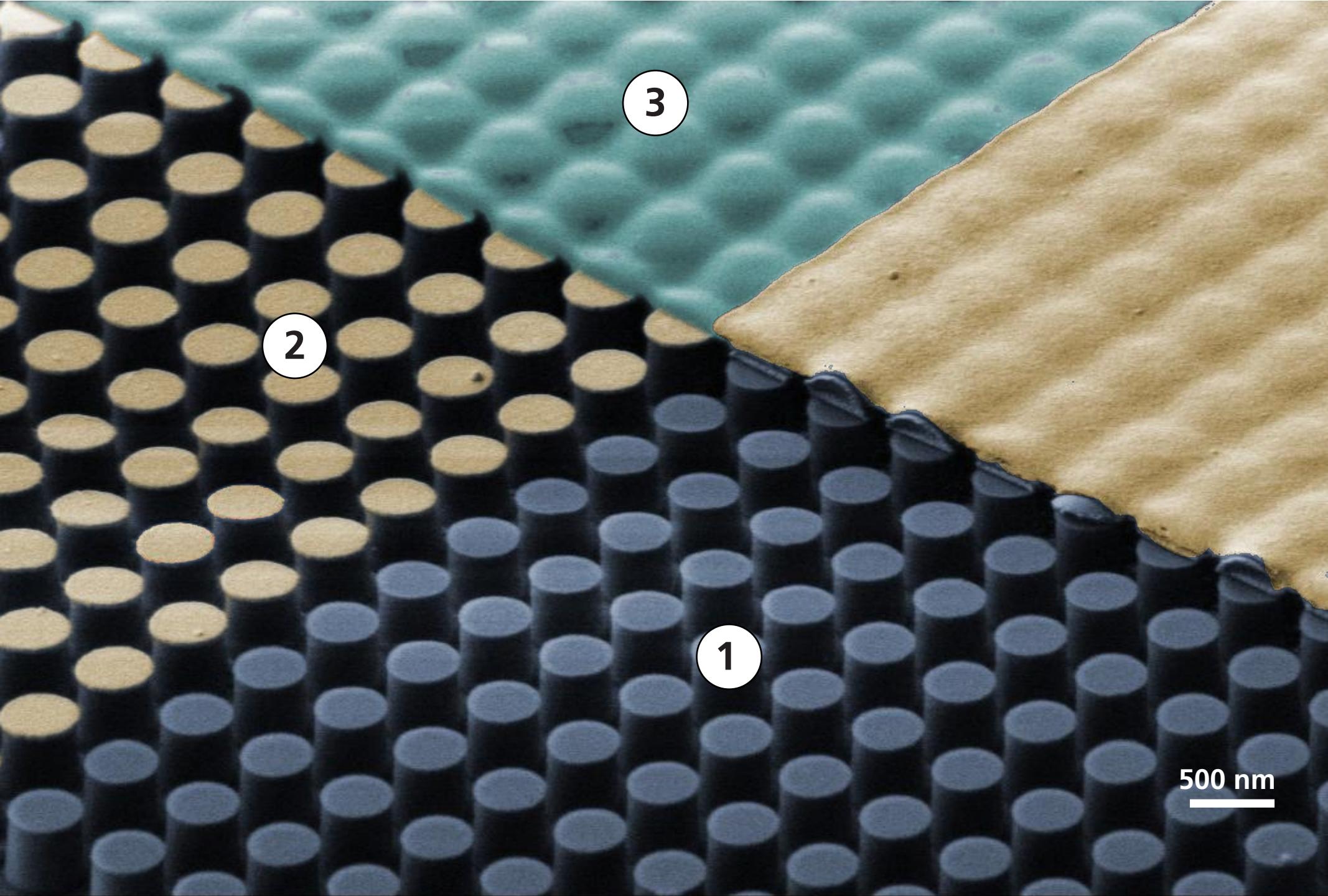
3 experiments



1 index

2 zero index

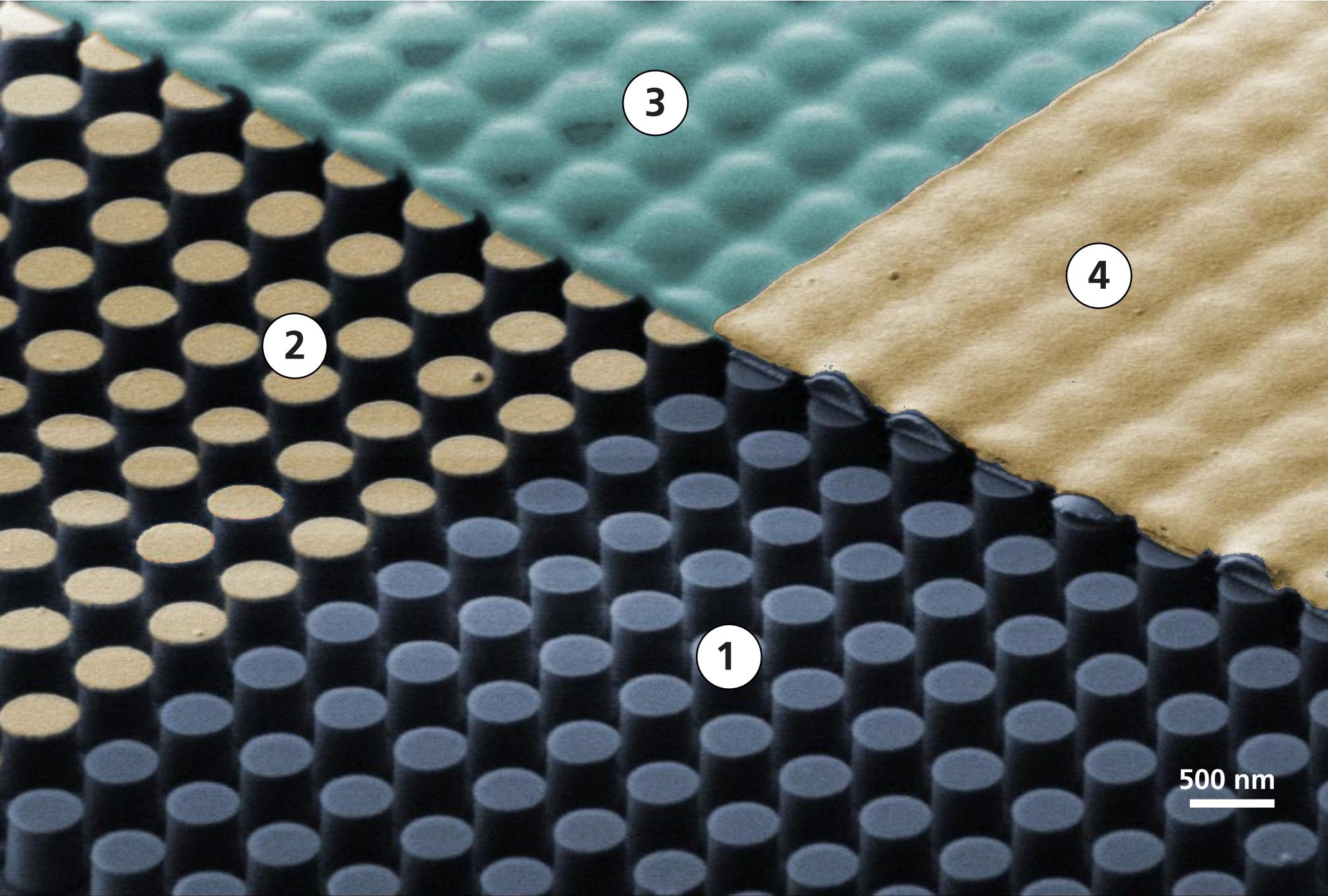
3 experiments



1 index

2 zero index

3 experiments



1 index

2 zero index

3 experiments



1 index

2 zero index

3 experiments

On-chip zero-index prism

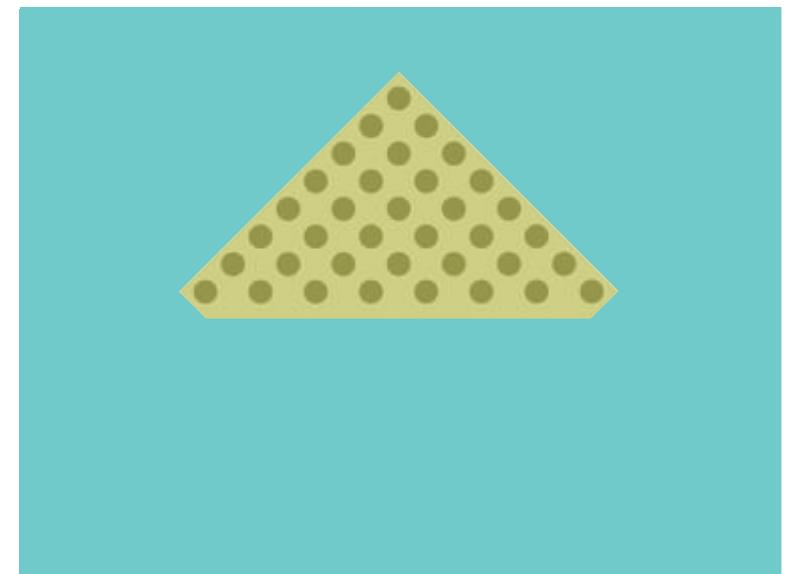


1 index

2 zero index

3 experiments

On-chip zero-index prism

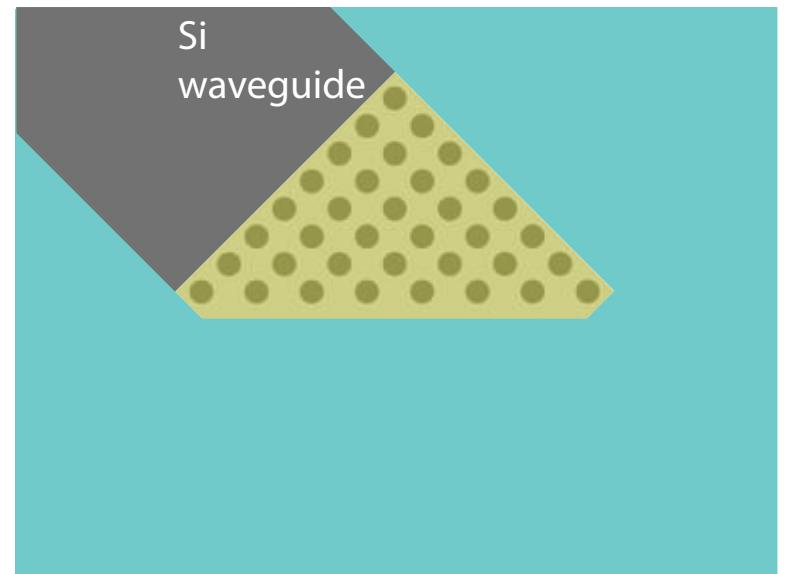


1 index

2 zero index

3 experiments

On-chip zero-index prism

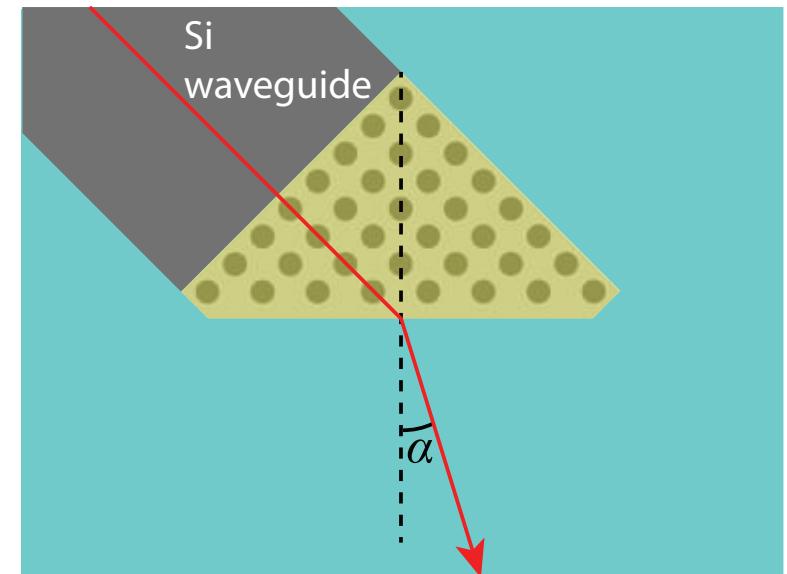


1 index

2 zero index

3 experiments

On-chip zero-index prism

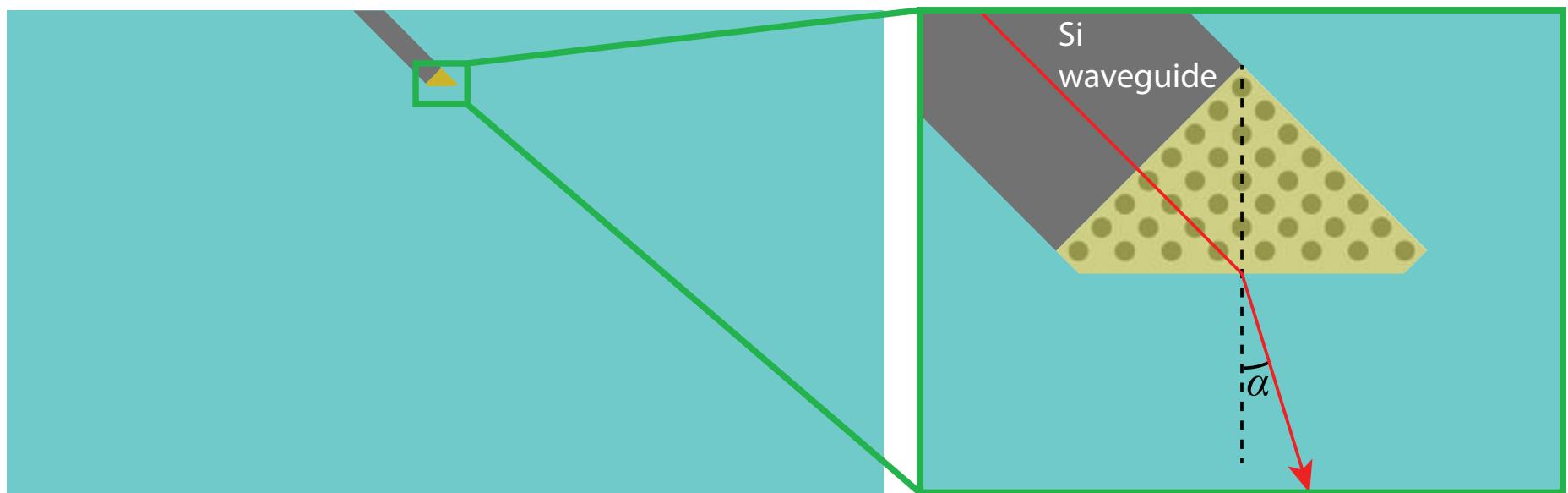


1 index

2 zero index

3 experiments

On-chip zero-index prism

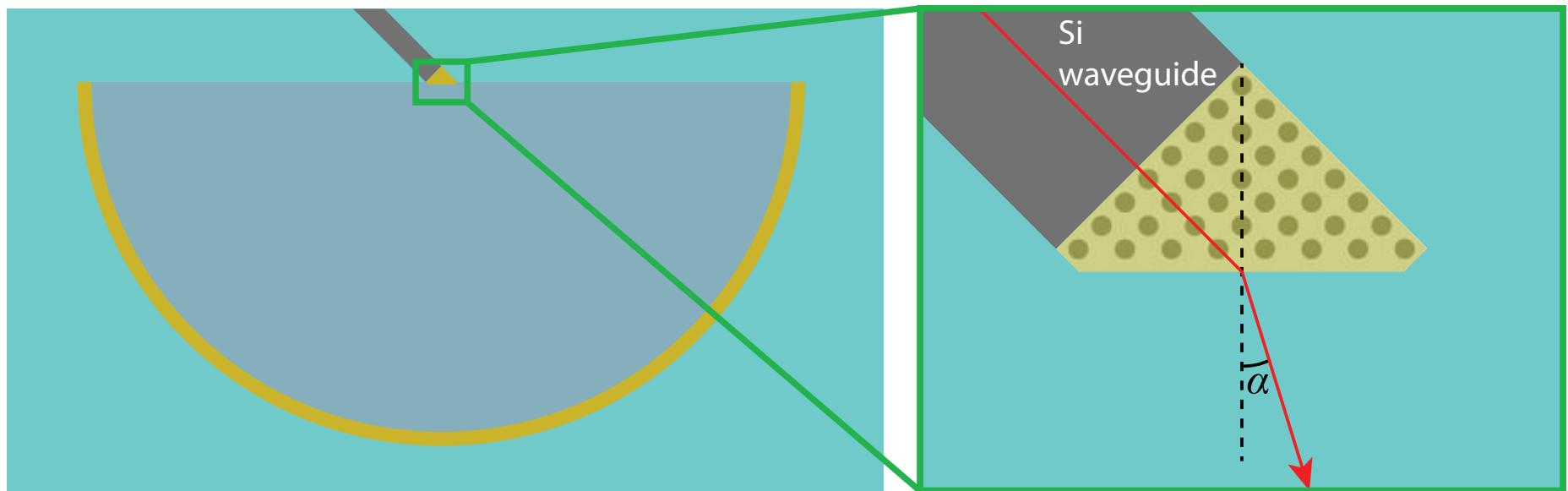


1 index

2 zero index

3 experiments

On-chip zero-index prism

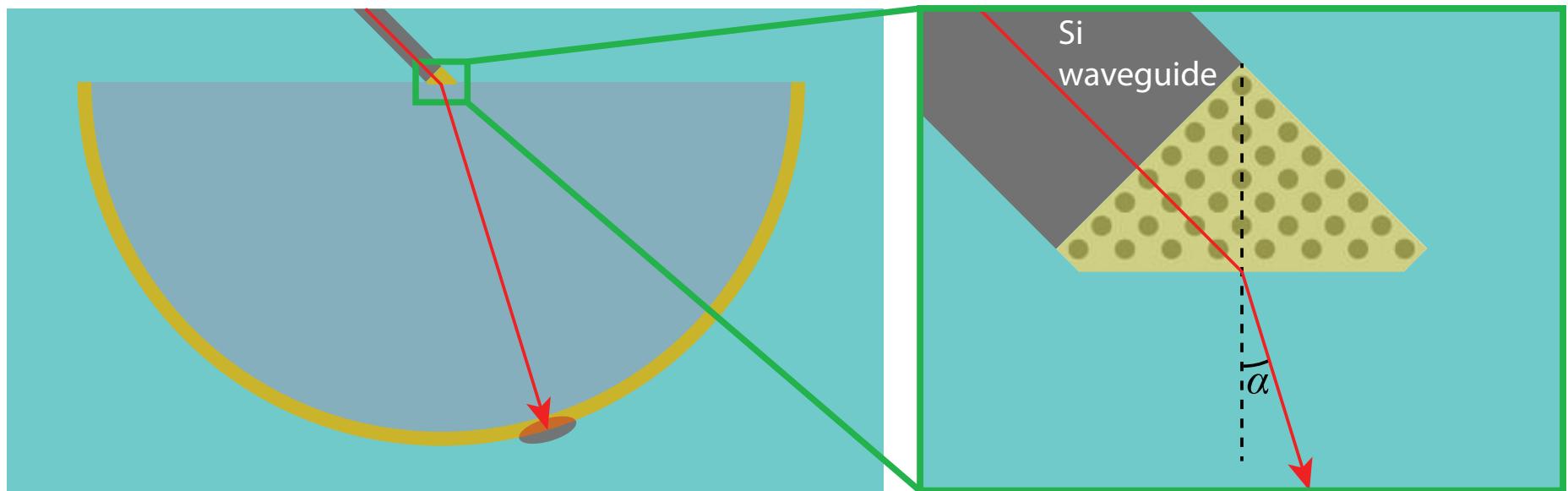


1 index

2 zero index

3 experiments

On-chip zero-index prism

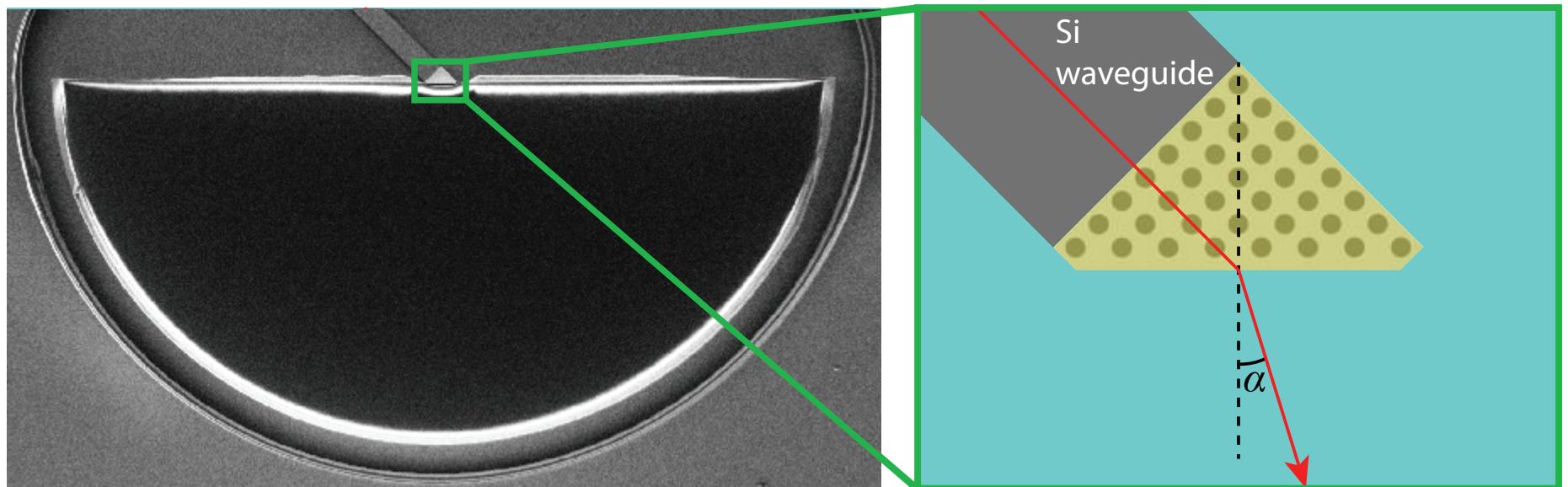


1 index

2 zero index

3 experiments

On-chip zero-index prism

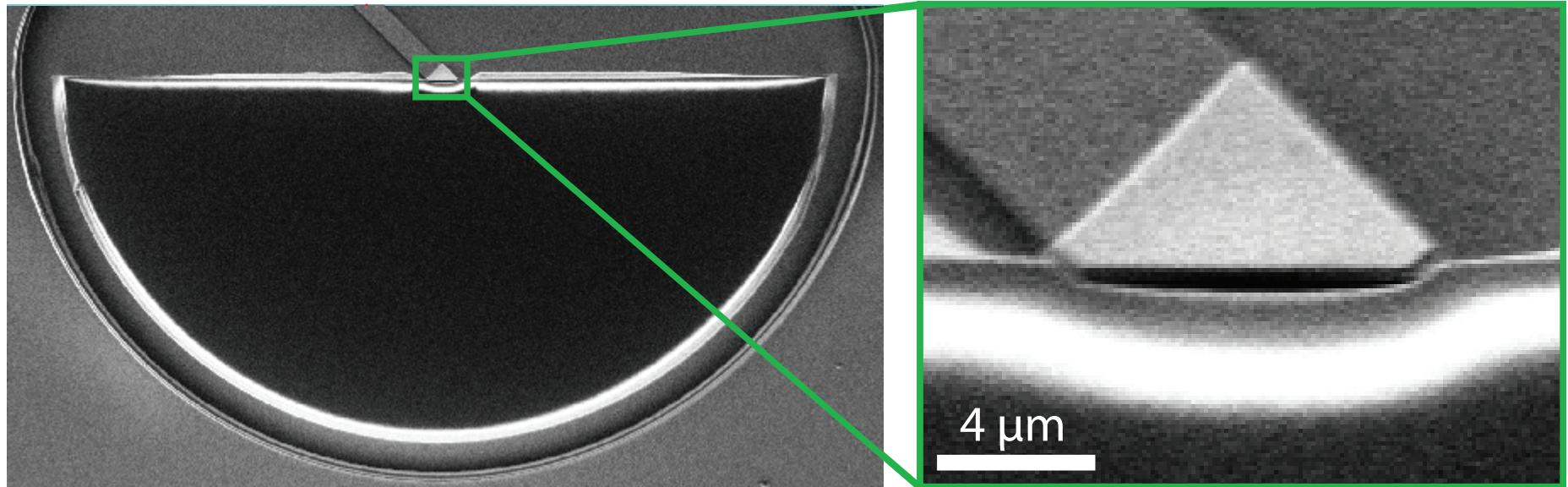


1 index

2 zero index

3 experiments

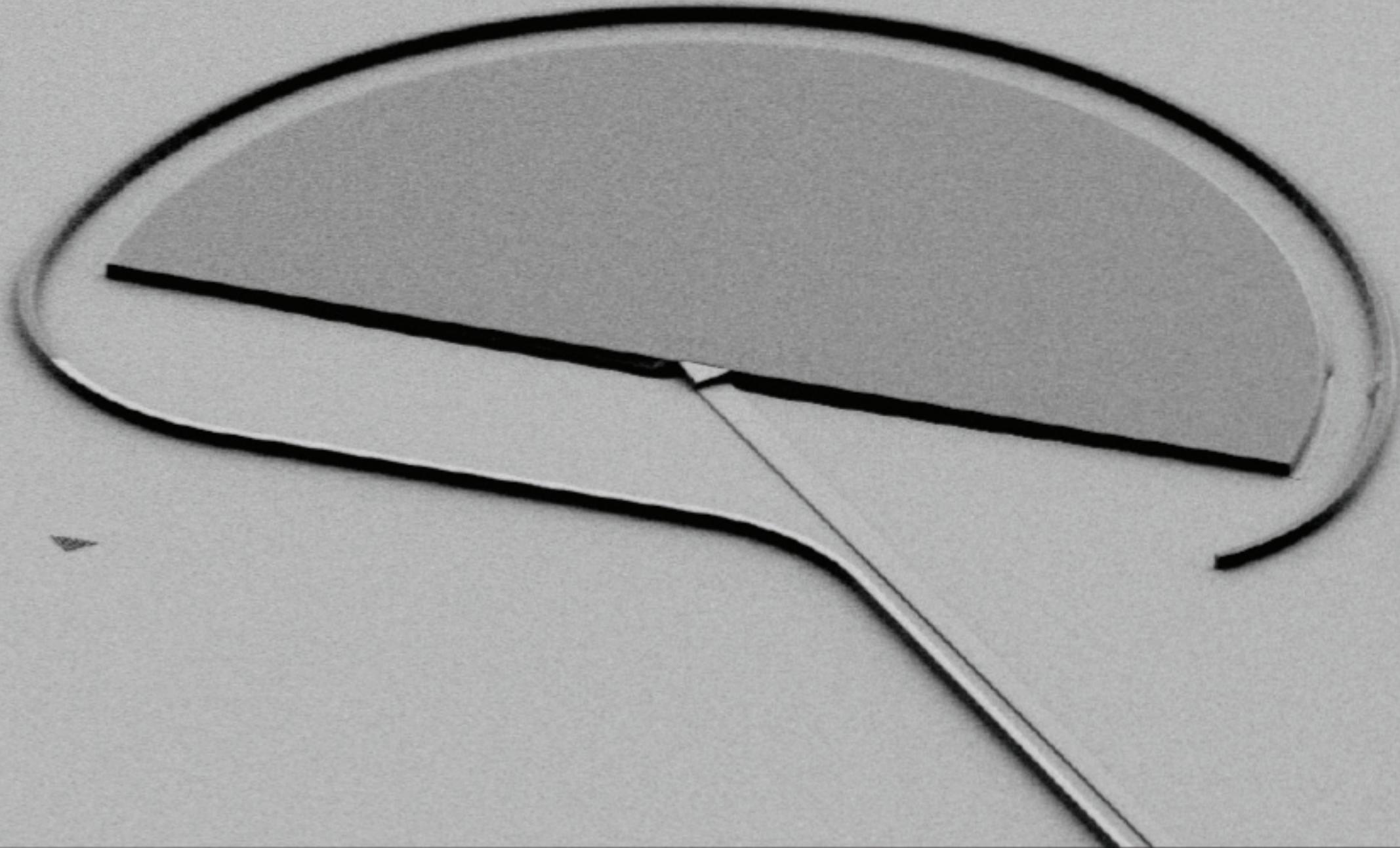
On-chip zero-index prism



1 index

2 zero index

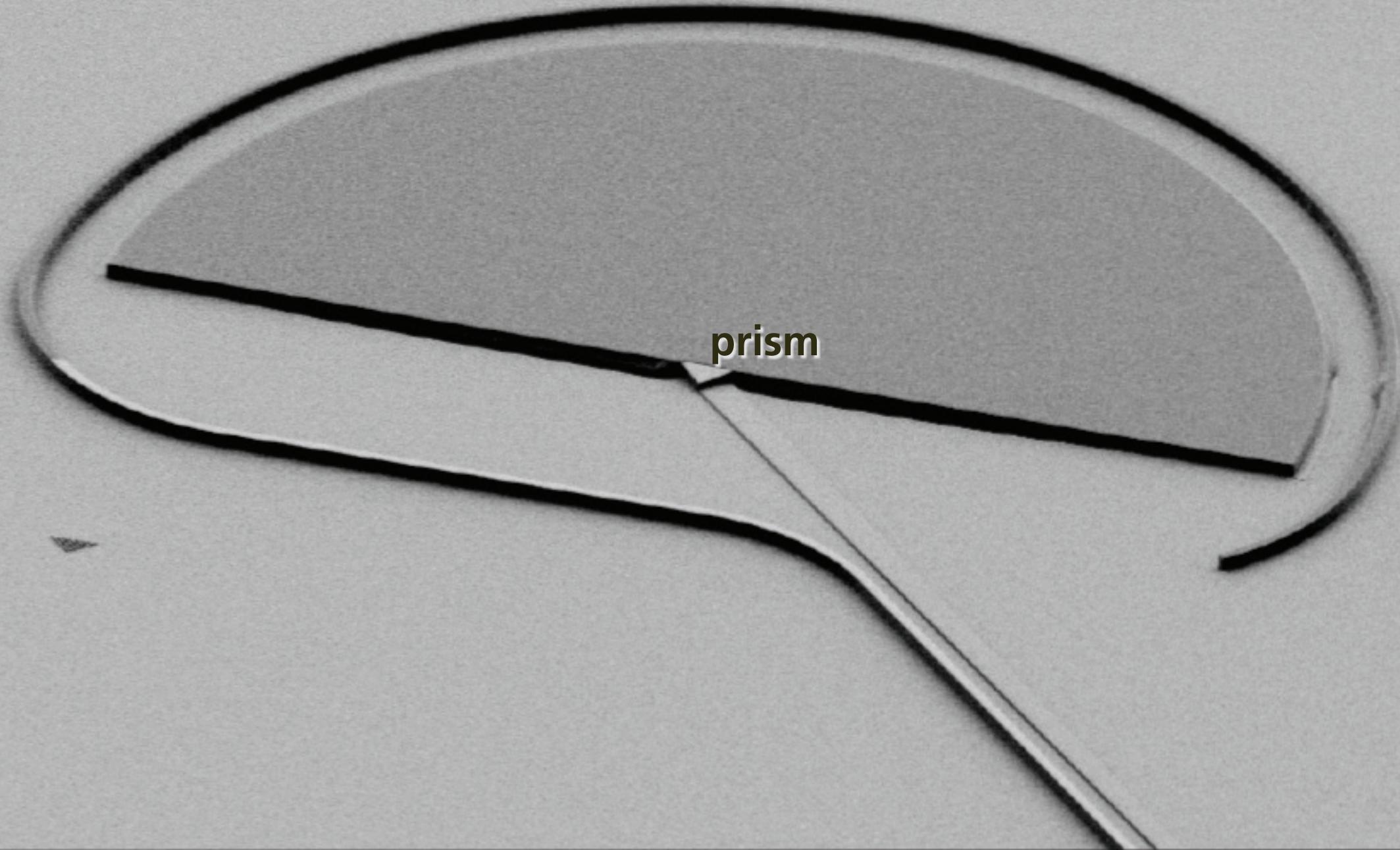
3 experiments



1 index

2 zero index

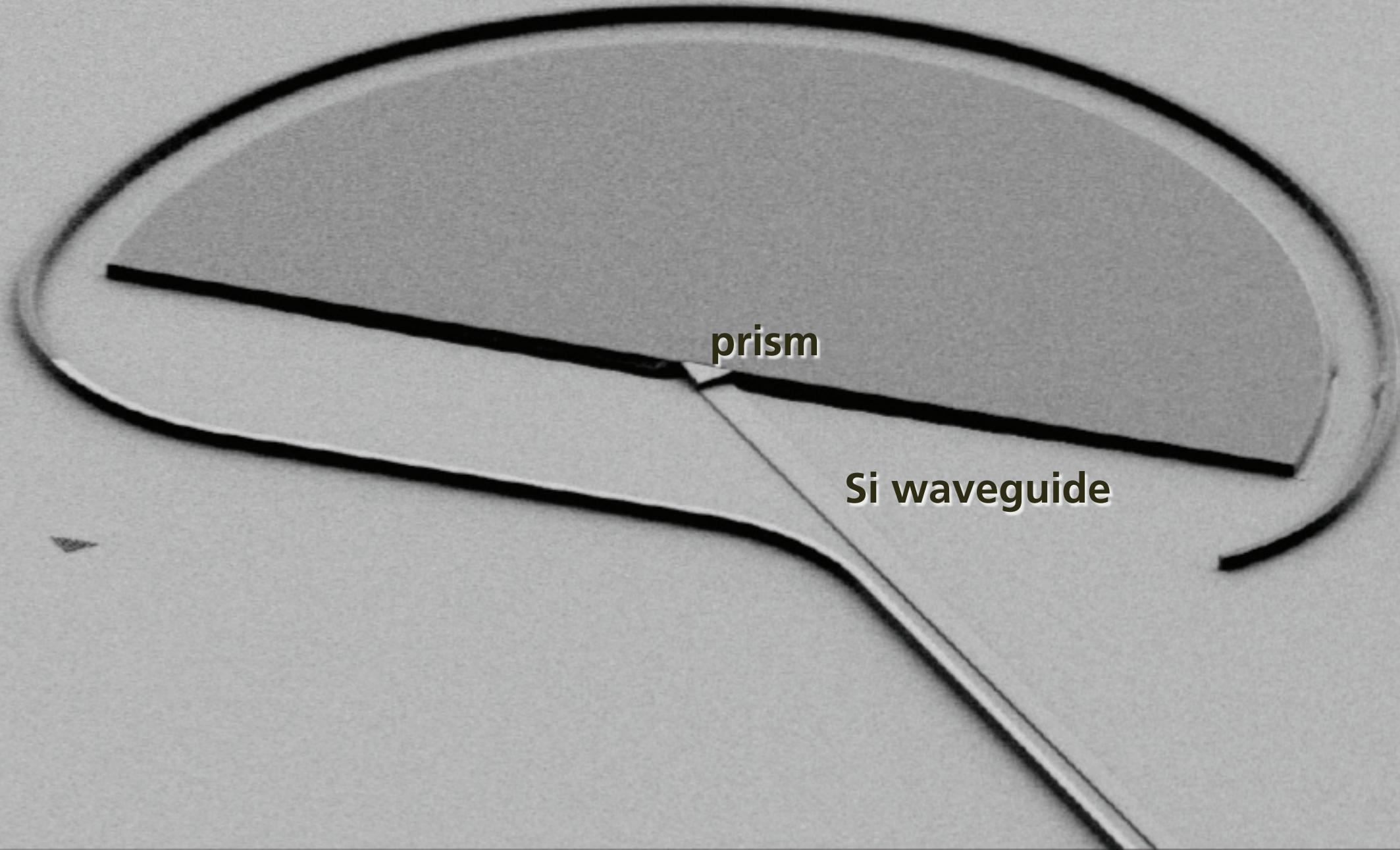
3 experiments



1 index

2 zero index

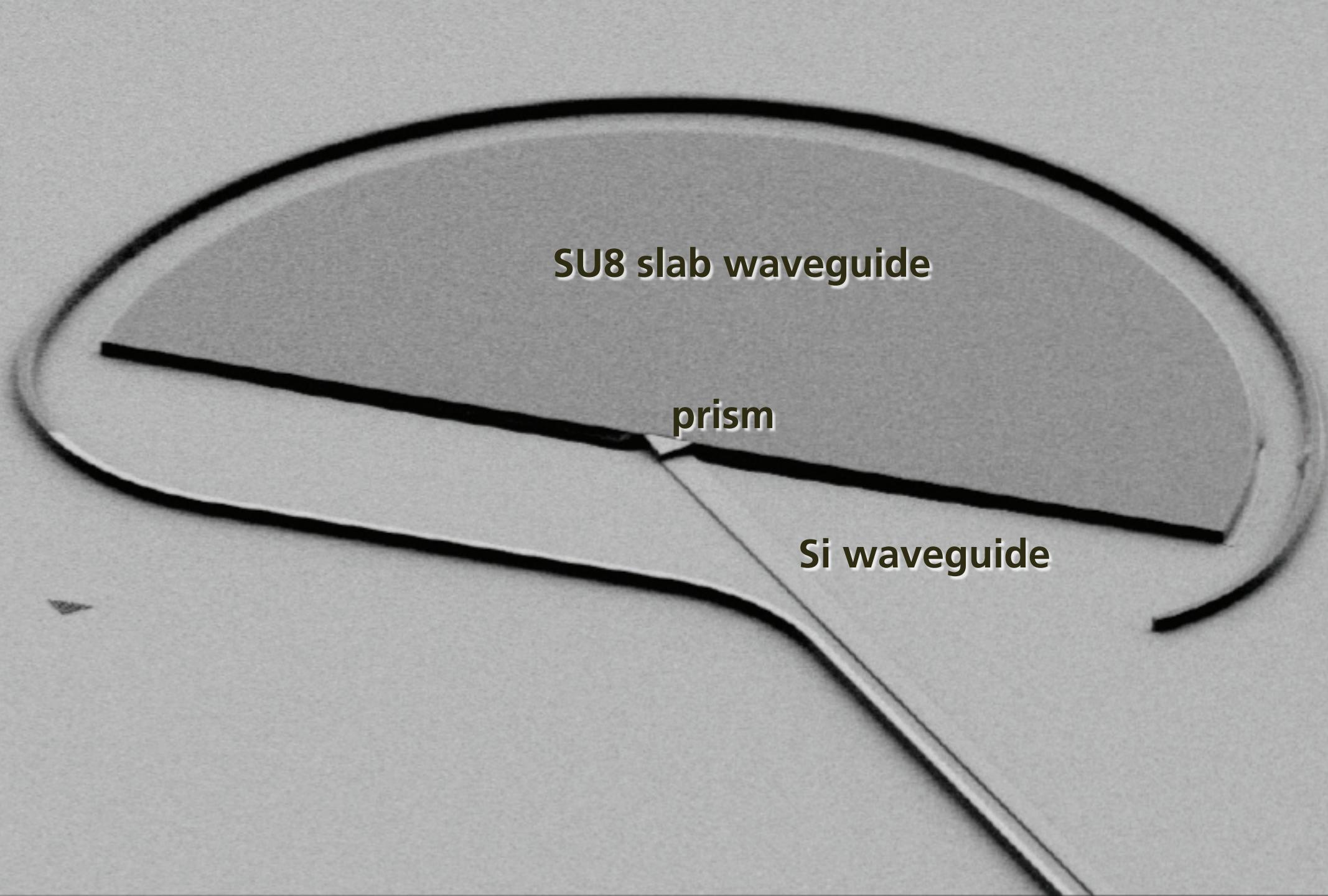
3 experiments



1 index

2 zero index

3 experiments



SU8 slab waveguide

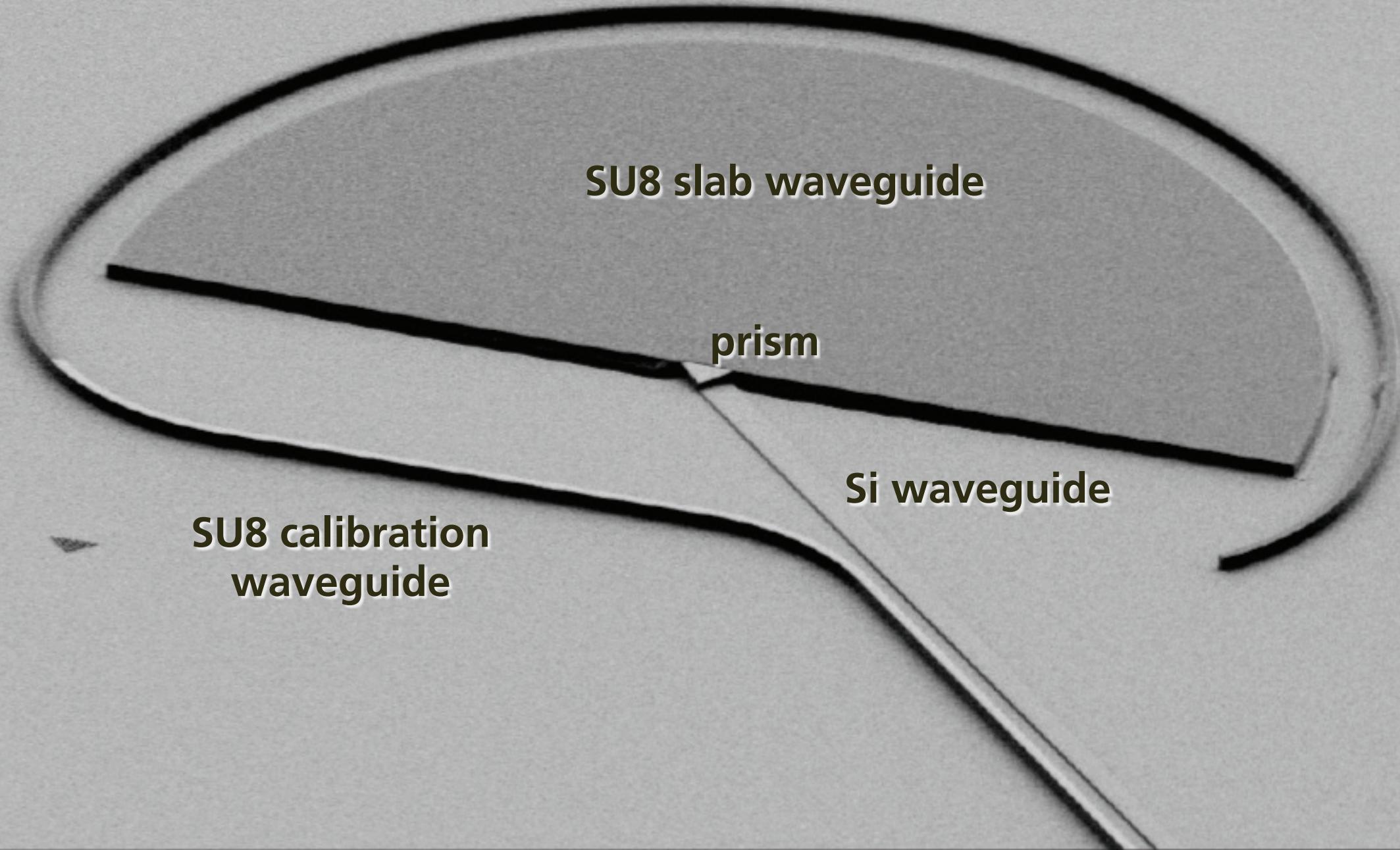
prism

Si waveguide

1 index

2 zero index

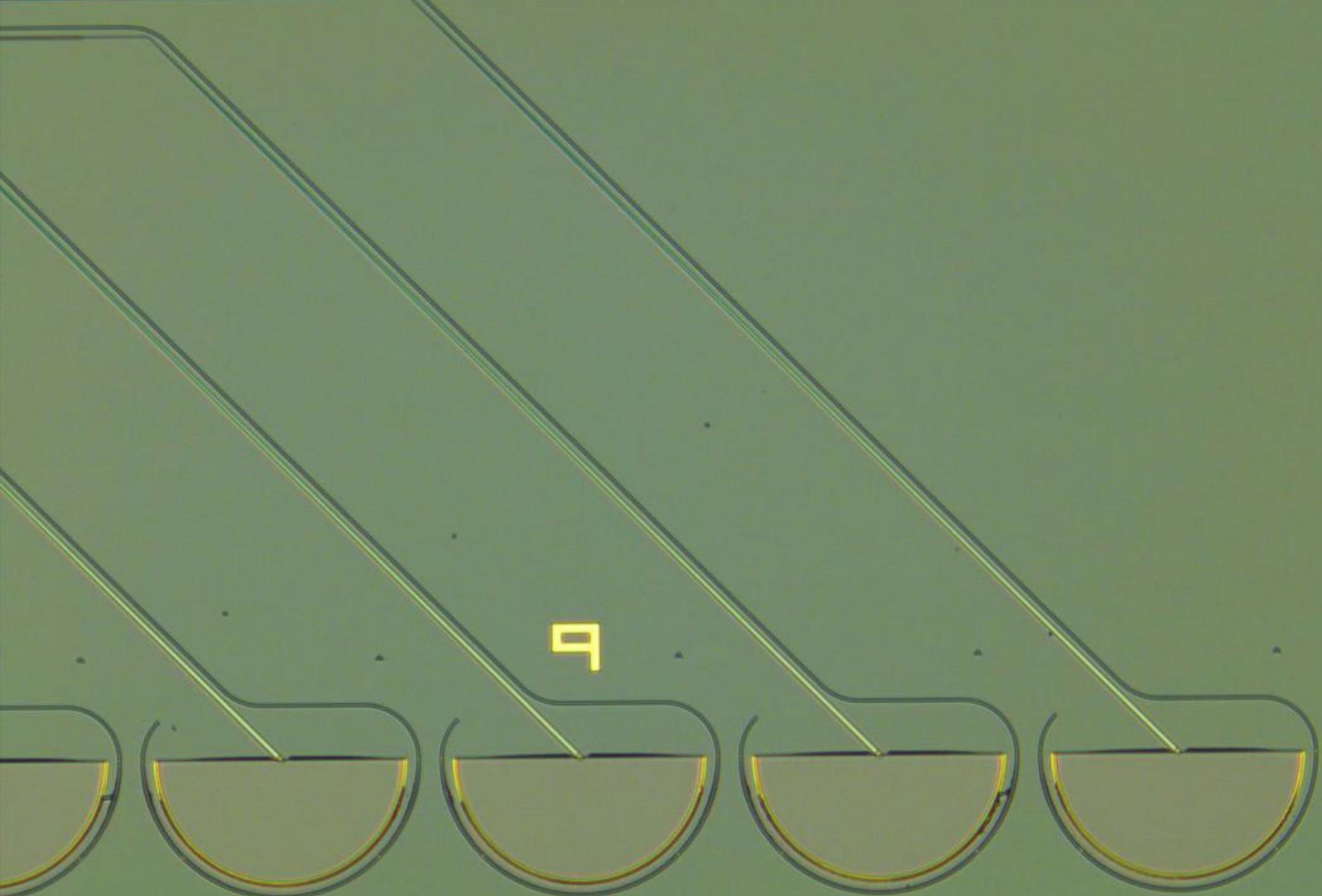
3 experiments



1 index

2 zero index

3 experiments

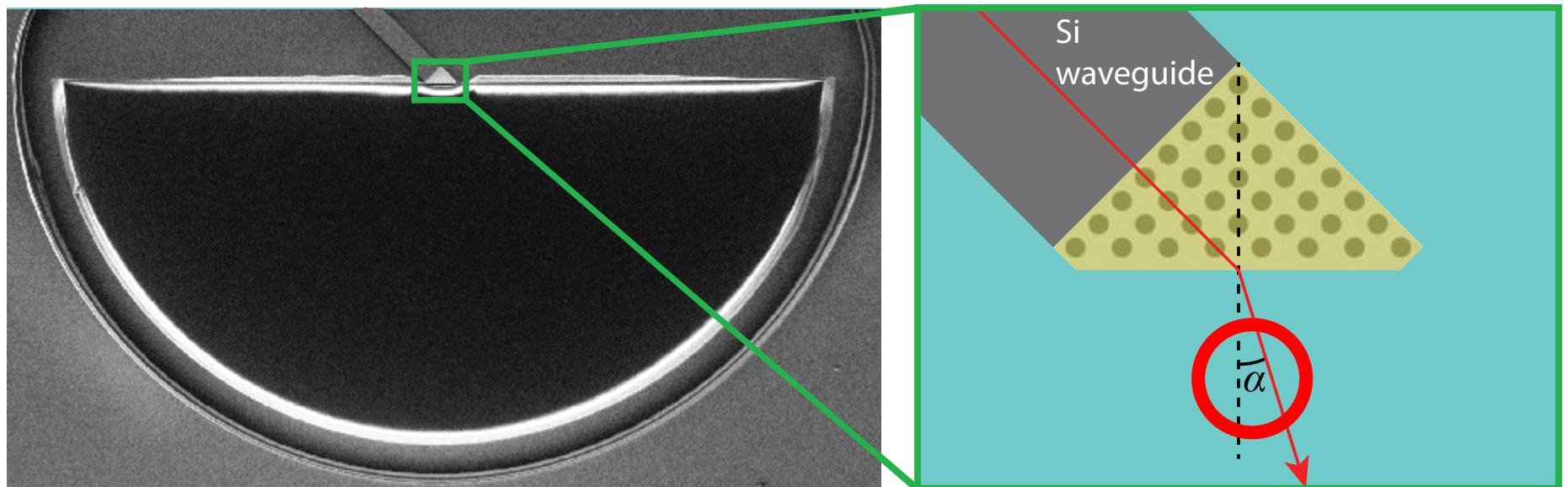


1 index

2 zero index

3 experiments

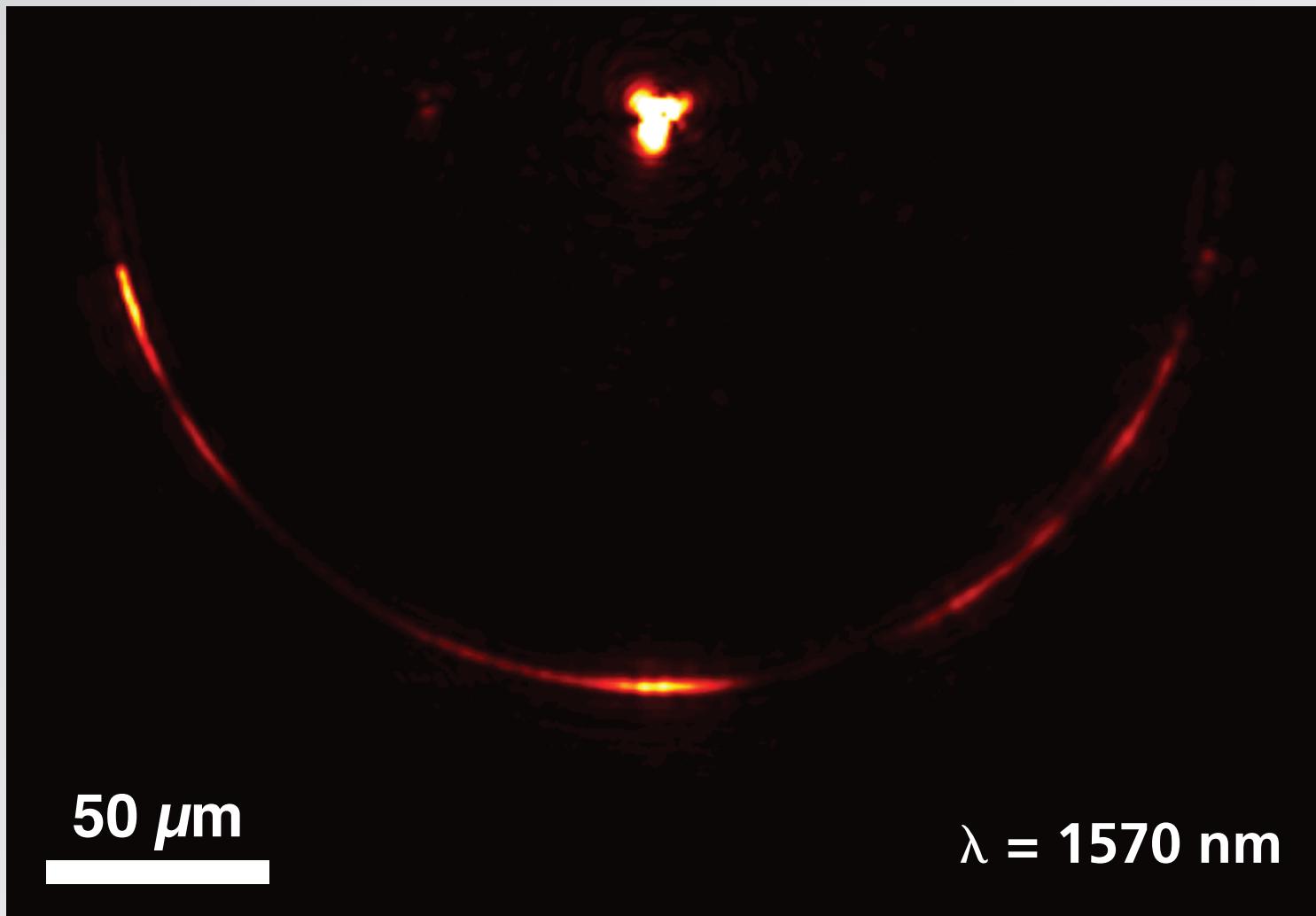
On-chip zero-index prism



1 index

2 zero index

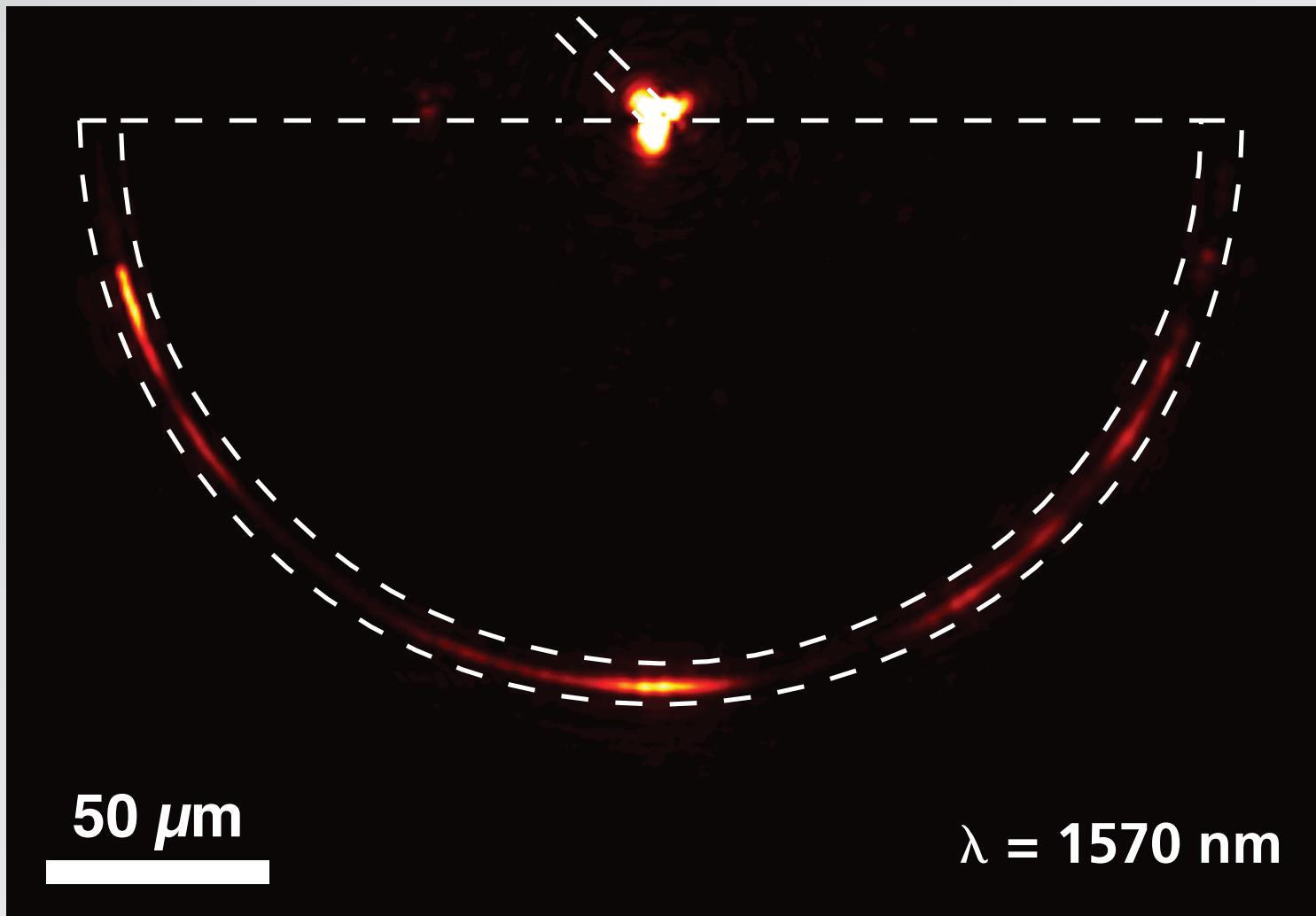
3 experiments



1 index

2 zero index

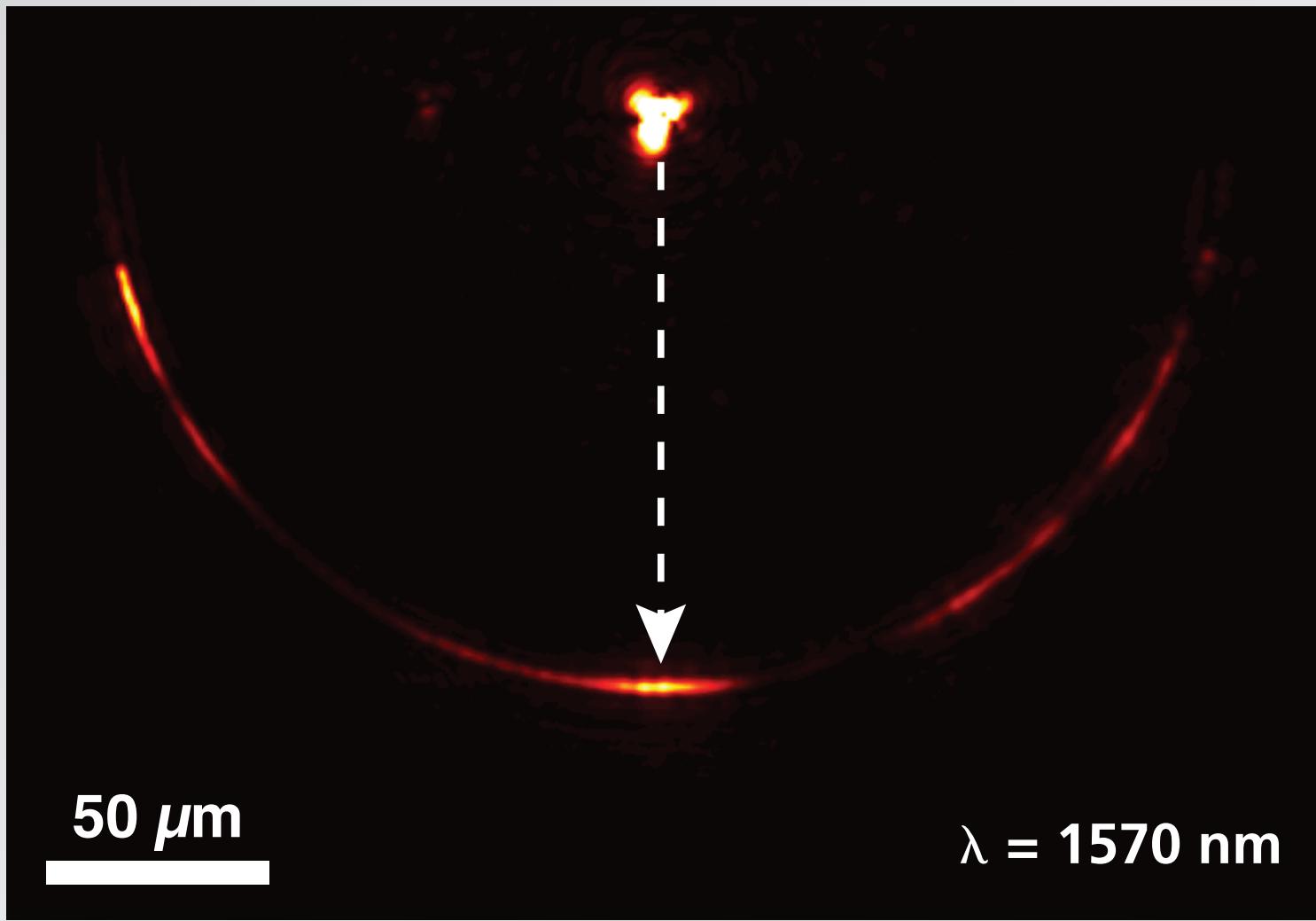
3 experiments



1 index

2 zero index

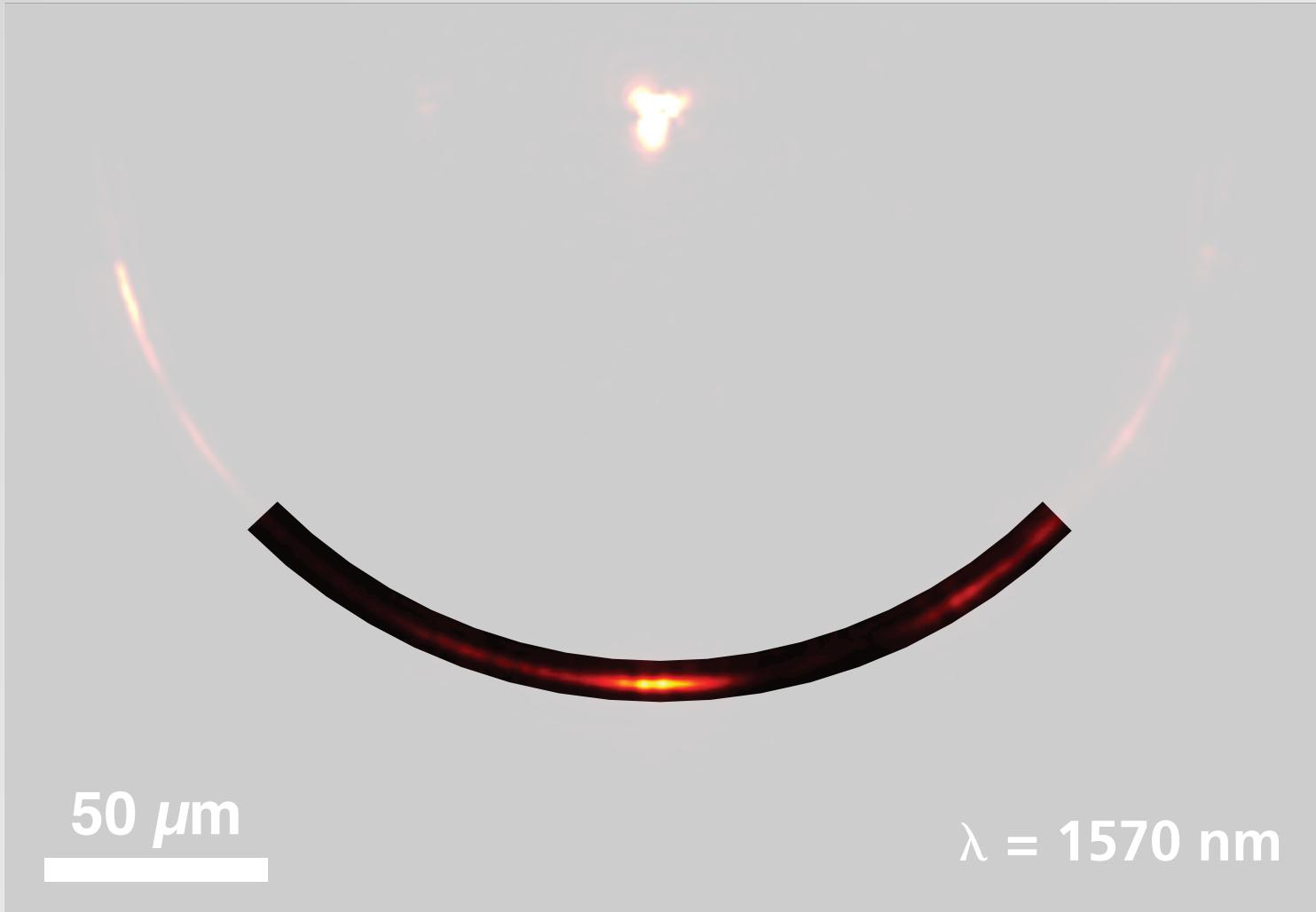
3 experiments



1 index

2 zero index

3 experiments

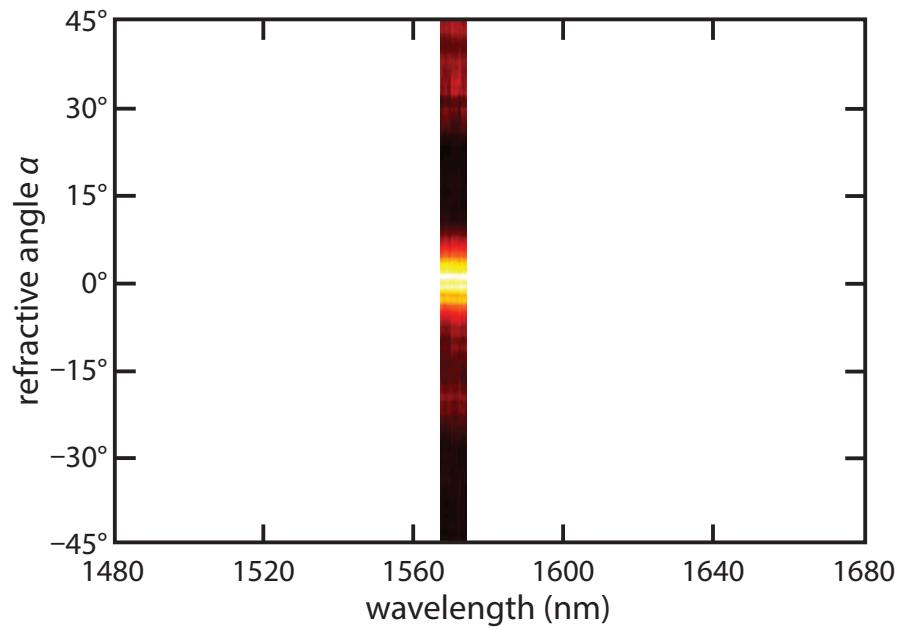


1 index

2 zero index

3 experiments

Wavelength dependence of refraction angle

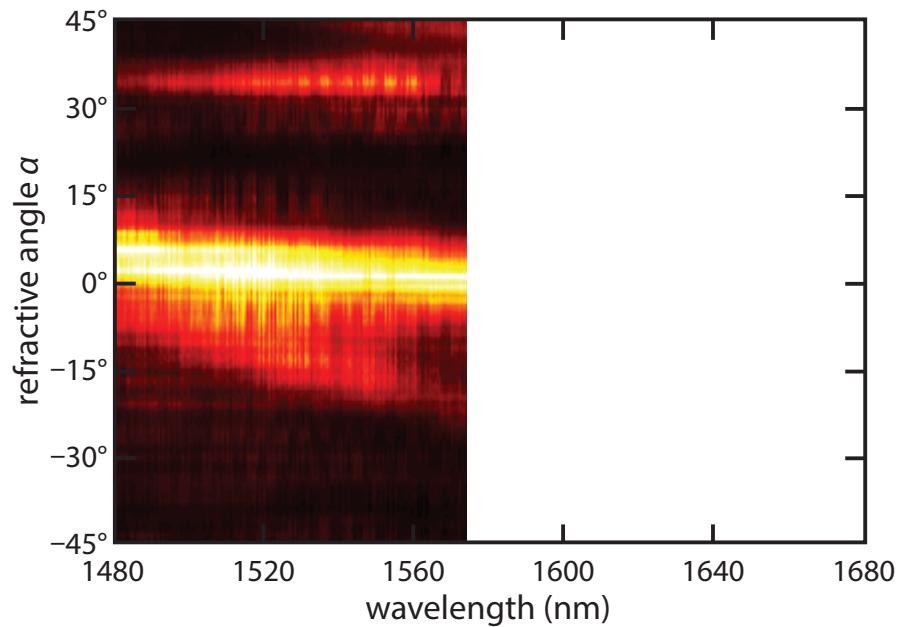


1 index

2 zero index

3 experiments

Wavelength dependence of refraction angle

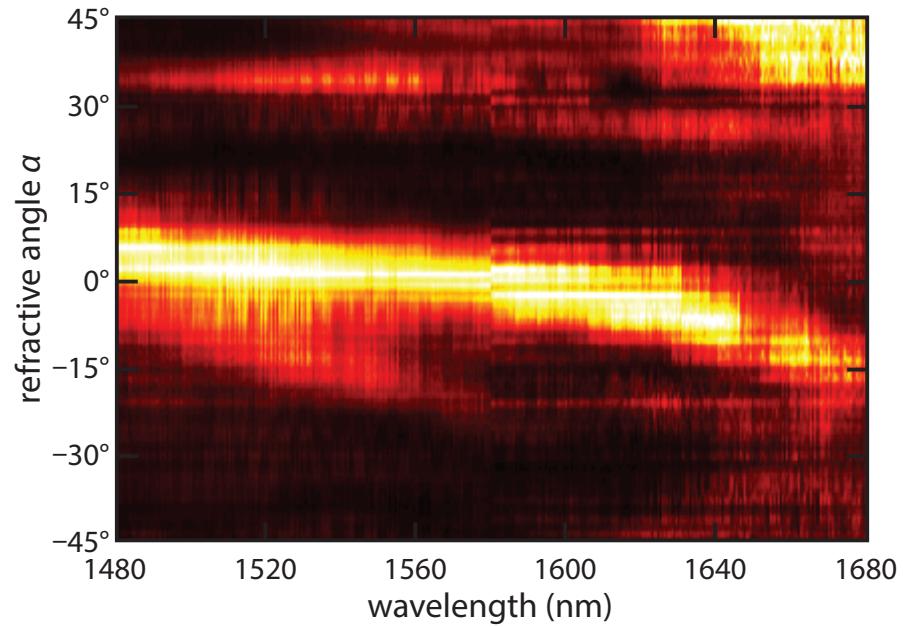


1 index

2 zero index

3 experiments

Wavelength dependence of refraction angle

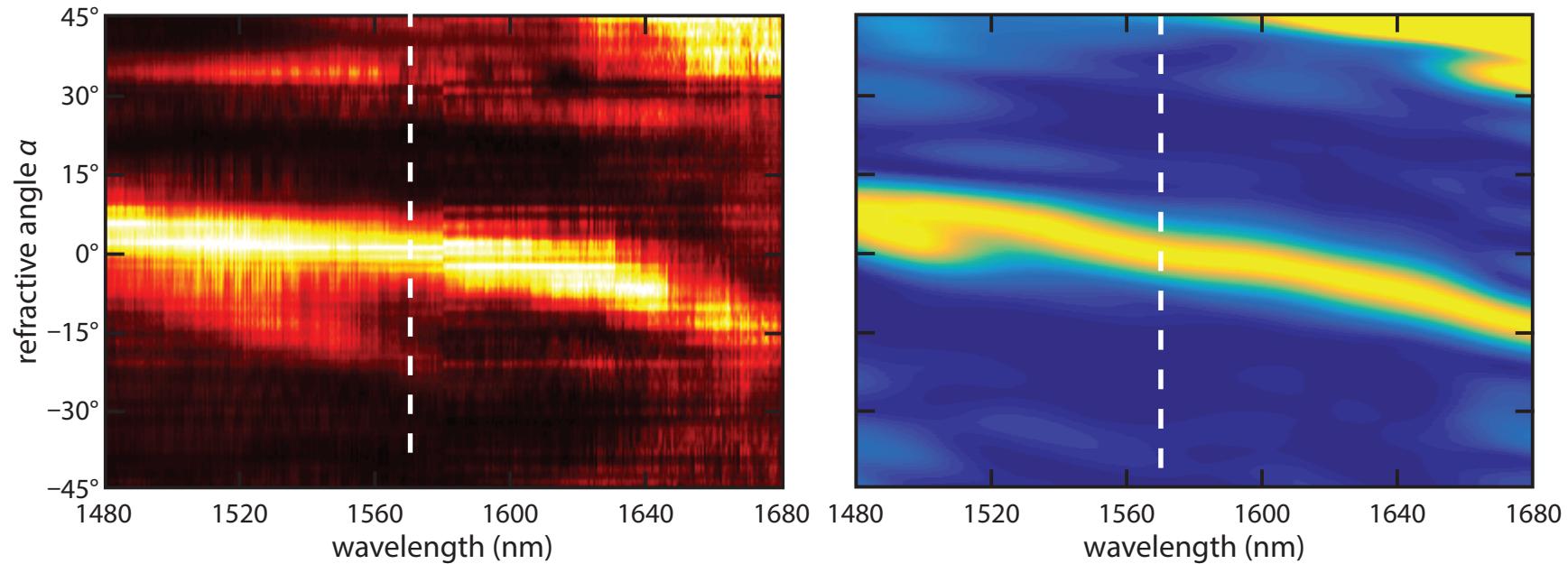


1 index

2 zero index

3 experiments

Wavelength dependence of refraction angle

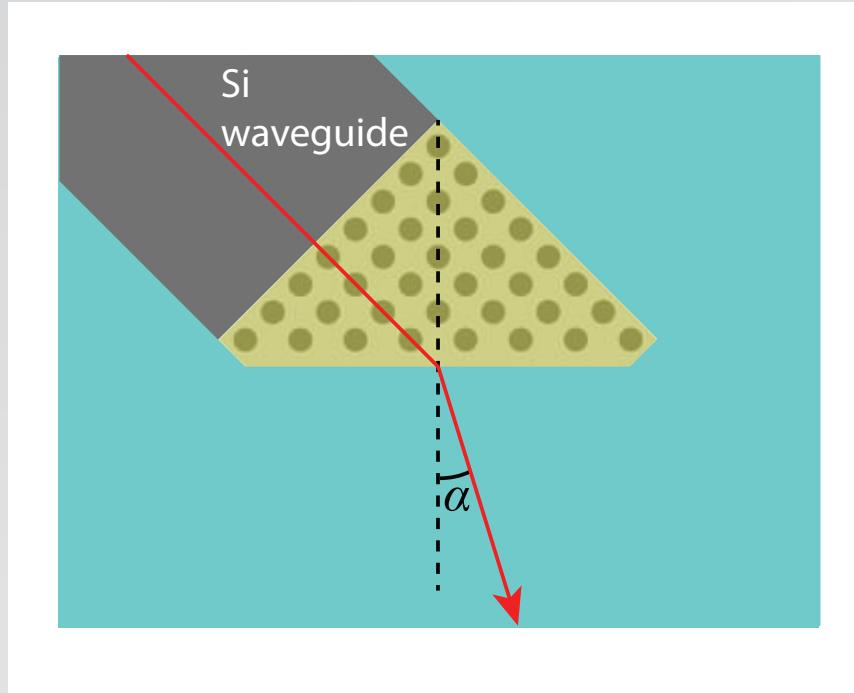


1 index

2 zero index

3 experiments

Wavelength dependence of index



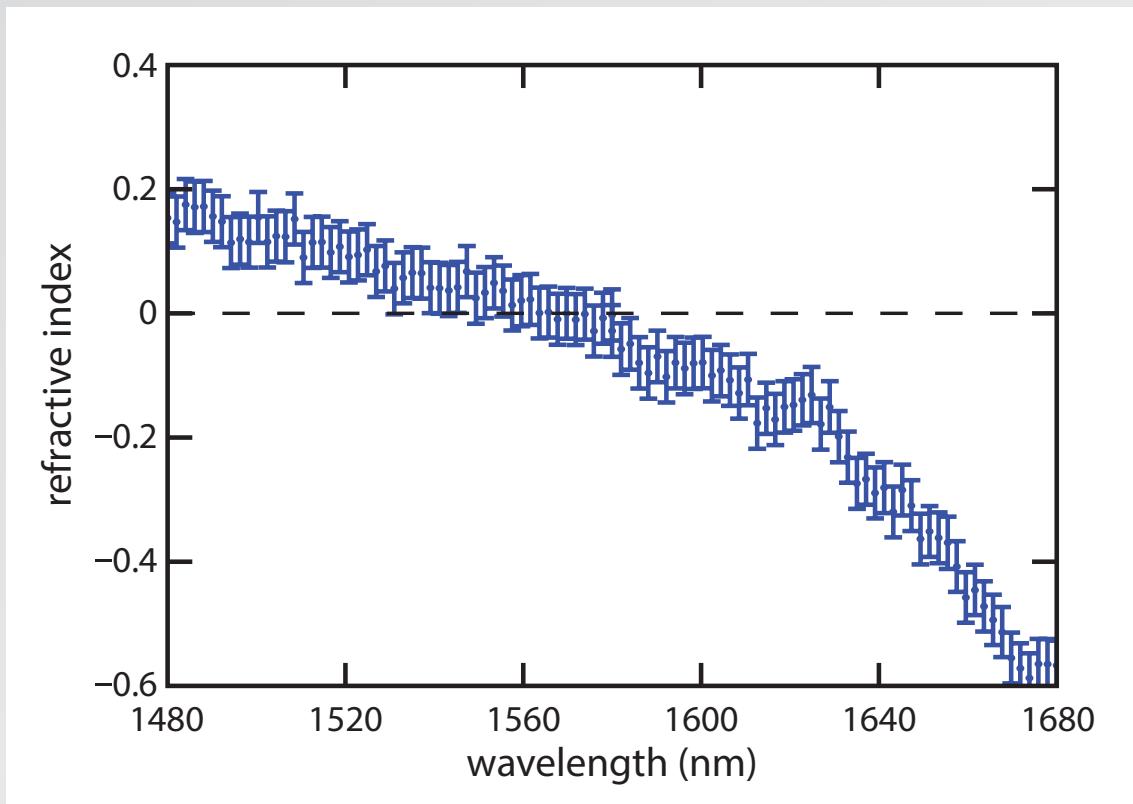
$$n_{\text{prism}} = n_{\text{slab}} \frac{\sin \alpha}{\sin 45^\circ}$$

1 index

2 zero index

3 experiments

Wavelength dependence of index

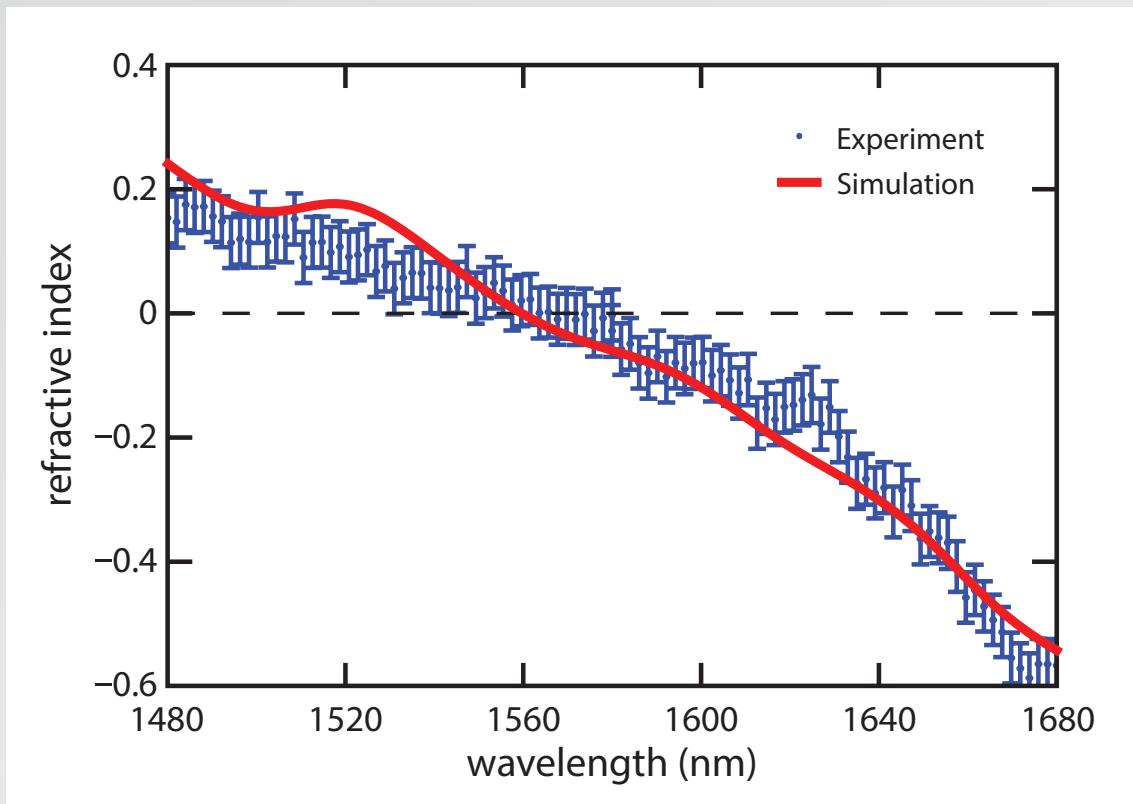


1 index

2 zero index

3 experiments

Wavelength dependence of index

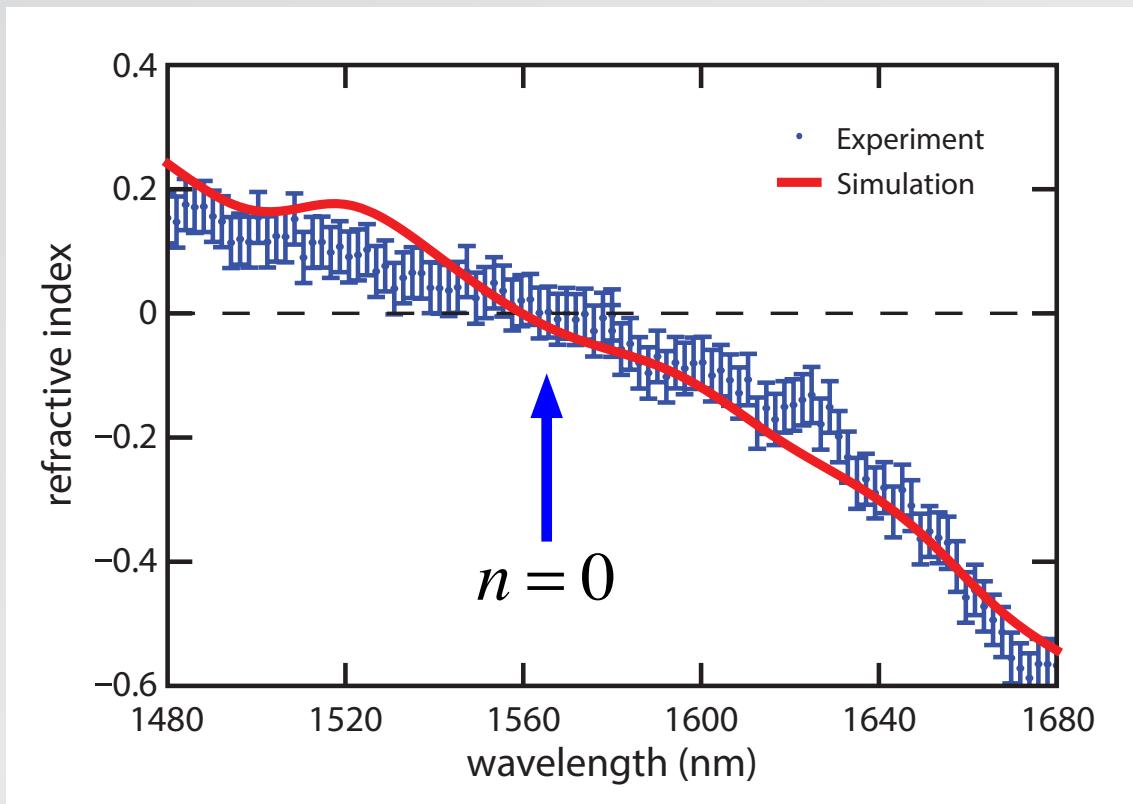


1 index

2 zero index

3 experiments

Wavelength dependence of index



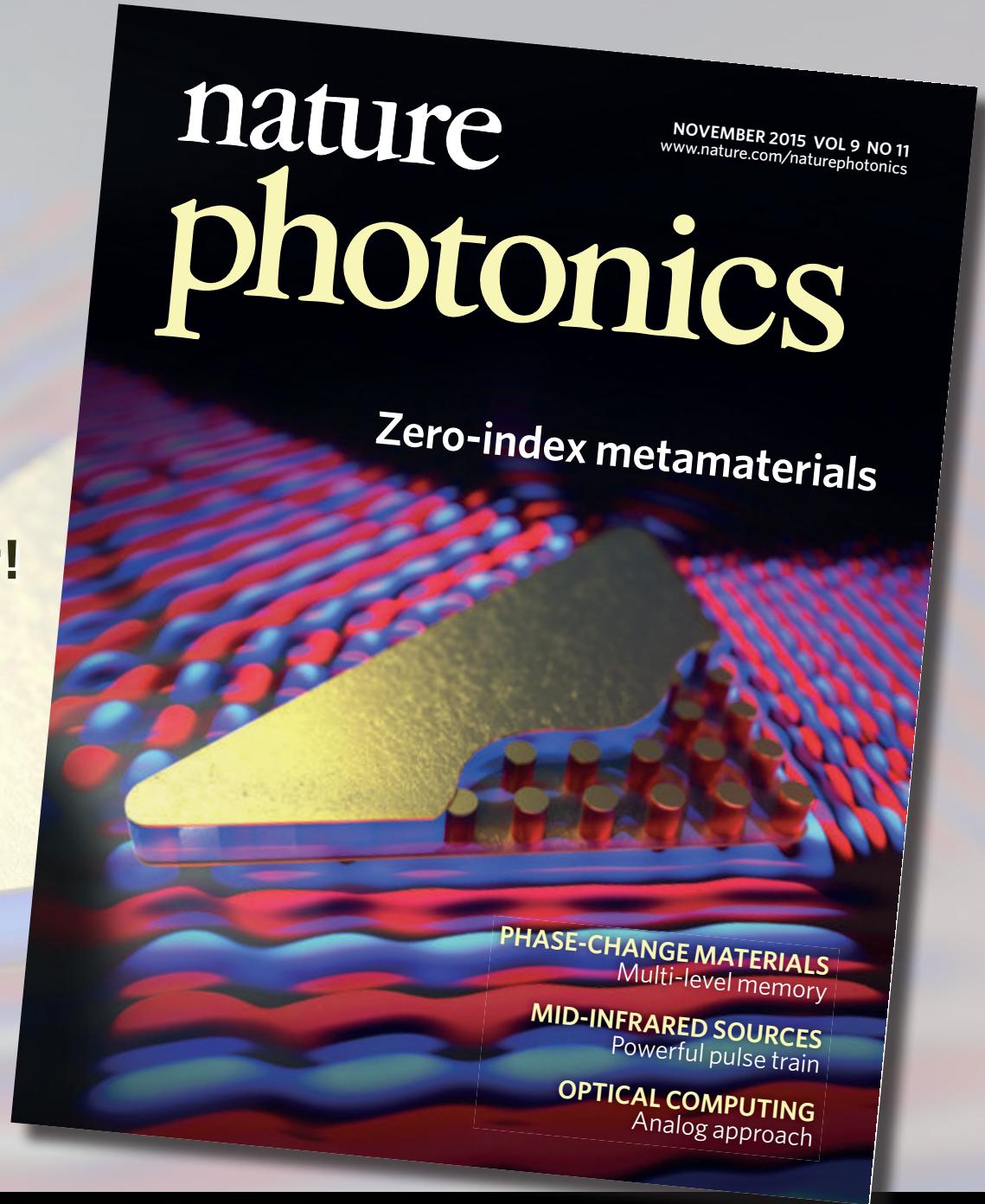
1 index

2 zero index

3 experiments



More info: download paper!



1 index

2 zero index

3 experiments

Where do we go from here?

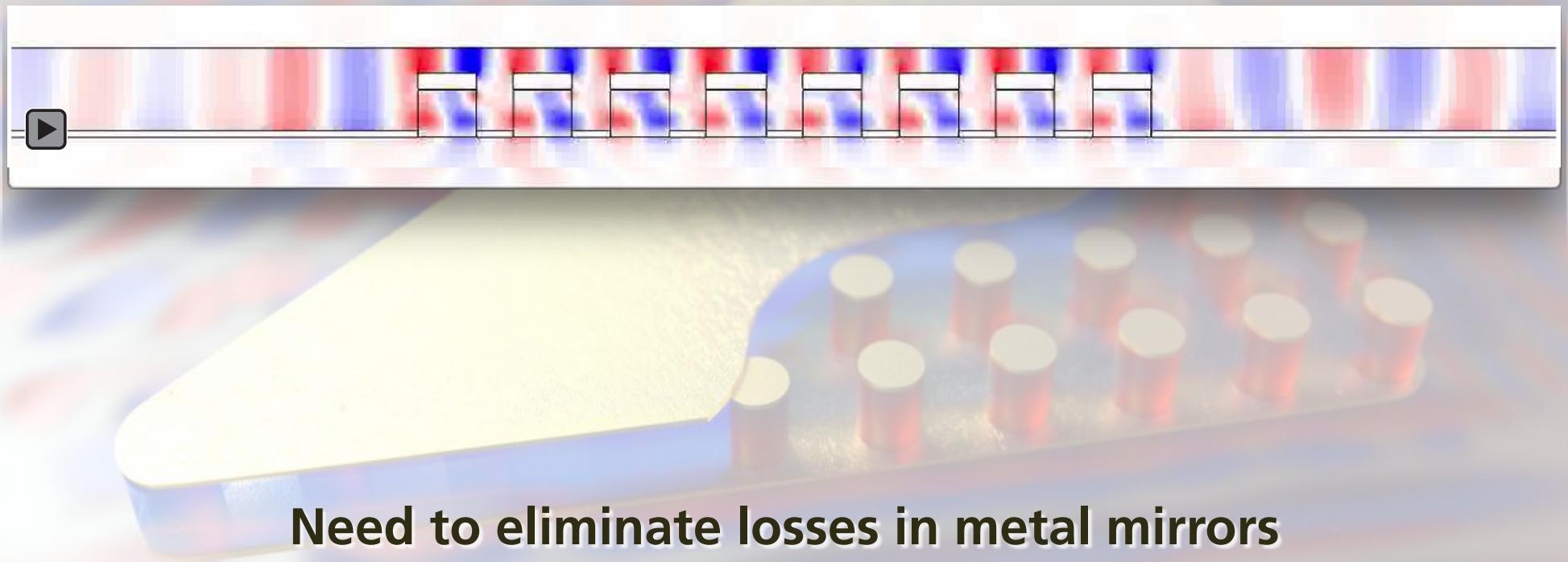


1 index

2 zero index

3 experiments

Where do we go from here?



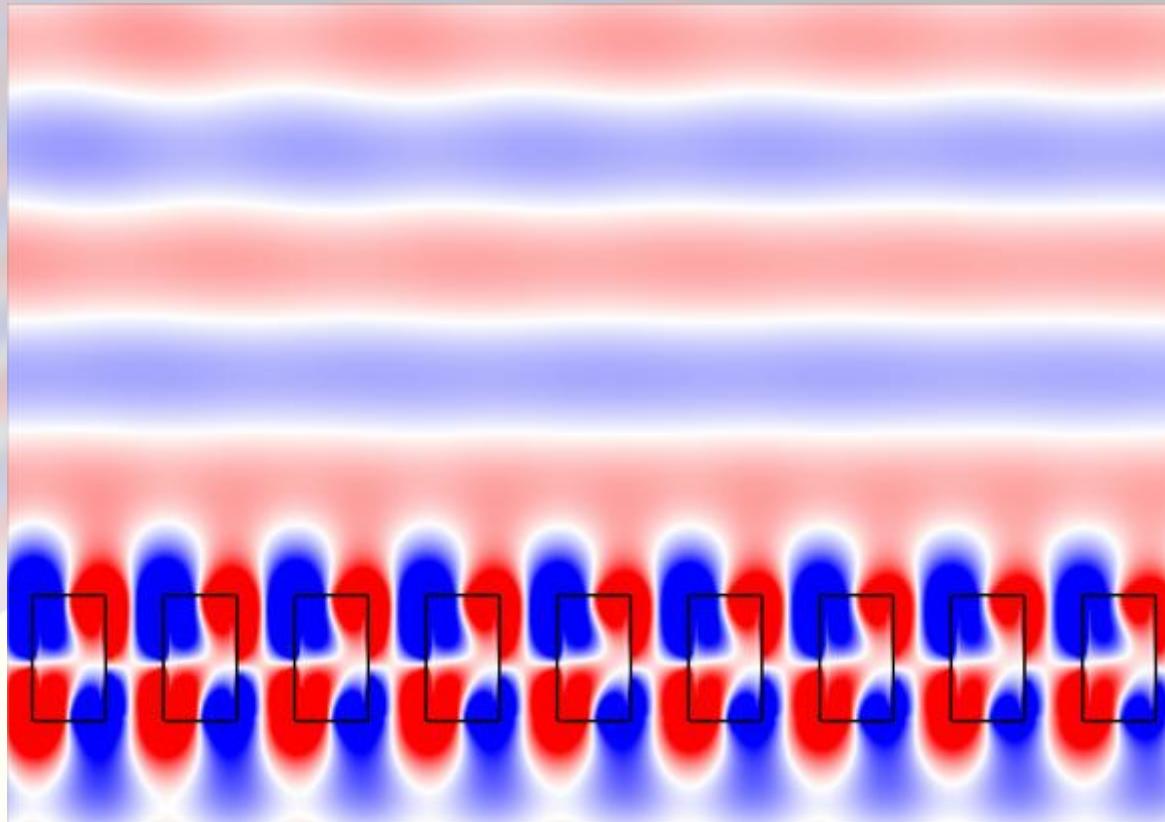
Need to eliminate losses in metal mirrors

1 index

2 zero index

3 experiments

Where do we go from here?



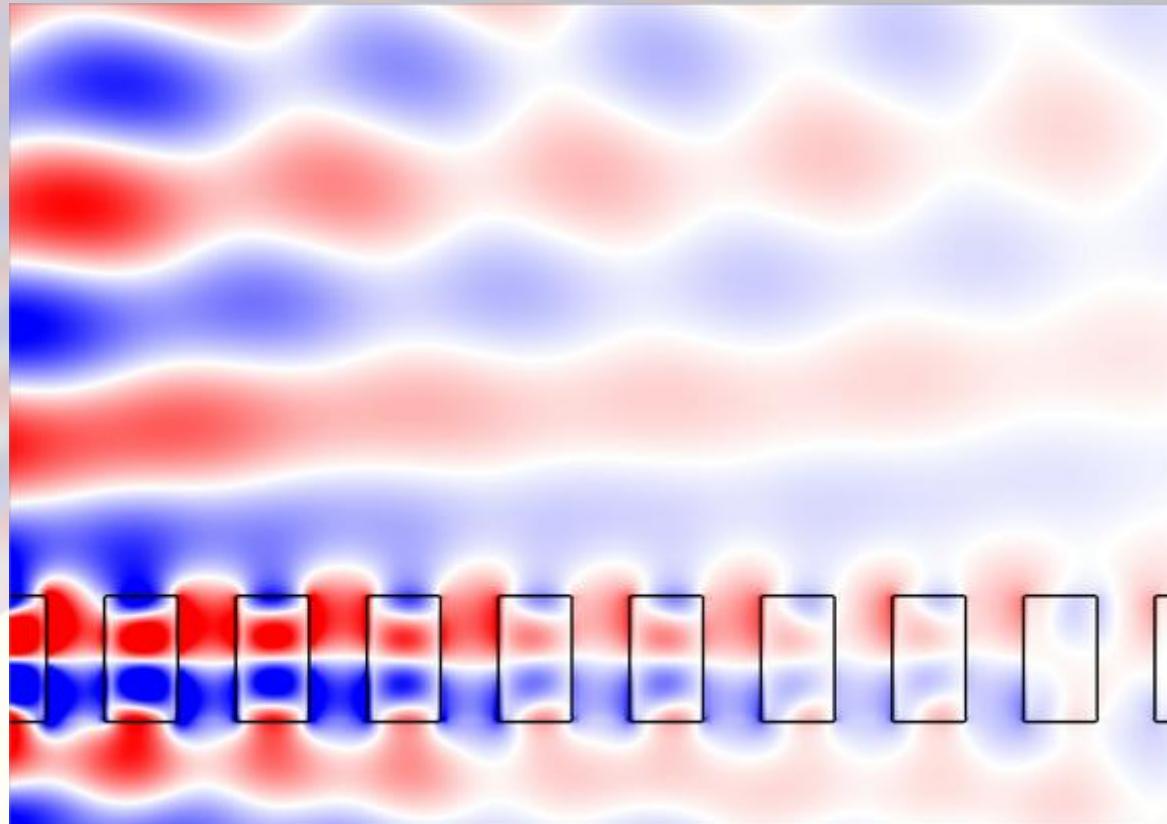
Removing mirrors causes radiative losses

1 index

2 zero index

3 experiments

Where do we go from here?



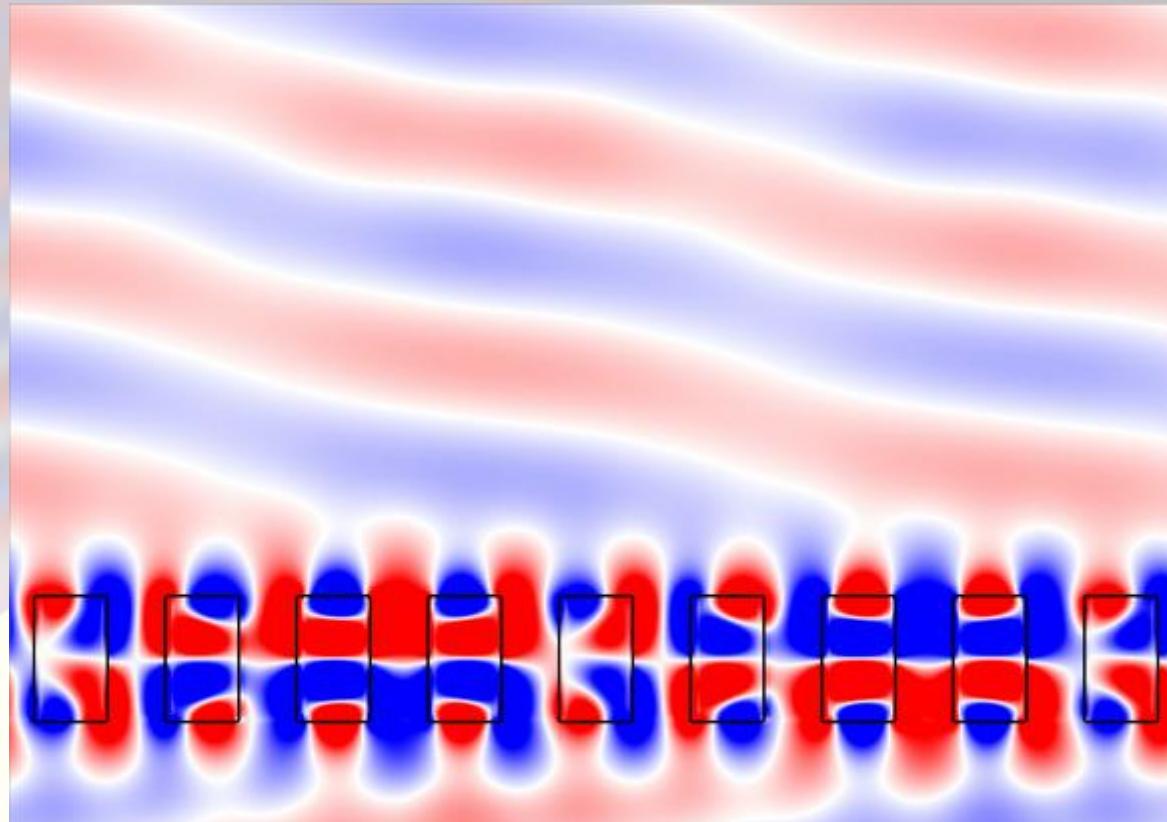
Radiative losses can be steered...

1 index

2 zero index

3 experiments

Where do we go from here?



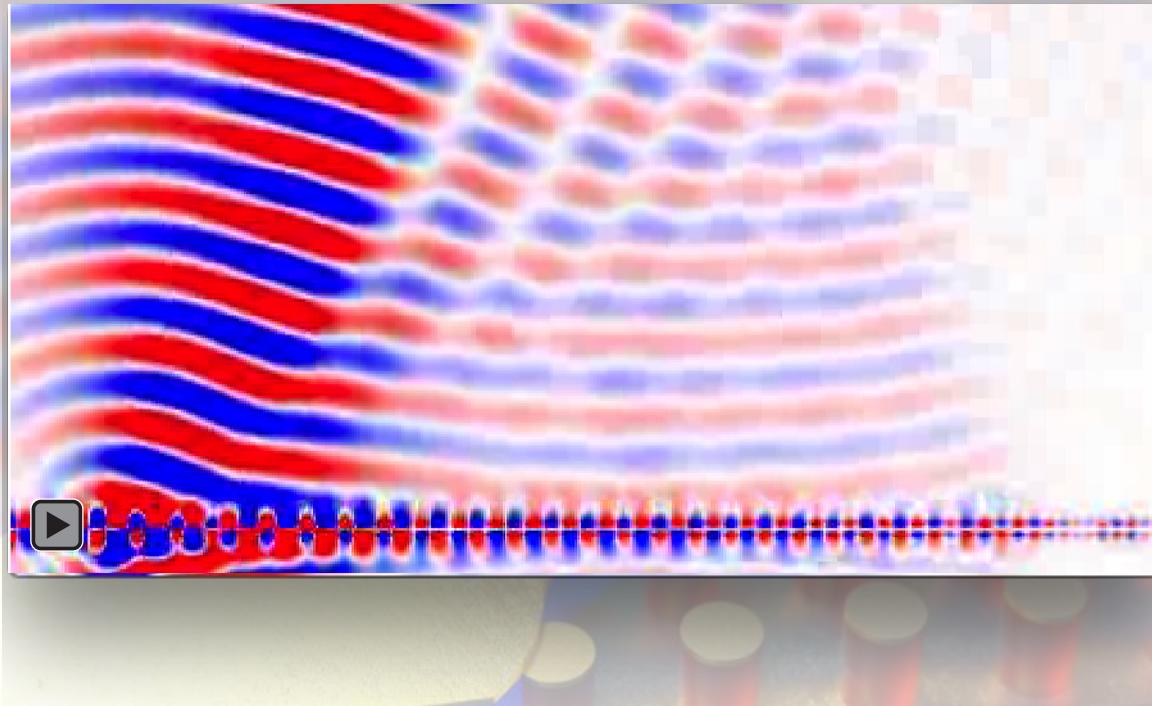
Radiative losses can be steered...

1 index

2 zero index

3 experiments

Where do we go from here?



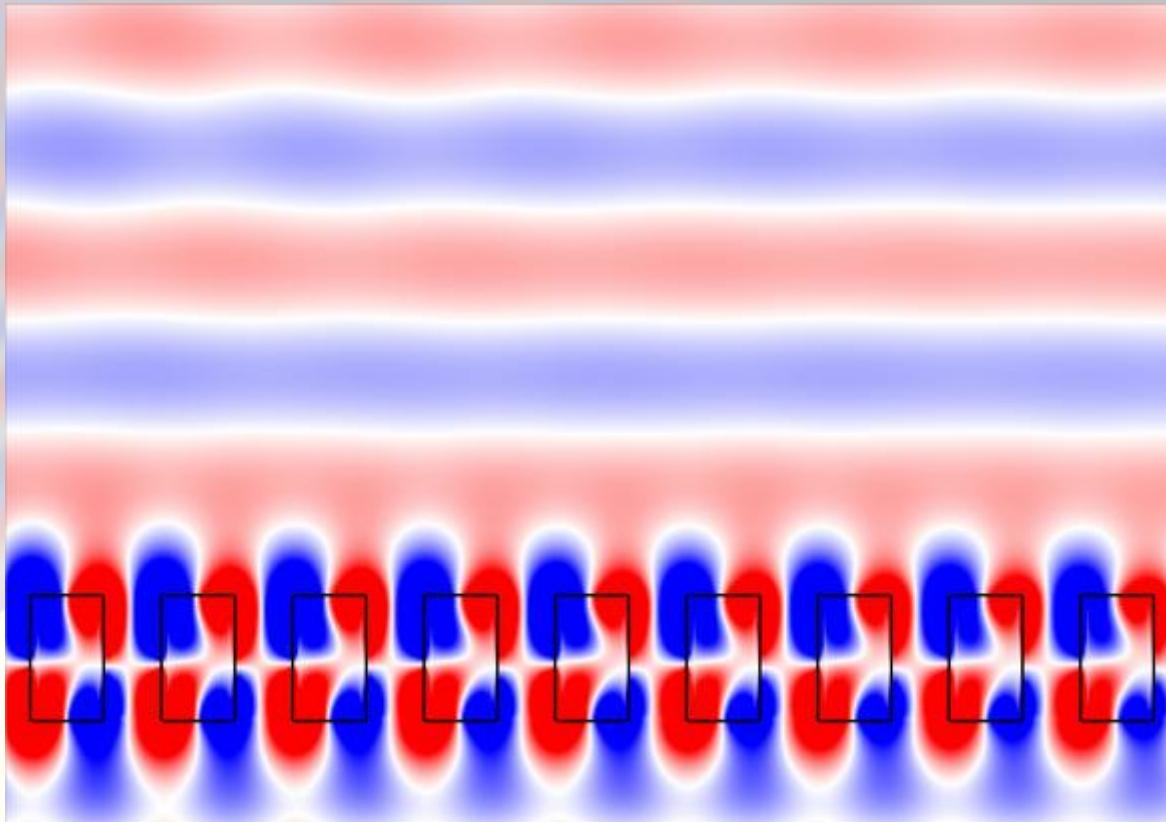
...or arranged to cause focusing...

1 index

2 zero index

3 experiments

Where do we go from here?



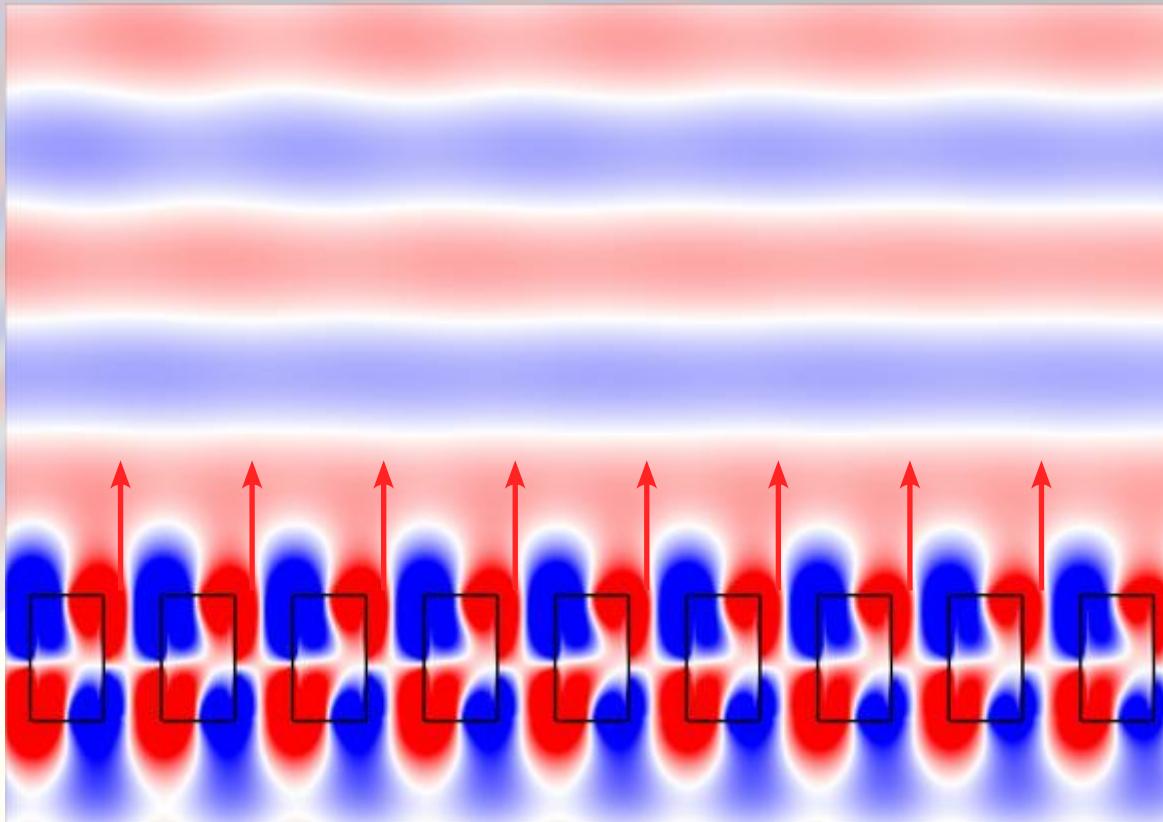
...or eliminated causing “bound in continuum” state

1 index

2 zero index

3 experiments

Where do we go from here?



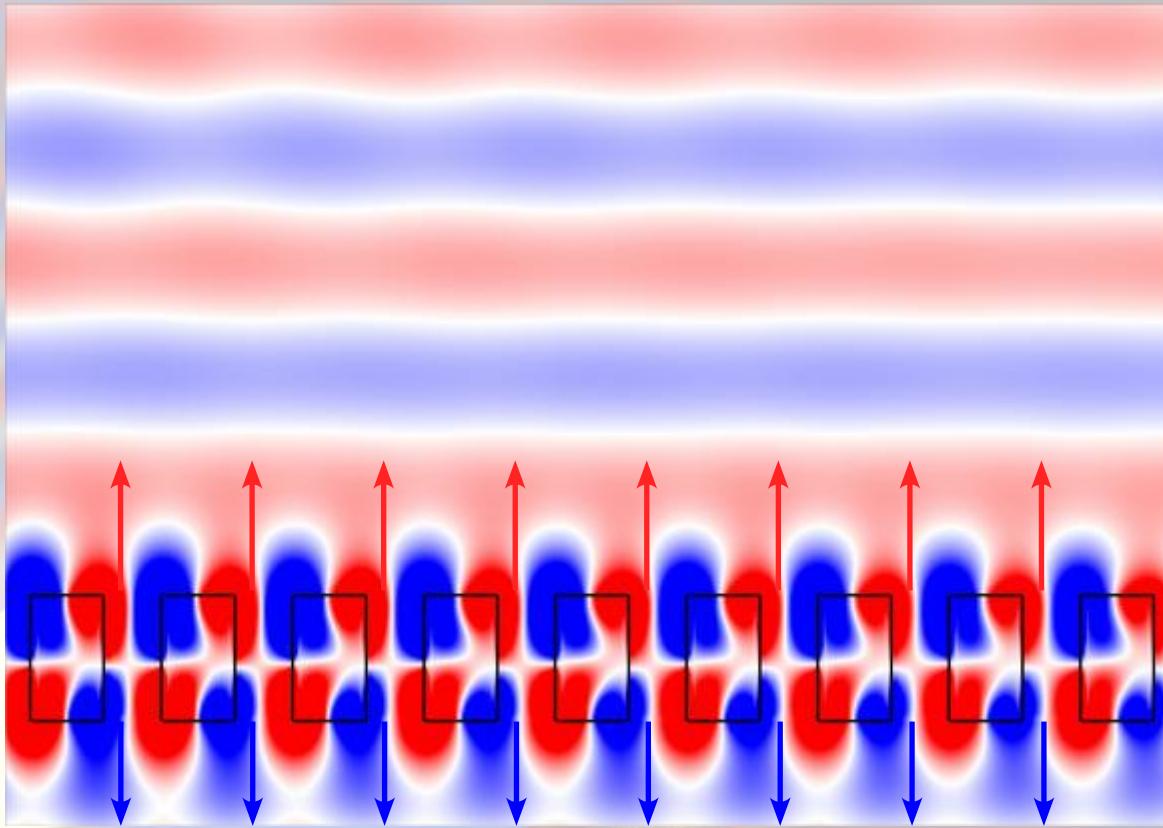
...or eliminated causing “bound in continuum” state

1 index

2 zero index

3 experiments

Where do we go from here?



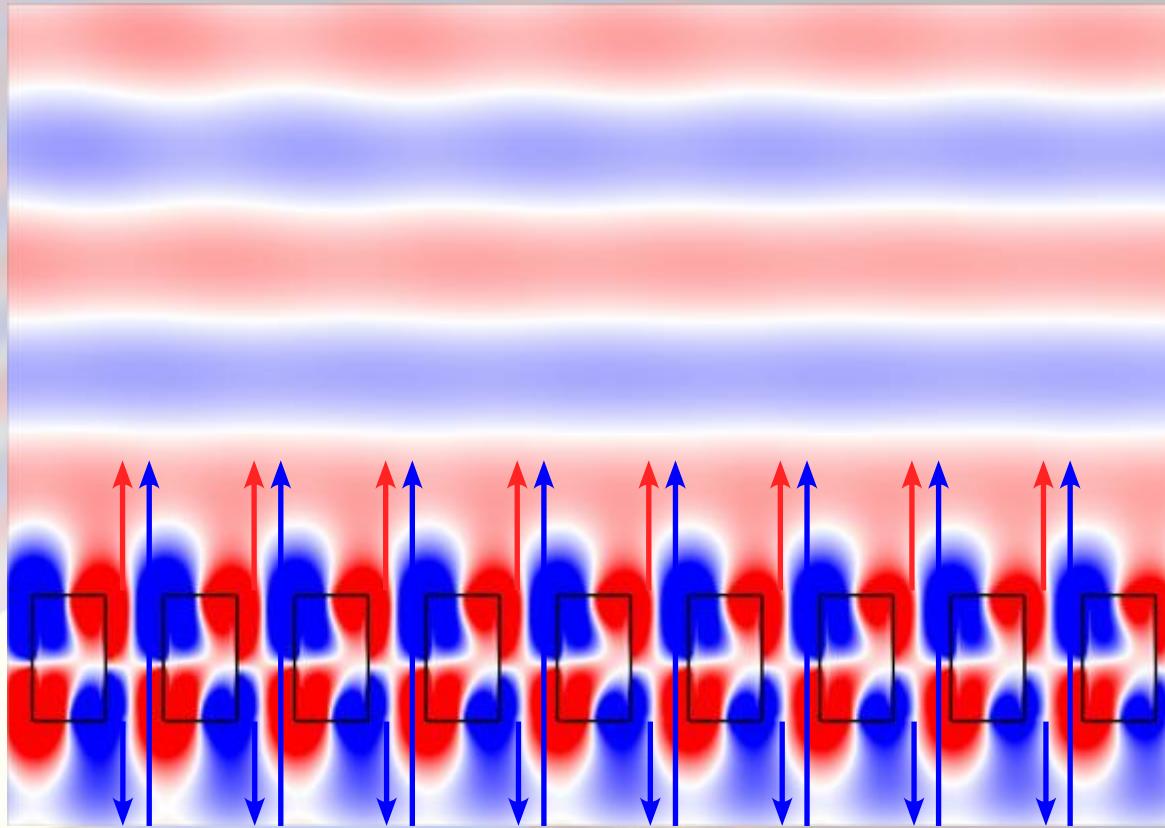
...or eliminated causing “bound in continuum” state

1 index

2 zero index

3 experiments

Where do we go from here?



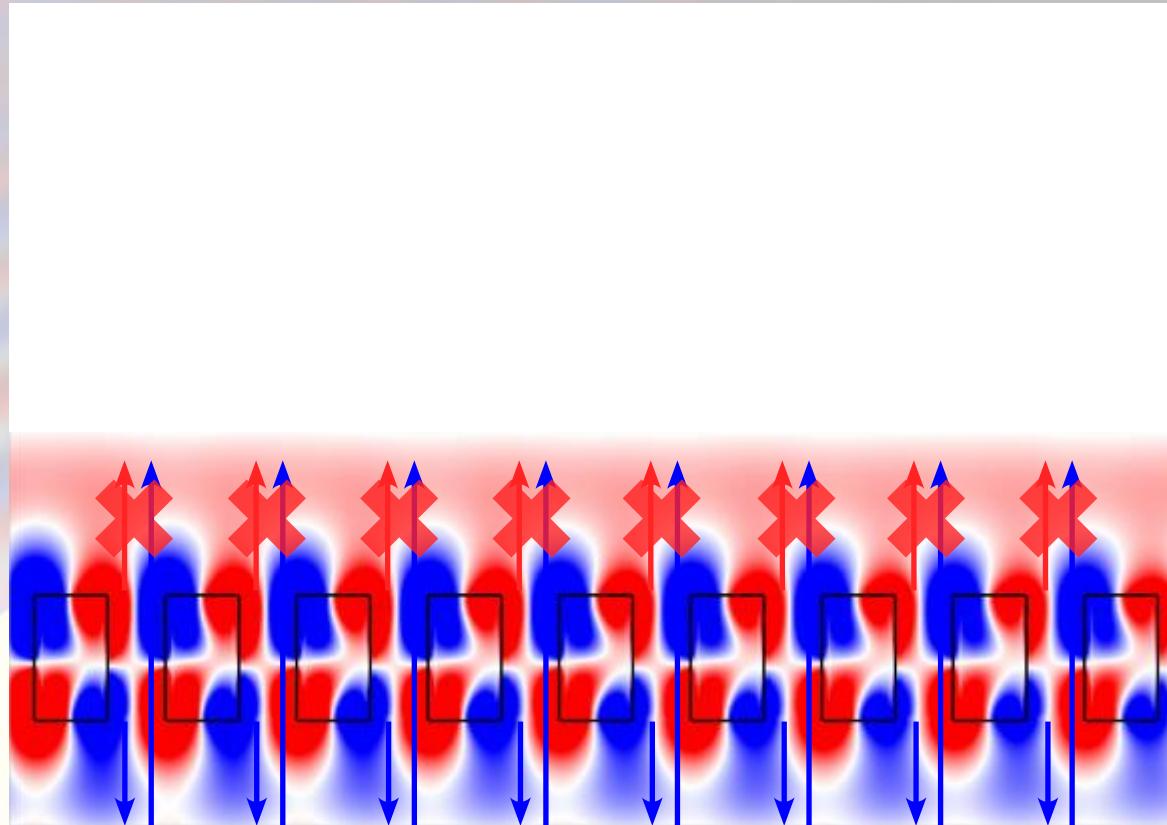
...or eliminated causing “bound in continuum” state

1 index

2 zero index

3 experiments

Where do we go from here?



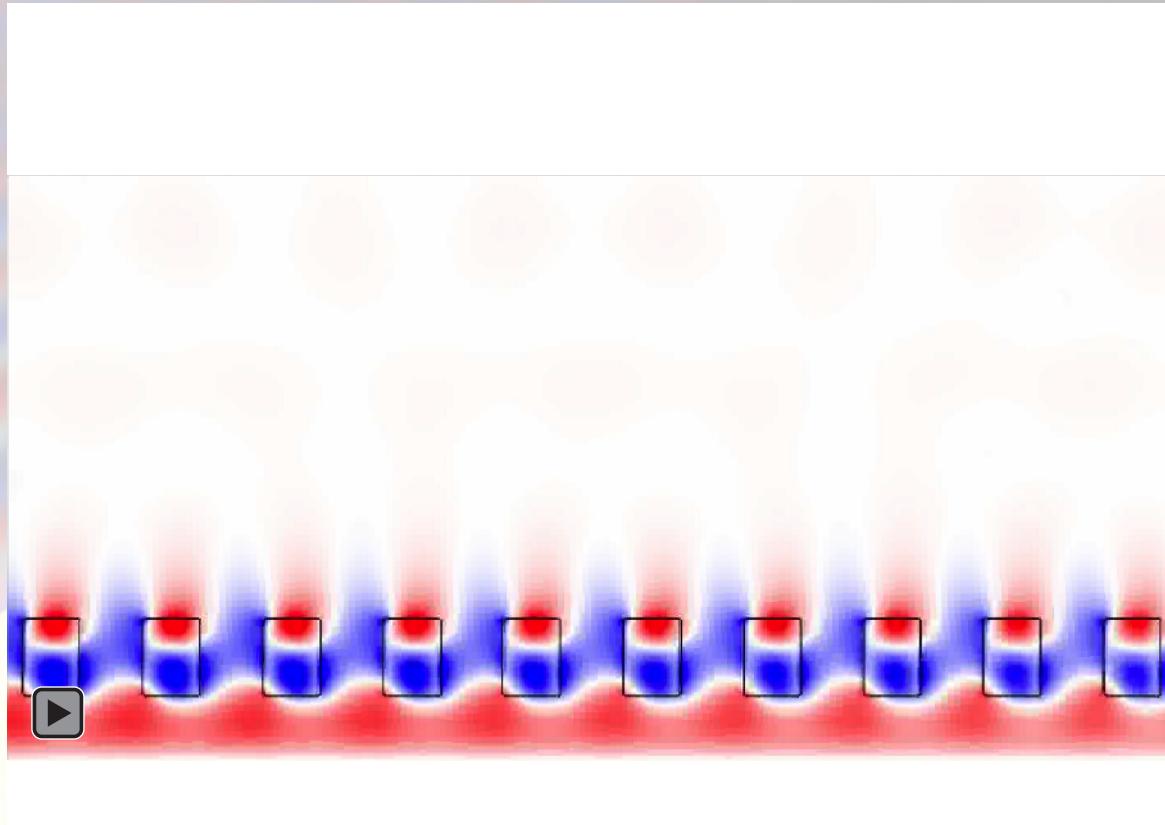
...or eliminated causing “bound in continuum” state

1 index

2 zero index

3 experiments

Where do we go from here?



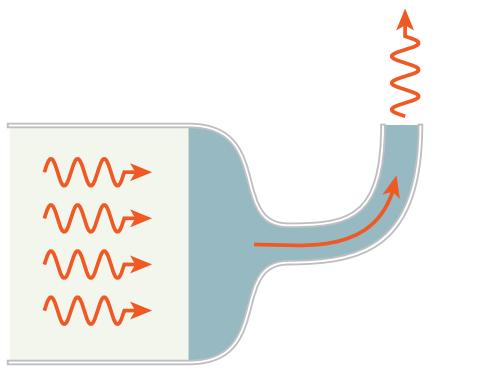
...or eliminated causing “bound in continuum” state

1 index

2 zero index

3 experiments

Exciting applications ahead



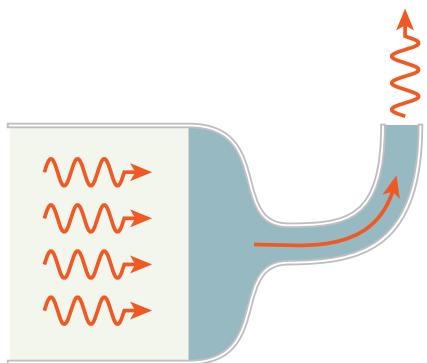
supercoupling

1 index

2 zero index

3 experiments

Exciting applications ahead



supercoupling



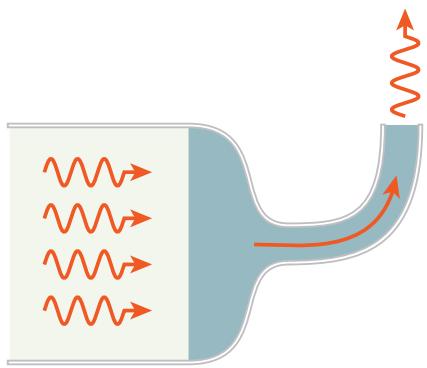
NLO

1 index

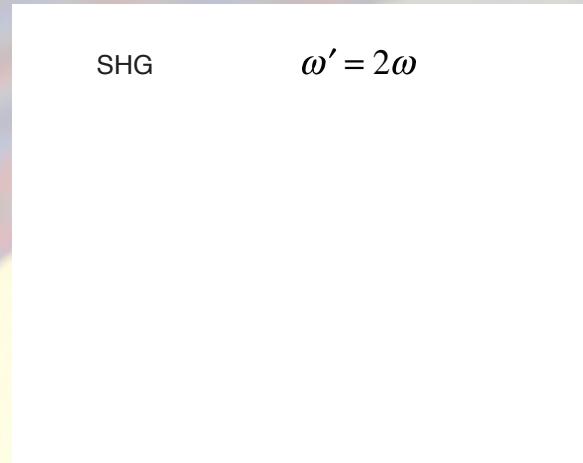
2 zero index

3 experiments

Exciting applications ahead



supercoupling



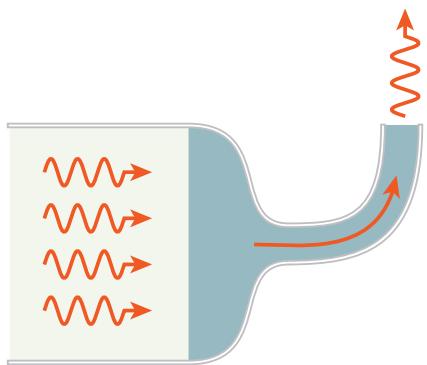
NLO

1 index

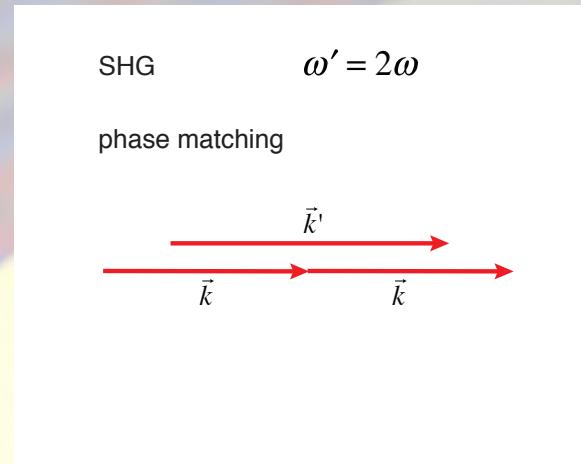
2 zero index

3 experiments

Exciting applications ahead



supercoupling



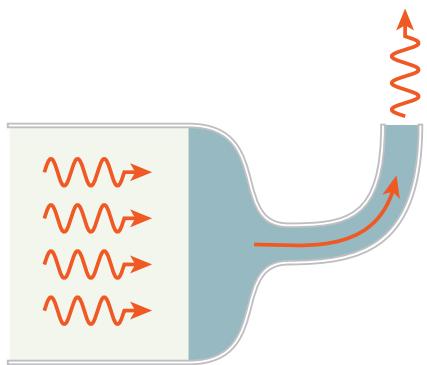
NLO

1 index

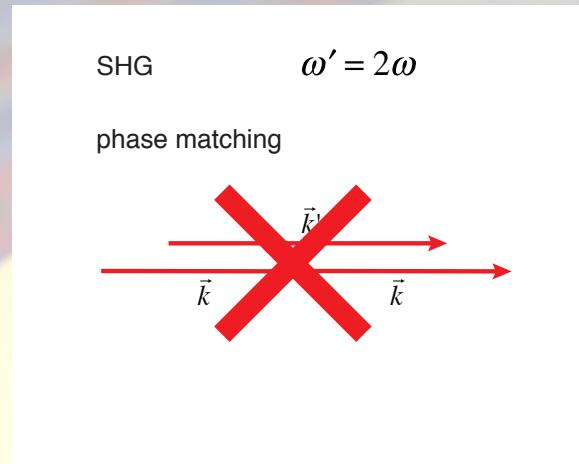
2 zero index

3 experiments

Exciting applications ahead



supercoupling



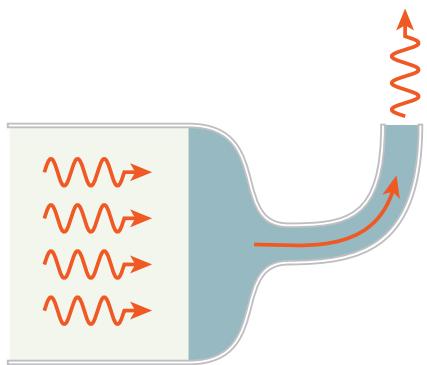
NLO

1 index

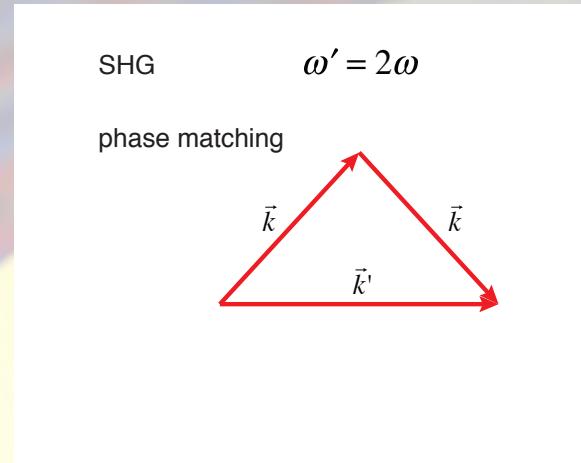
2 zero index

3 experiments

Exciting applications ahead



supercoupling



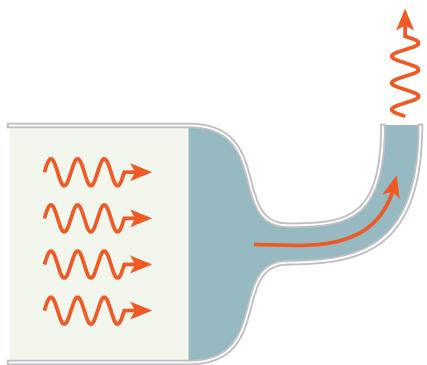
NLO

1 index

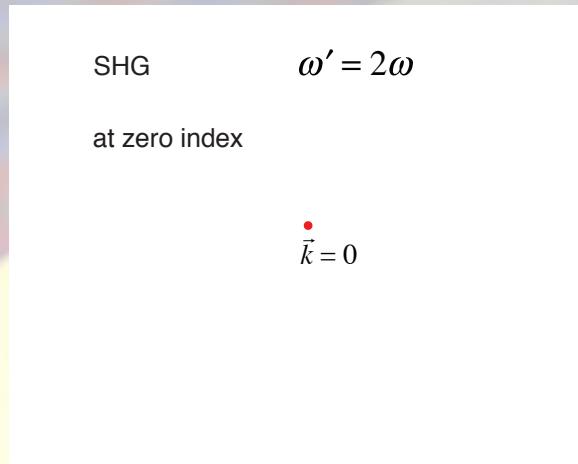
2 zero index

3 experiments

Exciting applications ahead



supercoupling



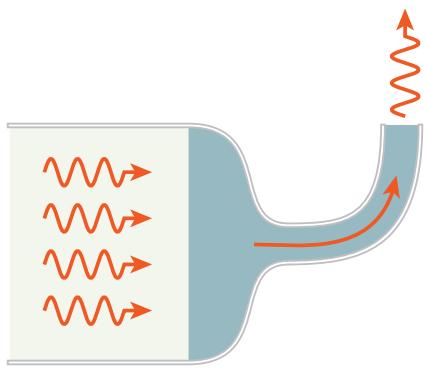
NLO

1 index

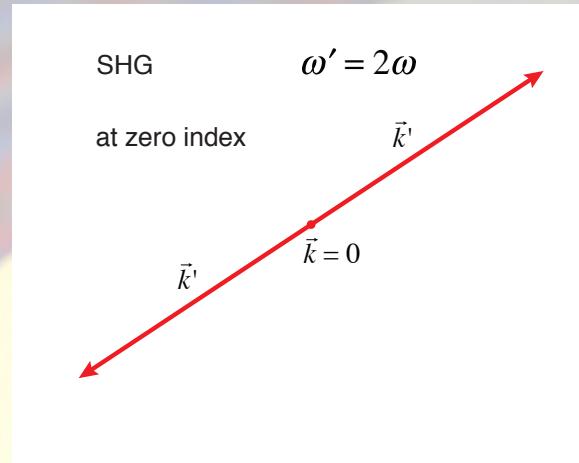
2 zero index

3 experiments

Exciting applications ahead



supercoupling



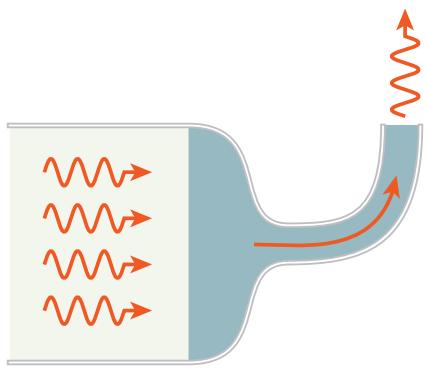
NLO

1 index

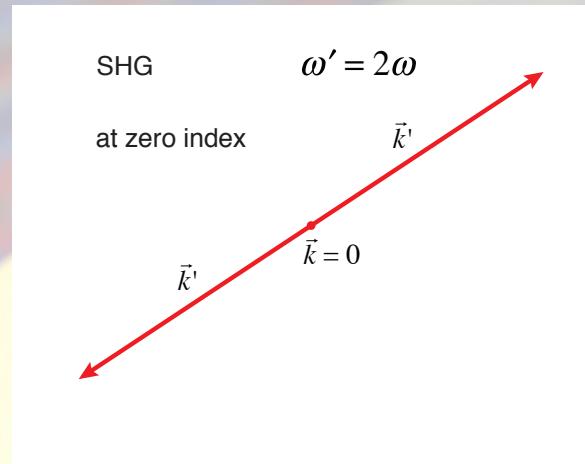
2 zero index

3 experiments

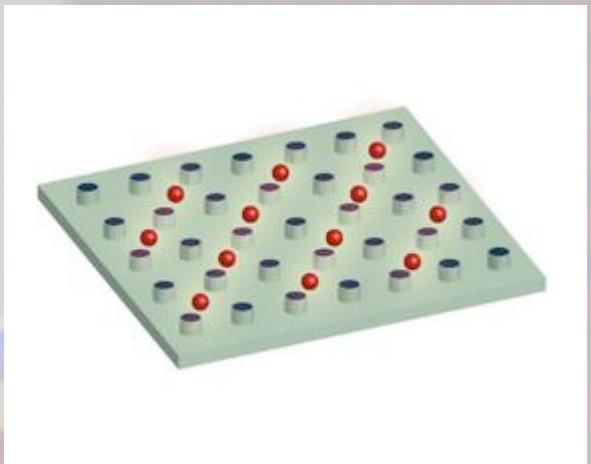
Exciting applications ahead



supercoupling



NLO



quantum optics

1 index

2 zero index

3 experiments



Yang Li, Shota Kita, Phil Muñoz, Orad Reshef,
Daryl Vulis, Mei Yin, Lysander Christakis, Zin Lin,
Cleaven Chia, Olivia Mello, Haoning Tang, Marko Lončar

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1 index

2 zero index

3 experiments