

# Optical Metamaterials and their Index of Refraction



**ENLIGHT Teaching and Learning Conference**  
**University of Ghent**  
**Gent, Belgium, 18 November 2021**



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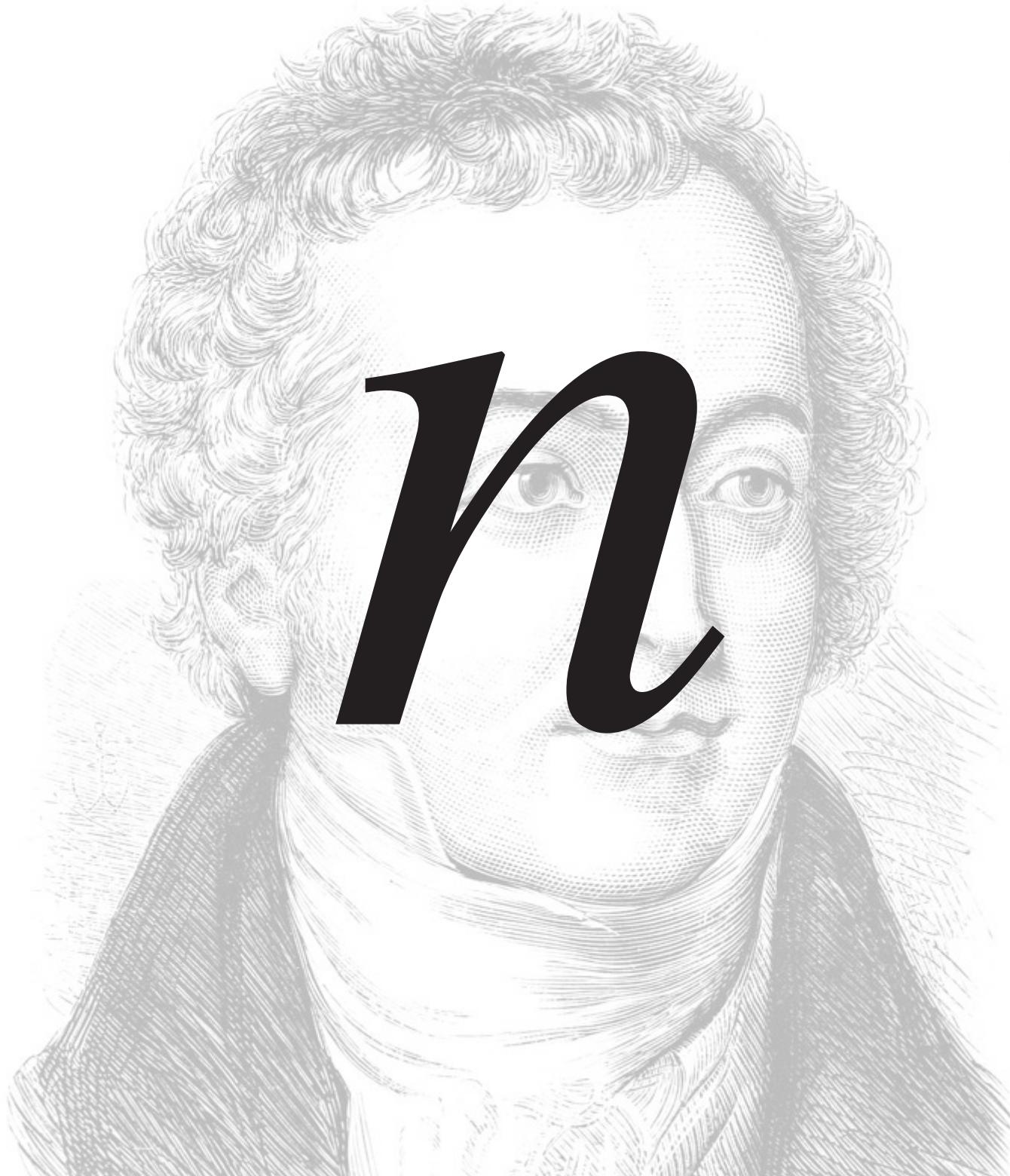
@eric\_mazur

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*n*



*n*



*n*

1 index

2 zero index



*n*

1 index

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3 experiments

# Propagation of EM wave

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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**  $n = n(\omega)$  .

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

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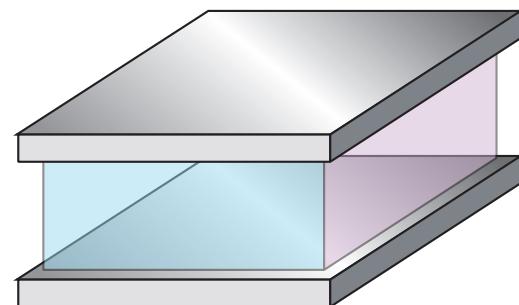
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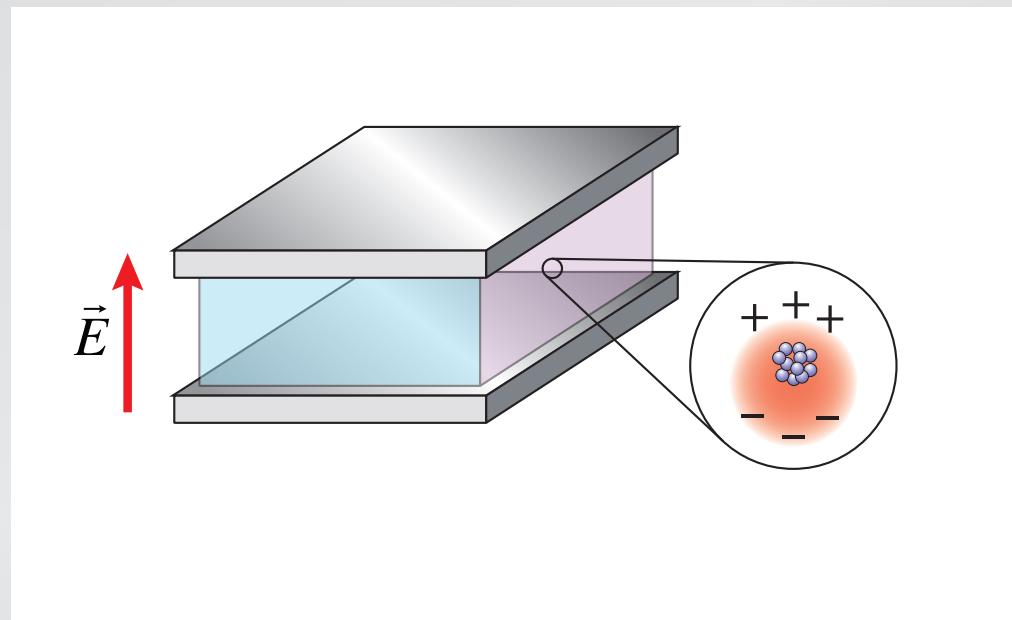
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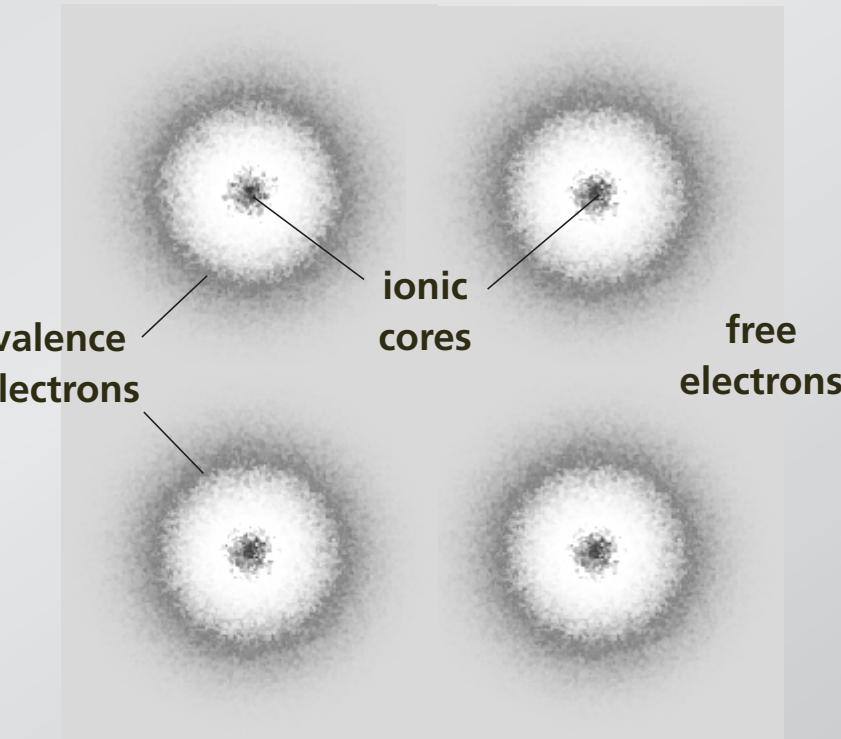


$\epsilon(\omega)$  measure of attenuation of electric field

# Index of refraction

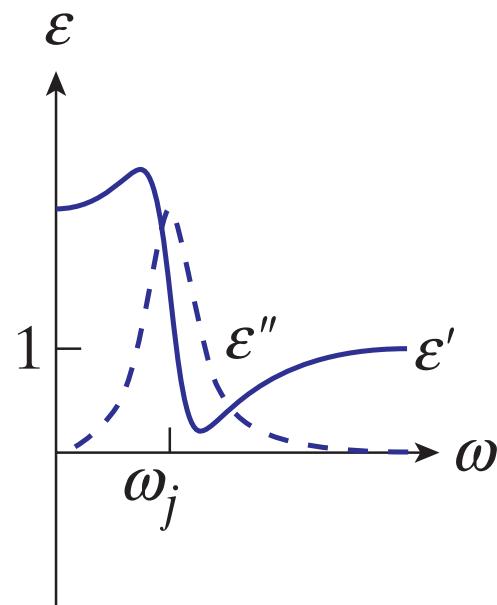
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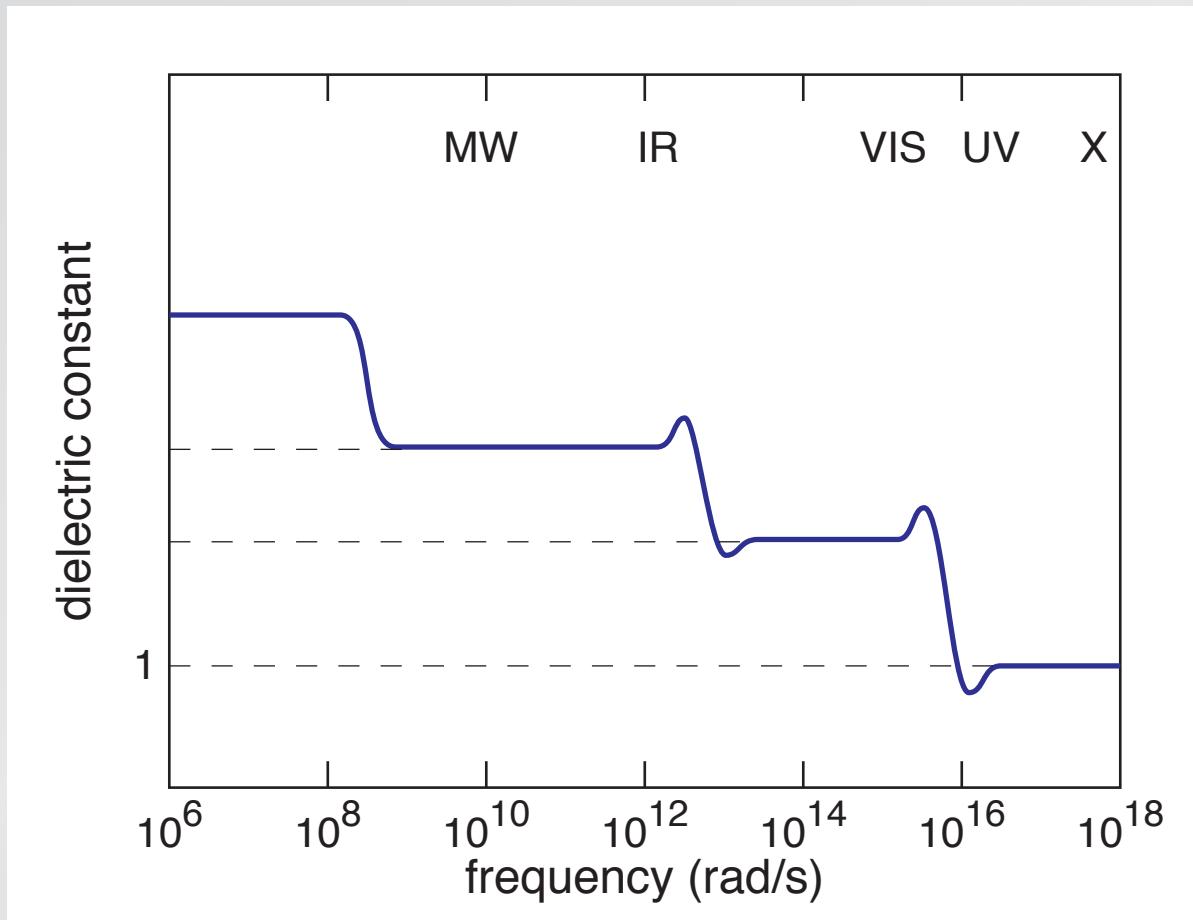


# Dielectric constant

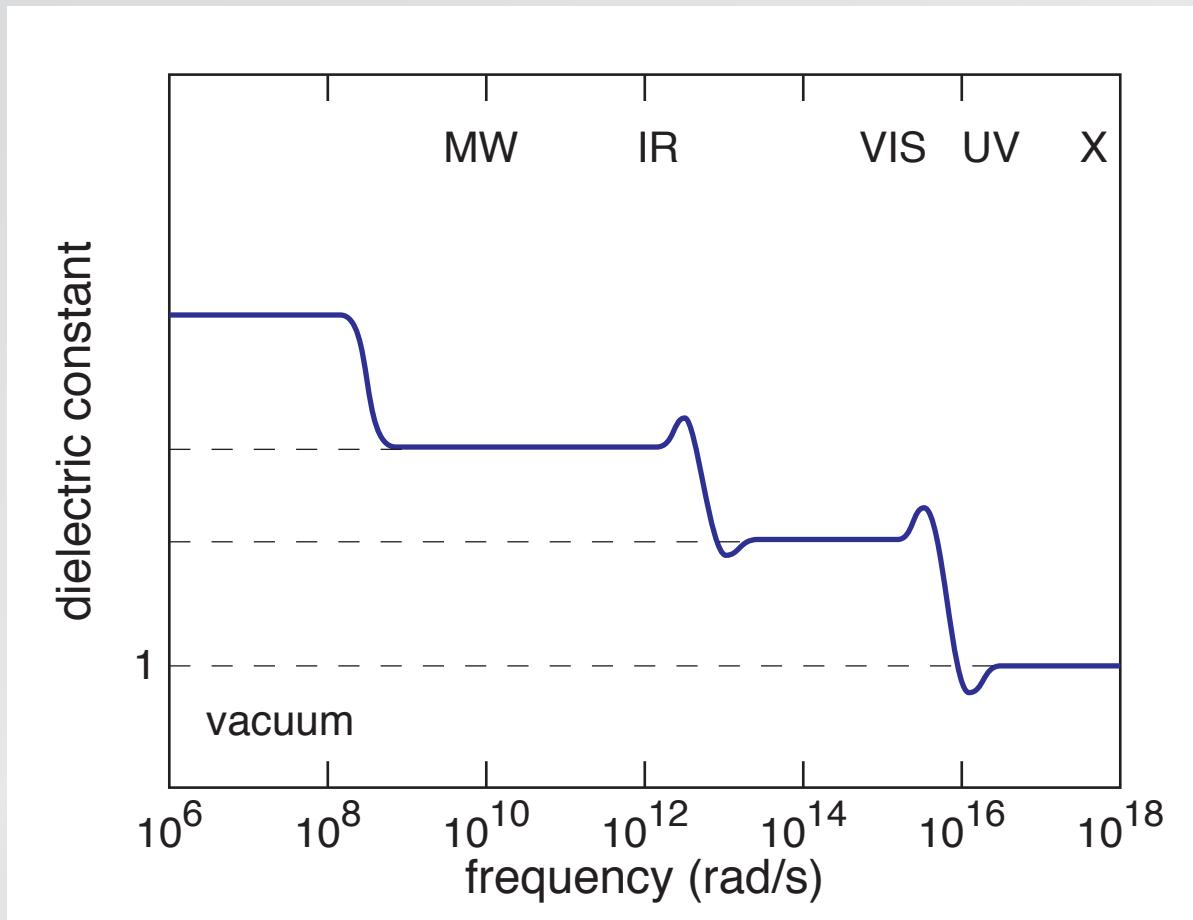
## Lorentz oscillator



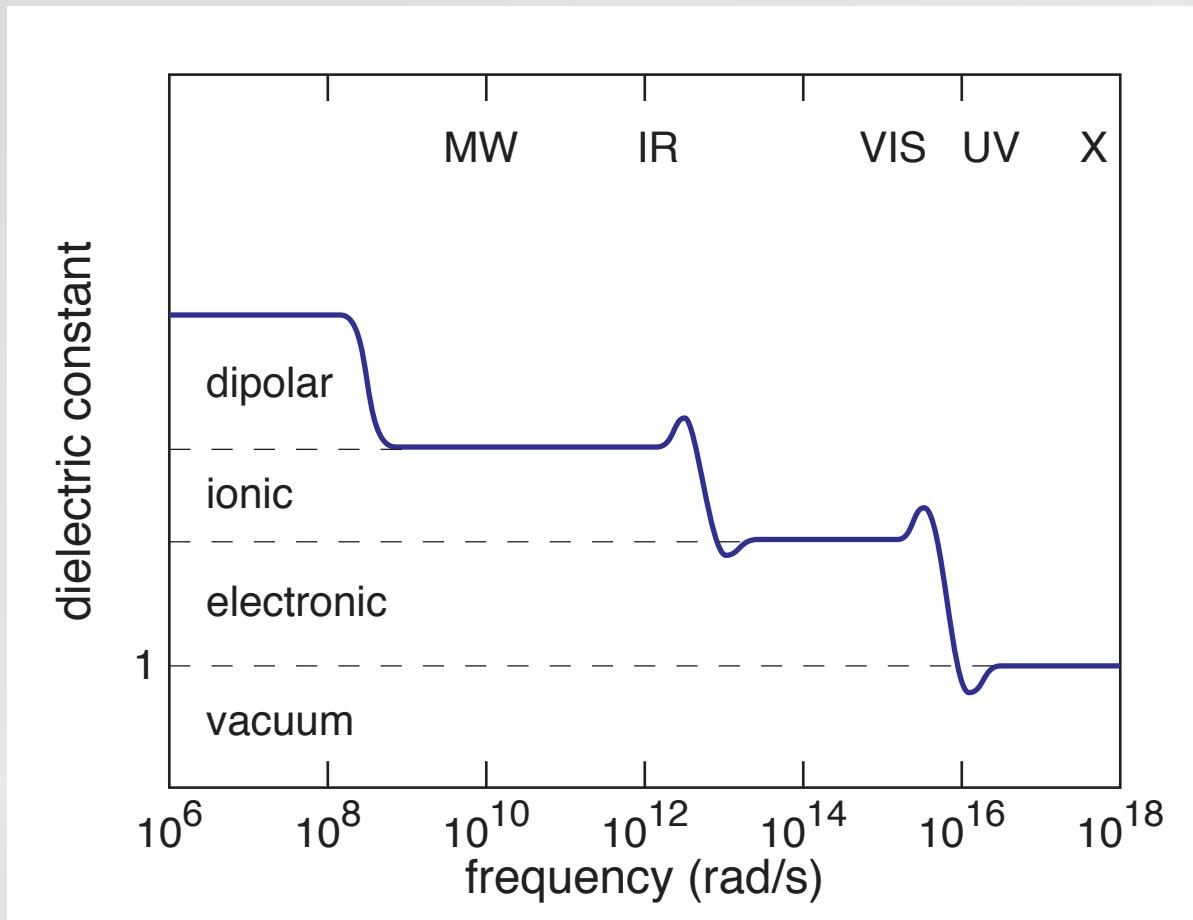
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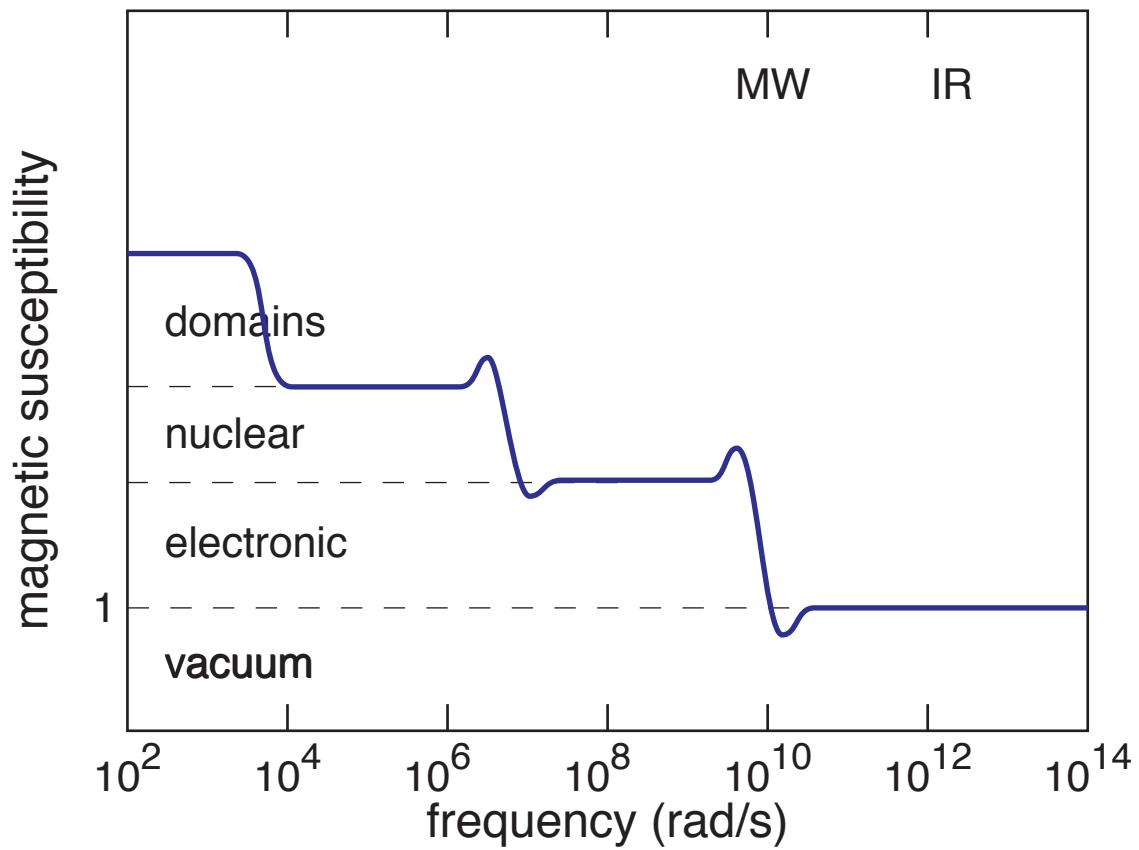
# Dielectric constant



**Index also determined by magnetic response**

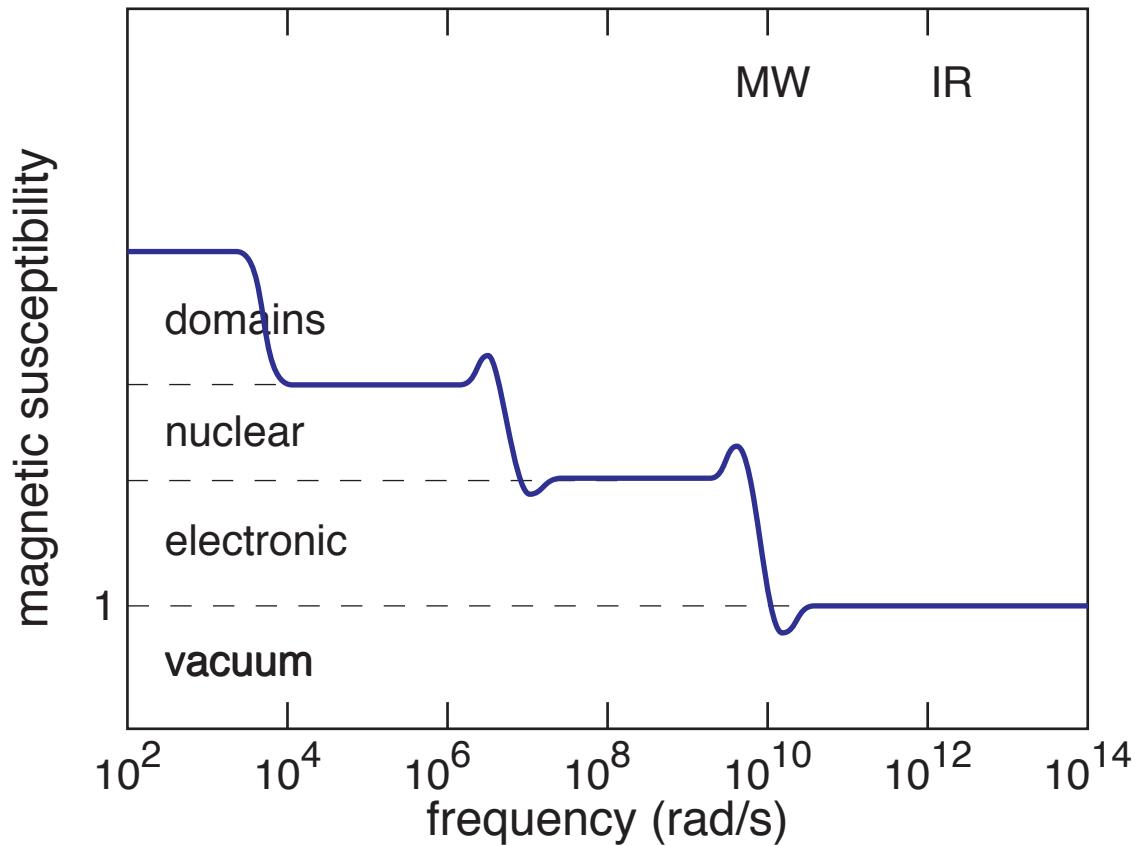
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# Magnetic response



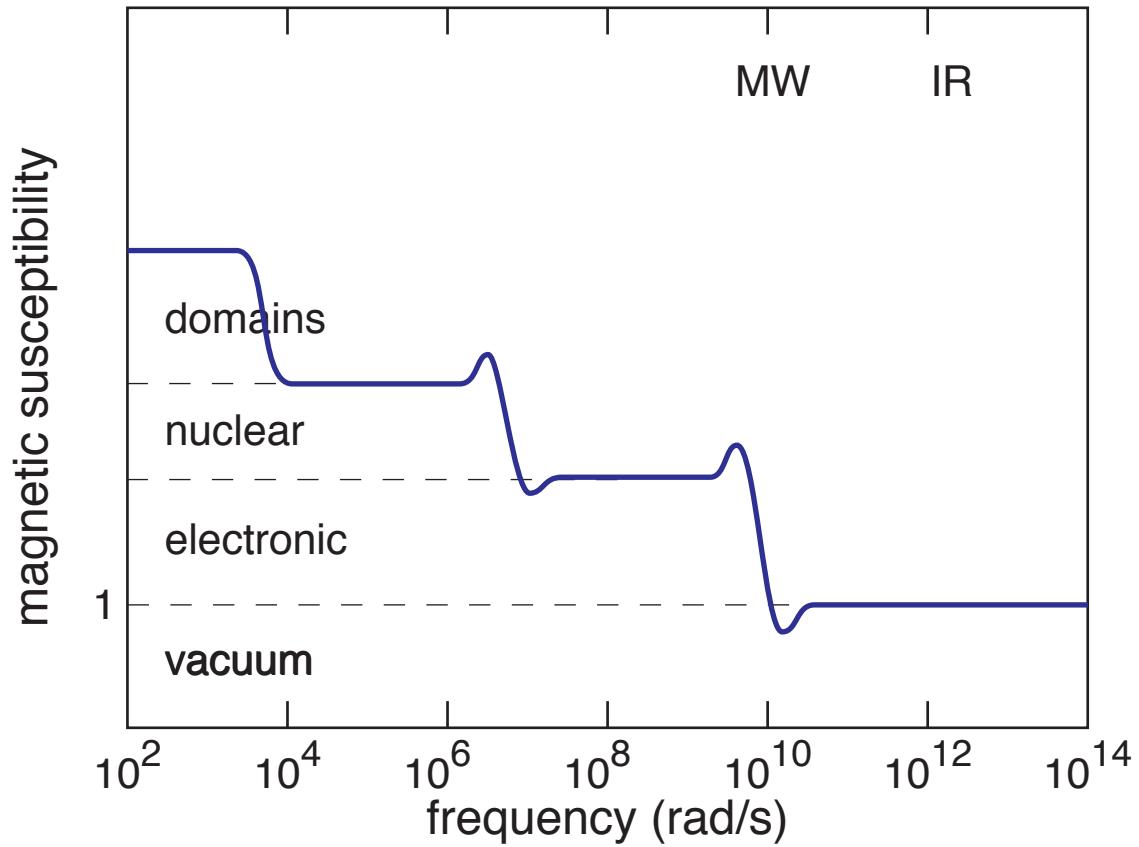
# Magnetic response

but magnetic resonances occur below optical frequencies



# Magnetic response

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



## Index of refraction

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Both  $\epsilon$  and  $\mu$  are complex and their real parts can be negative.

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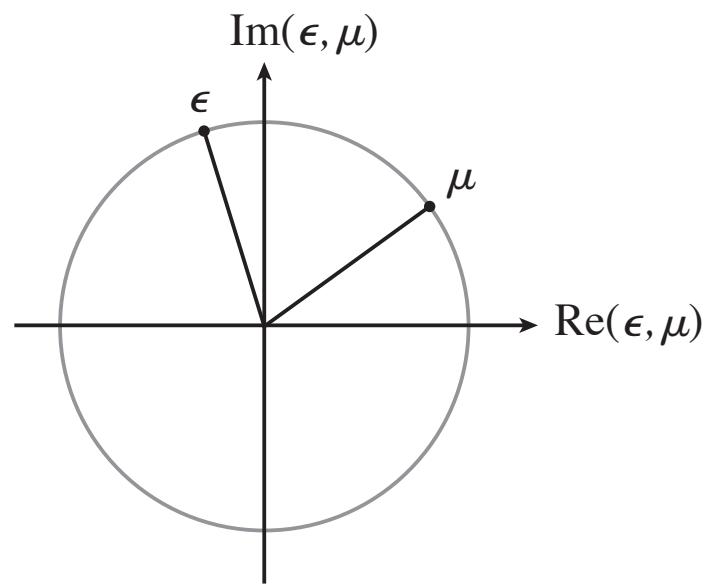
What happens when  $\text{Re}\epsilon$  and/or  $\text{Re}\mu$  is negative?

**Write complex quantities as**

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

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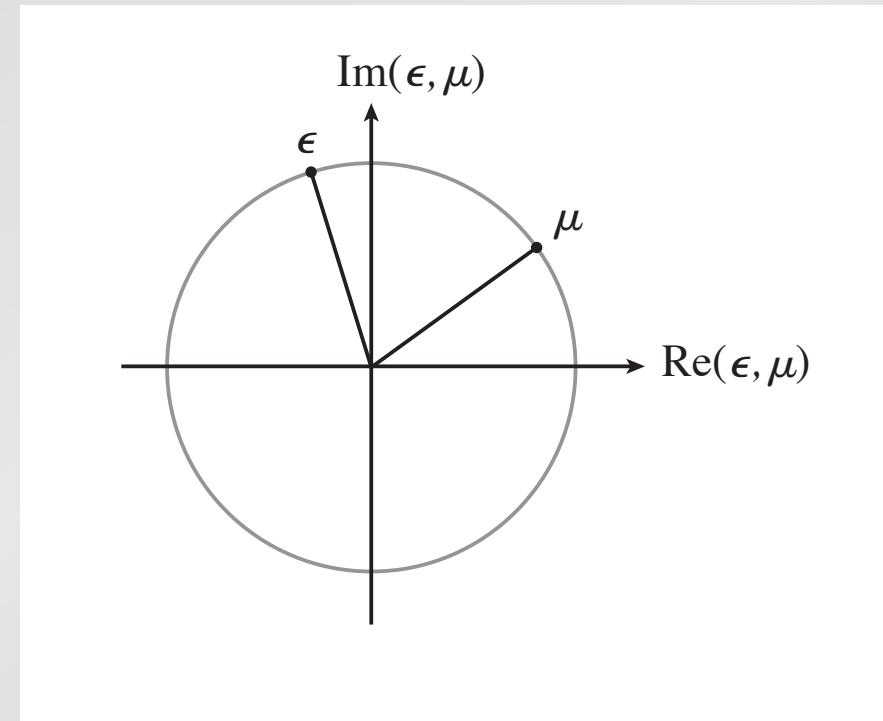


**Write complex quantities as**

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**Index**

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

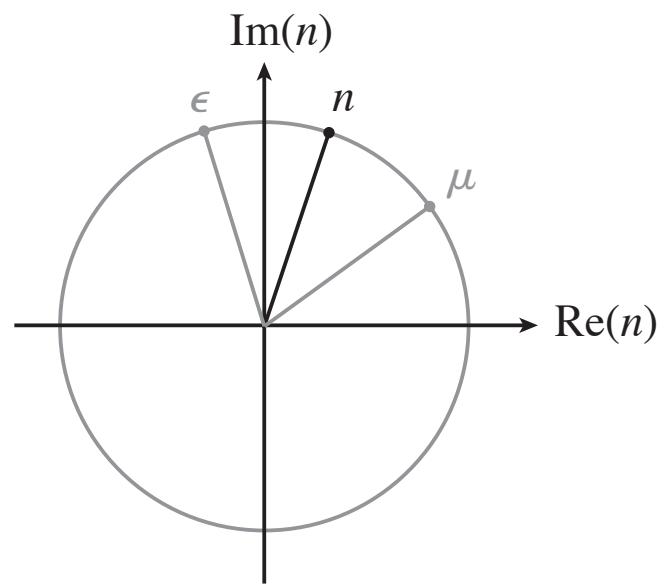


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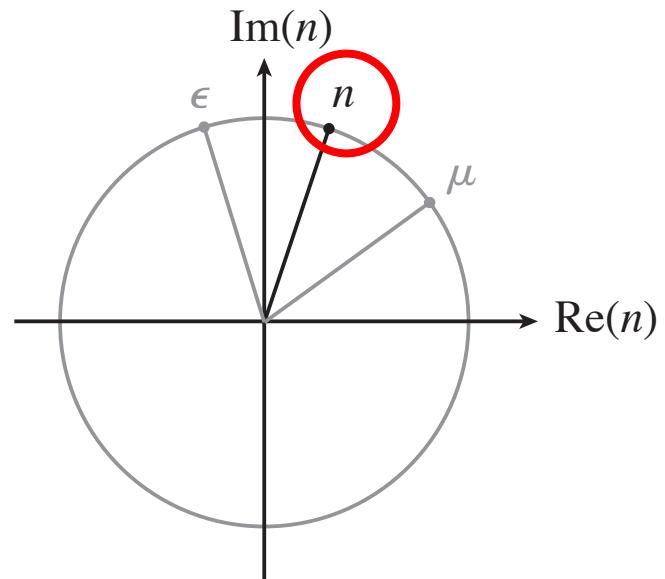
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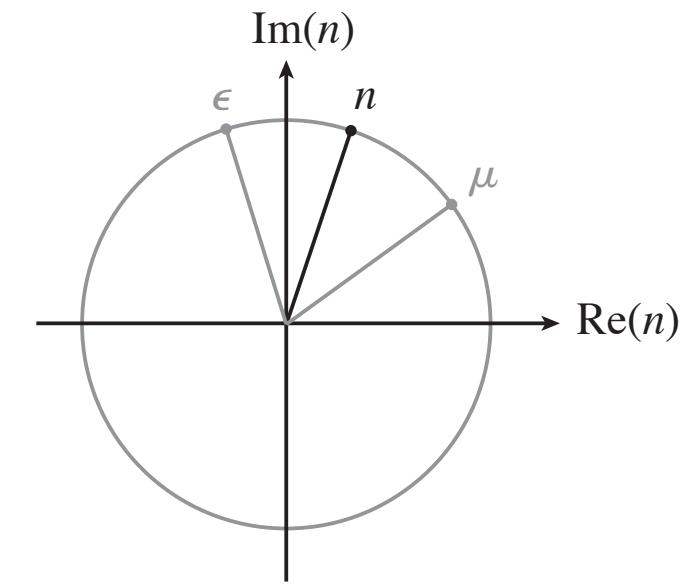
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**Q: Is this only possible value?**

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



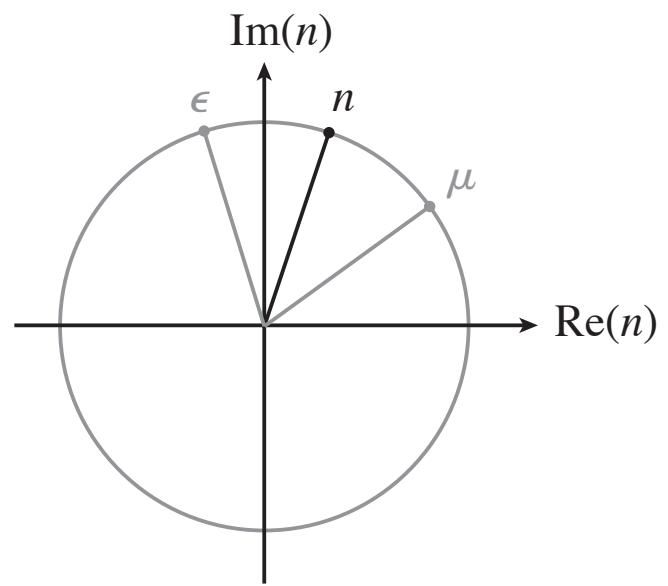
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**Can add  $2\pi$  to exponent**

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



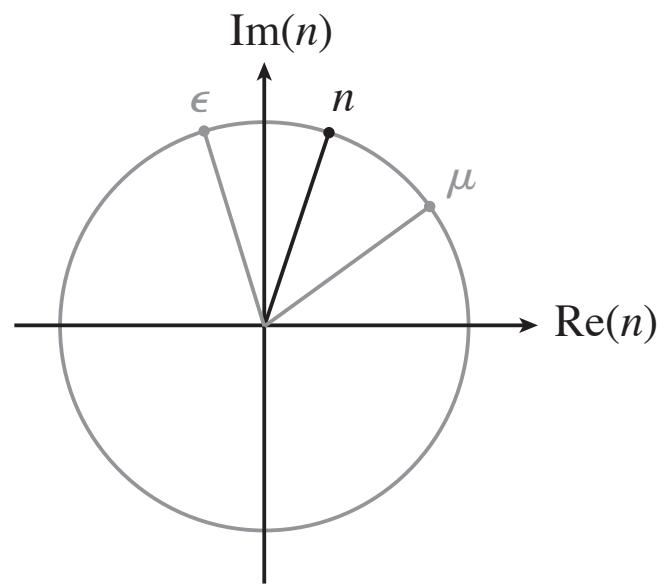
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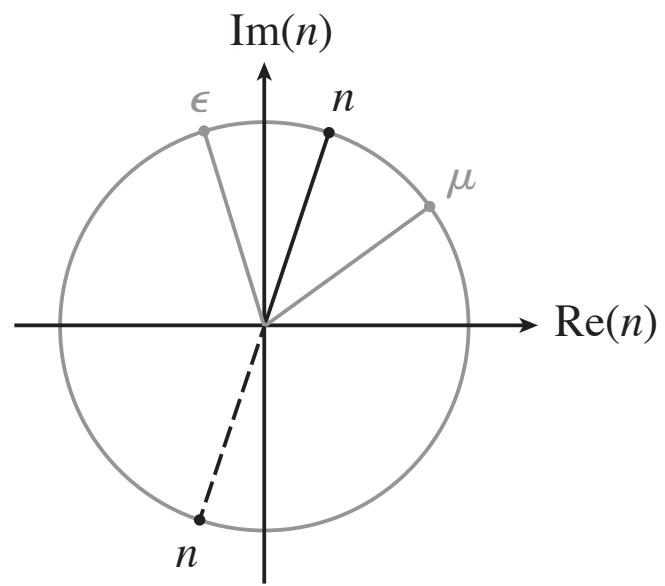
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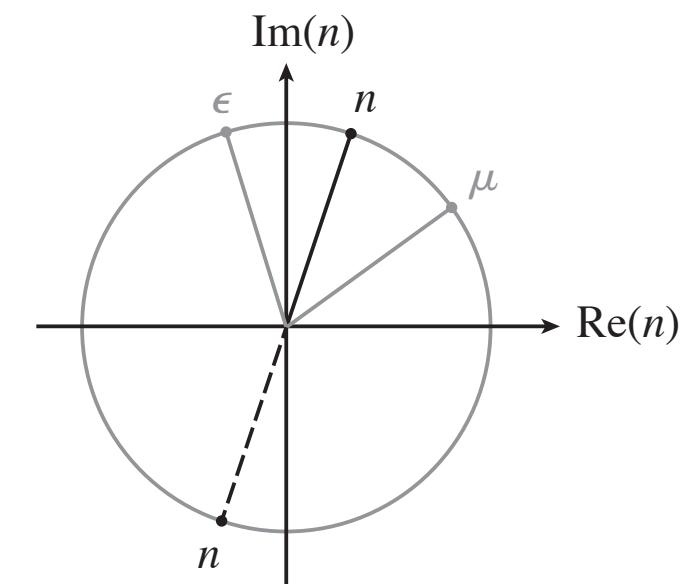
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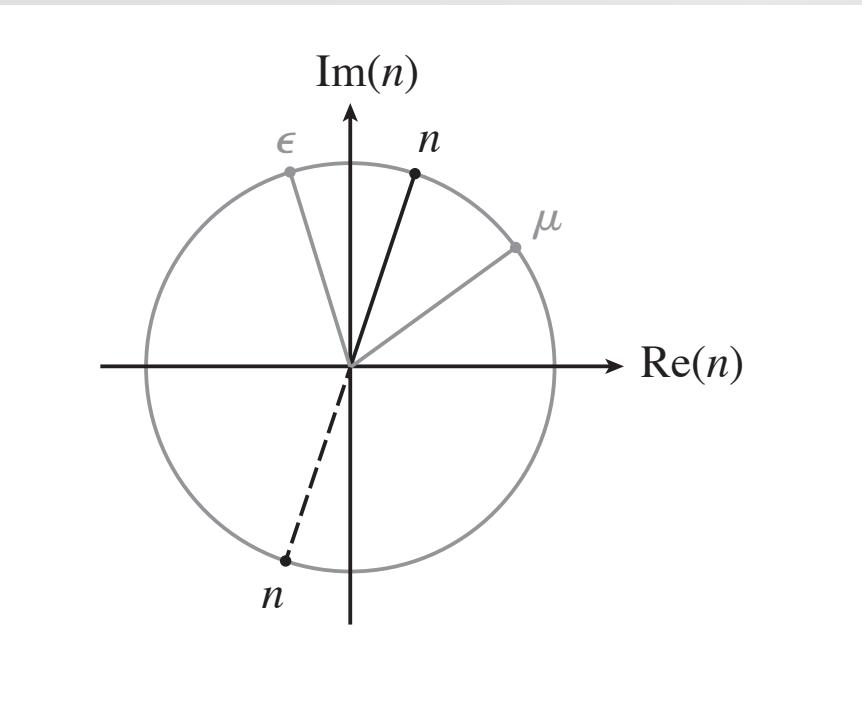
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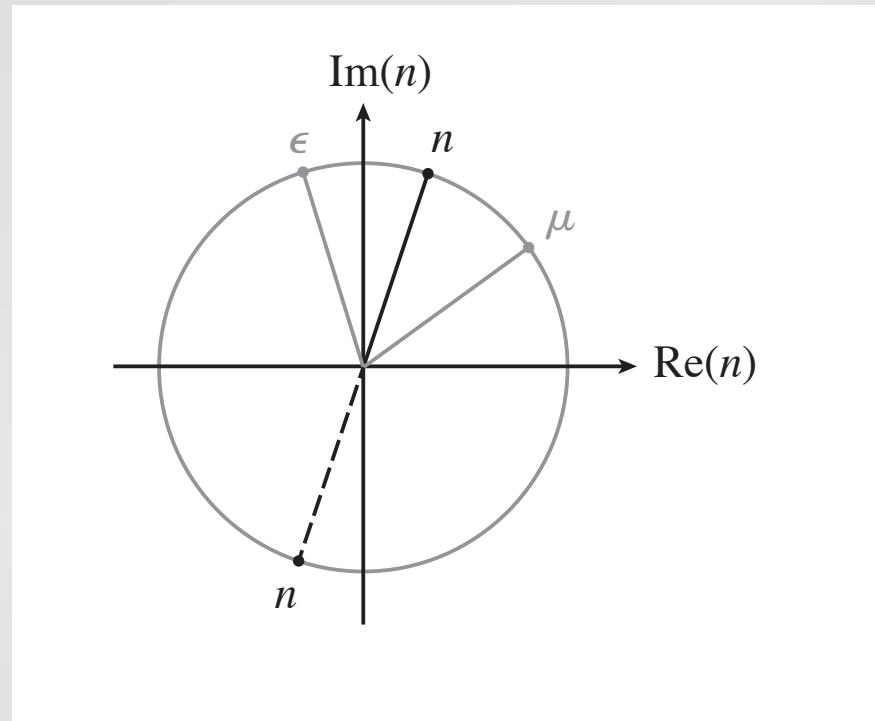
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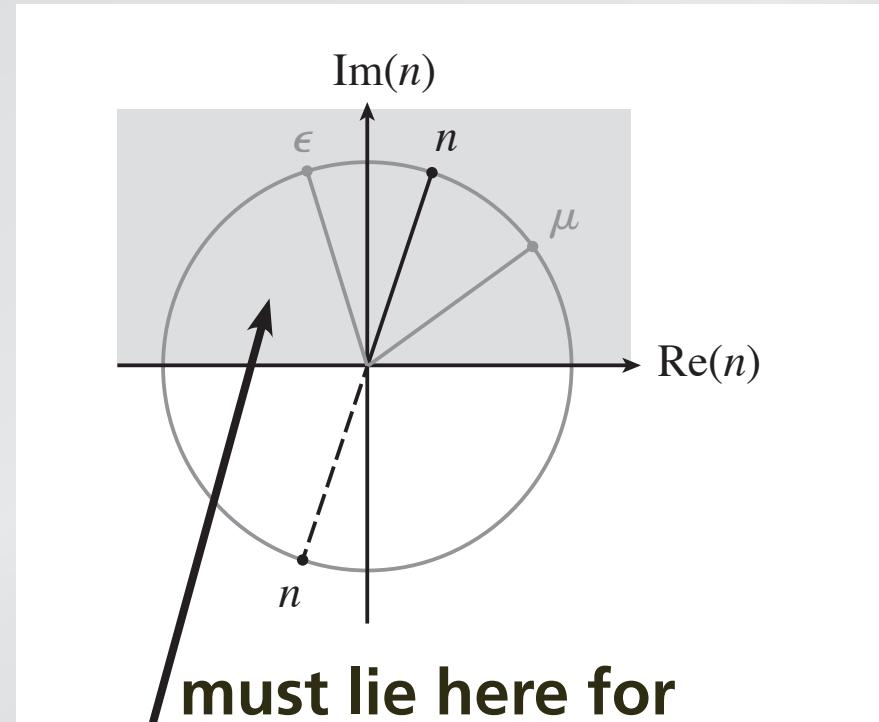
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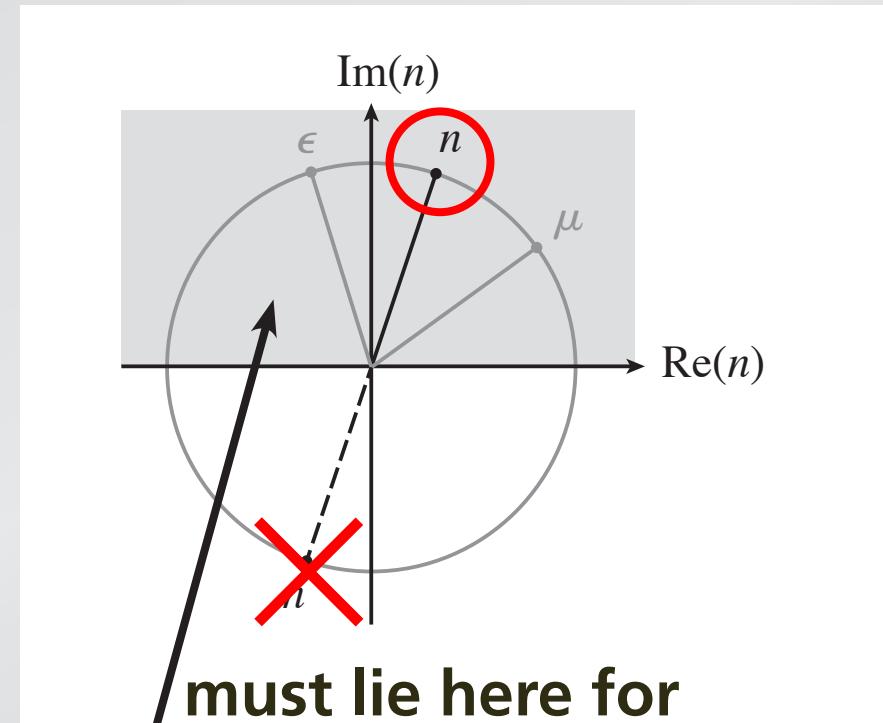
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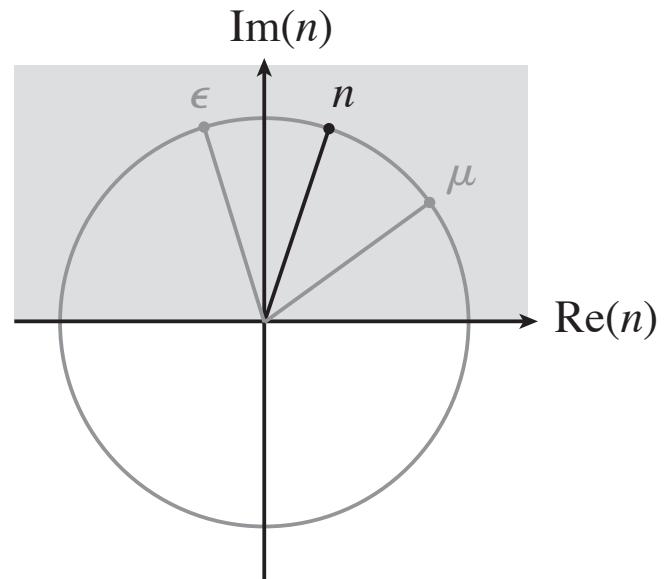
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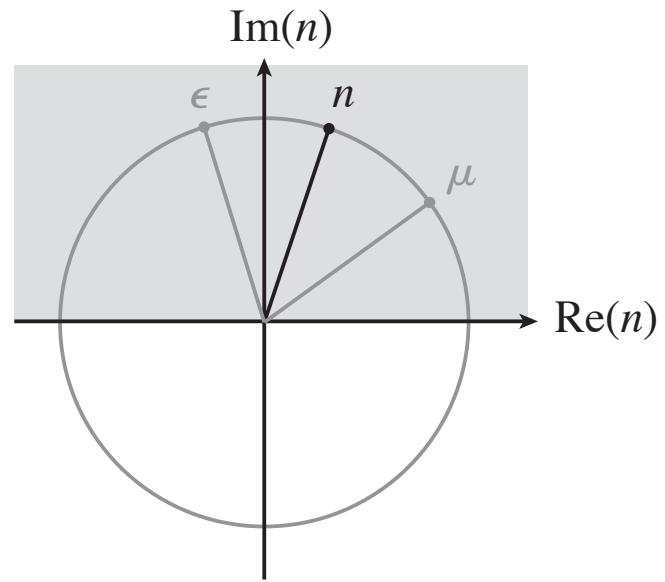
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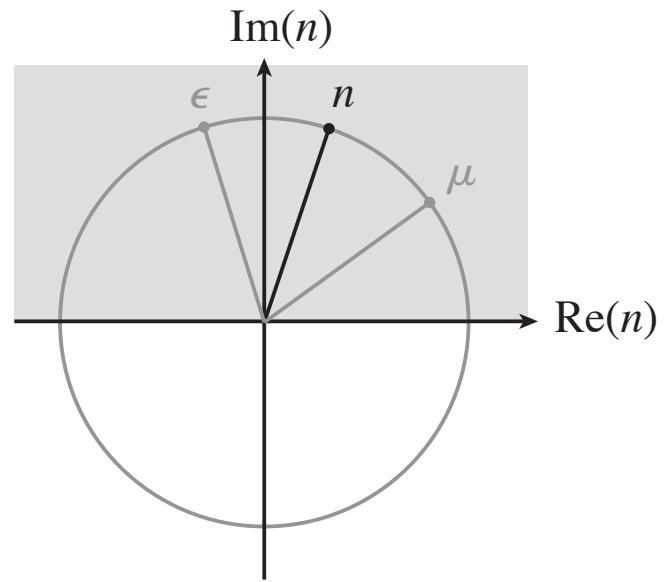
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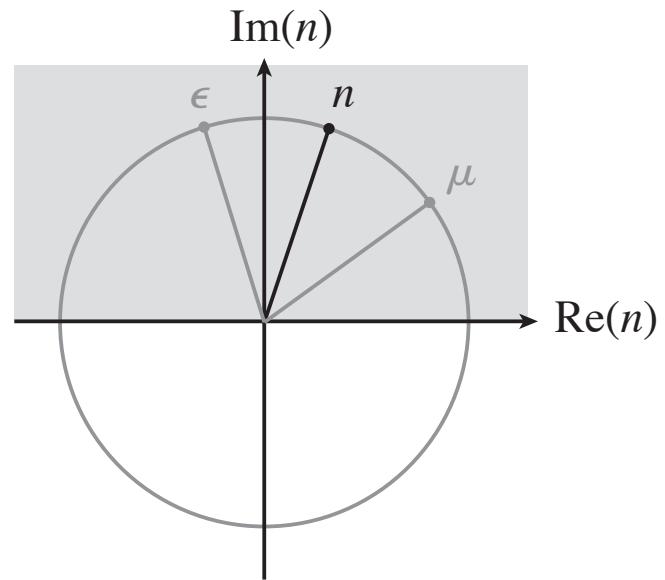
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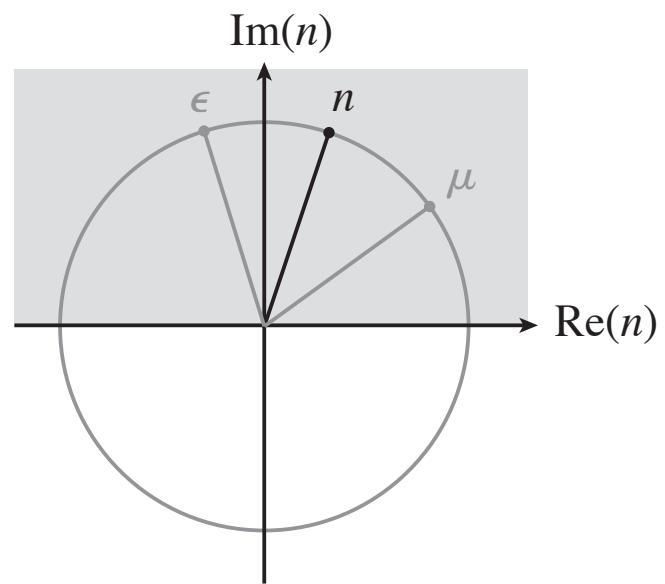
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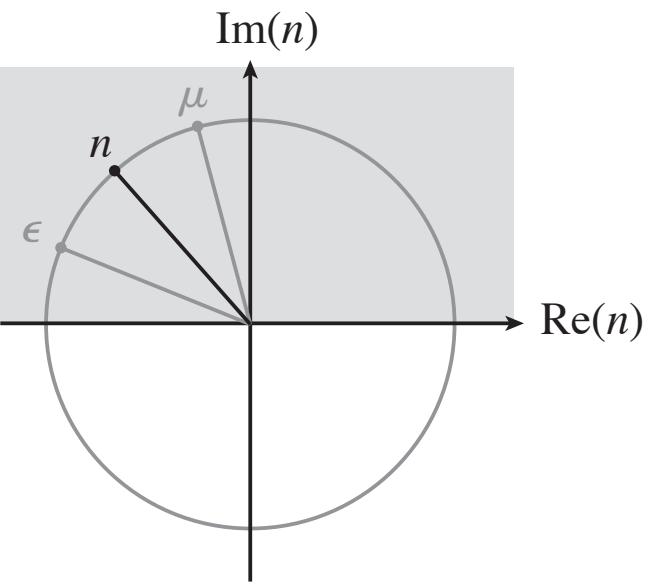
To find  $n$  (passive materials):

1. Draw line that bisects  $\epsilon$  and  $\mu$
2. Choose upper branch



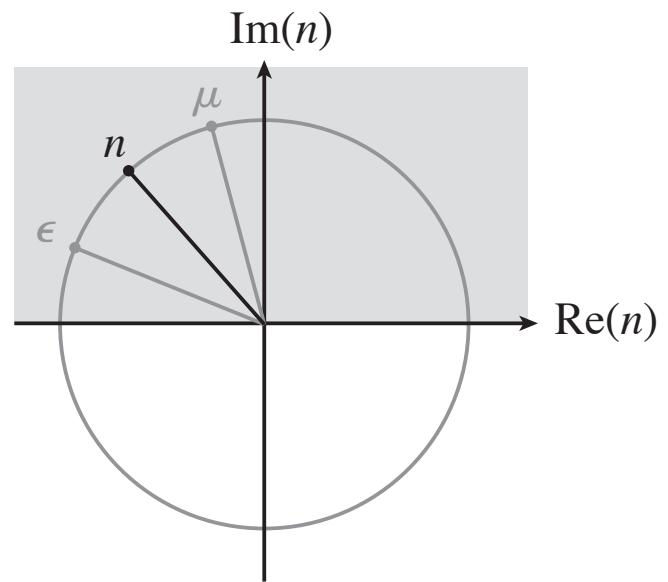
**What happens when  $\text{Re}\epsilon$  and/or  $\text{Re}\mu$  is negative?**

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



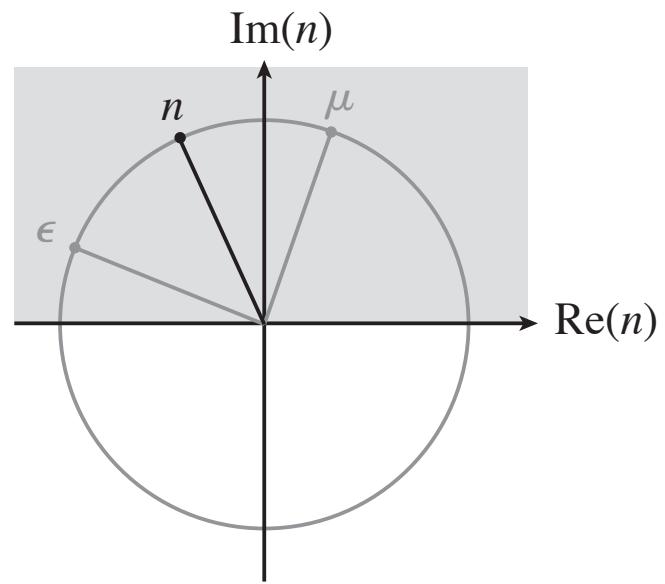
**Q: Must both  $\operatorname{Re}\epsilon < 0$  and  $\operatorname{Re}\mu < 0$  to get a negative  $\operatorname{Re}(n)$ ?**

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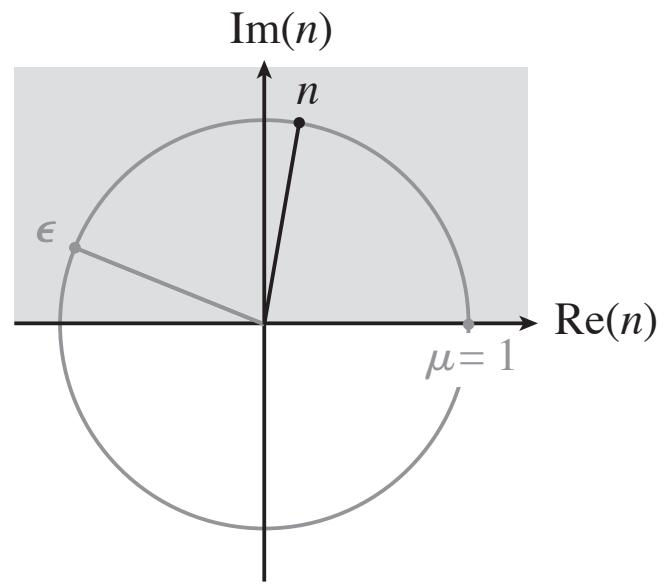


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1. yes
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**However, need magnetic response  
to achieve  $\text{Re}(n) \leq 0$ !**



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

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

**Remember**

$$k = \frac{2\pi n}{\lambda_o} = \frac{2\pi(n' + in'')}{\lambda_o} = k' + ik''$$

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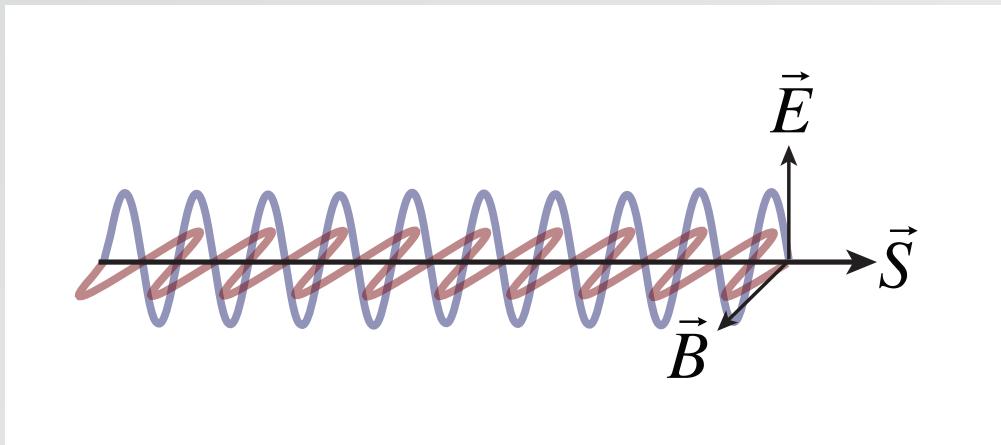


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What about causality?

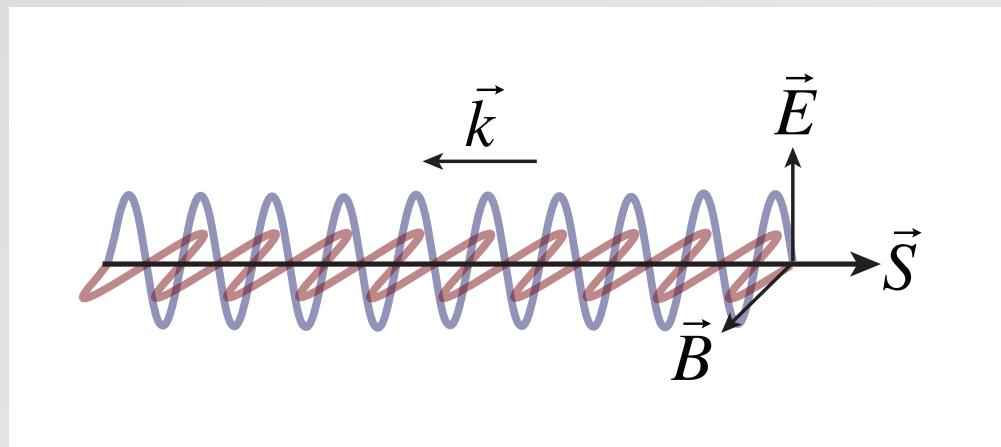
**“Superluminal”?**

## What about causality?



Poynting vector still points in the same direction!

## What about causality?

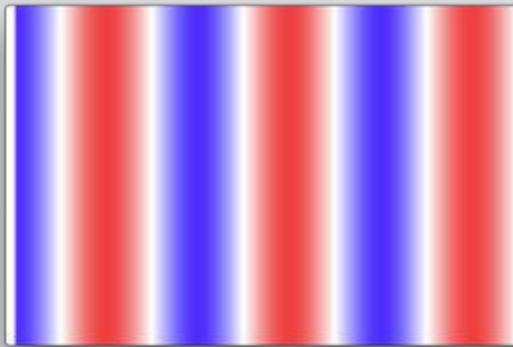


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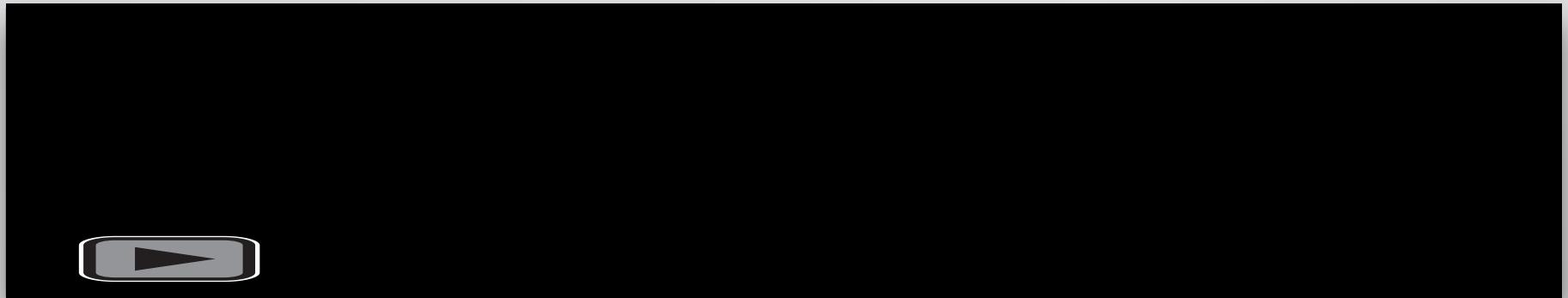
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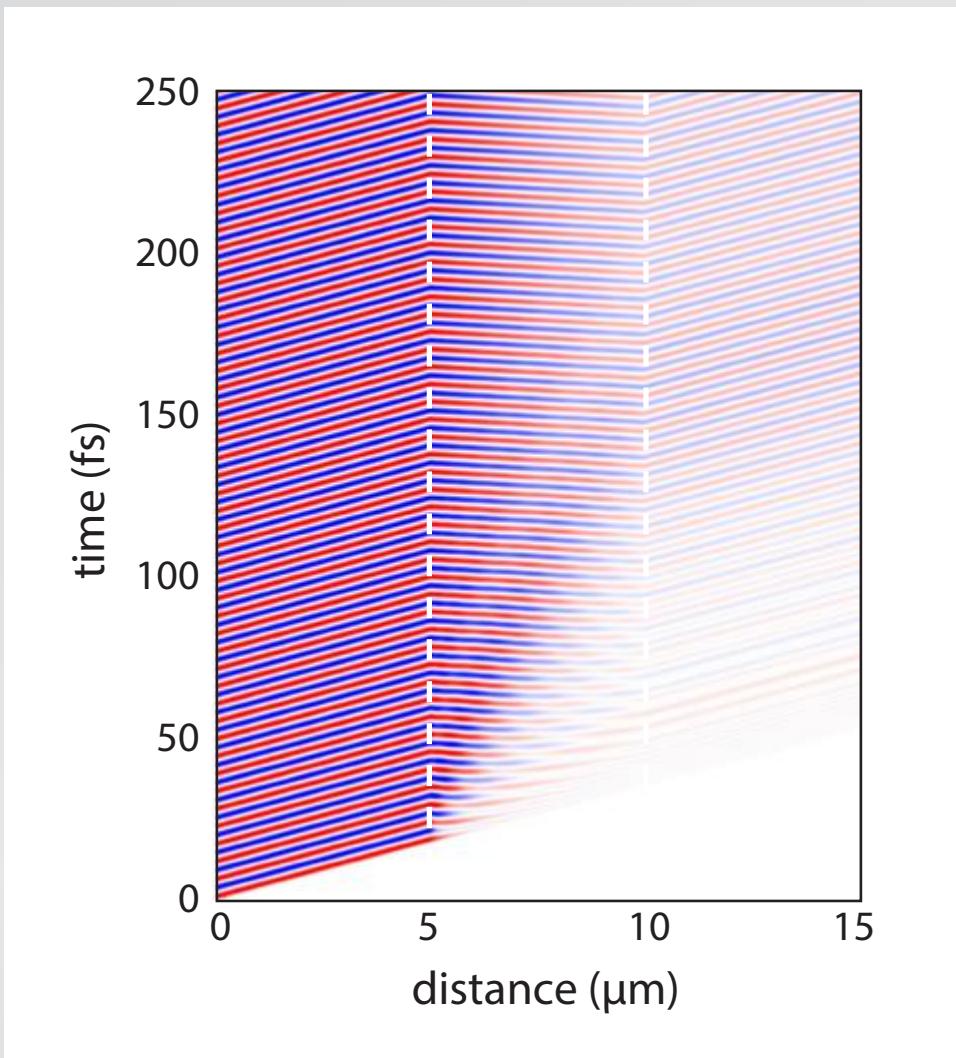
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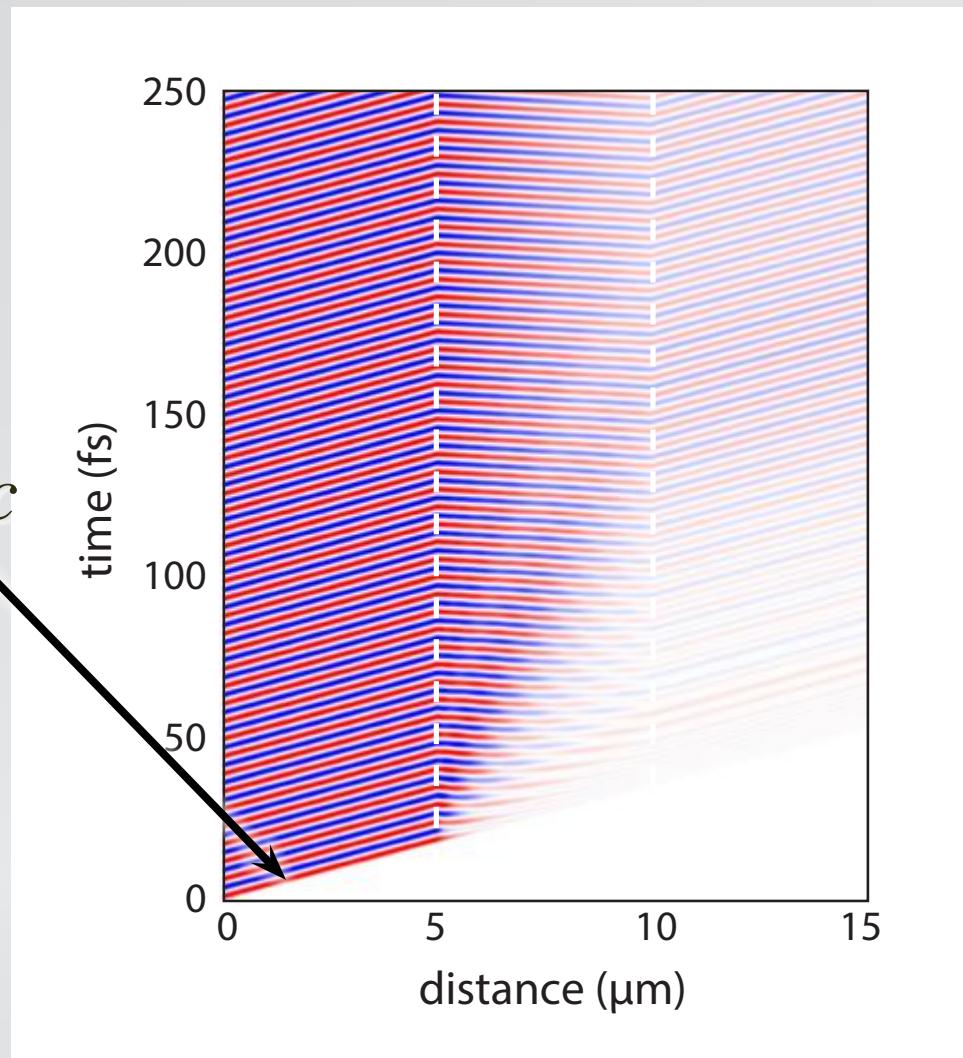


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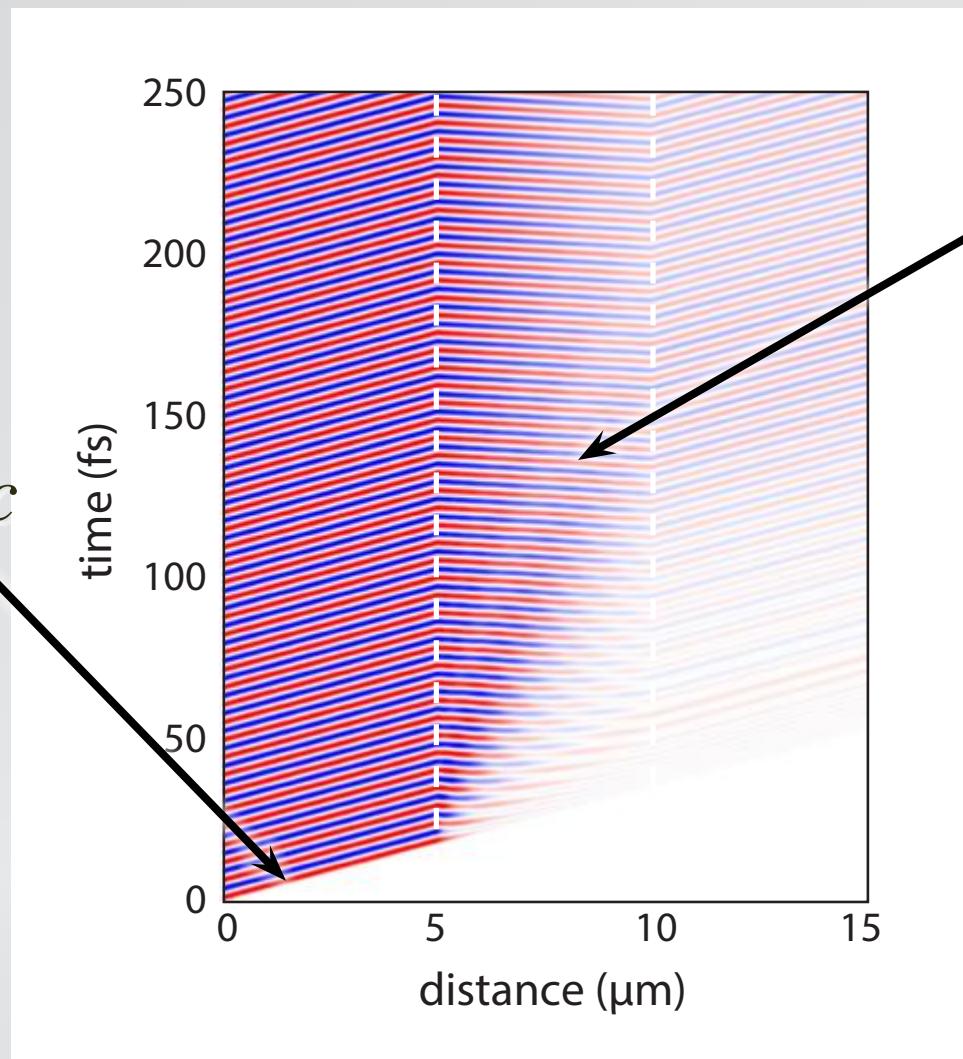
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speed of light  $c$



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reverse phase  
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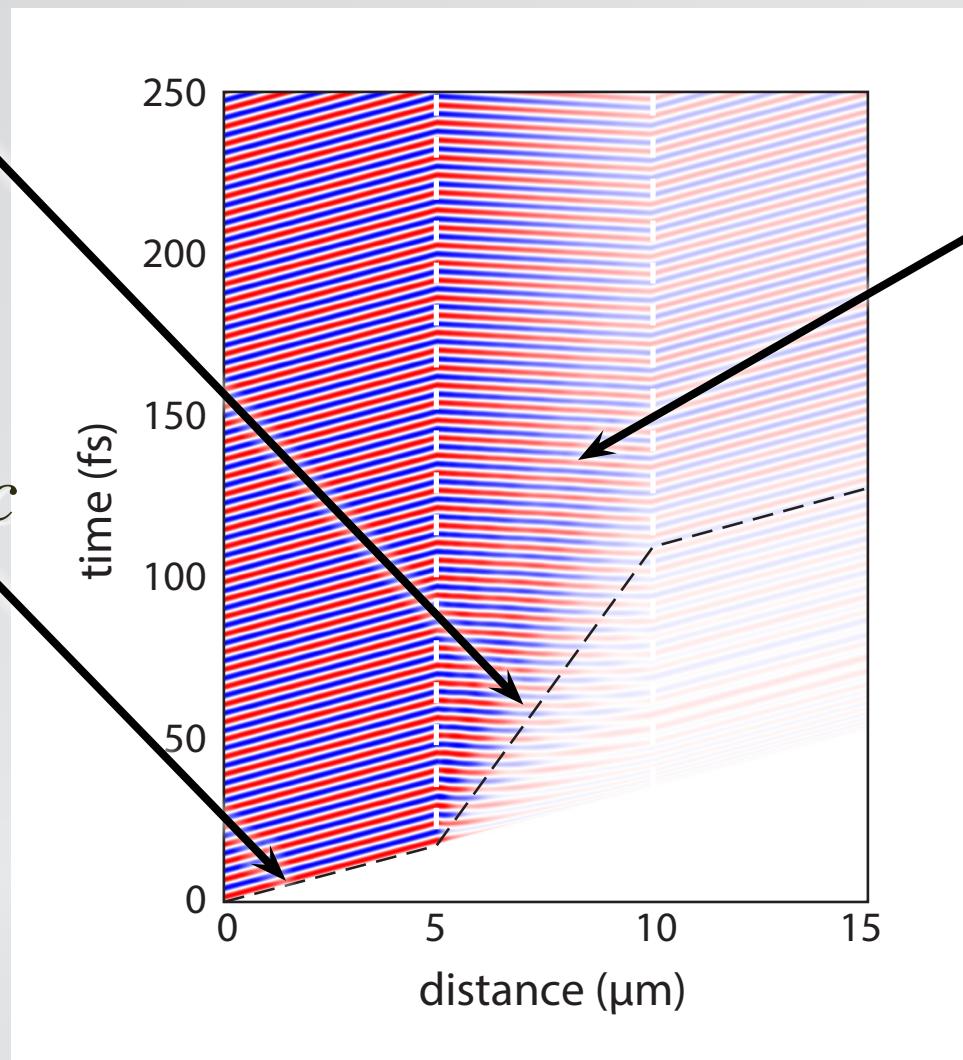
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group velocity

$$v_g < c$$

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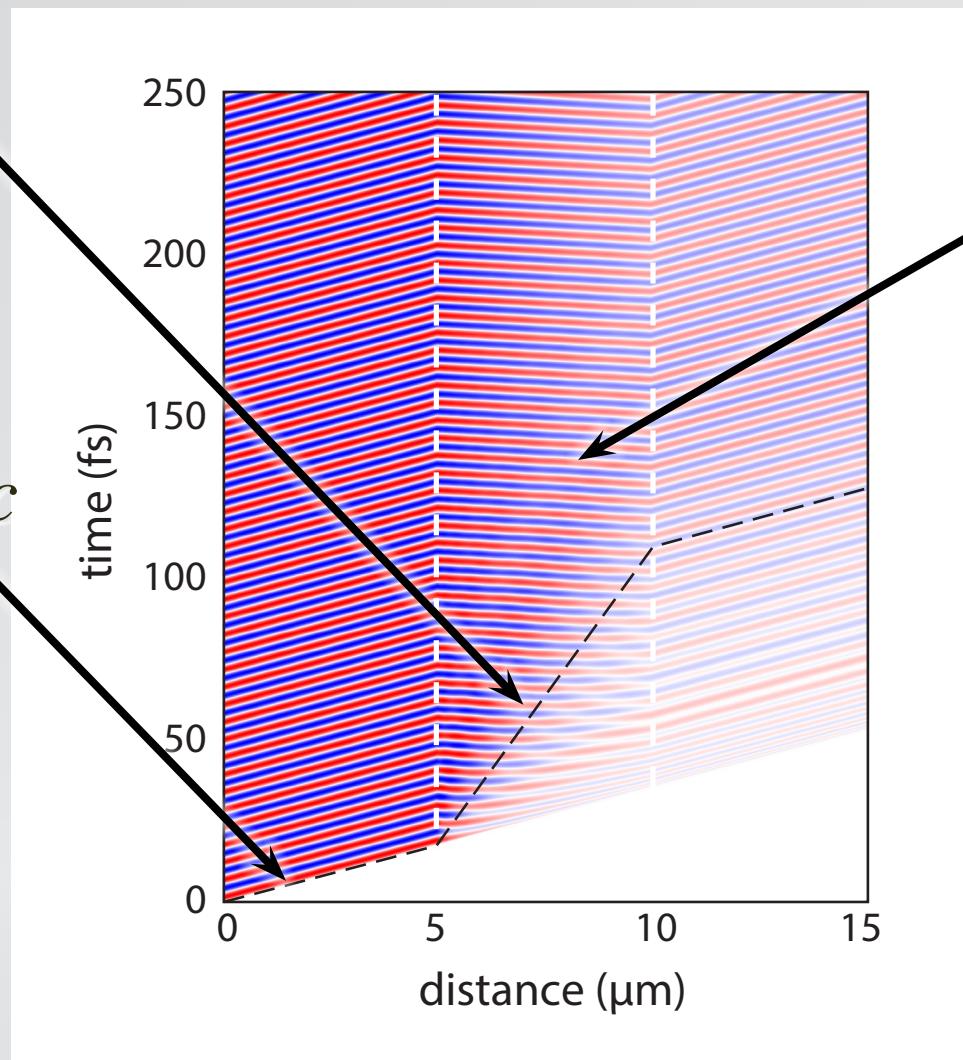
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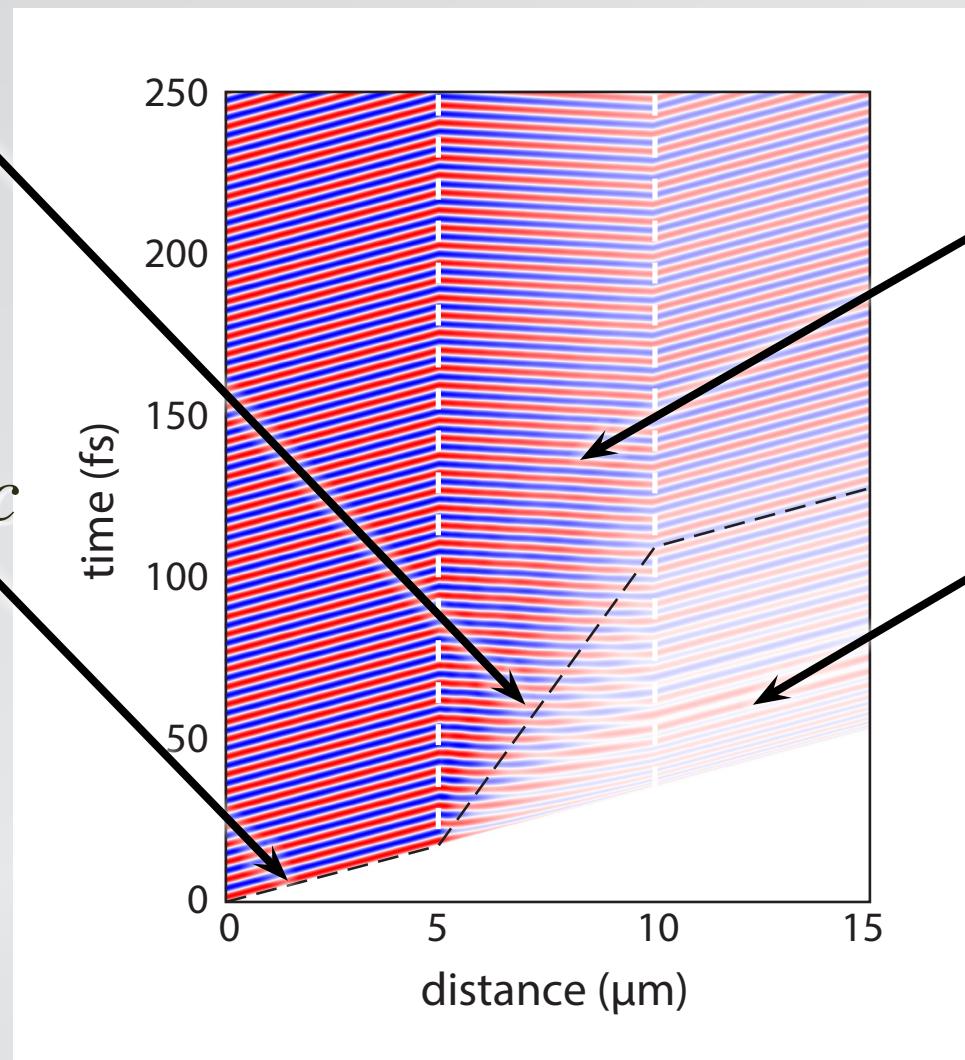


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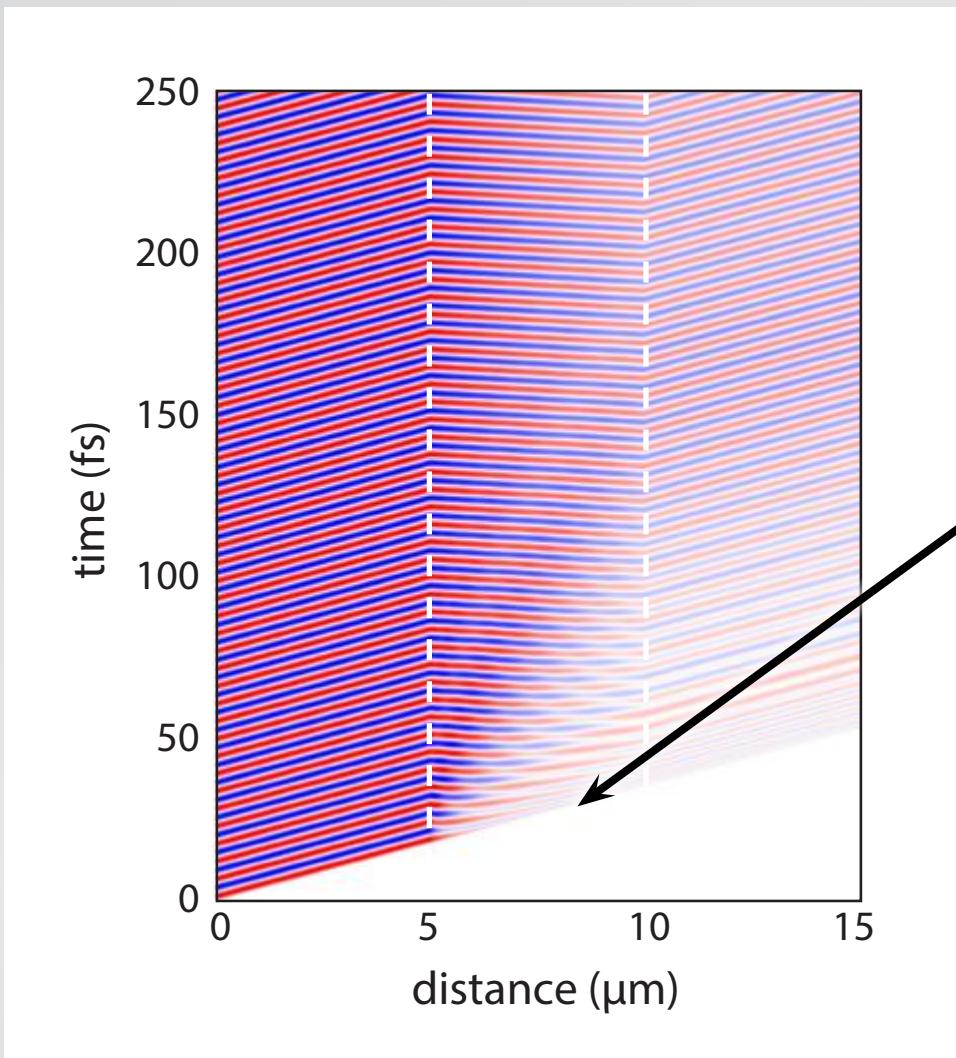
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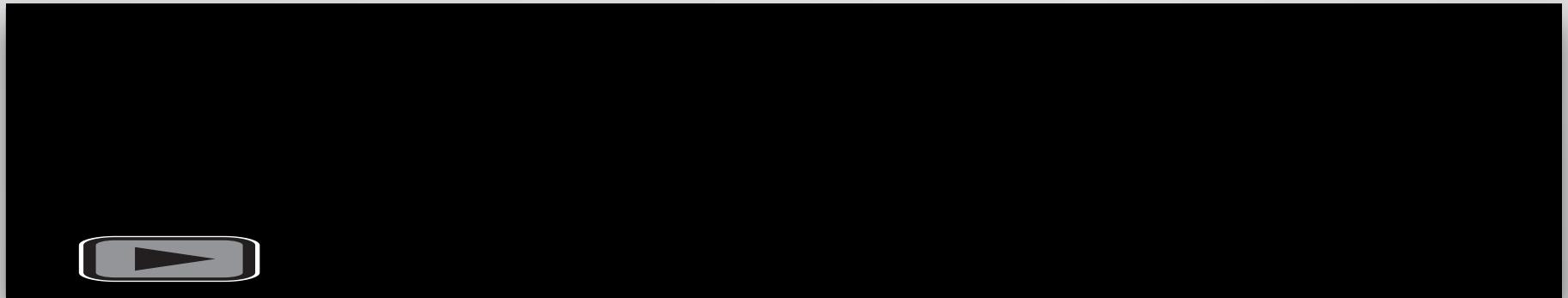
high-frequency  
precursors

## What about causality?

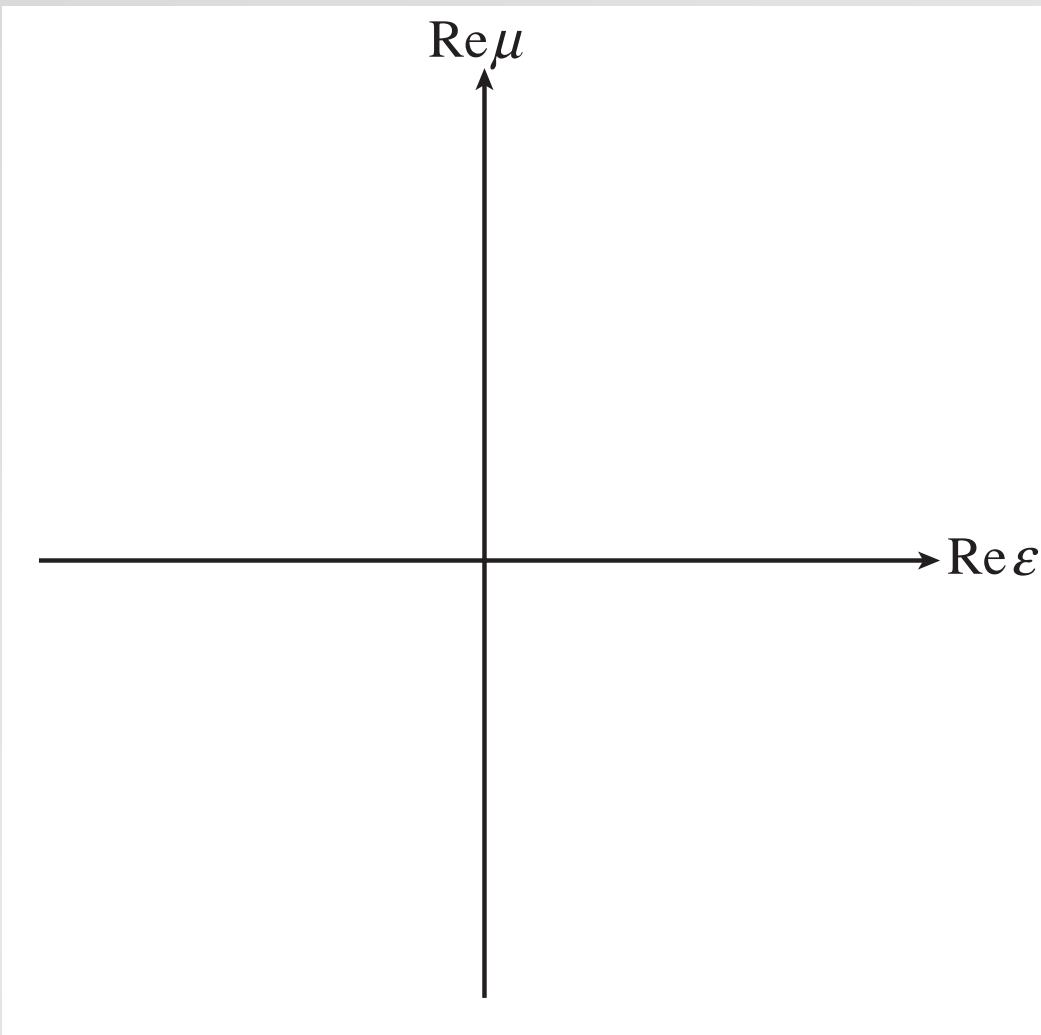


**signal *always*  
travels at speed  $c$ !**

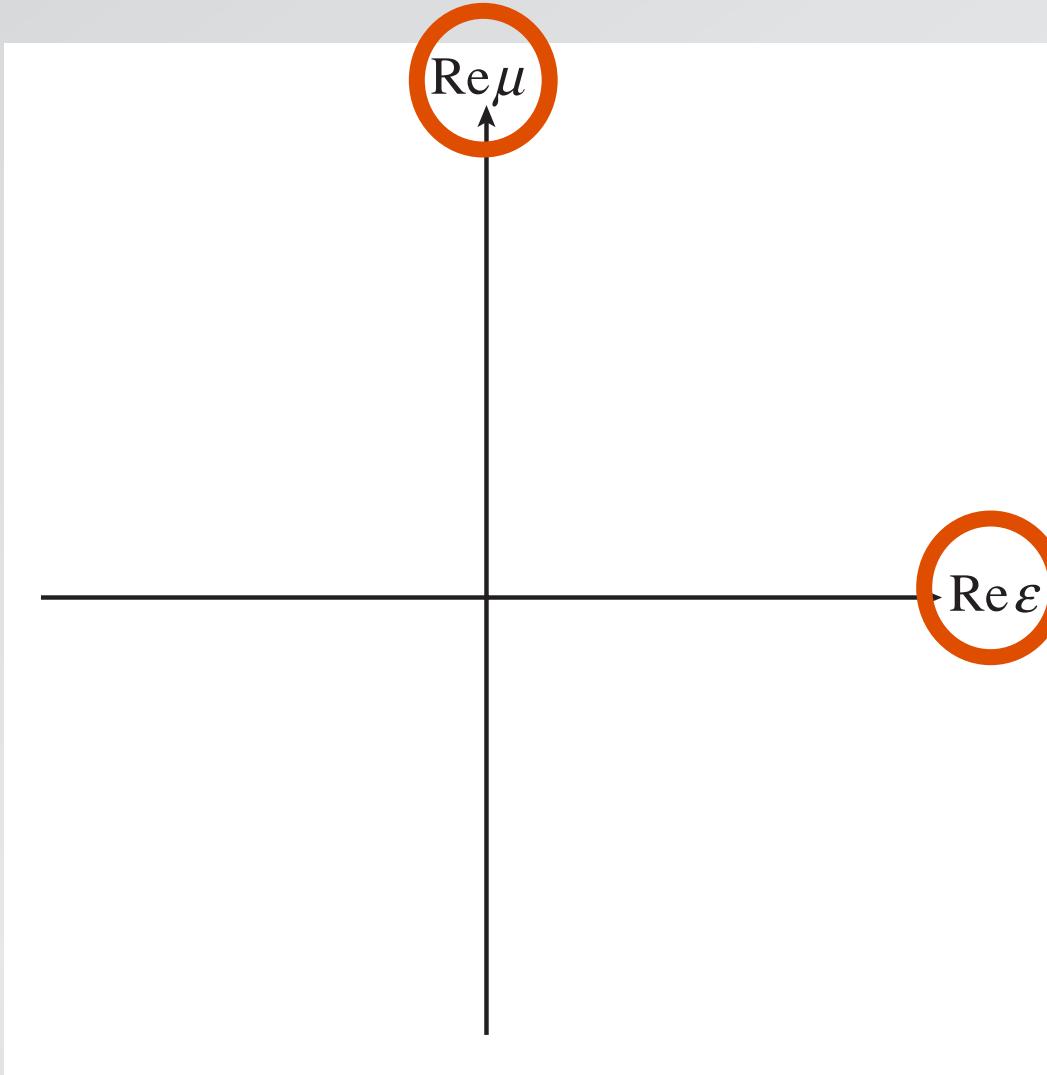
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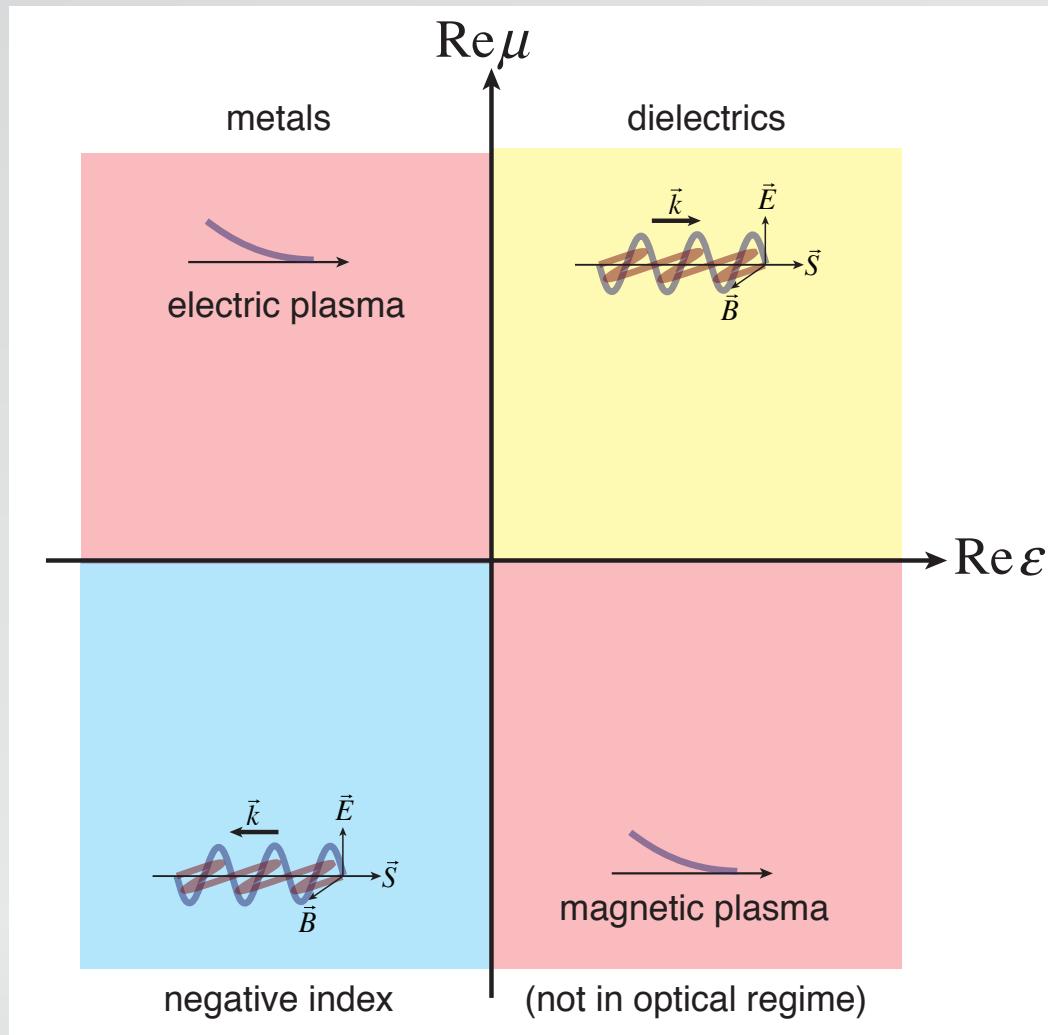
## classification of (non-lossy) materials



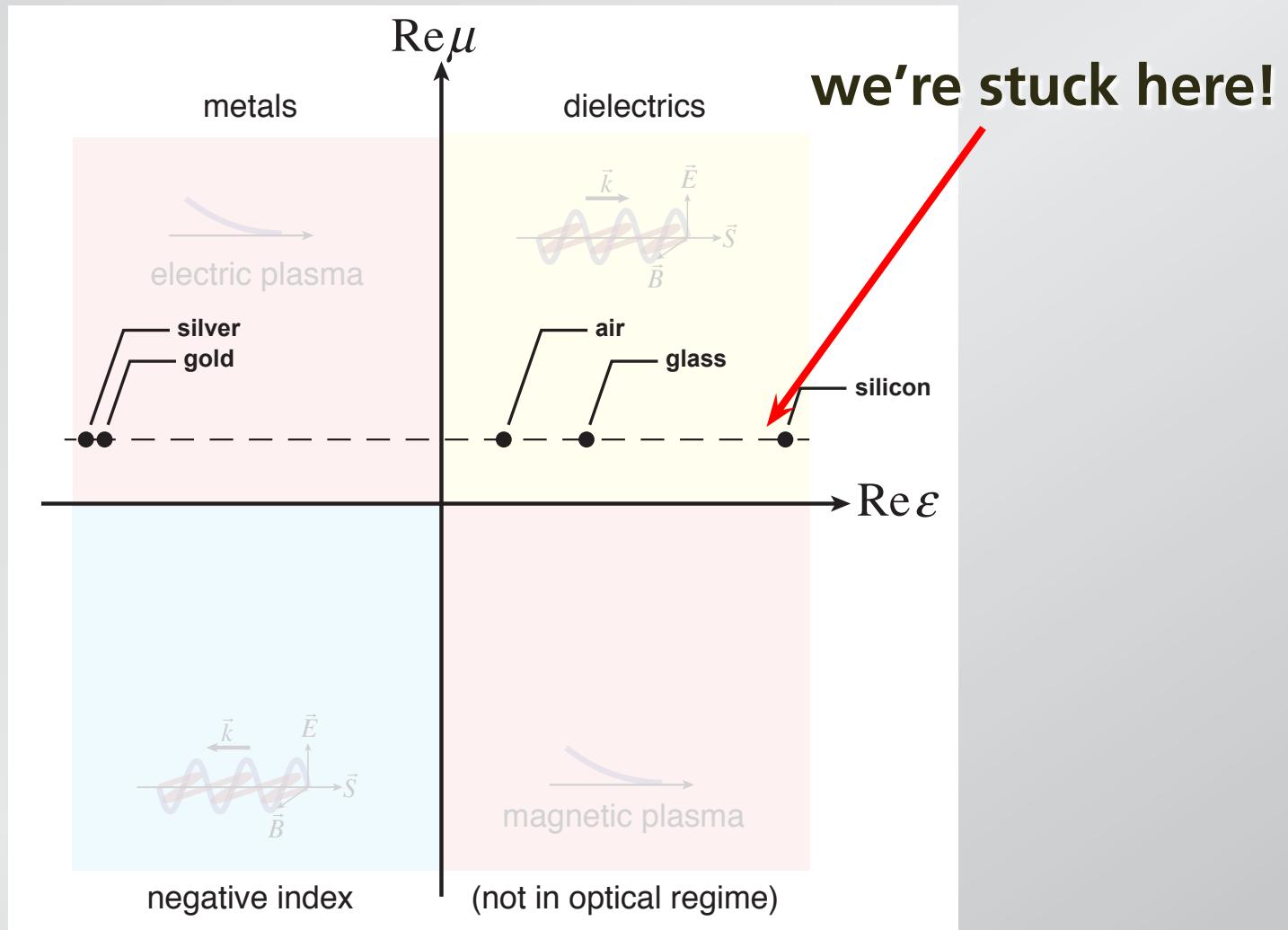
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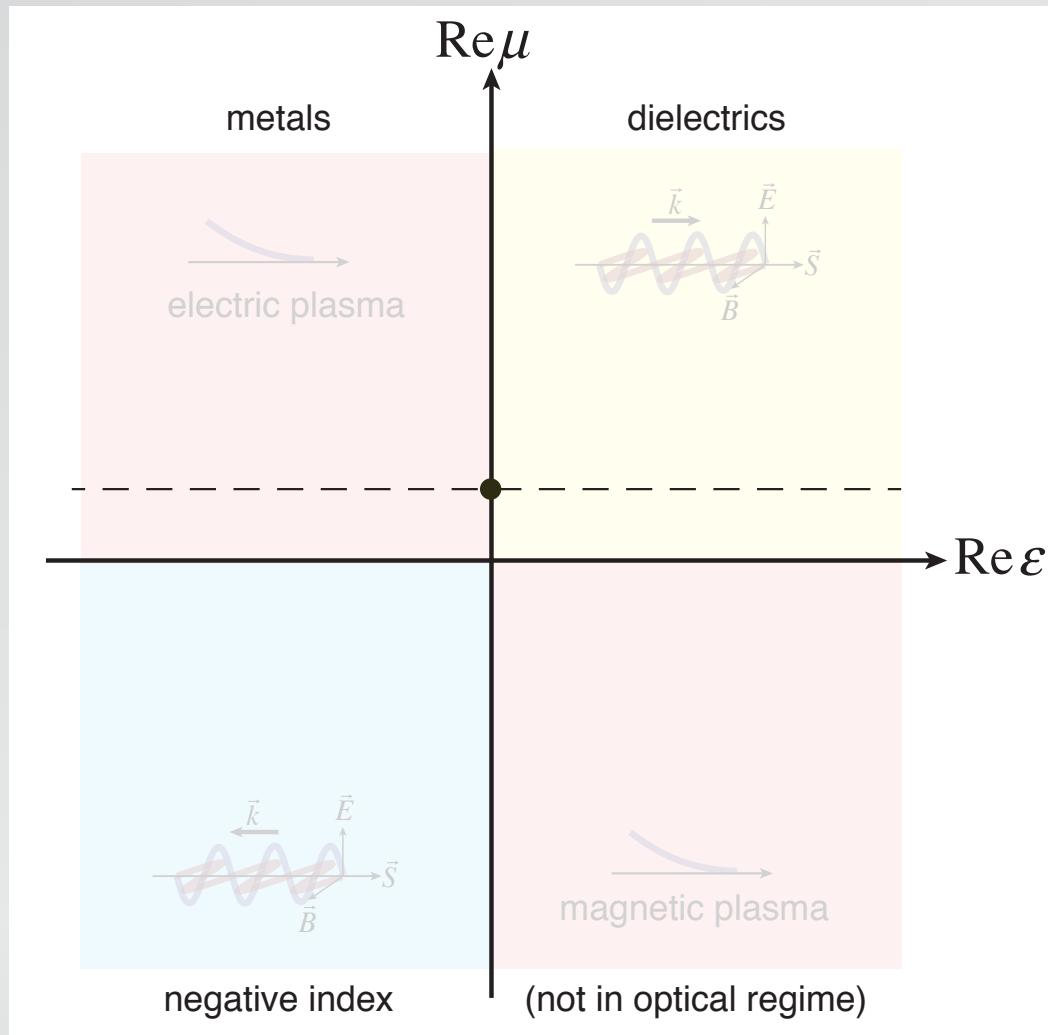
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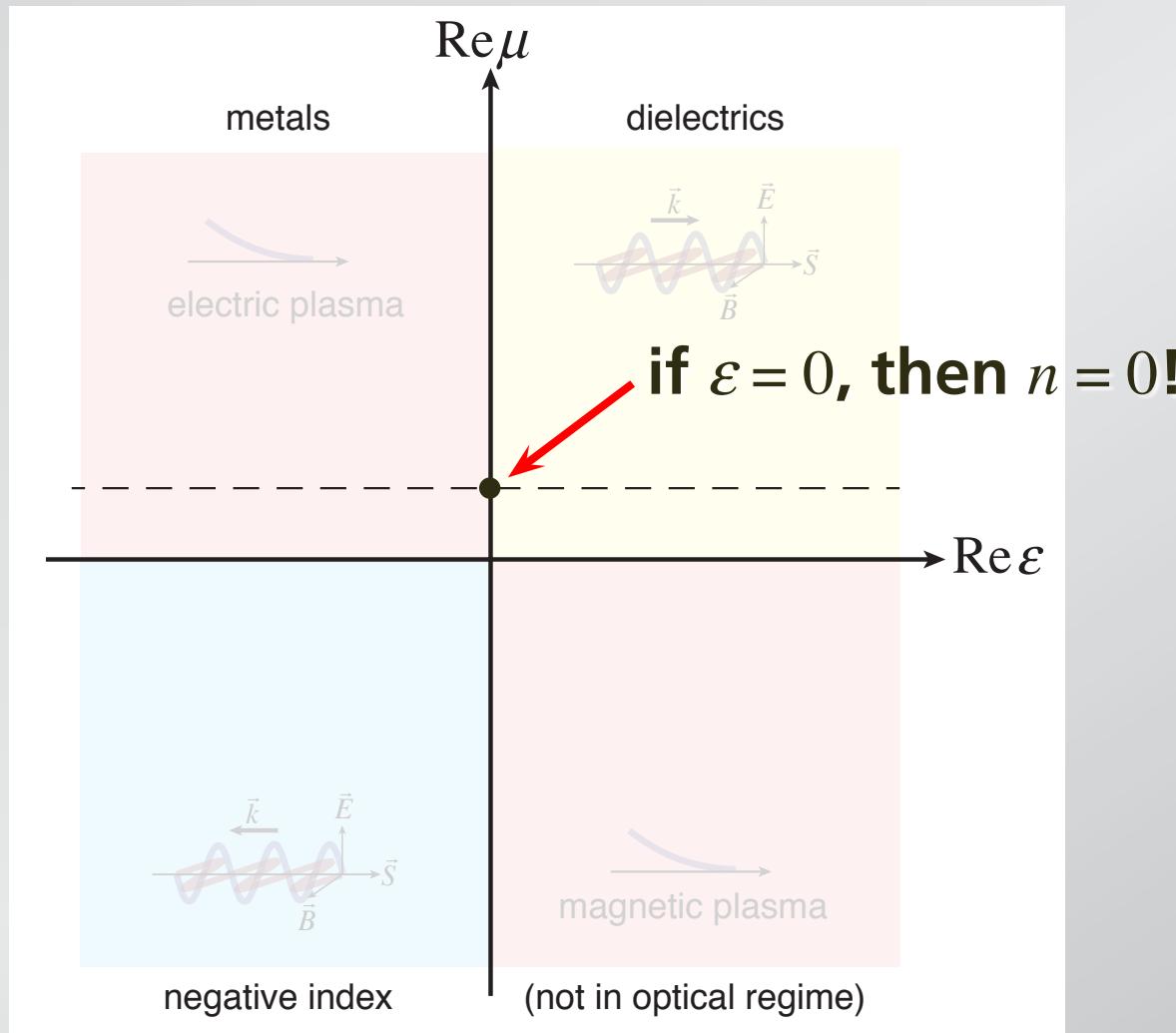
# common materials very limited



# 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

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

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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

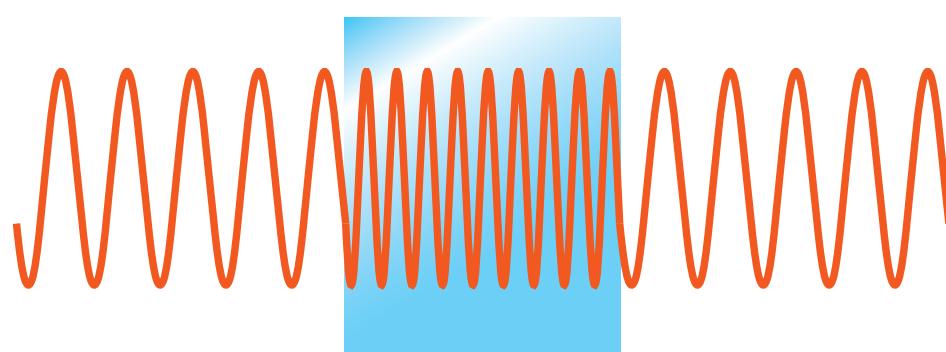
**Q: If  $n = 0$ , which of the following is true?**

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

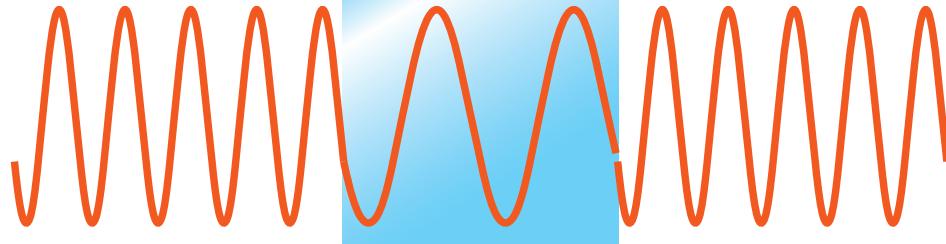
$n > 1$



1 index

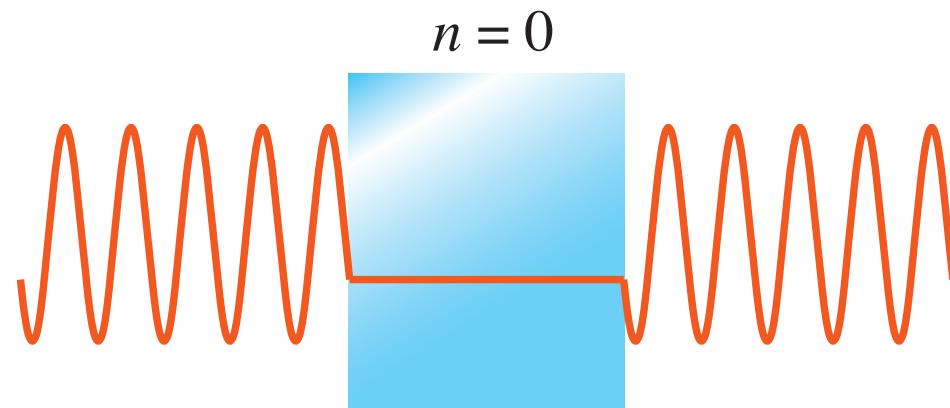
2 zero index

$$0 < n < 1$$



1 index

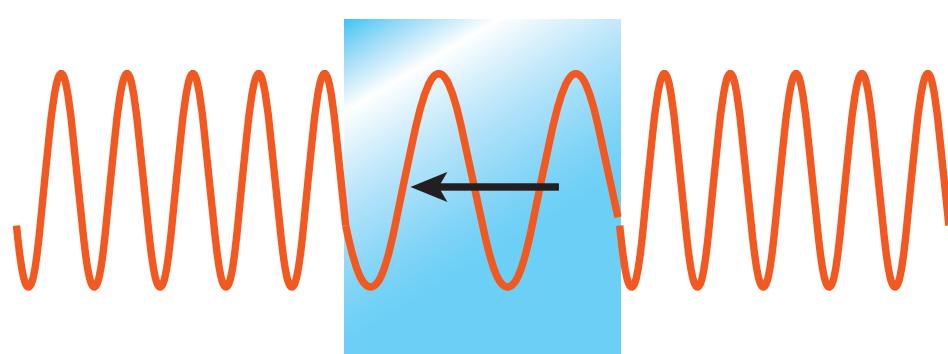
2 zero index



1 index

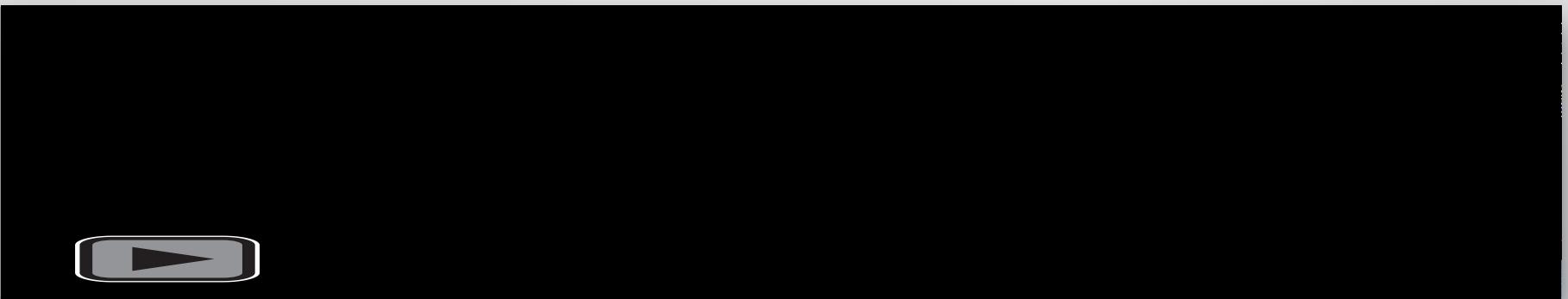
2 zero index

$n < 0$



1 index

2 zero index



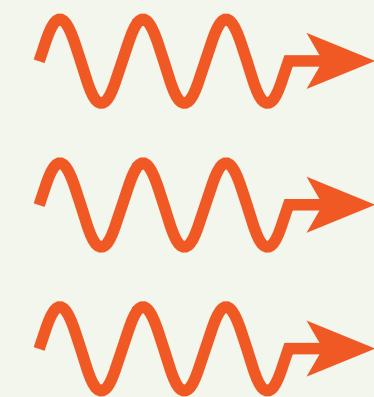
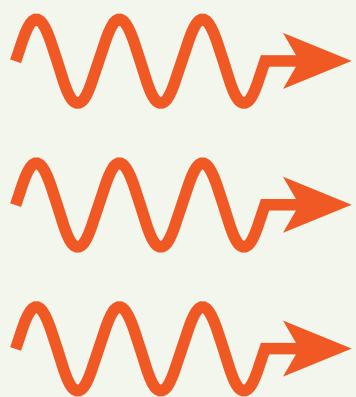
1 index

2 zero index

**What can we do with uniform phase?**

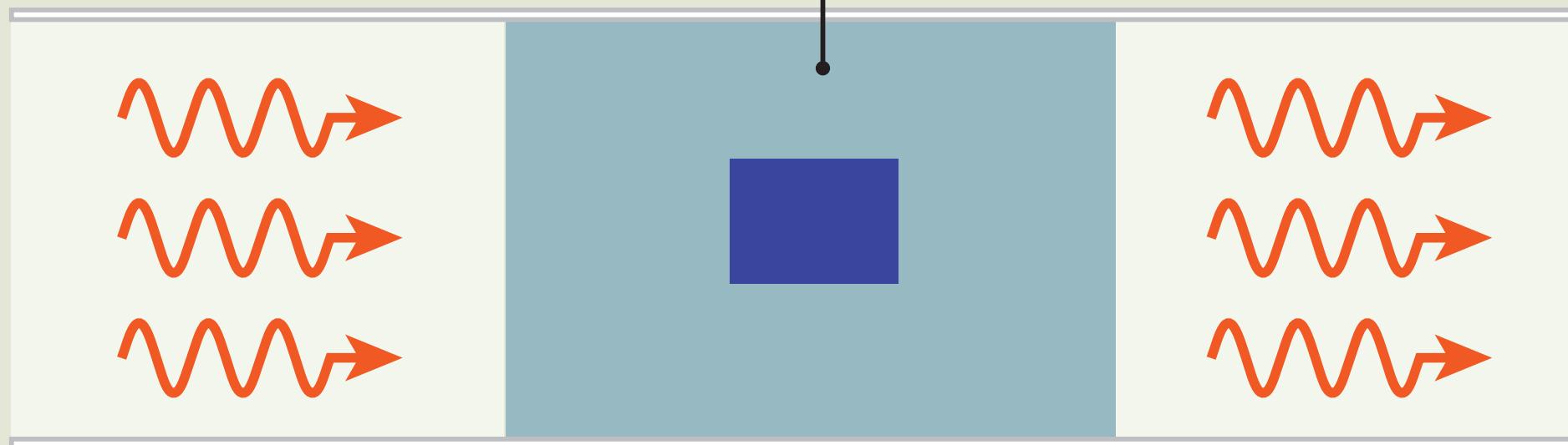
**1** index

**2** zero index

$n = 0$ 

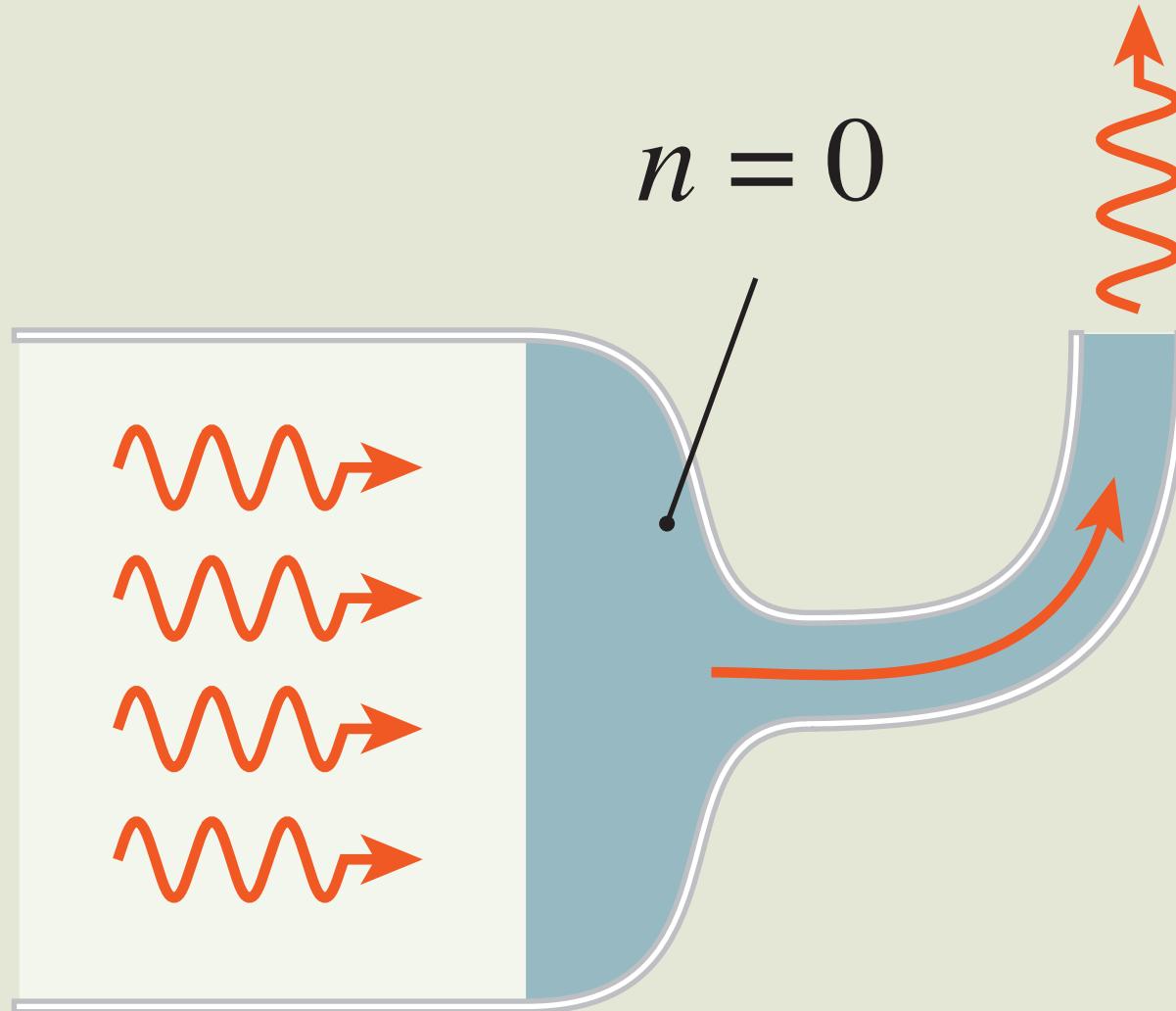
1 index

2 zero index

$n = 0$ 

1 index

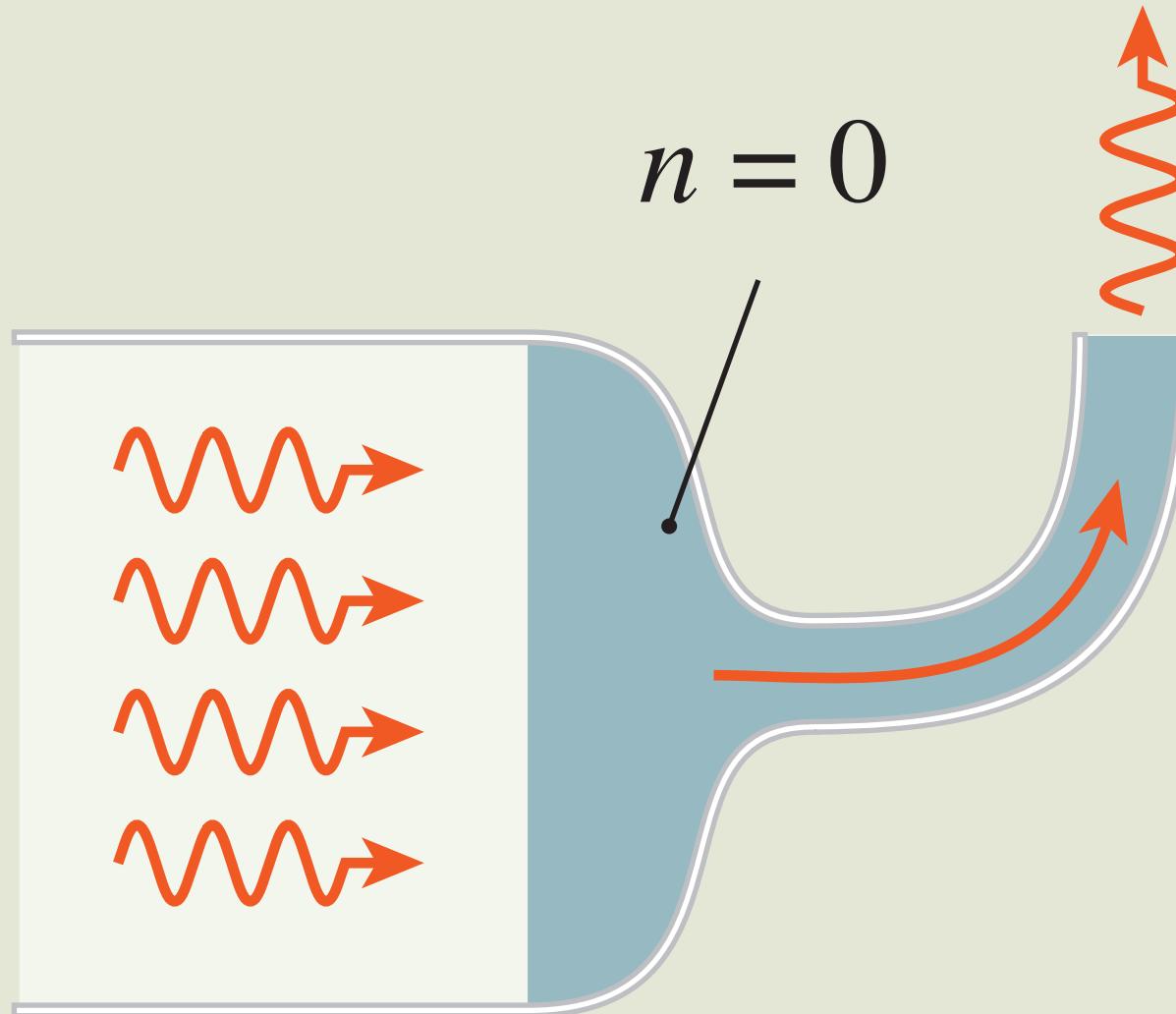
2 zero index



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  $\epsilon$  and  $\mu$  also determine reflectivity

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

1 index

2 zero index

how?

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

but  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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  $\epsilon$  and  $\mu$  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

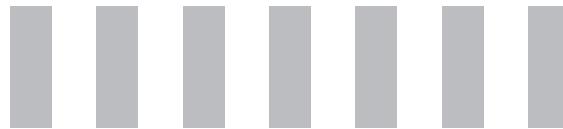
1 index

2 zero index

3 experiments

# Engineering a magnetic response

use array of dielectric rods



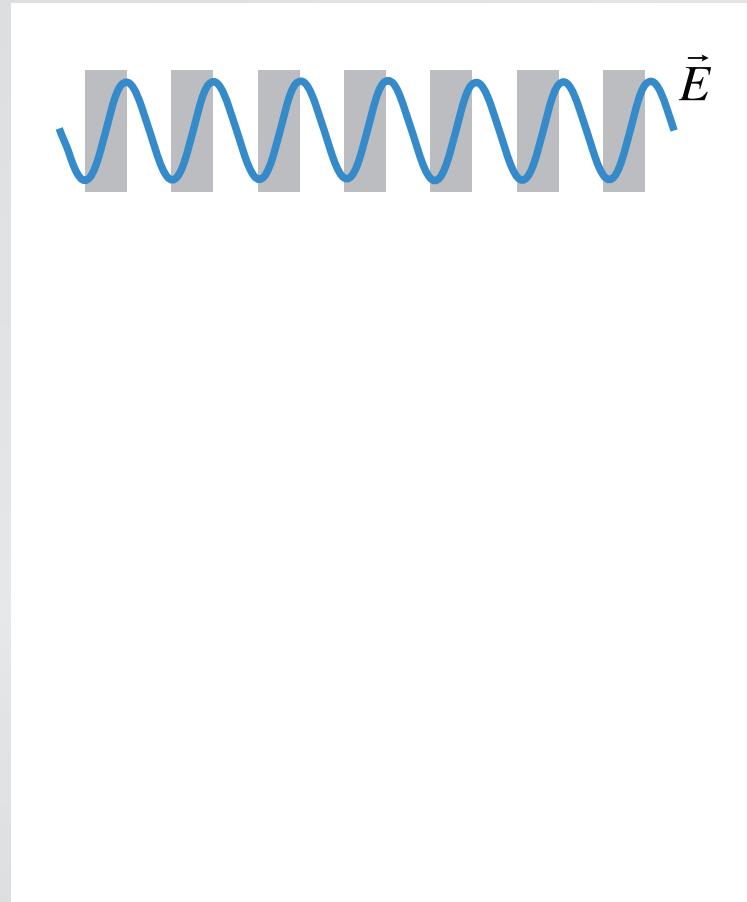
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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

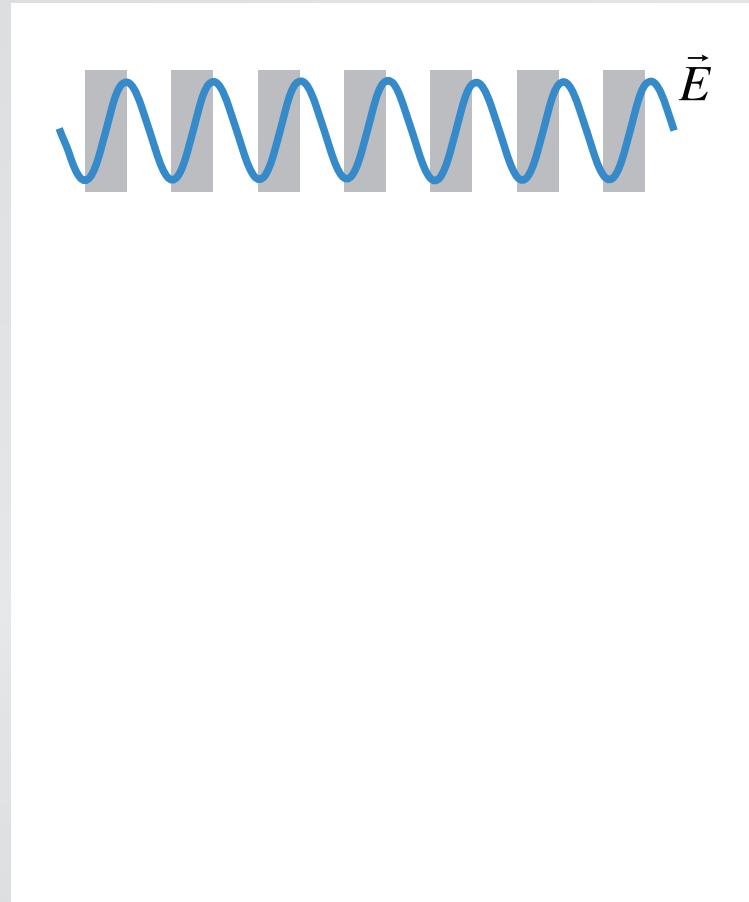


1 index

2 zero index

# Engineering a magnetic response

produces an electric response...



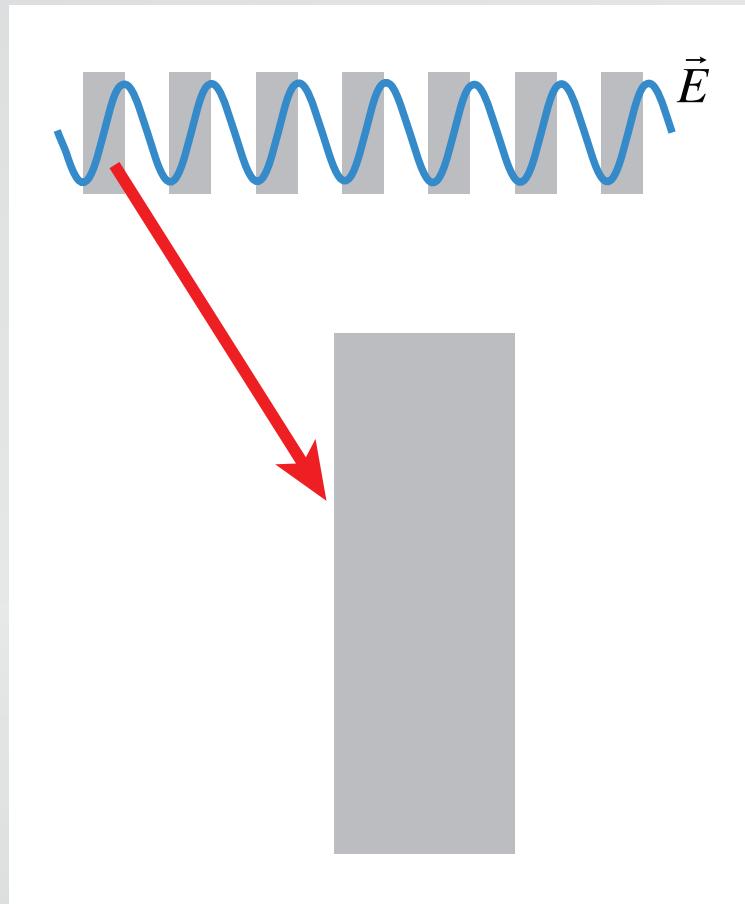
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



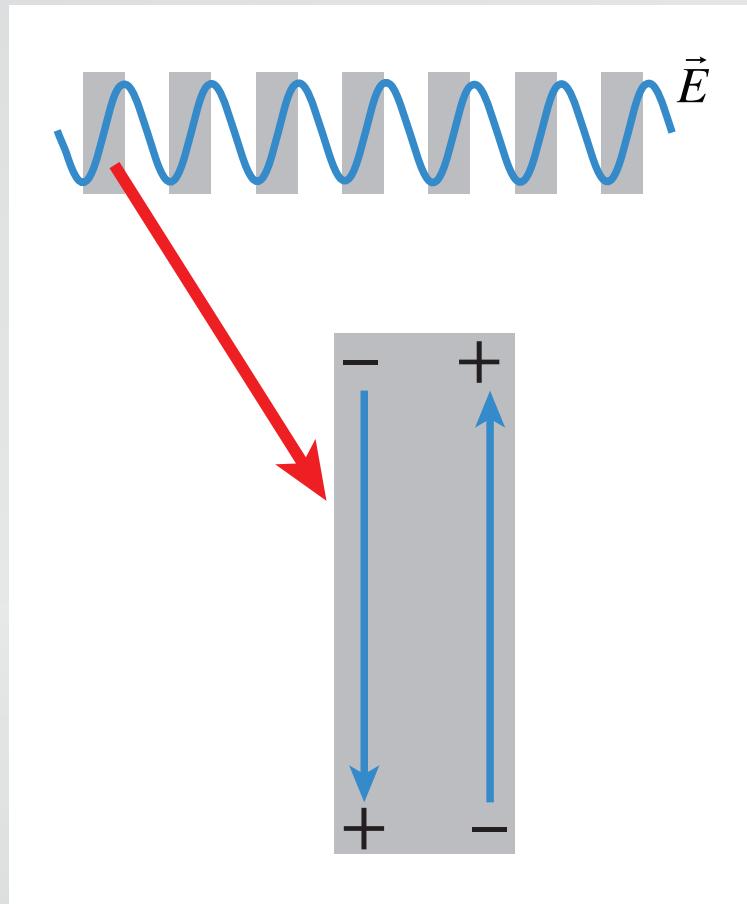
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



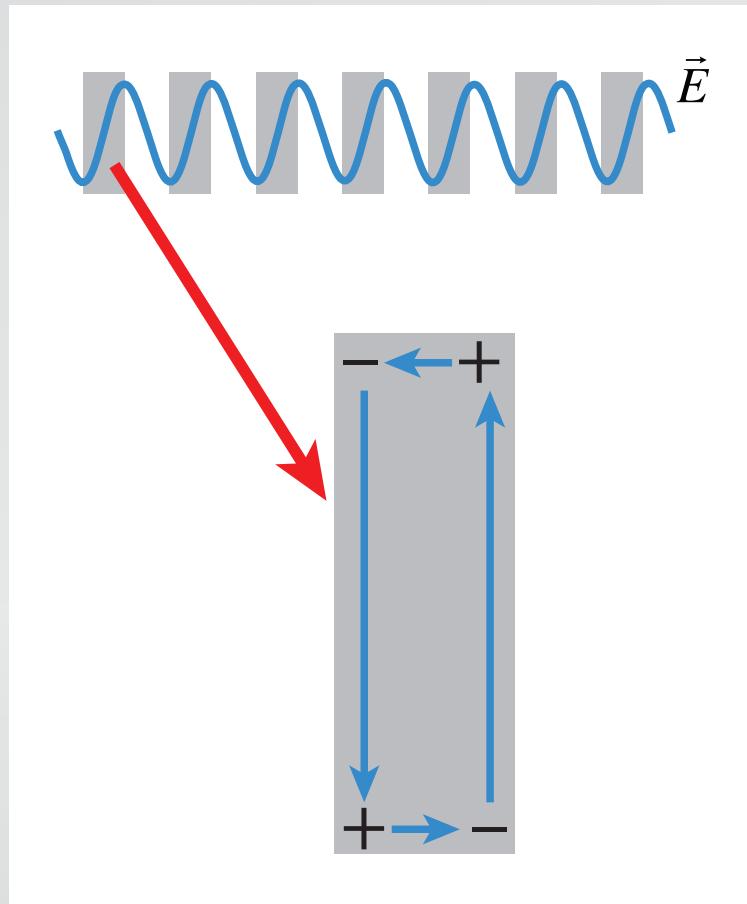
1 index

2 zero index

3 experiments

# Engineering a magnetic response

...causing a current loop...



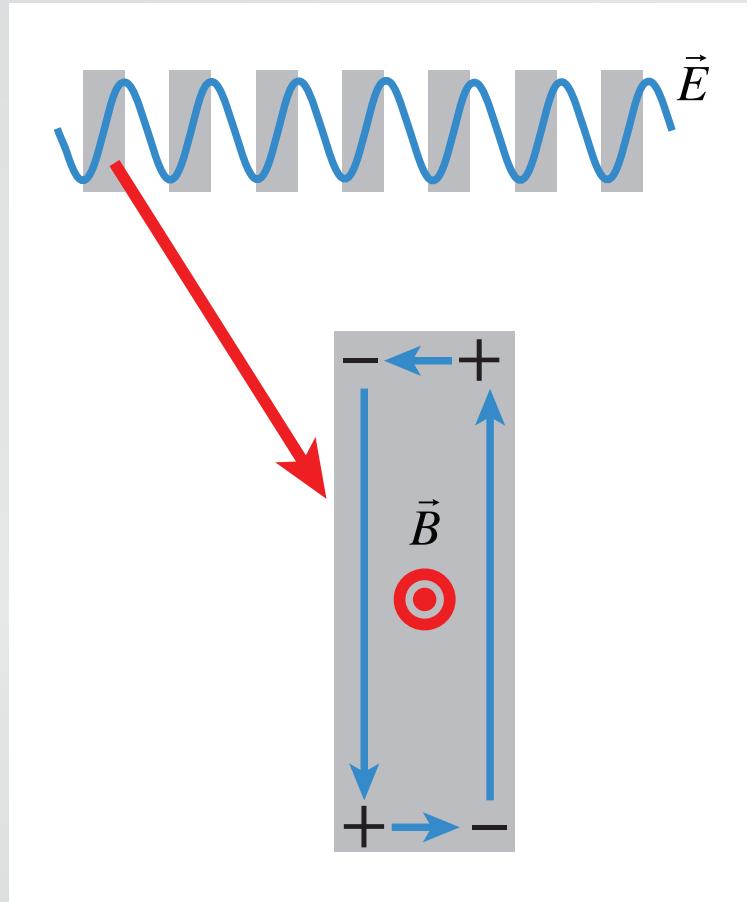
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



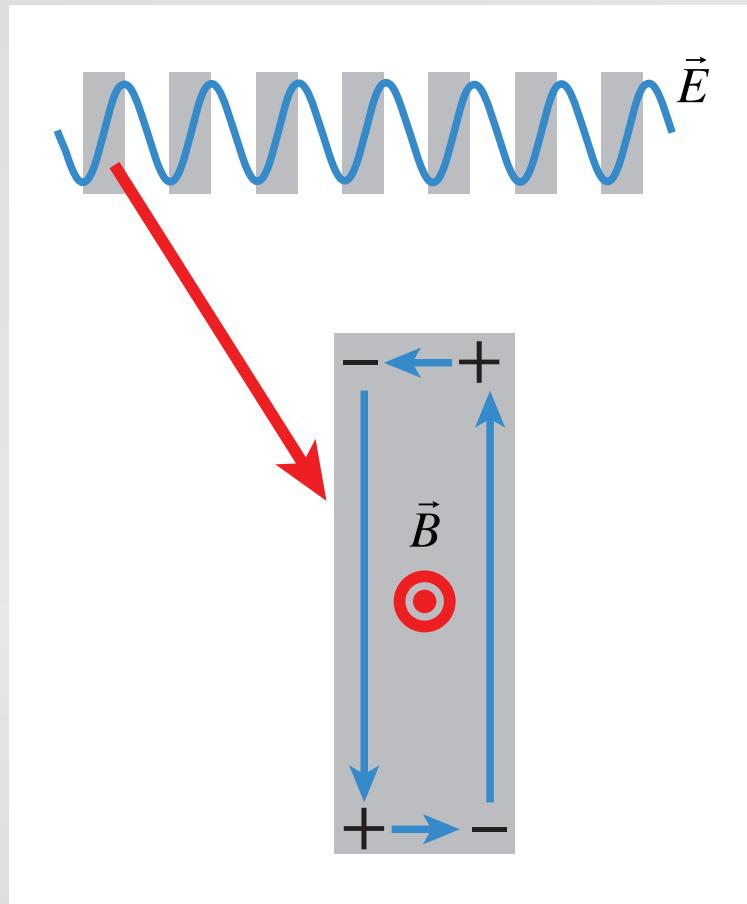
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide



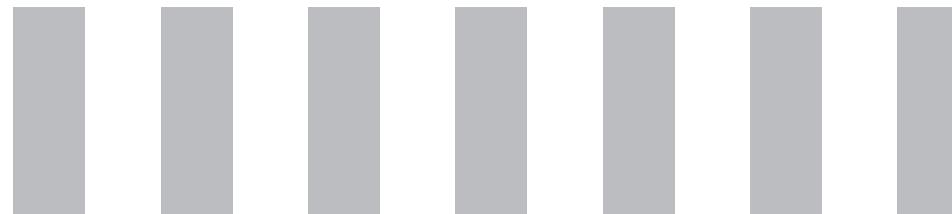
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



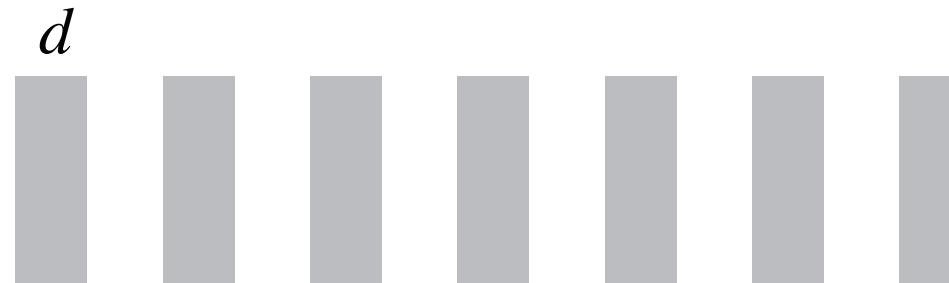
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



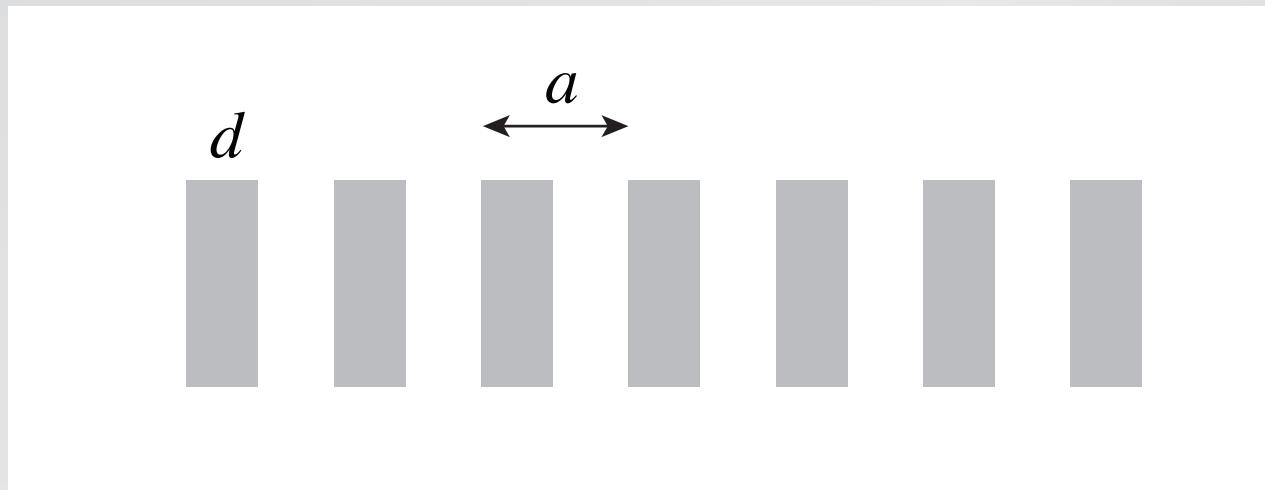
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



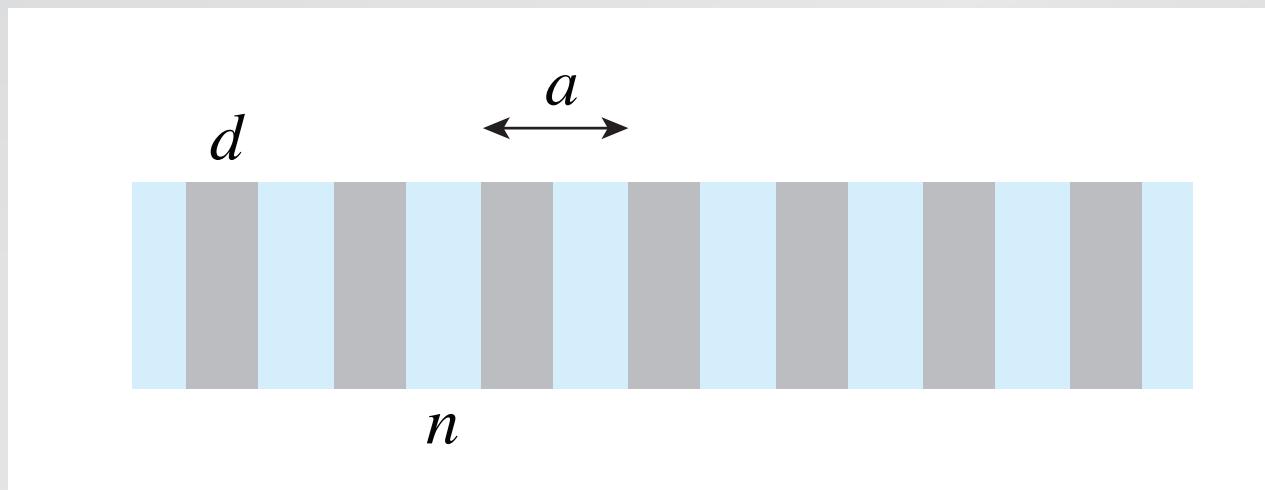
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



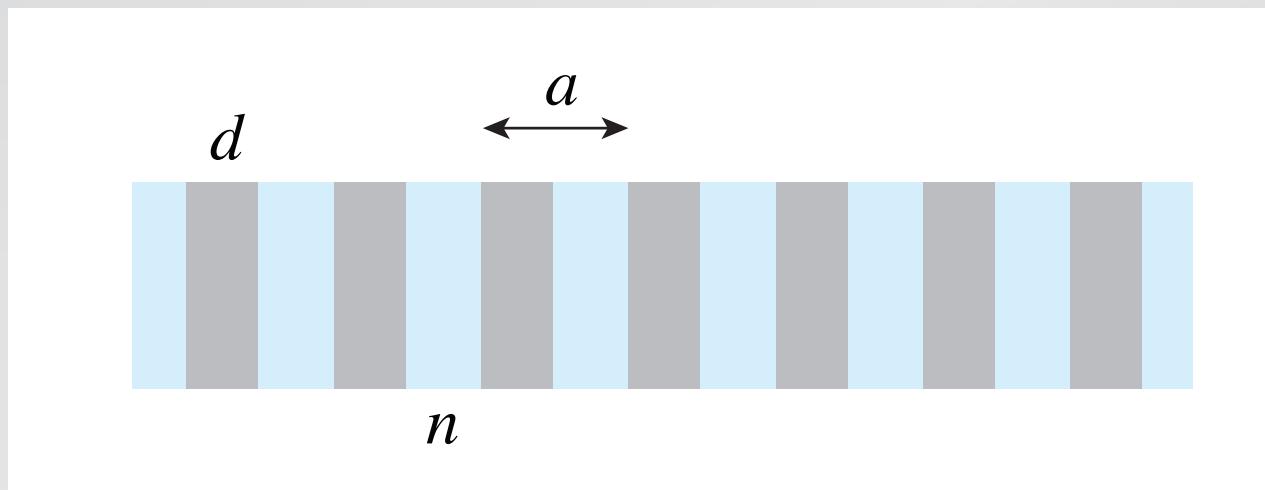
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters

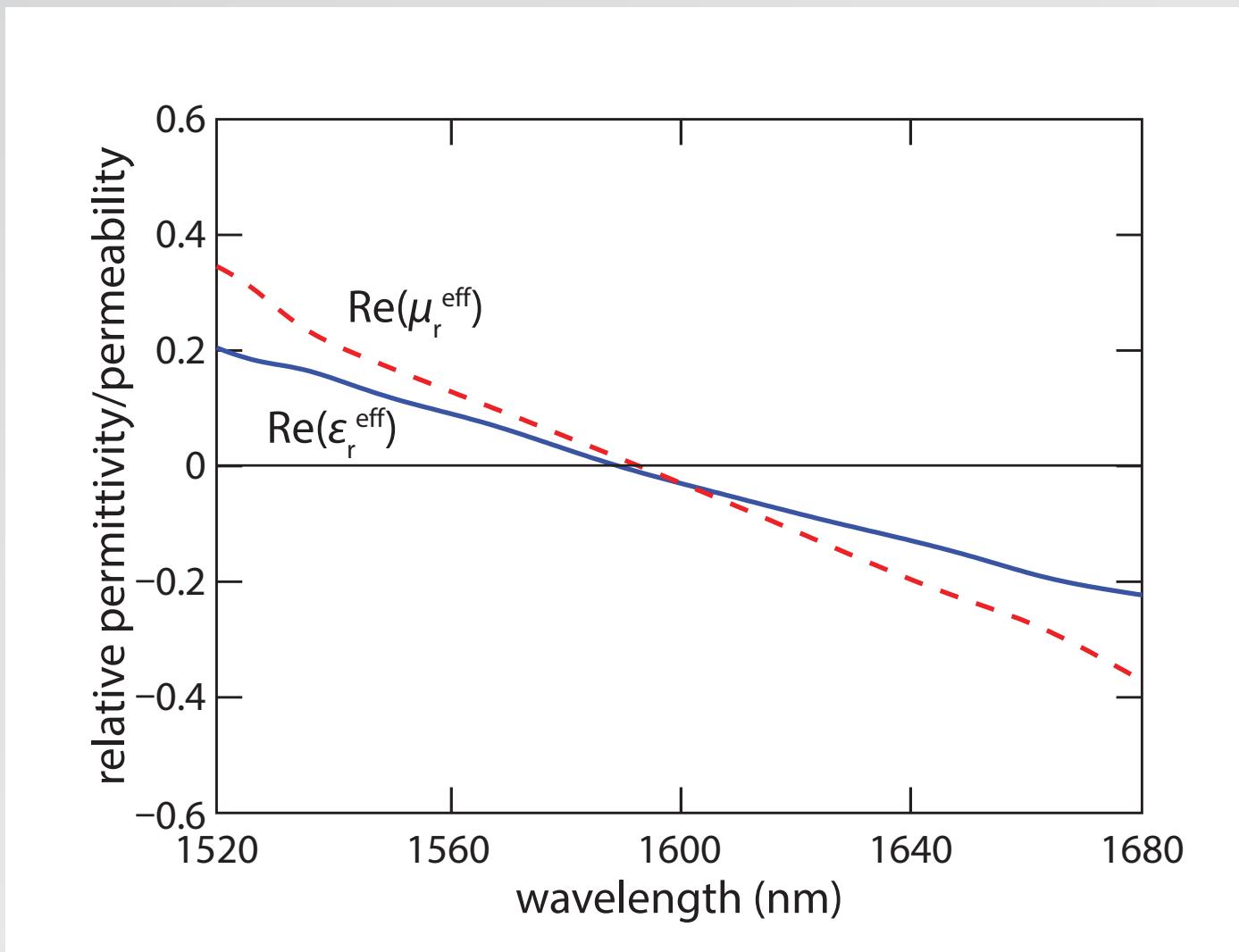


$$d = 422 \text{ nm}, \quad a = 690 \text{ nm}, \quad n = 1.57 \text{ (SU8)}$$

1 index

2 zero index

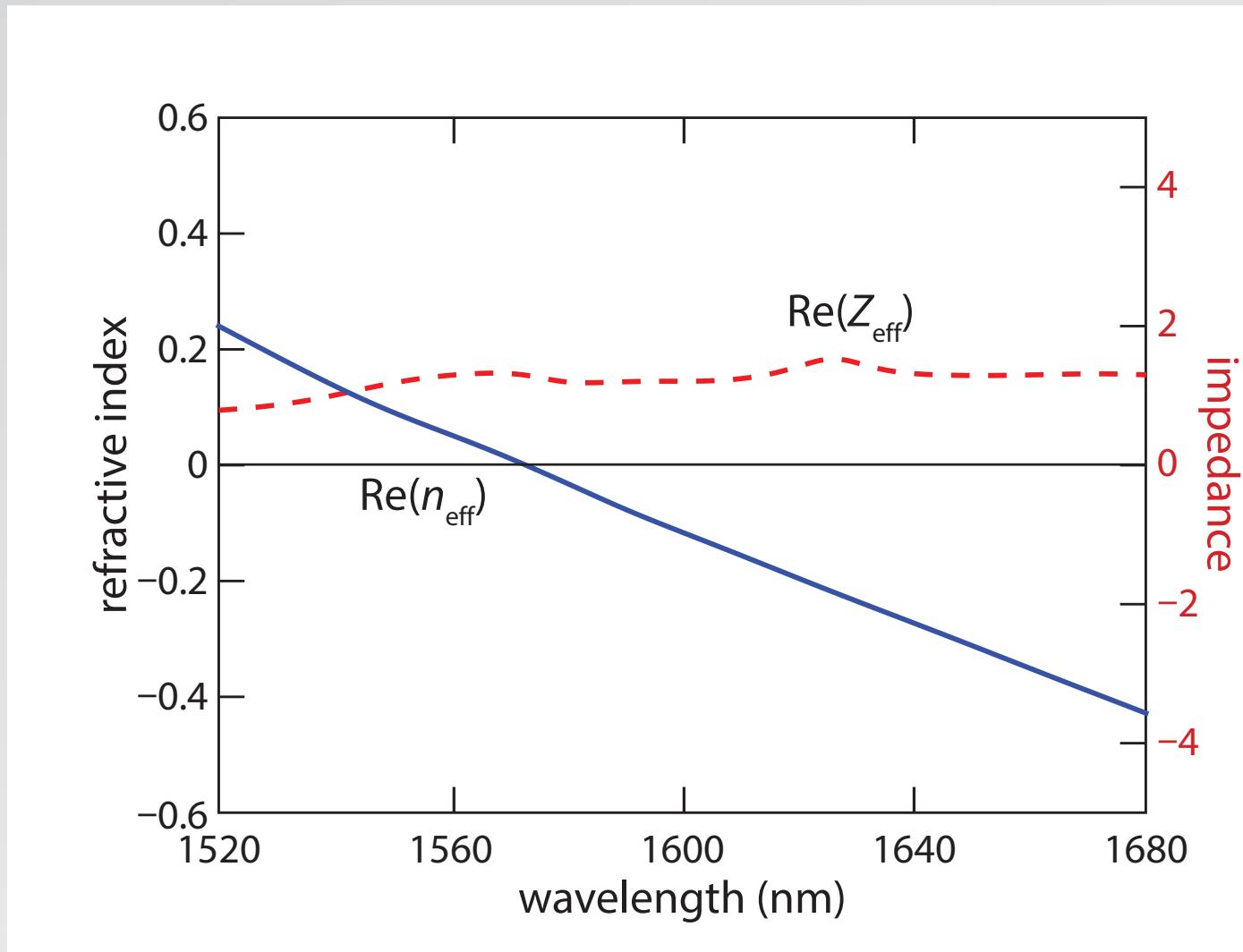
3 experiments



1 index

2 zero index

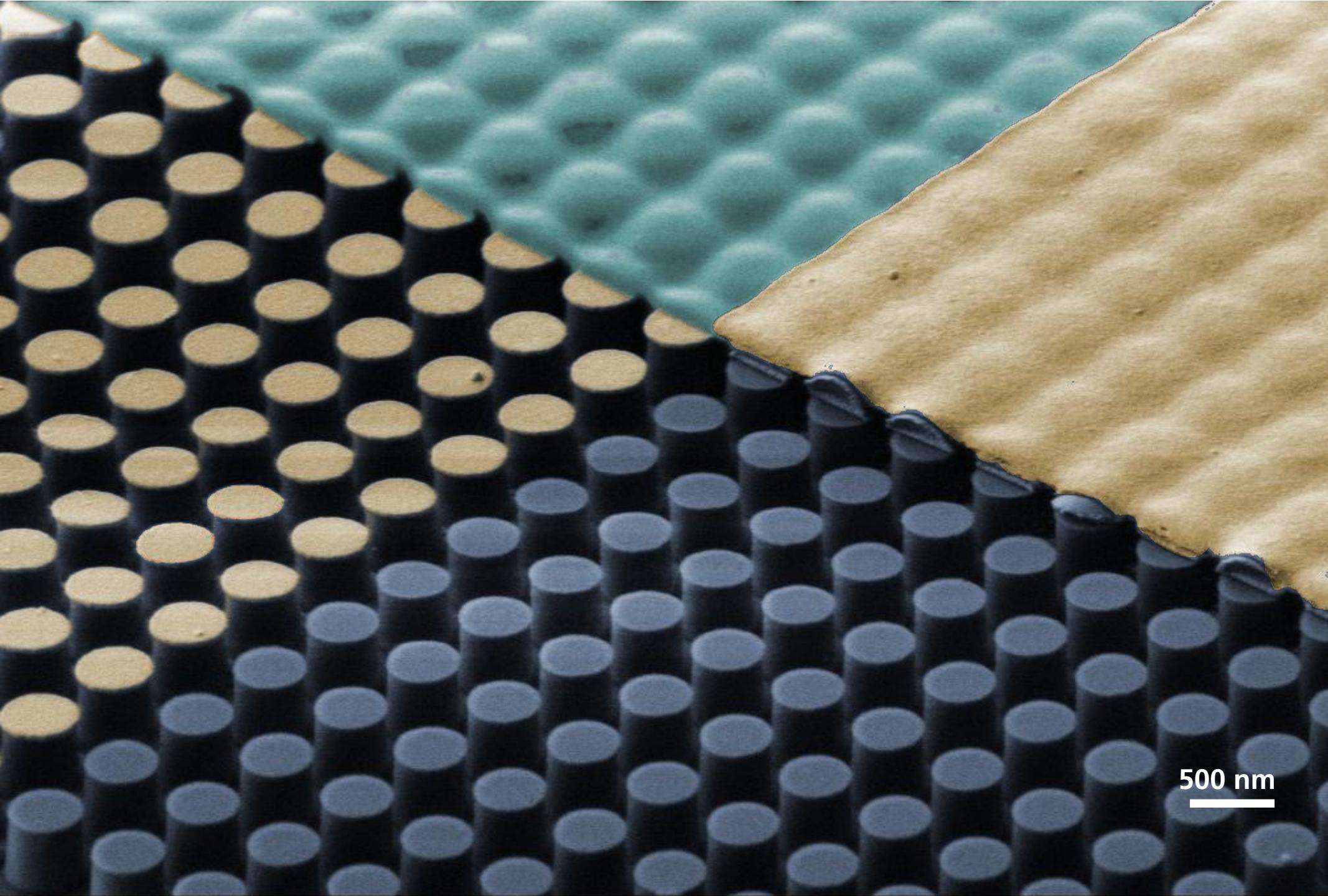
3 experiments



1 index

2 zero index

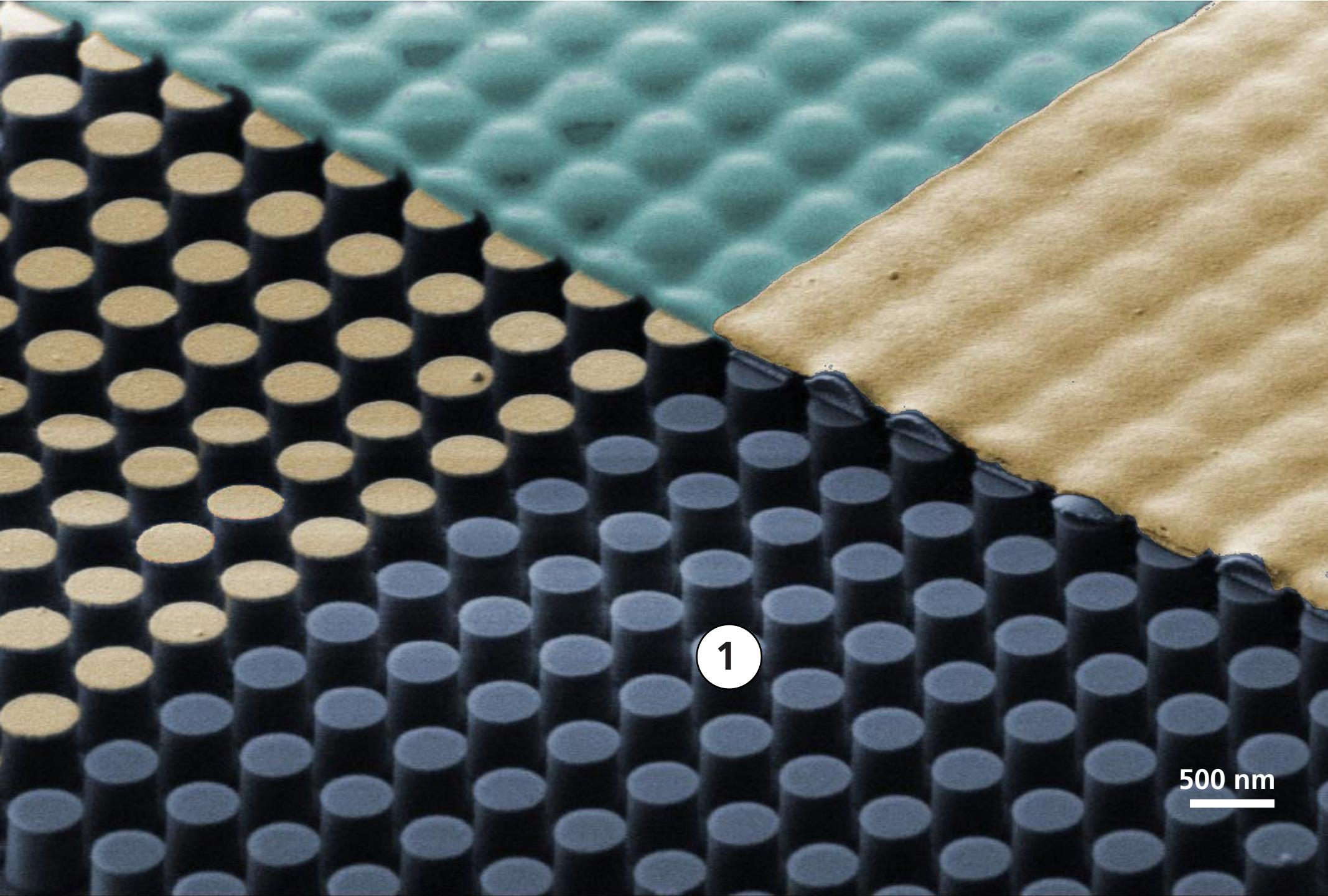
3 experiments



1 index

2 zero index

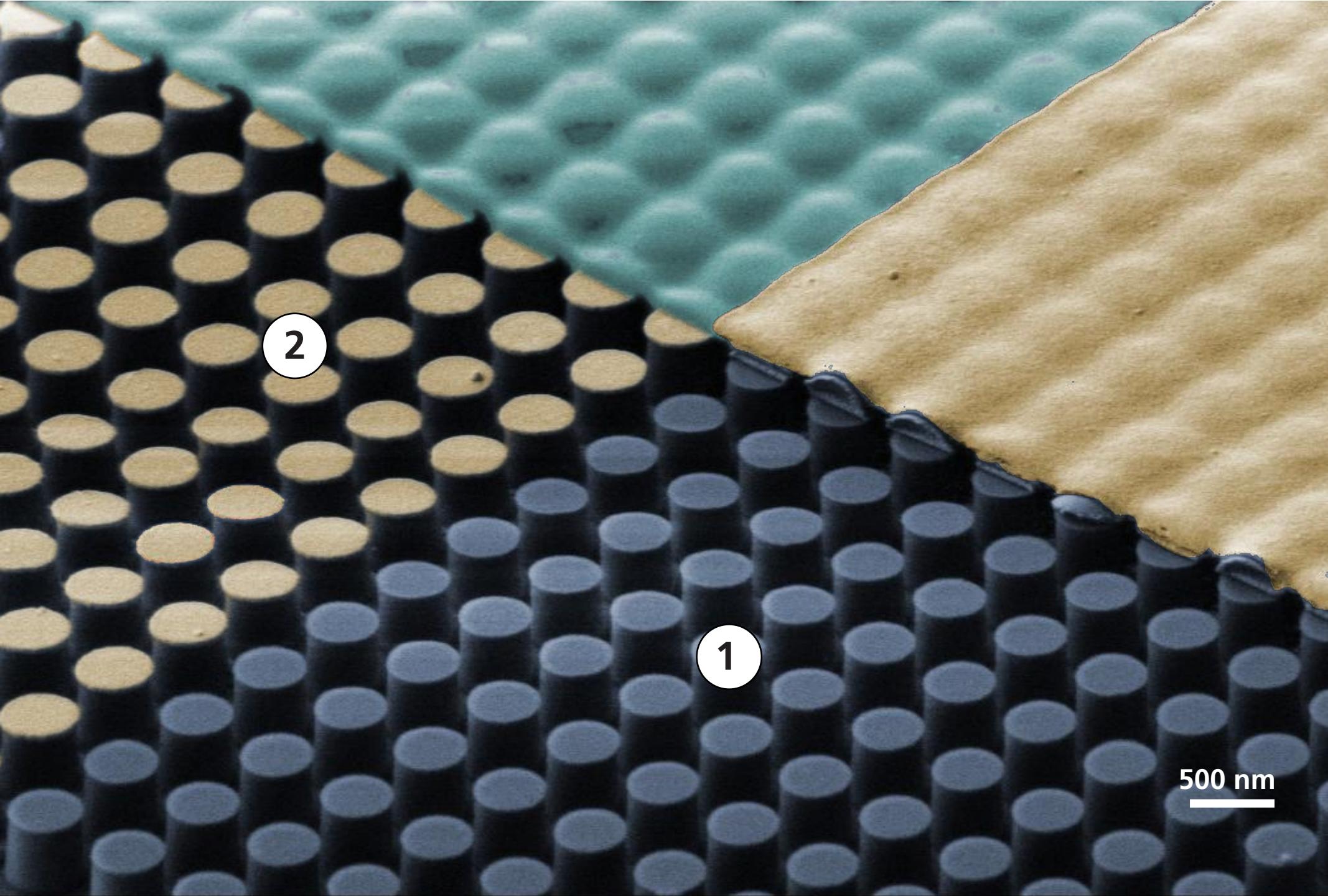
3 experiments



1 index

2 zero index

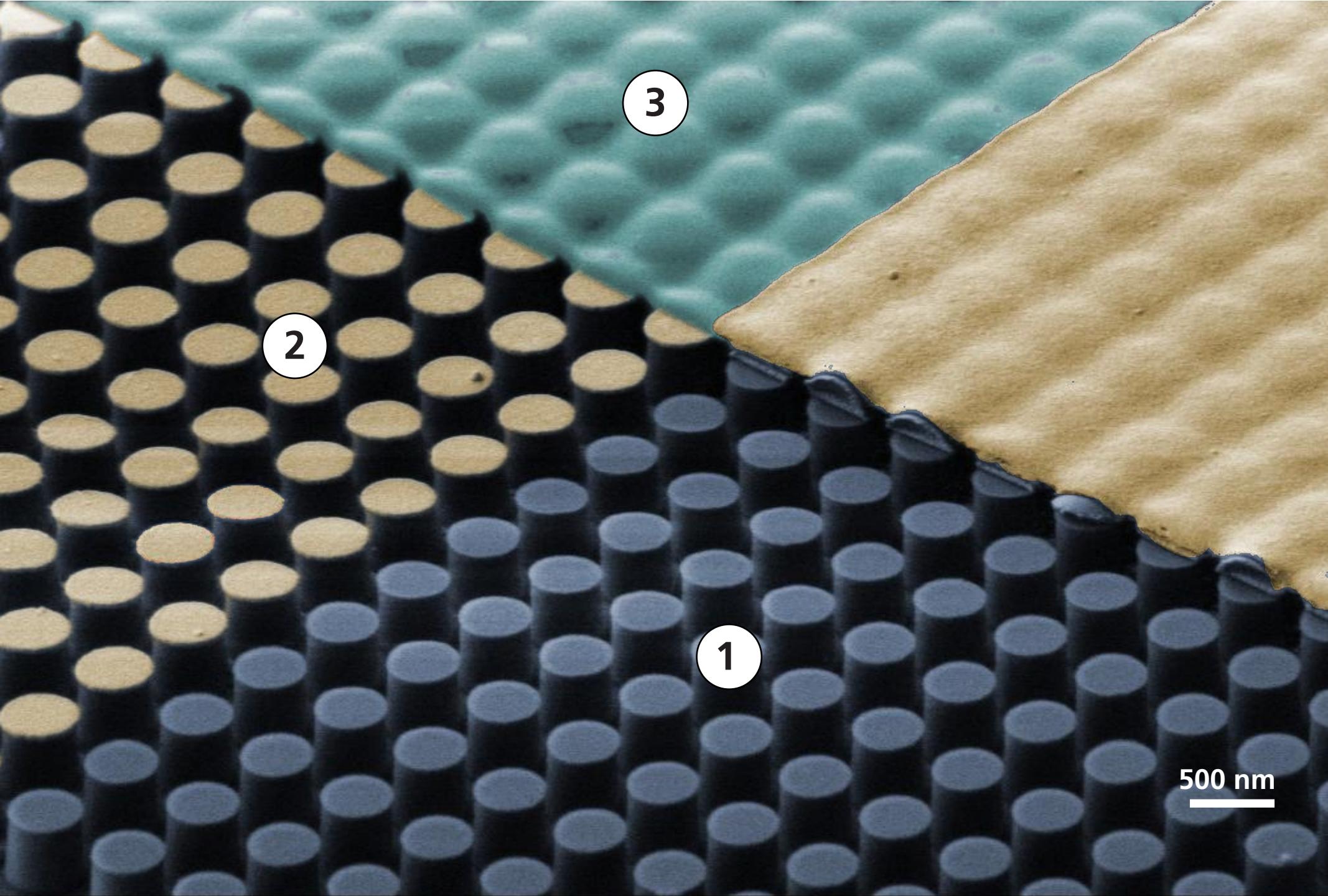
3 experiments



1 index

2 zero index

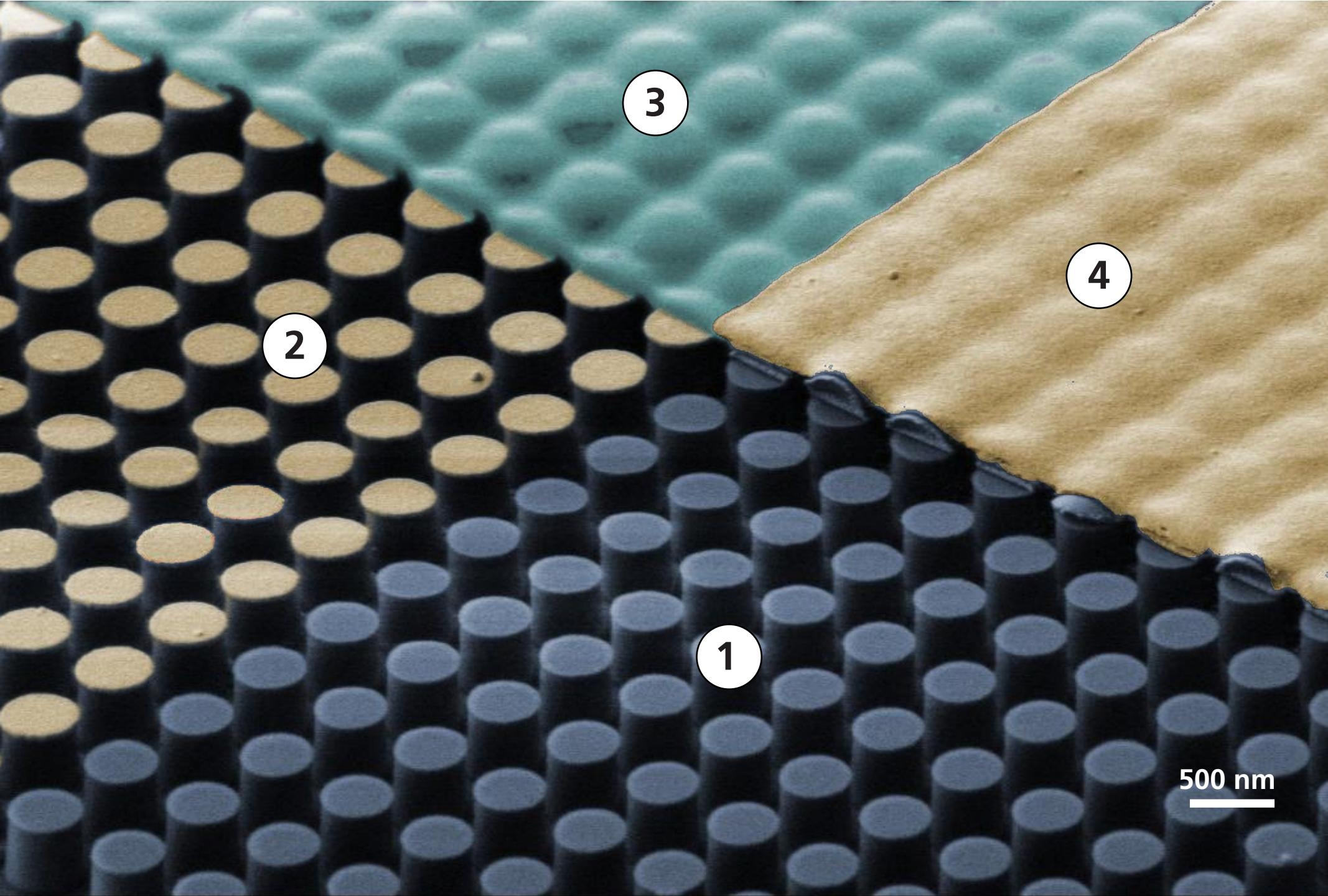
3 experiments



1 index

2 zero index

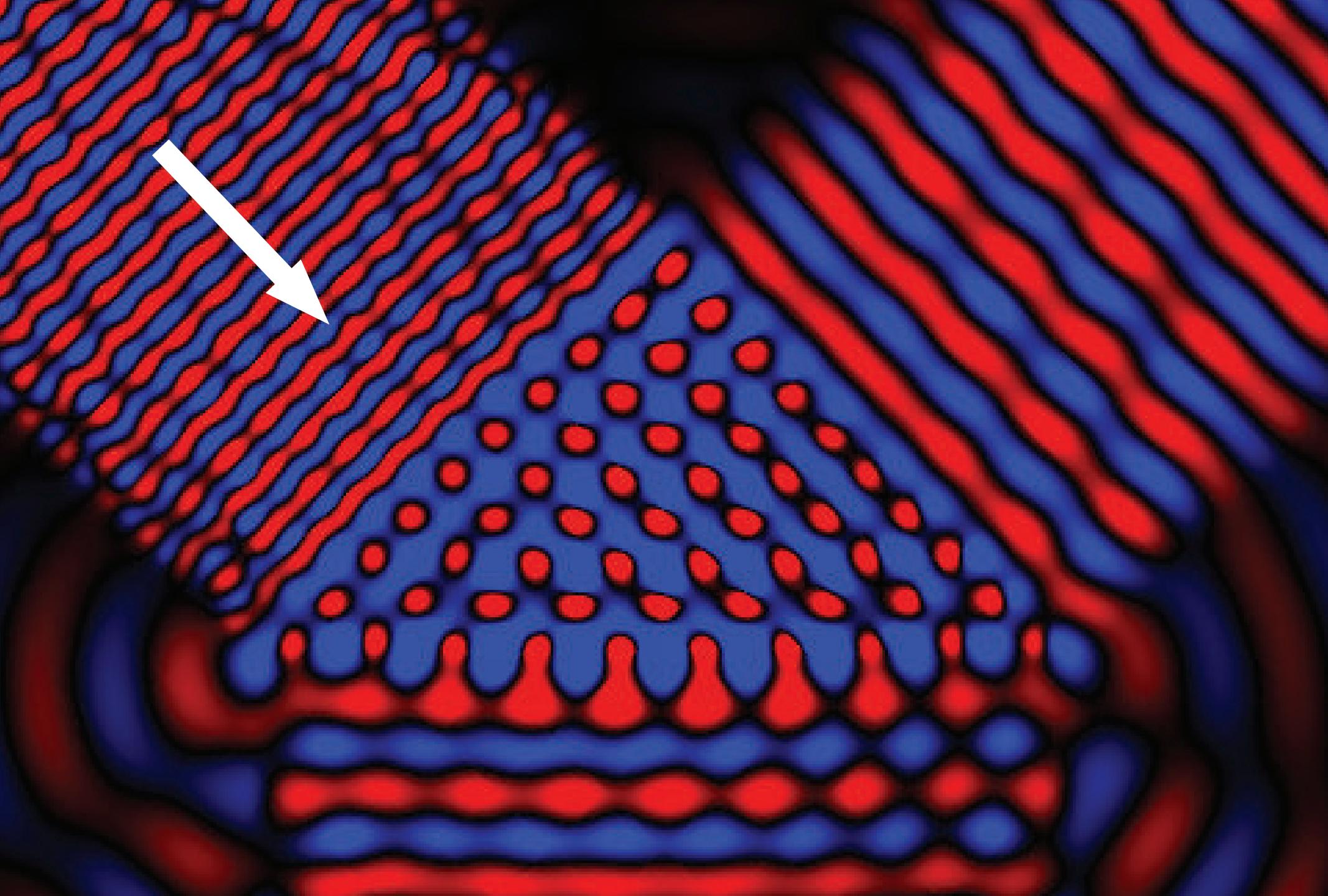
3 experiments



1 index

2 zero index

3 experiments



1 index

2 zero index

3 experiments

# On-chip zero-index prism

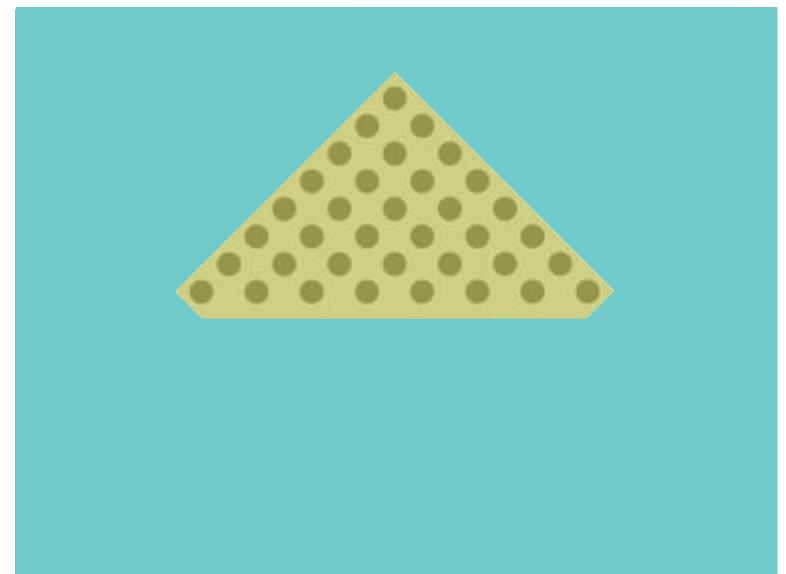


1 index

2 zero index

3 experiments

# On-chip zero-index prism

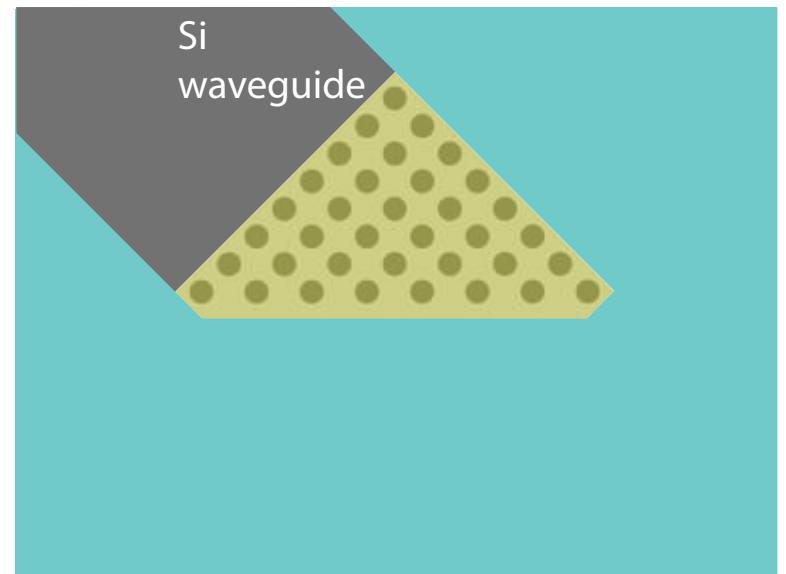


1 index

2 zero index

3 experiments

# On-chip zero-index prism

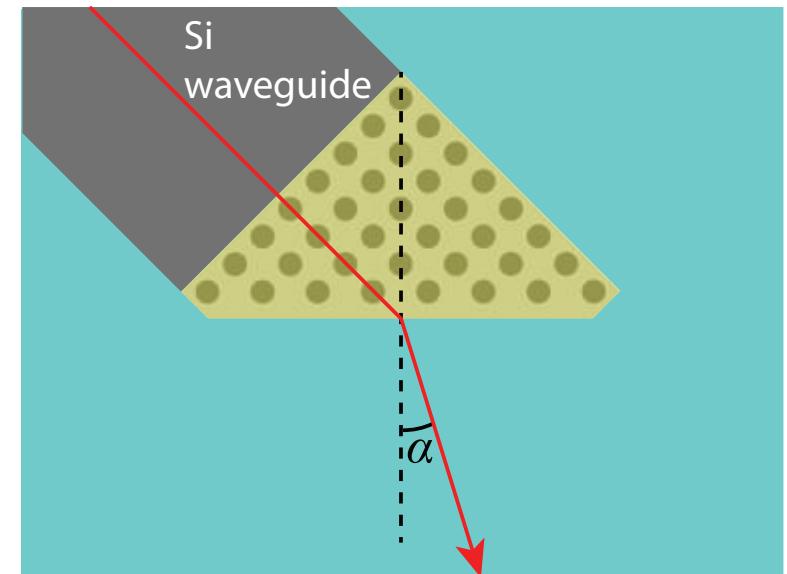


1 index

2 zero index

3 experiments

# On-chip zero-index prism

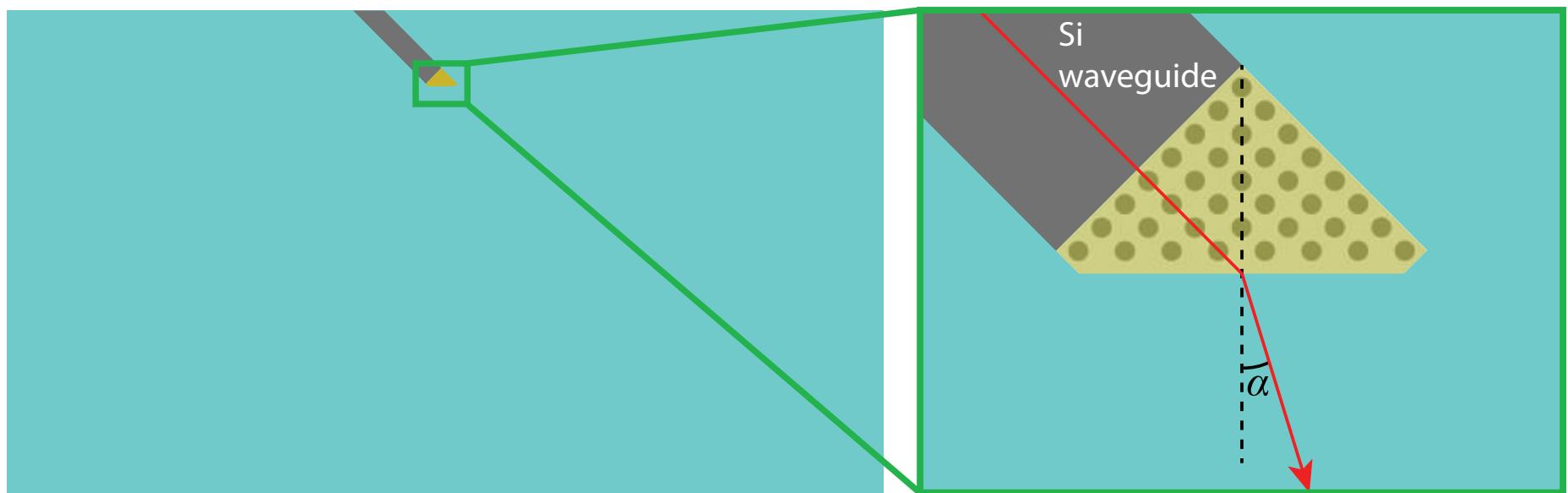


1 index

2 zero index

3 experiments

# On-chip zero-index prism

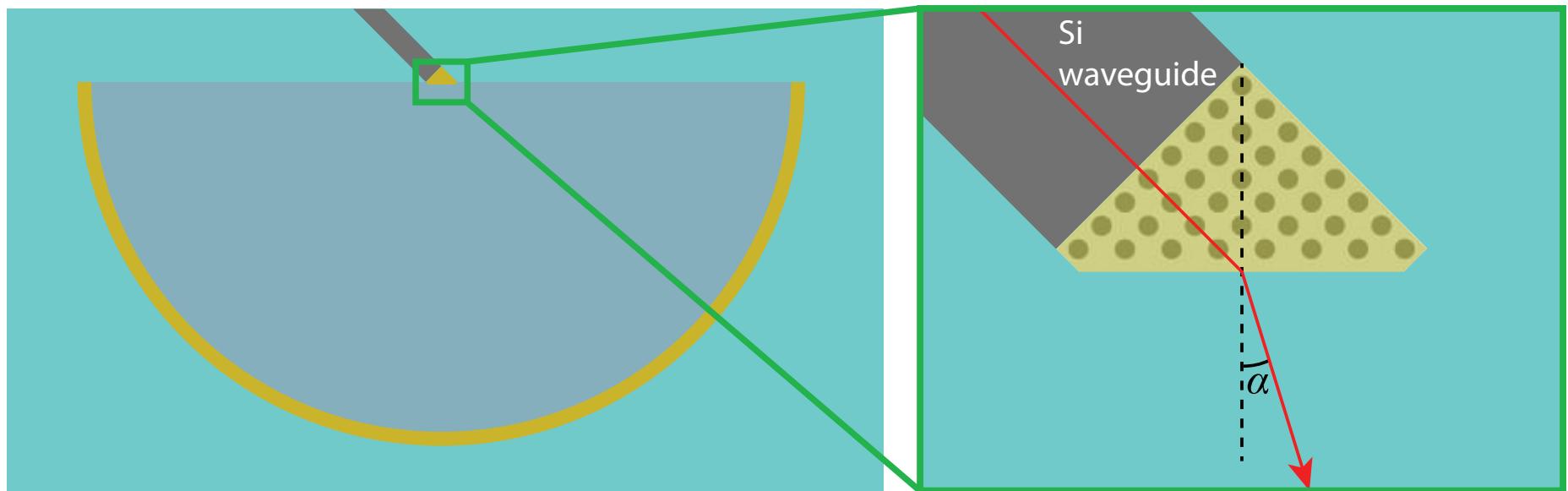


1 index

2 zero index

3 experiments

# On-chip zero-index prism

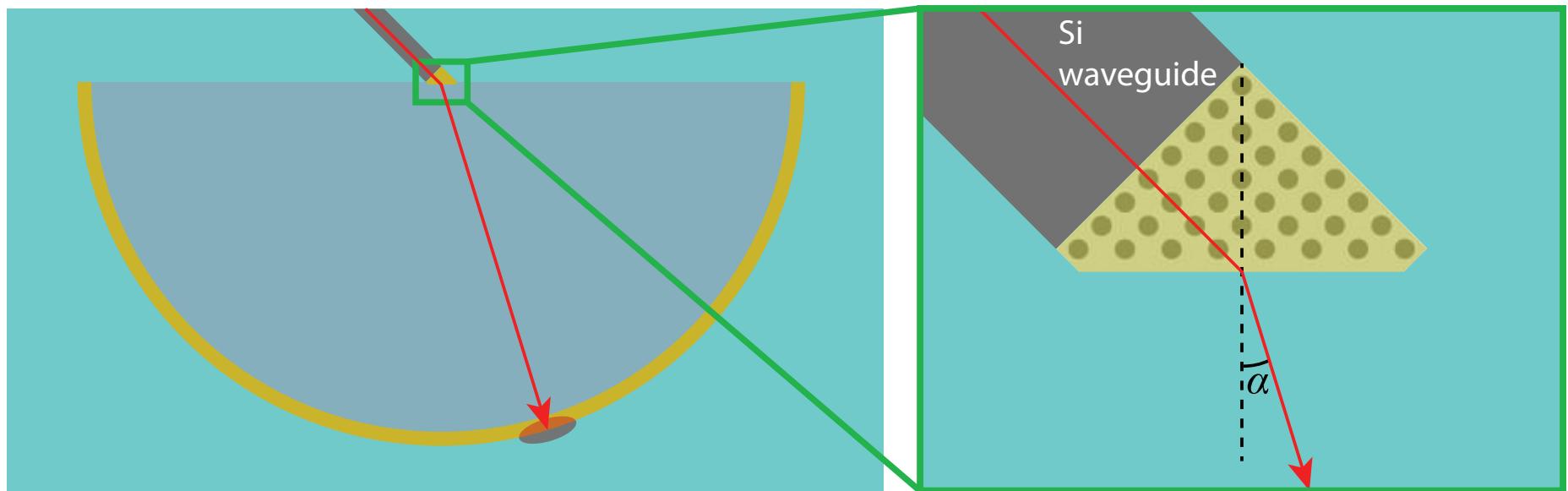


1 index

2 zero index

3 experiments

# On-chip zero-index prism

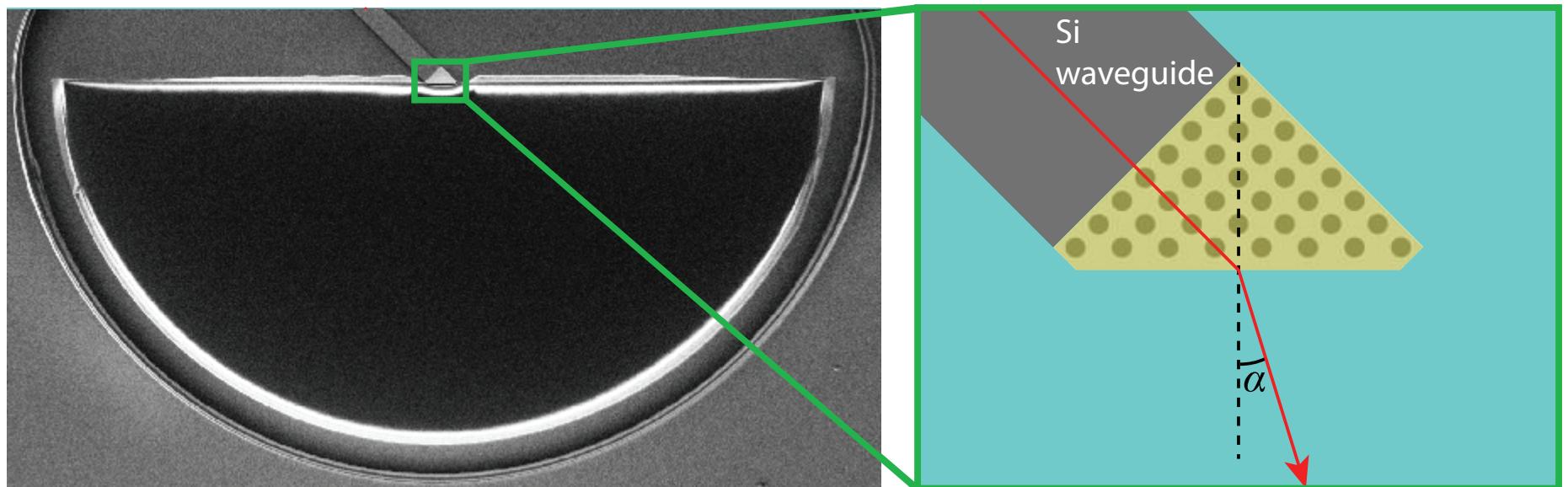


1 index

2 zero index

3 experiments

# On-chip zero-index prism

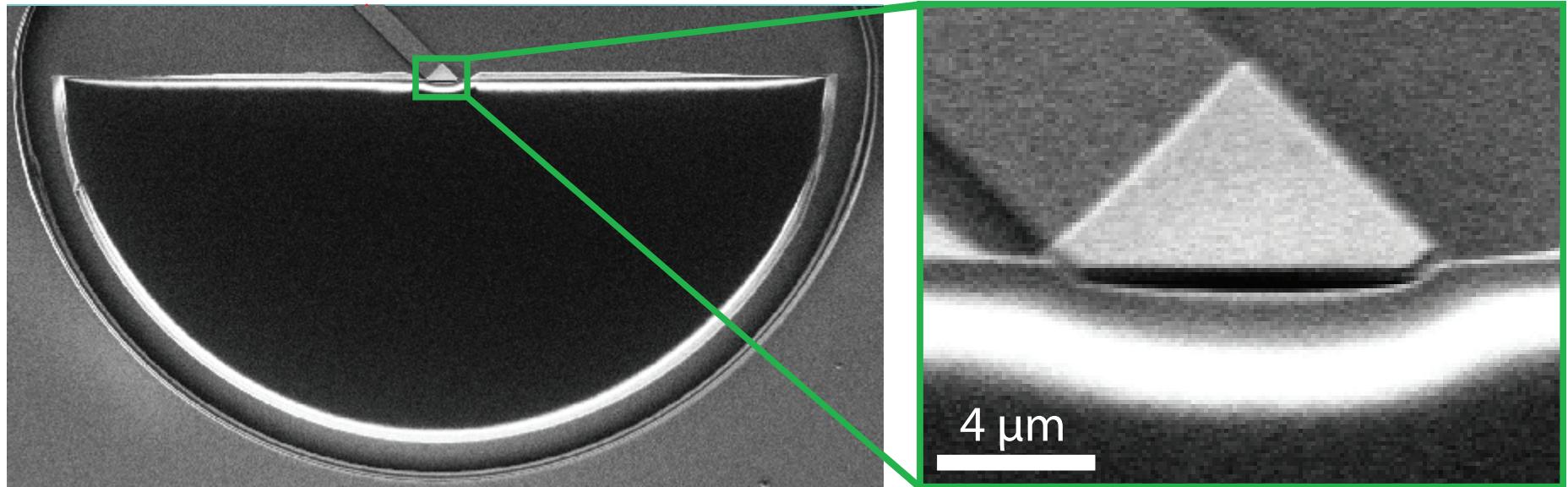


1 index

2 zero index

3 experiments

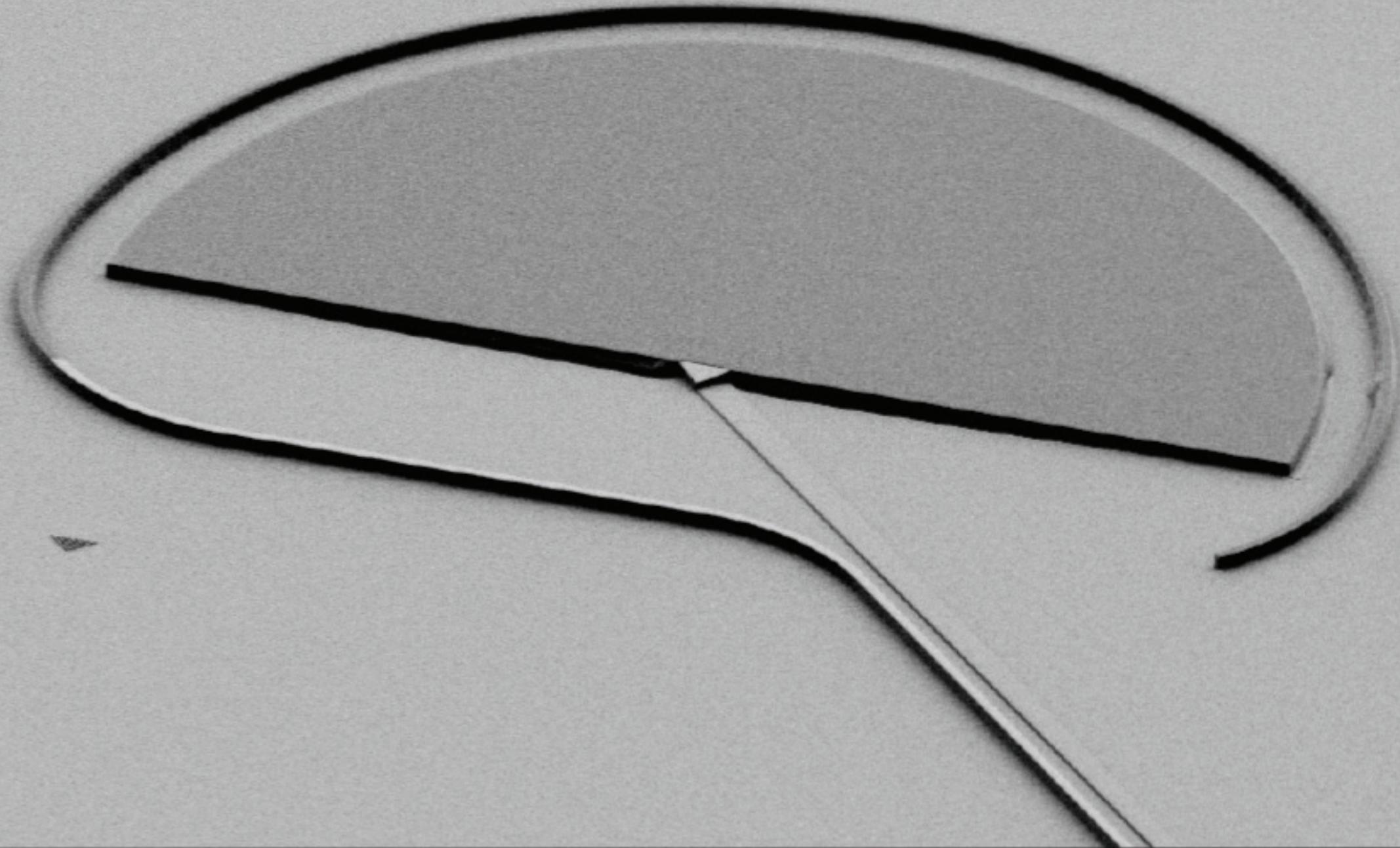
# On-chip zero-index prism



1 index

2 zero index

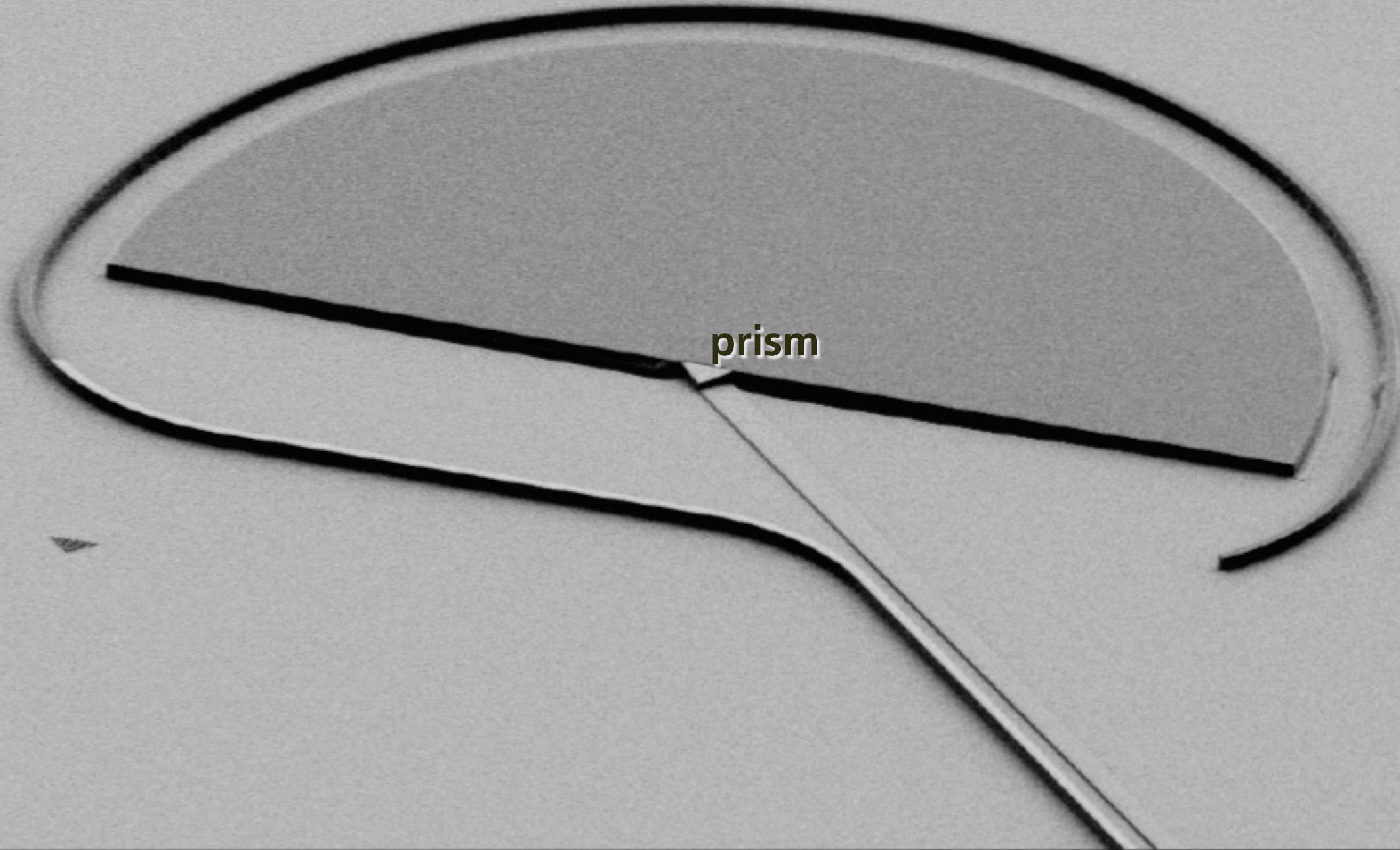
3 experiments



1 index

2 zero index

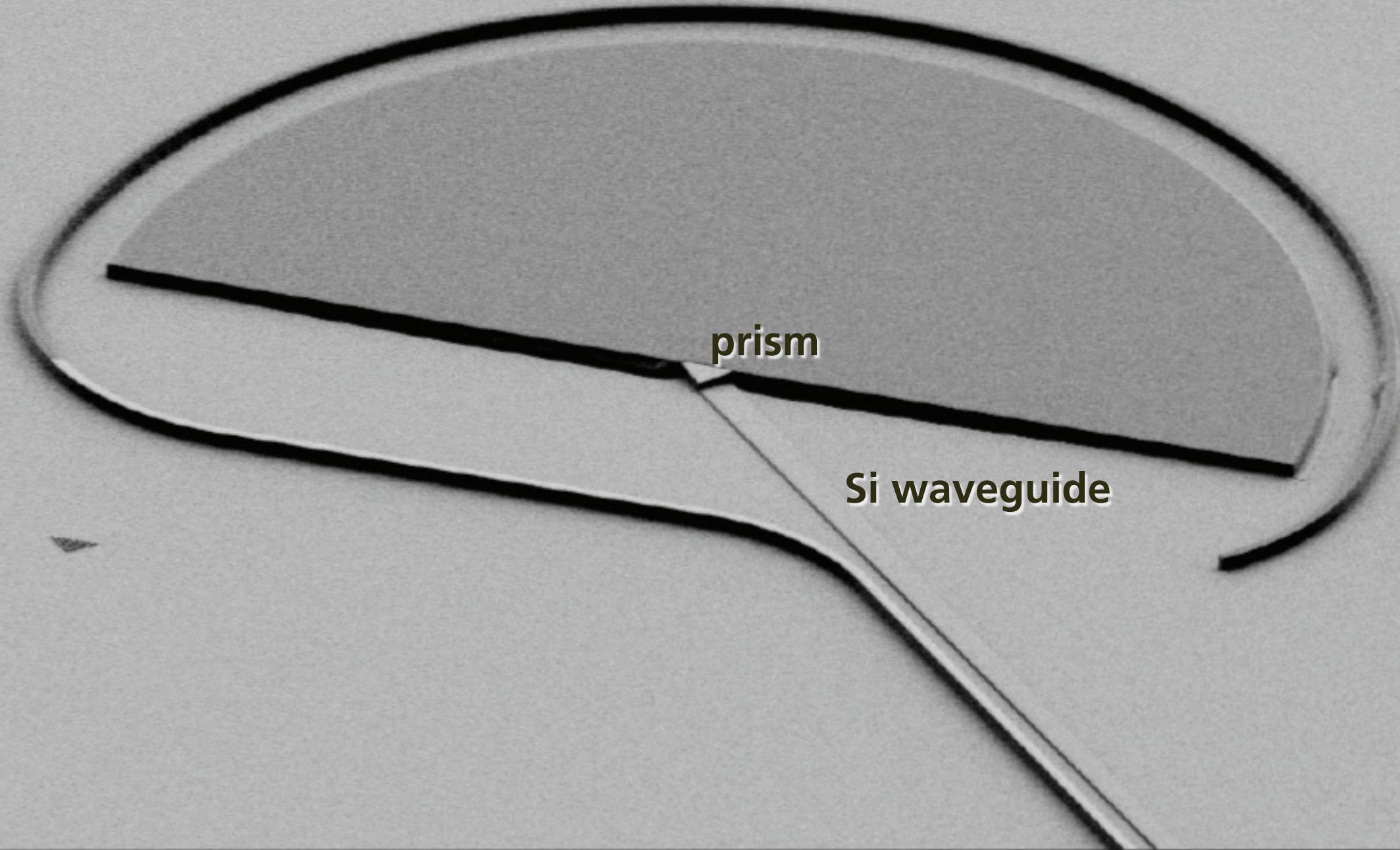
3 experiments



1 index

2 zero index

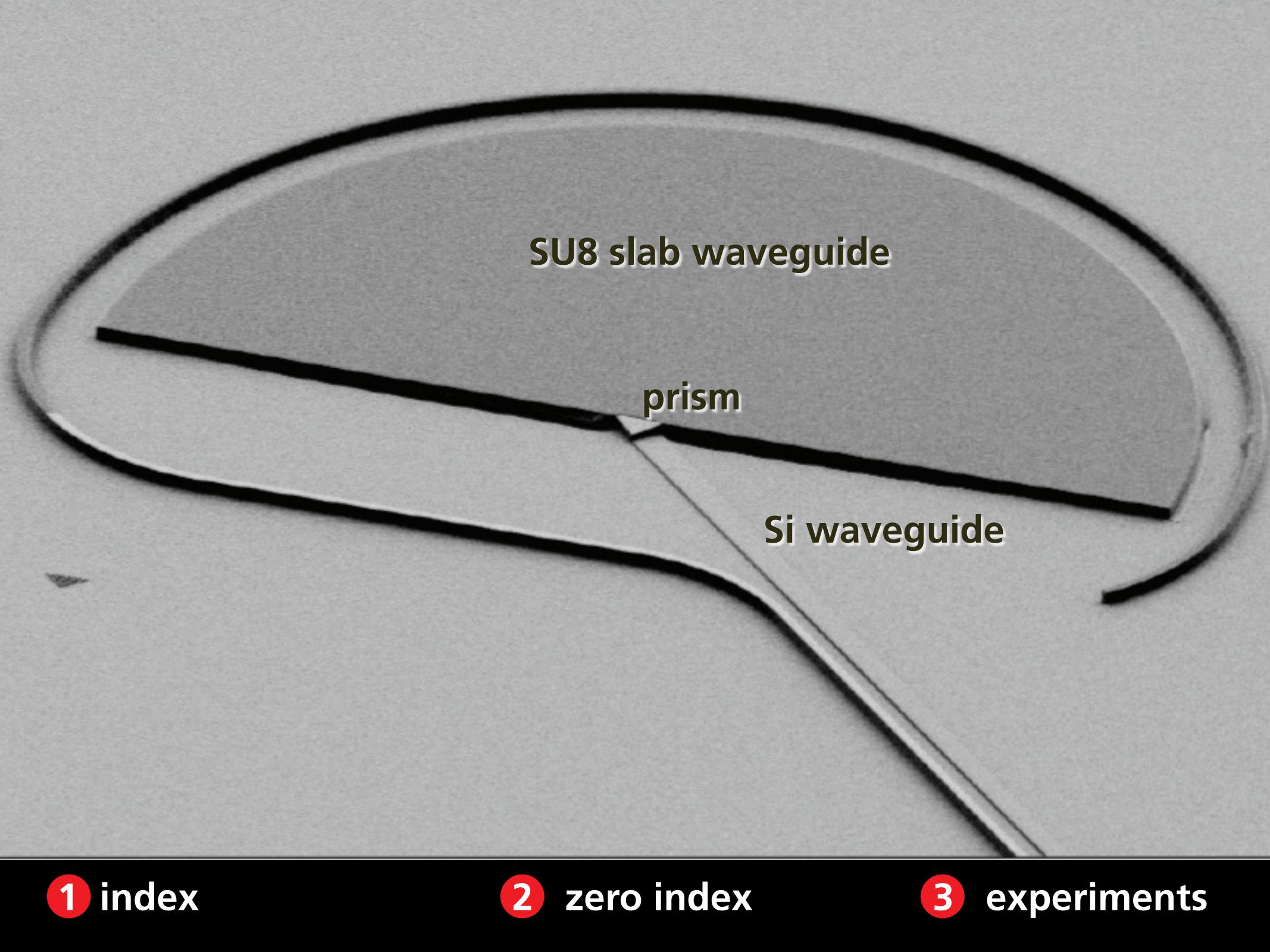
3 experiments



1 index

2 zero index

3 experiments



SU8 slab waveguide

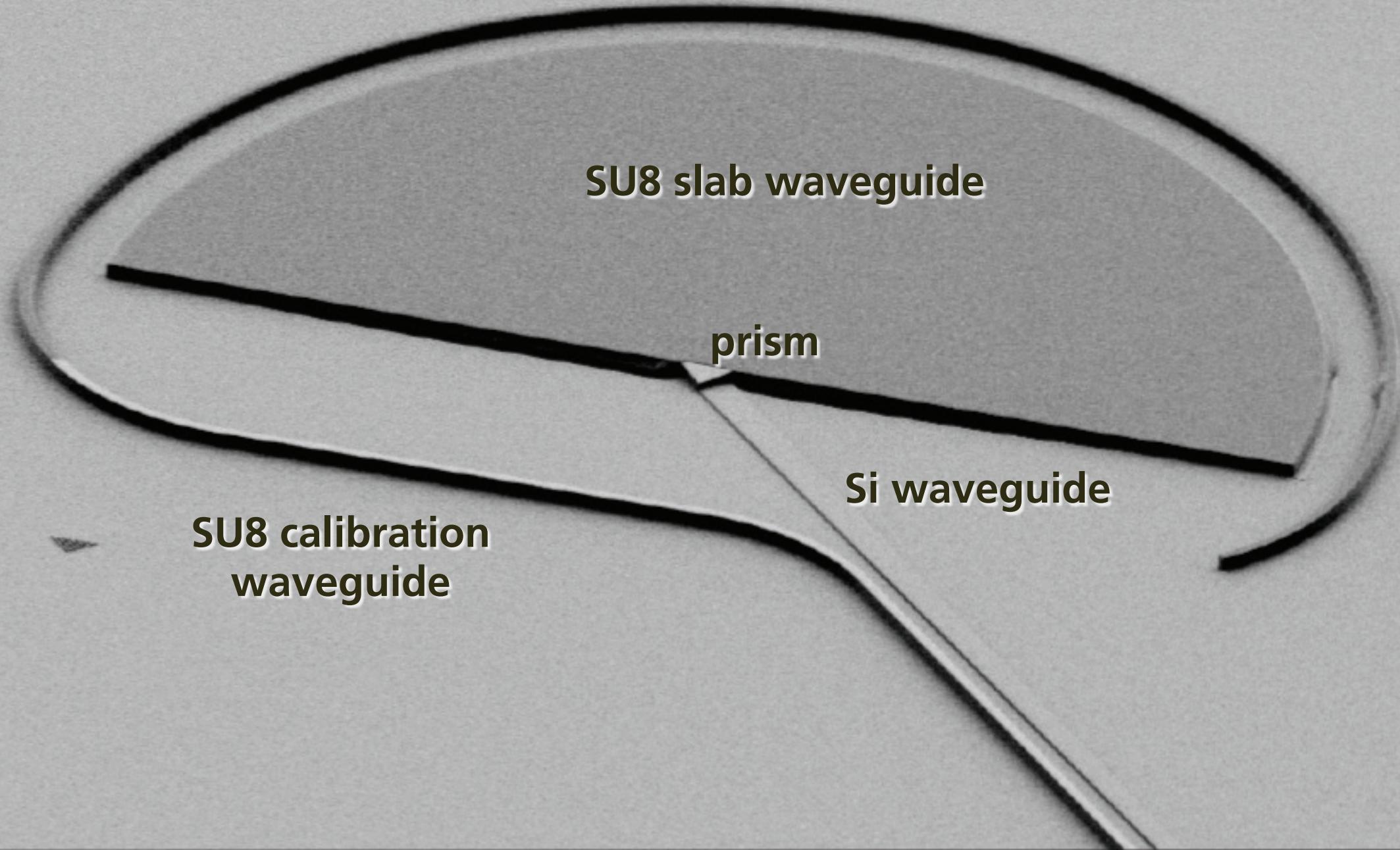
prism

Si waveguide

1 index

2 zero index

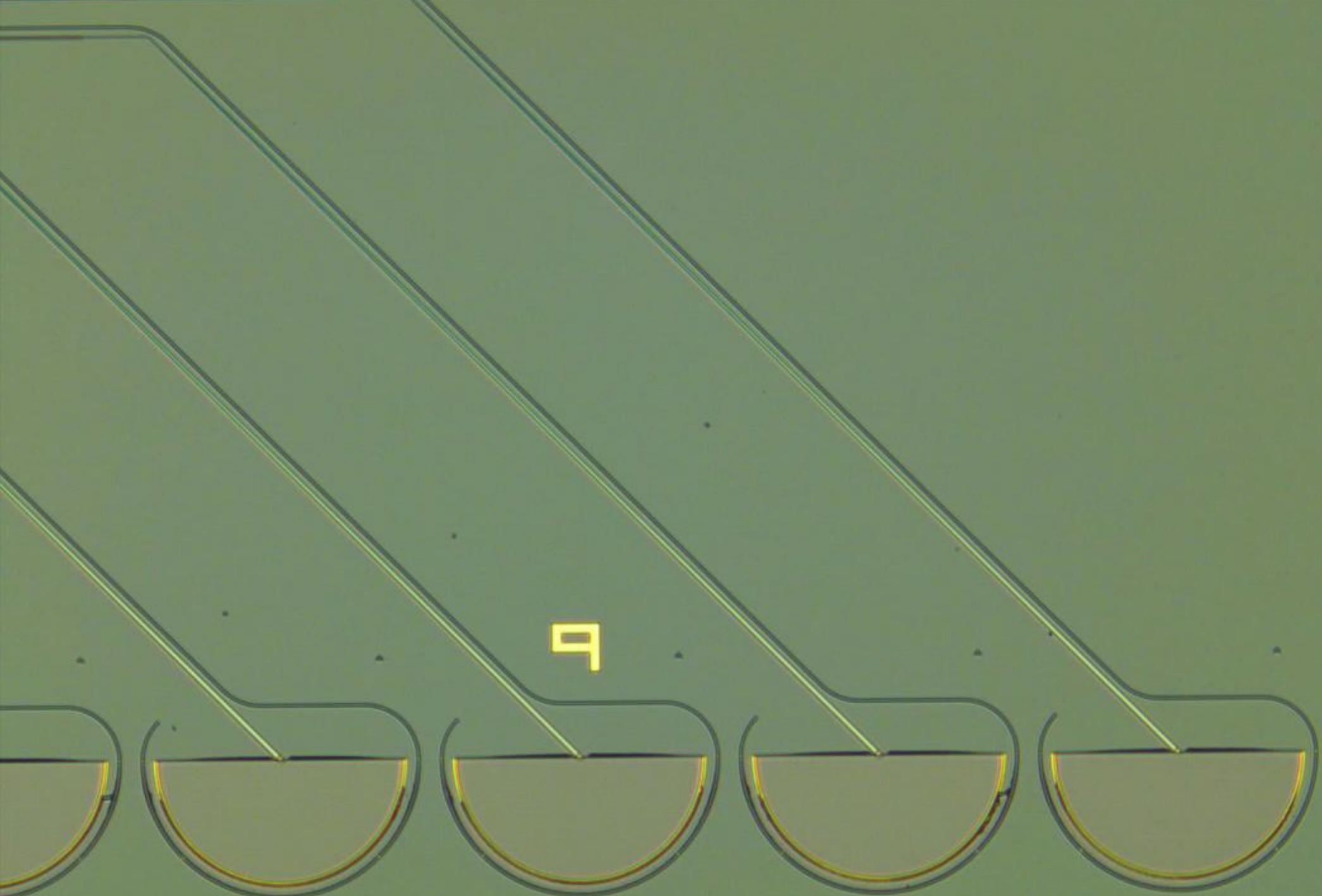
3 experiments



**1** index

**2** zero index

**3** experiments

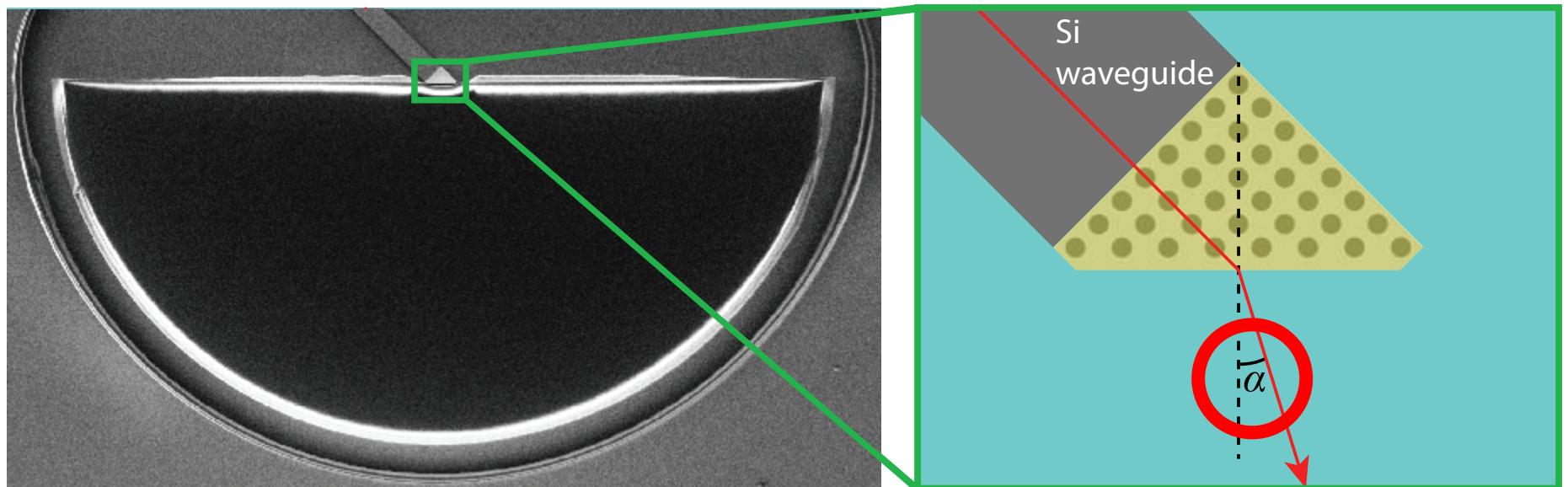


1 index

2 zero index

3 experiments

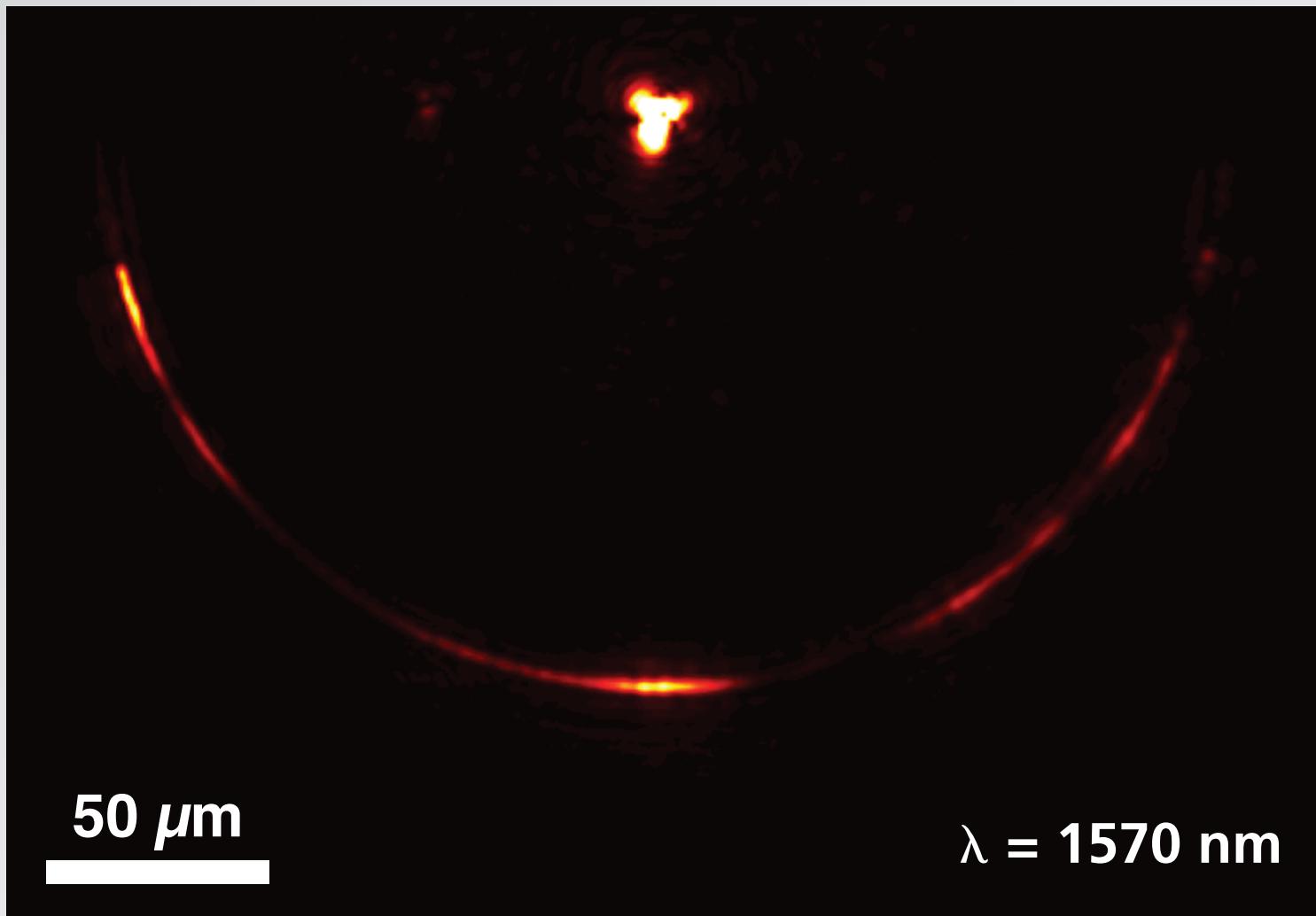
# On-chip zero-index prism



1 index

2 zero index

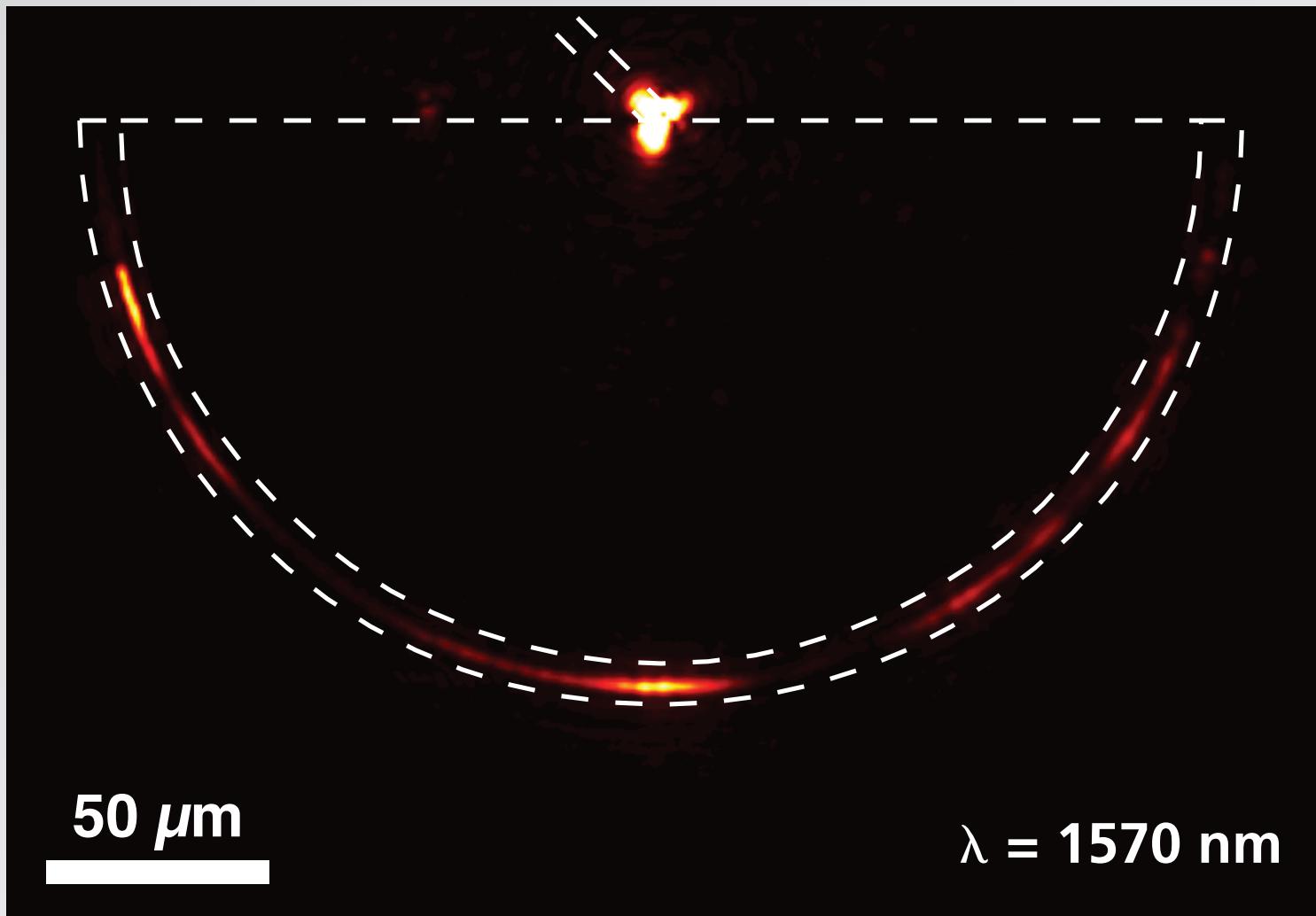
3 experiments



1 index

2 zero index

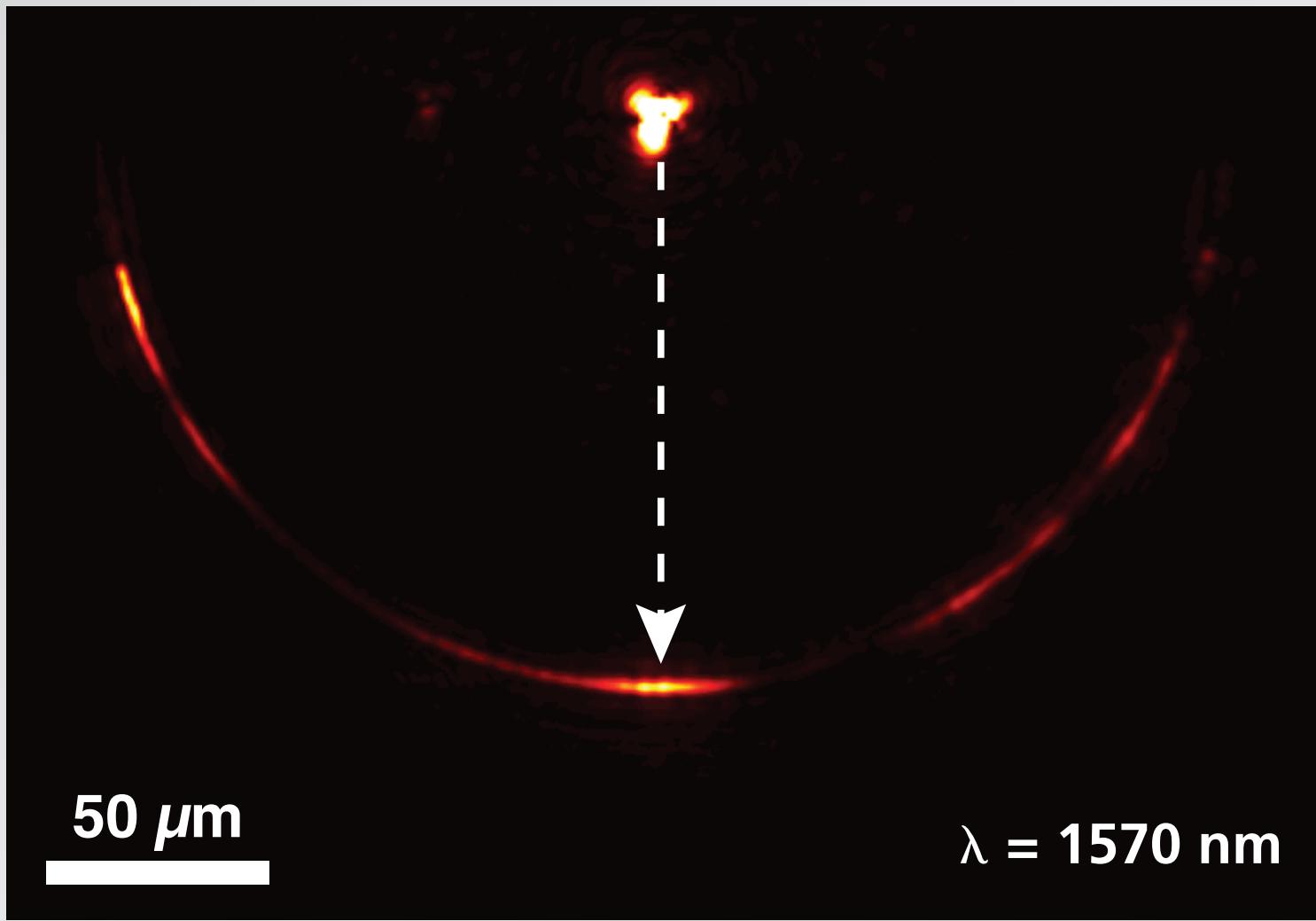
3 experiments



1 index

2 zero index

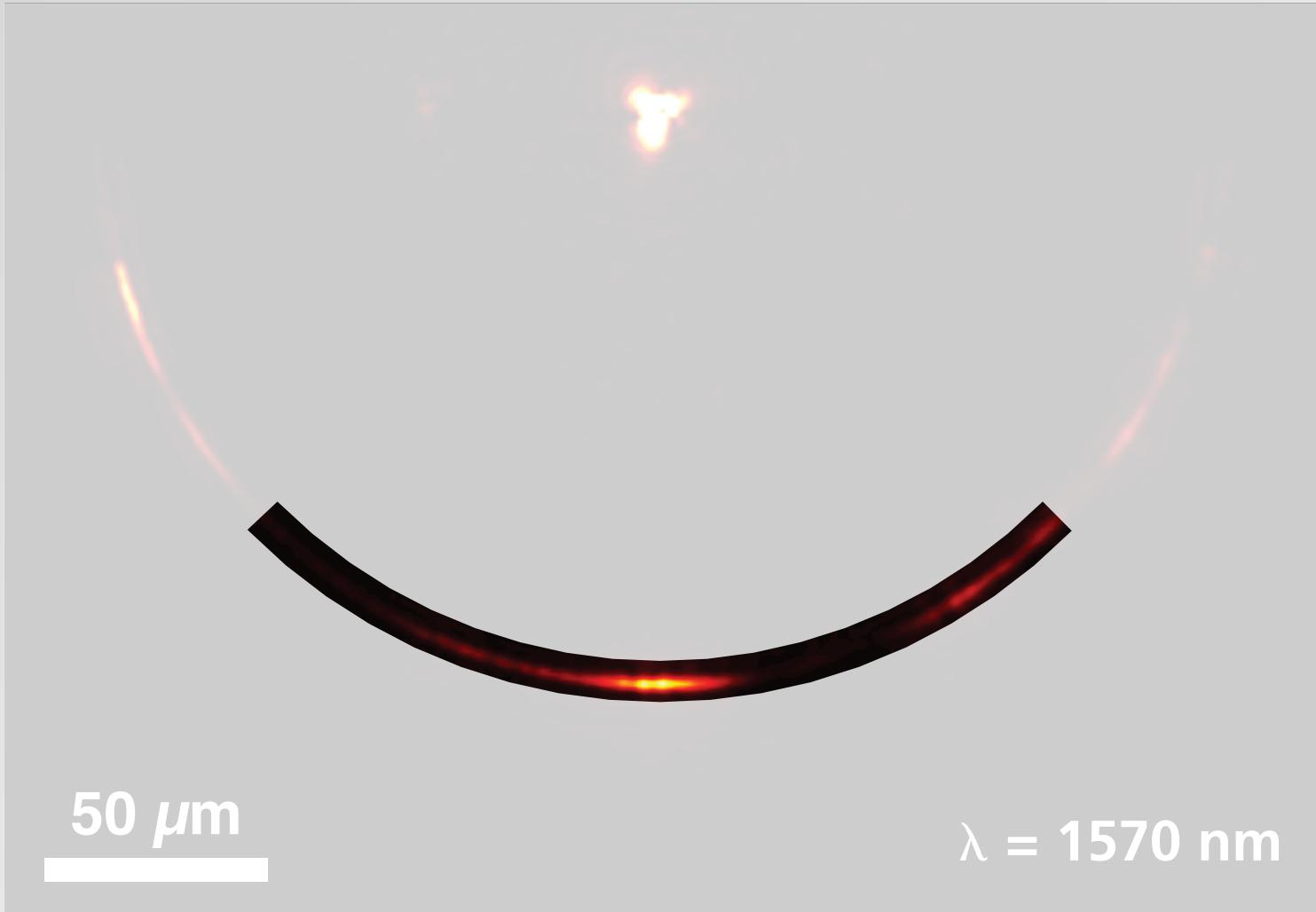
3 experiments



1 index

2 zero index

3 experiments

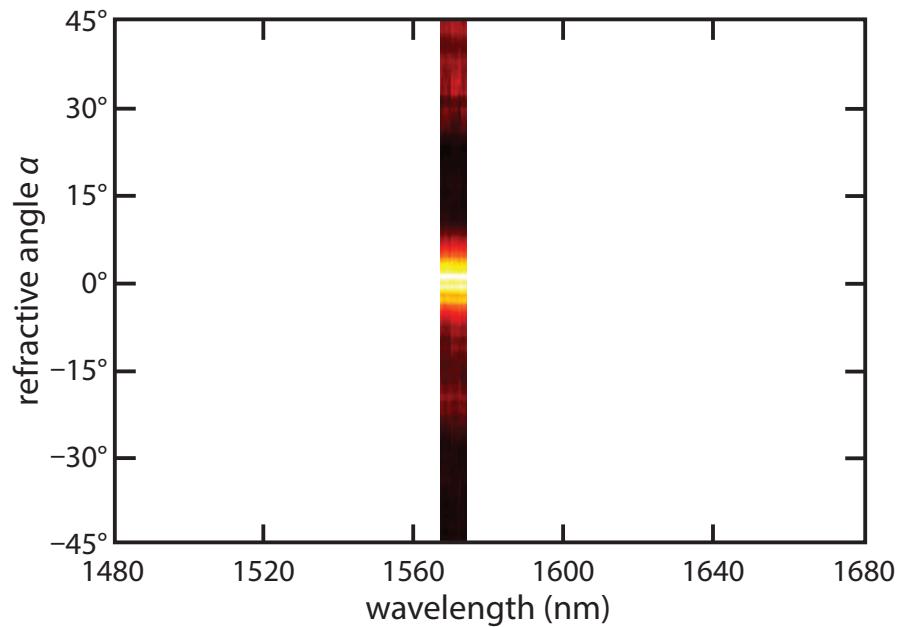


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

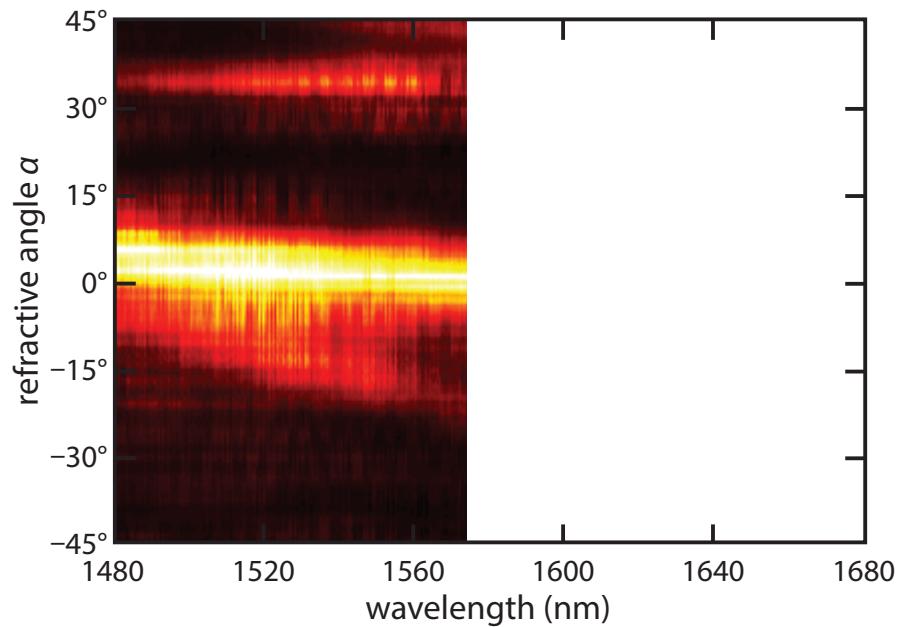


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

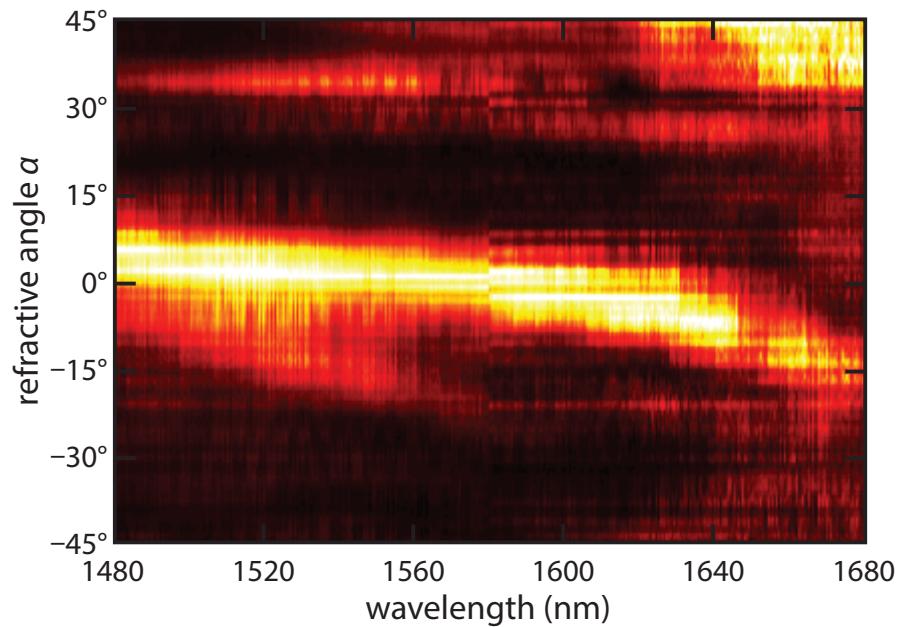


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

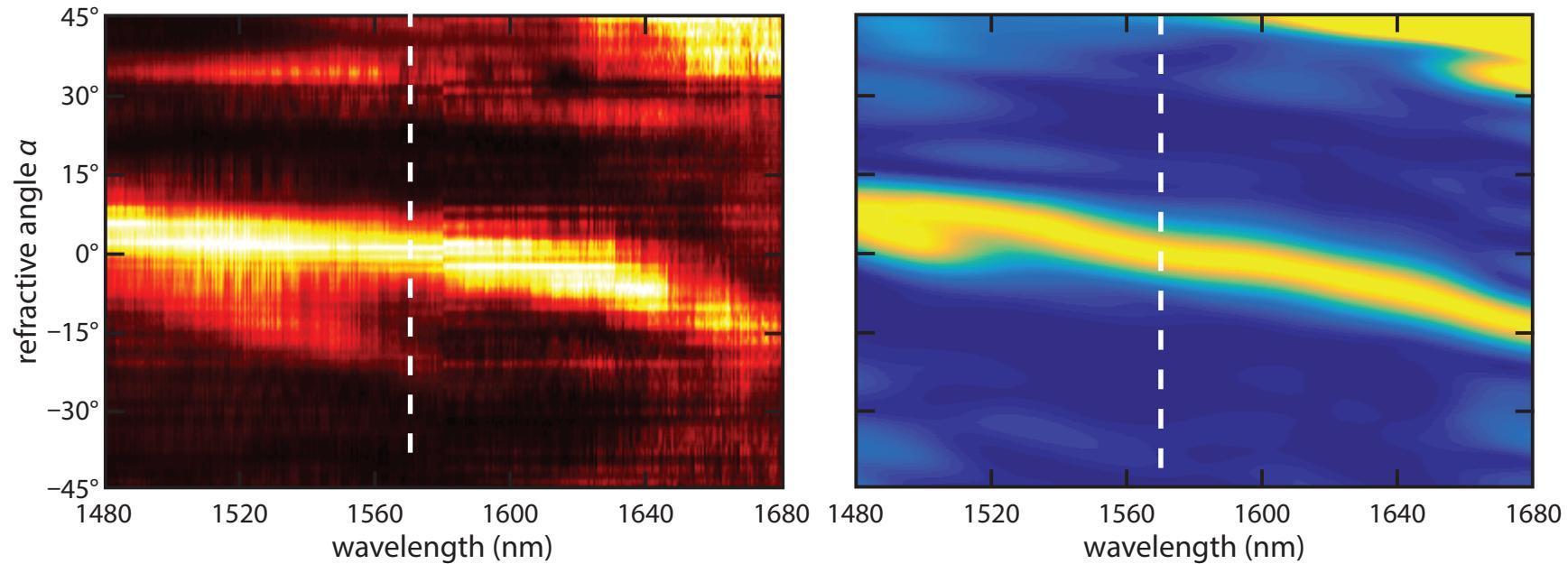


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

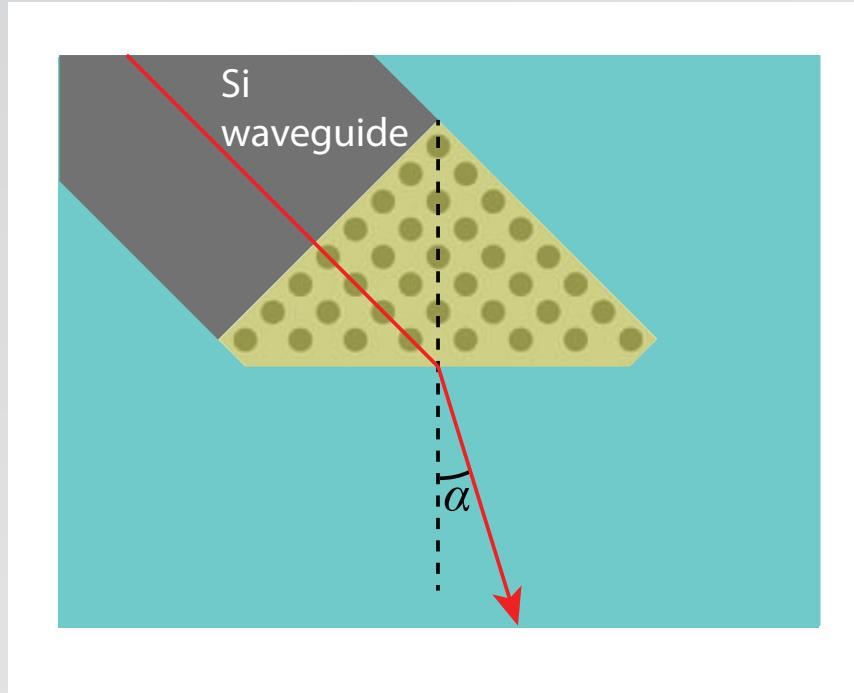


1 index

2 zero index

3 experiments

# Wavelength dependence of index



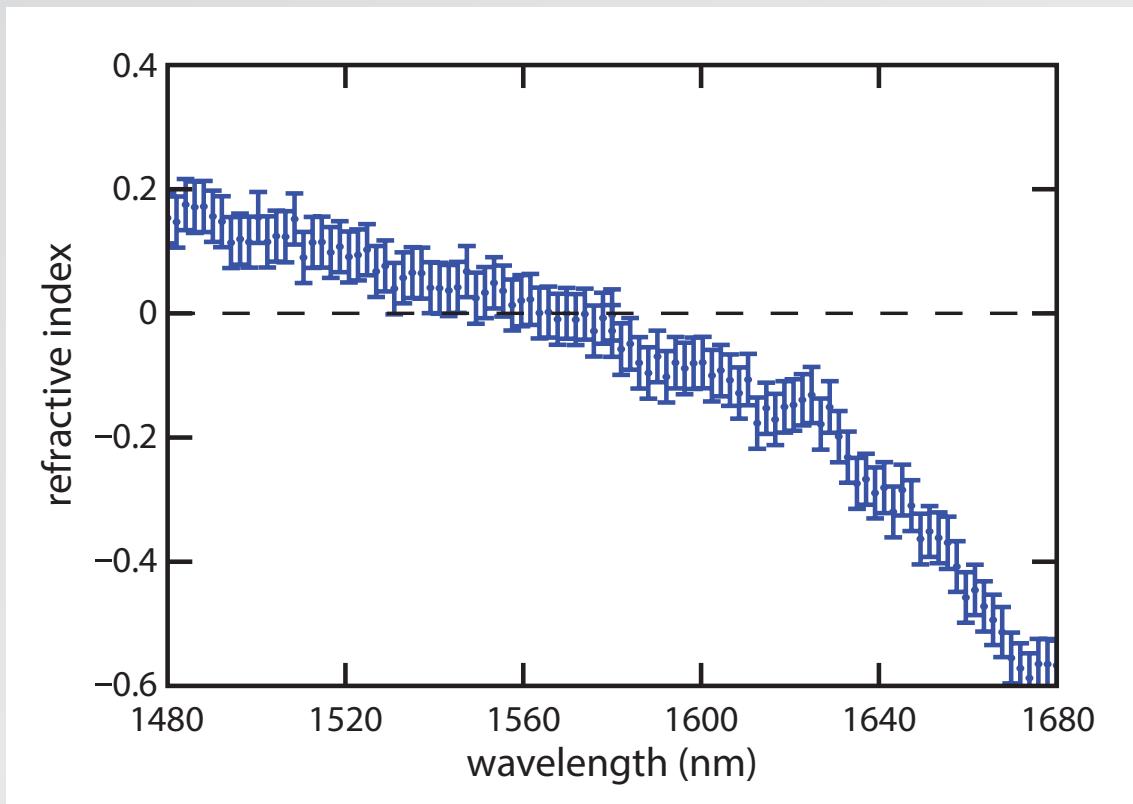
$$n_{\text{prism}} = n_{\text{slab}} \frac{\sin \alpha}{\sin 45^\circ}$$

1 index

2 zero index

3 experiments

# Wavelength dependence of index

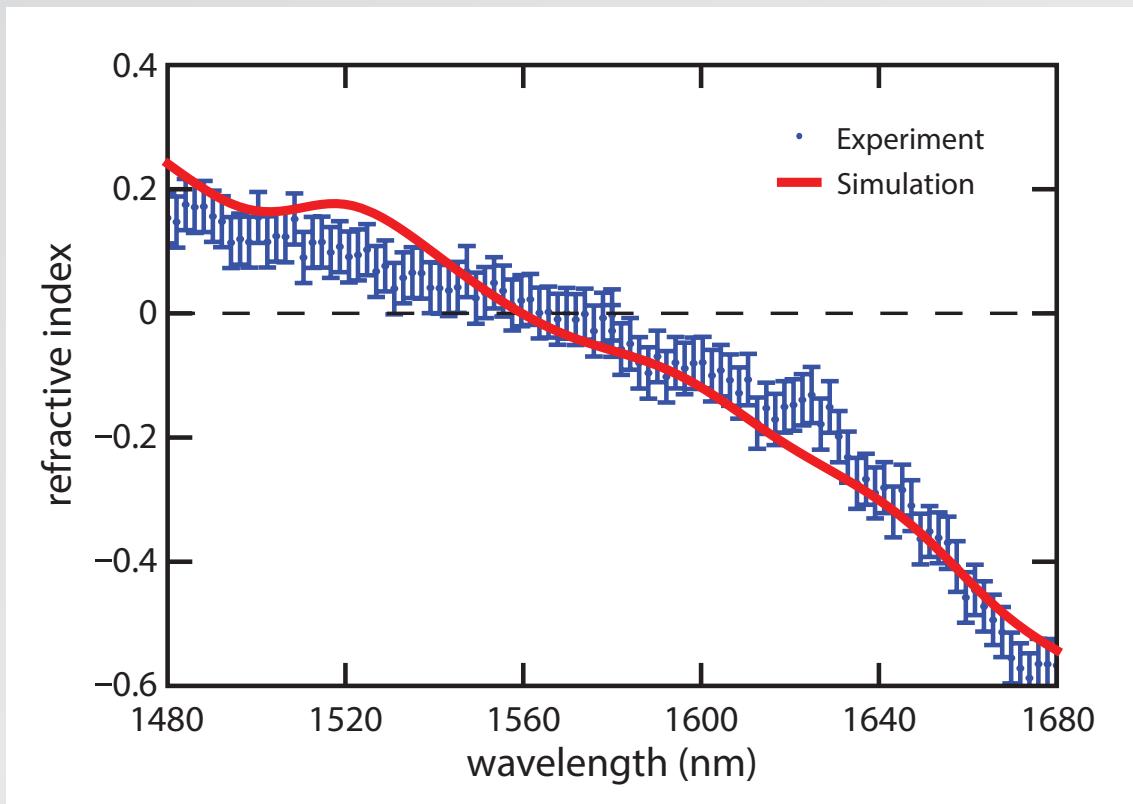


1 index

2 zero index

3 experiments

# Wavelength dependence of index

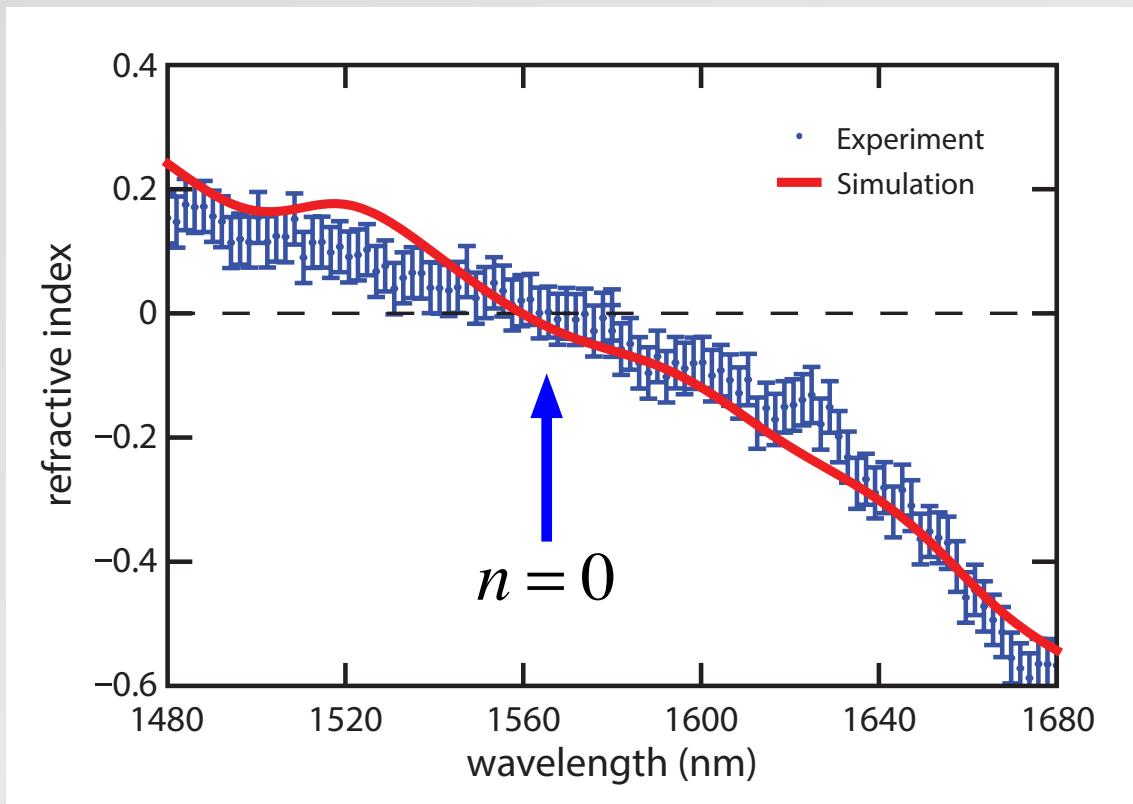


1 index

2 zero index

3 experiments

# Wavelength dependence of index



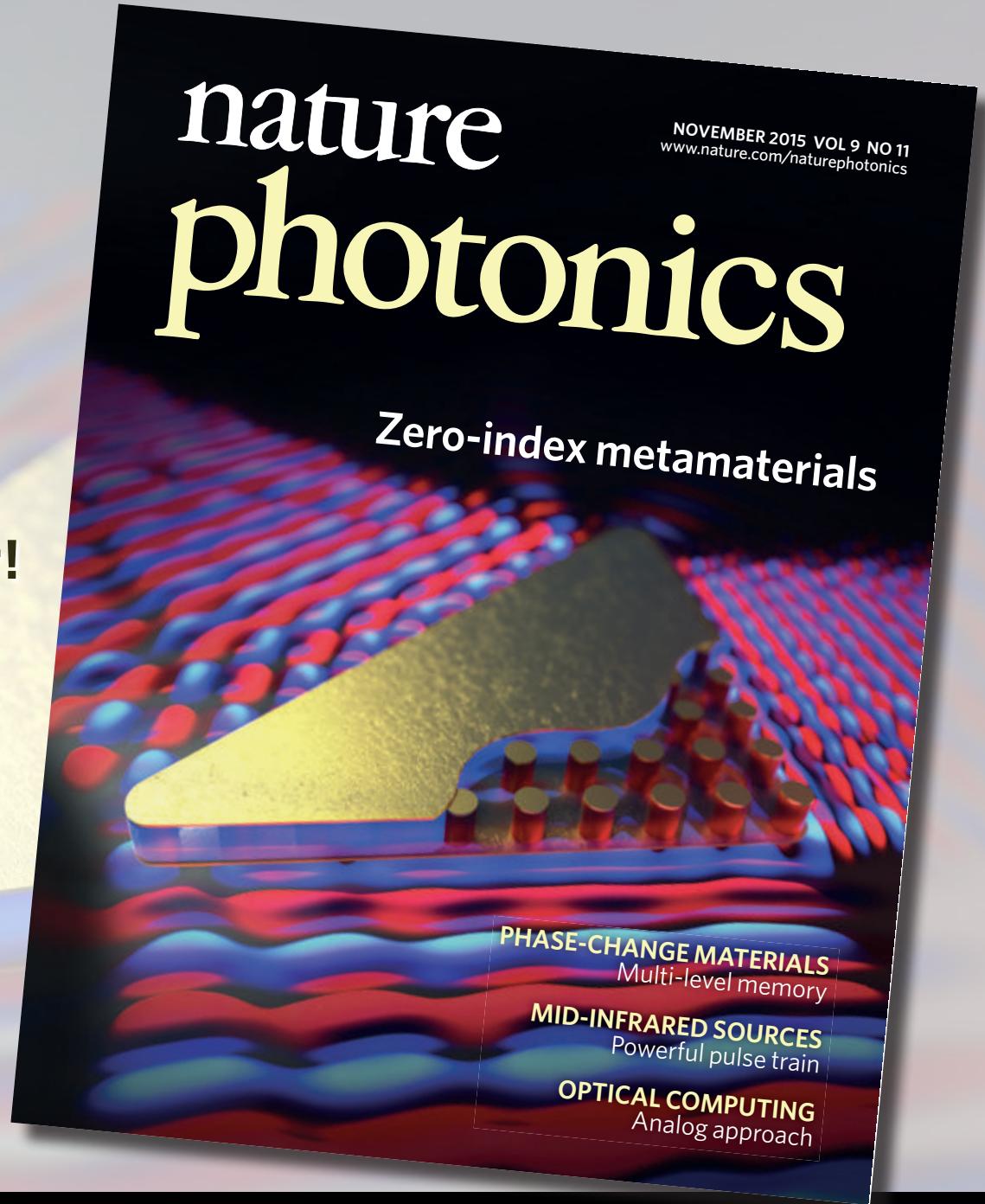
1 index

2 zero index

3 experiments



More info: download paper!



1 index

2 zero index

3 experiments

# Where do we go from here?

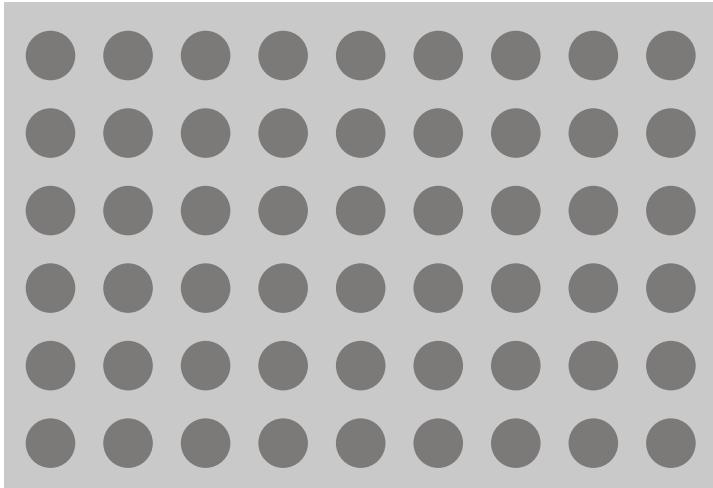
1 index

2 zero index

3 experiments

simplify fabrication

## pillar array



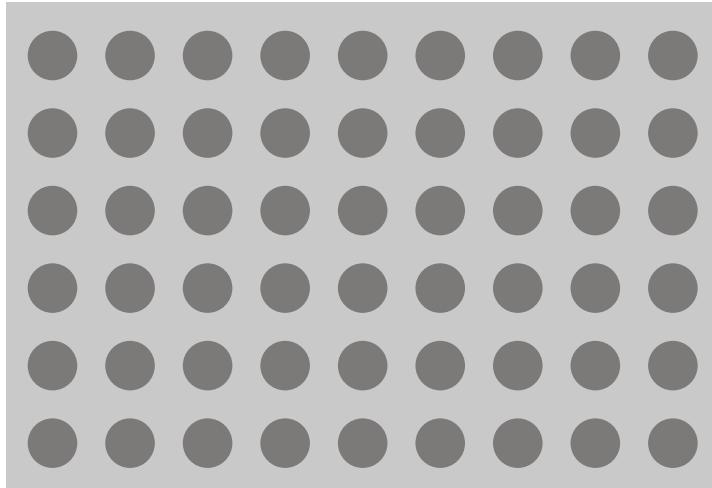
1 index

2 zero index

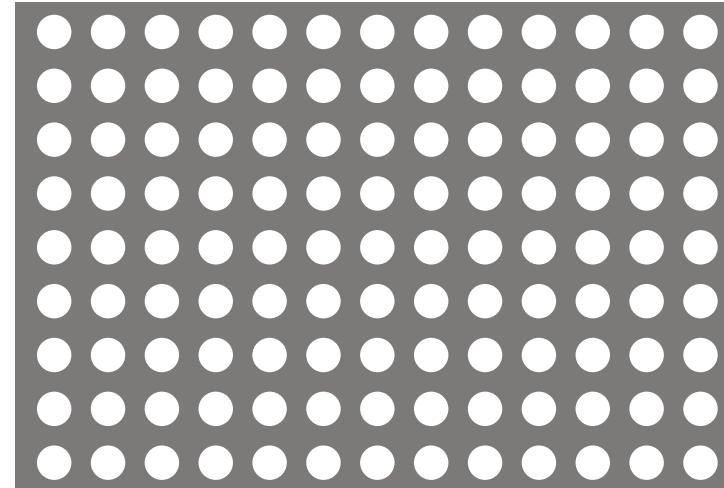
3 experiments

**simplify fabrication**

**pillar array**



**airhole array**

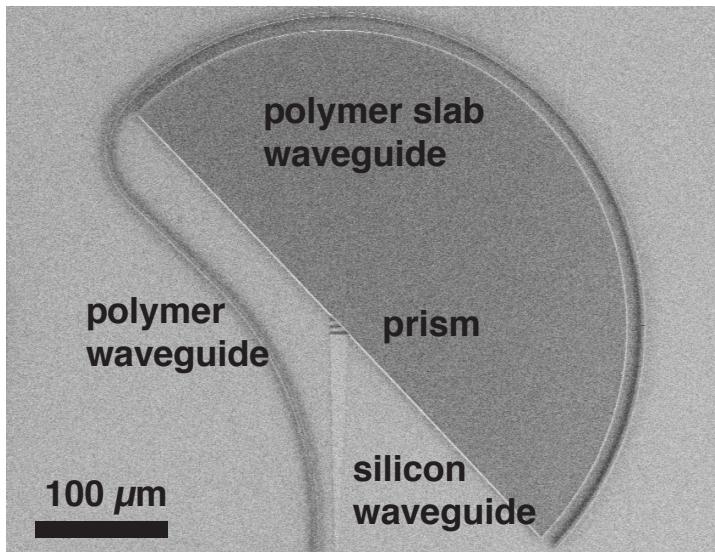


**1** index

**2** zero index

**3** experiments

# simplify fabrication

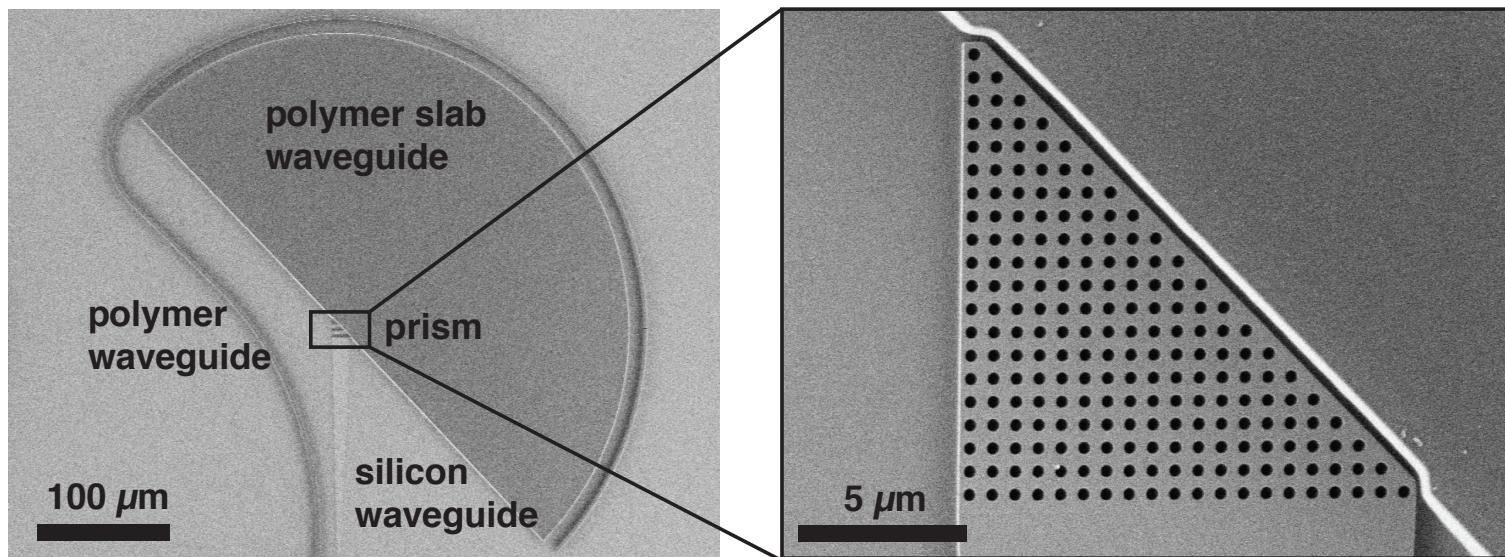


1 index

2 zero index

3 experiments

# simplify fabrication



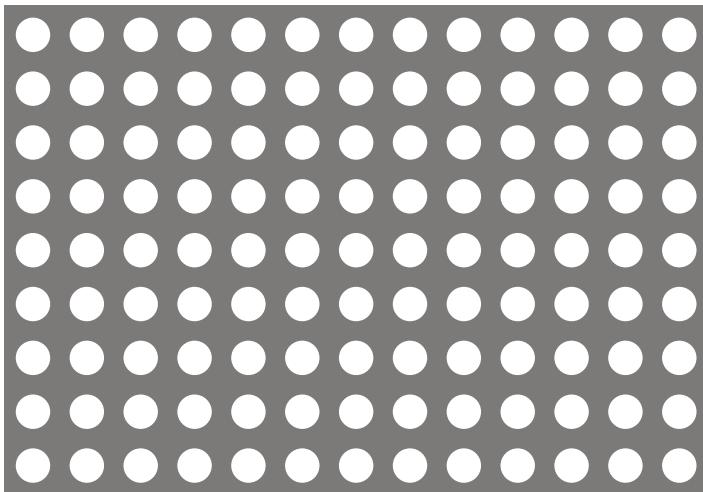
1 index

2 zero index

3 experiments

simplify further!

airhole array



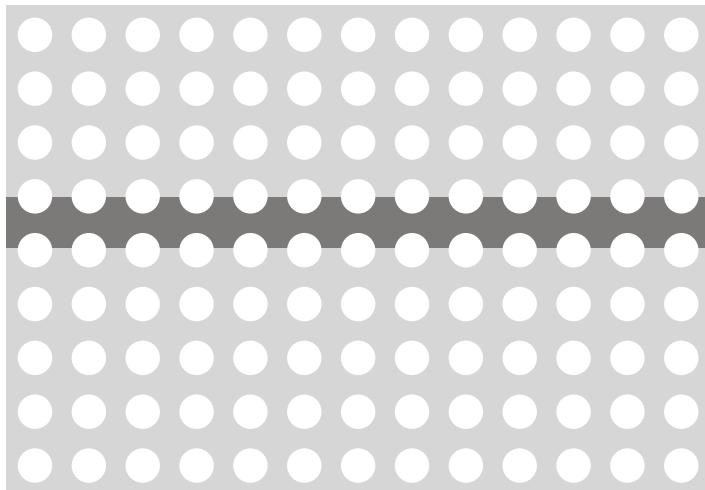
1 index

2 zero index

3 experiments

simplify further!

## airhole array



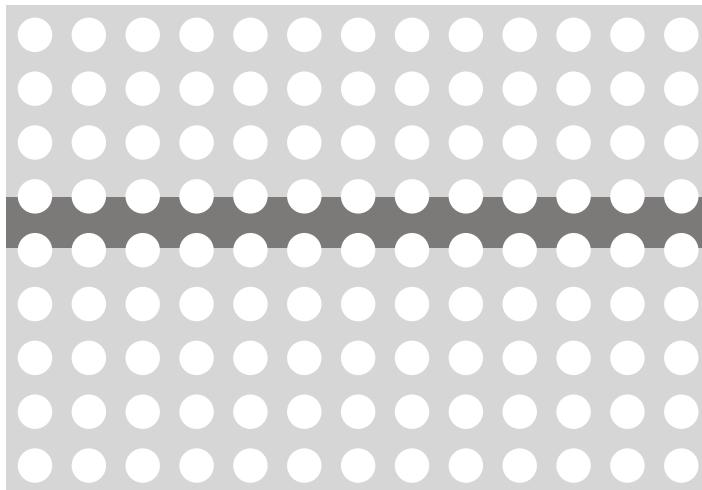
1 index

2 zero index

3 experiments

simplify further!

airhole array



1D ZIM waveguide



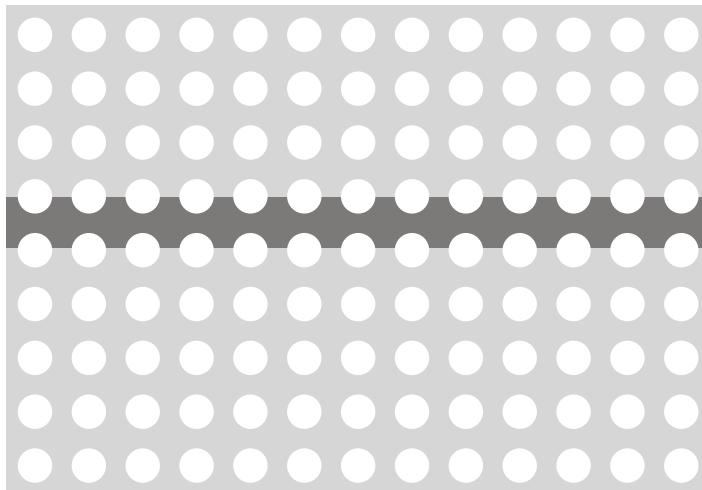
1 index

2 zero index

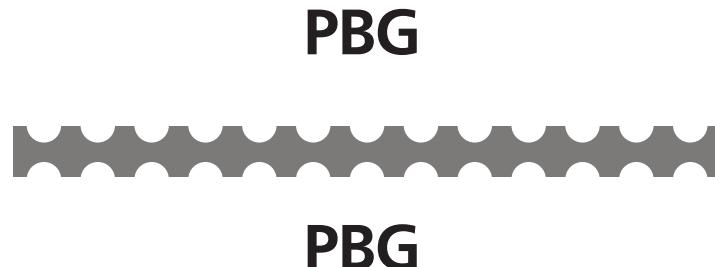
3 experiments

simplify further!

airhole array



1D ZIM waveguide



PBG

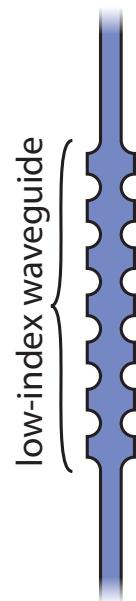
PBG

1 index

2 zero index

3 experiments

# waveguiding

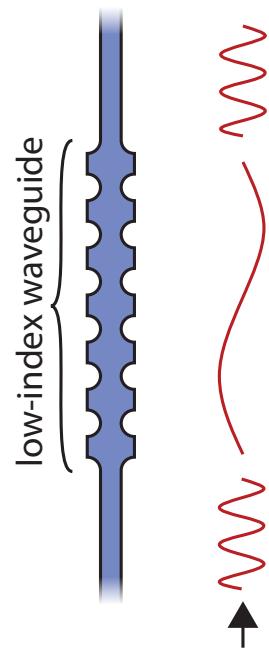


1 index

2 zero index

3 experiments

# waveguiding

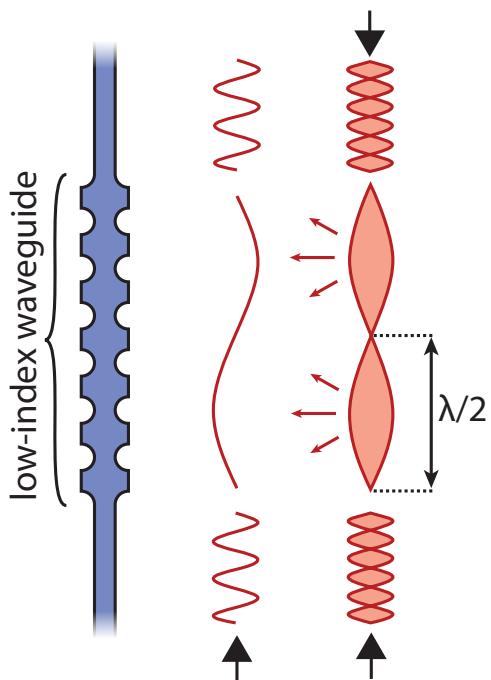


1 index

2 zero index

3 experiments

# waveguiding

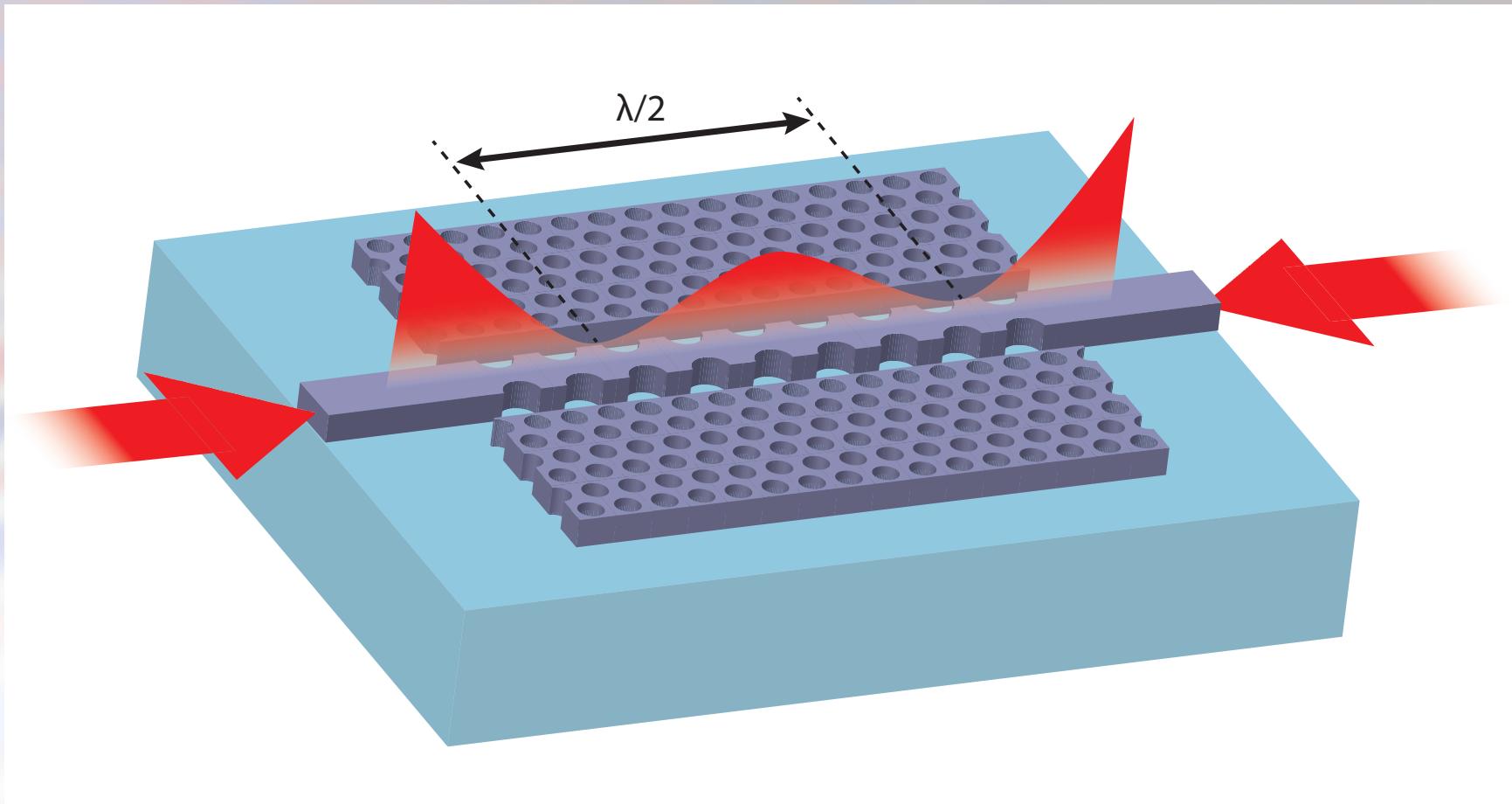


1 index

2 zero index

3 experiments

look at standing waves

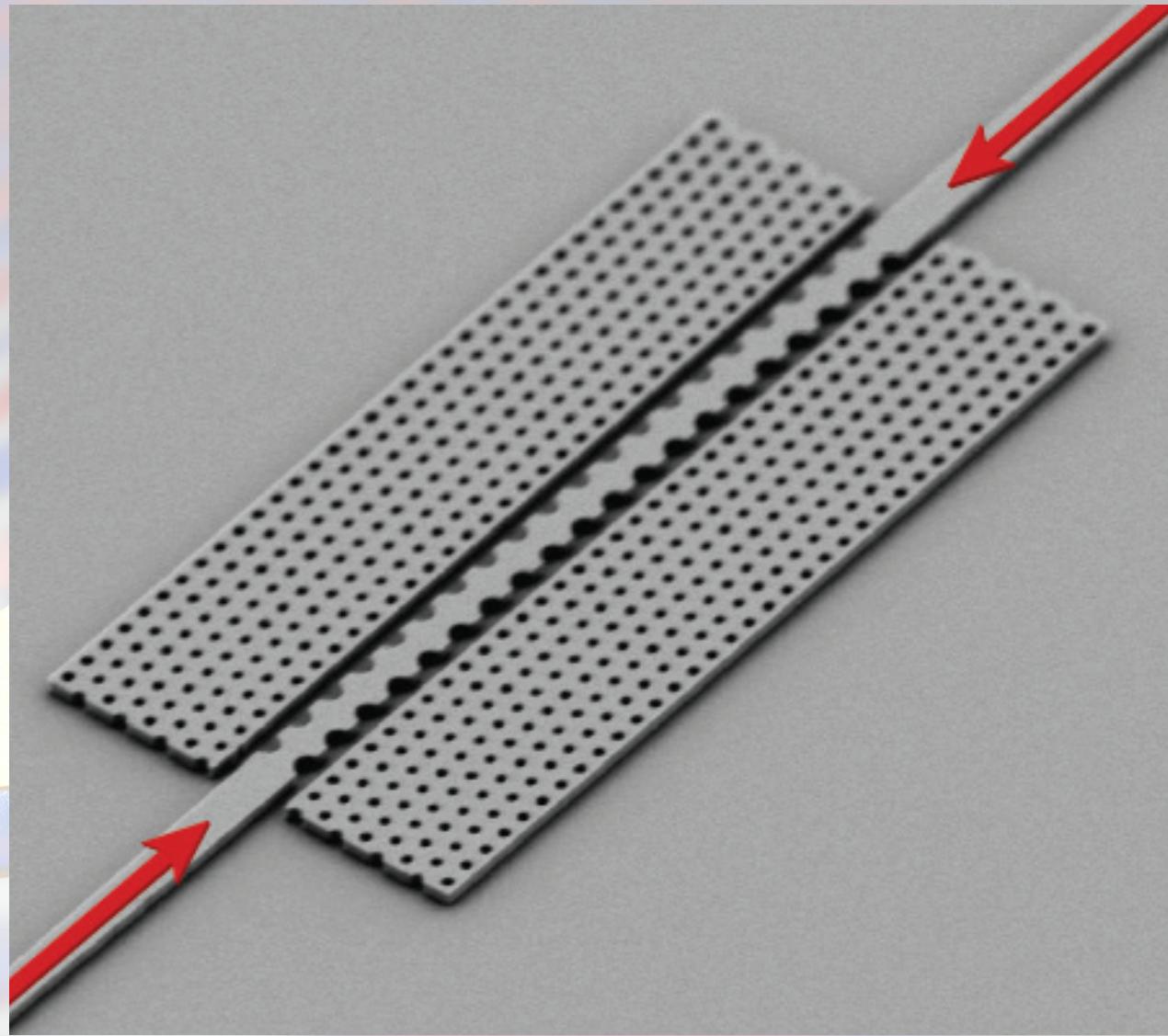


1 index

2 zero index

3 experiments

look at standing waves

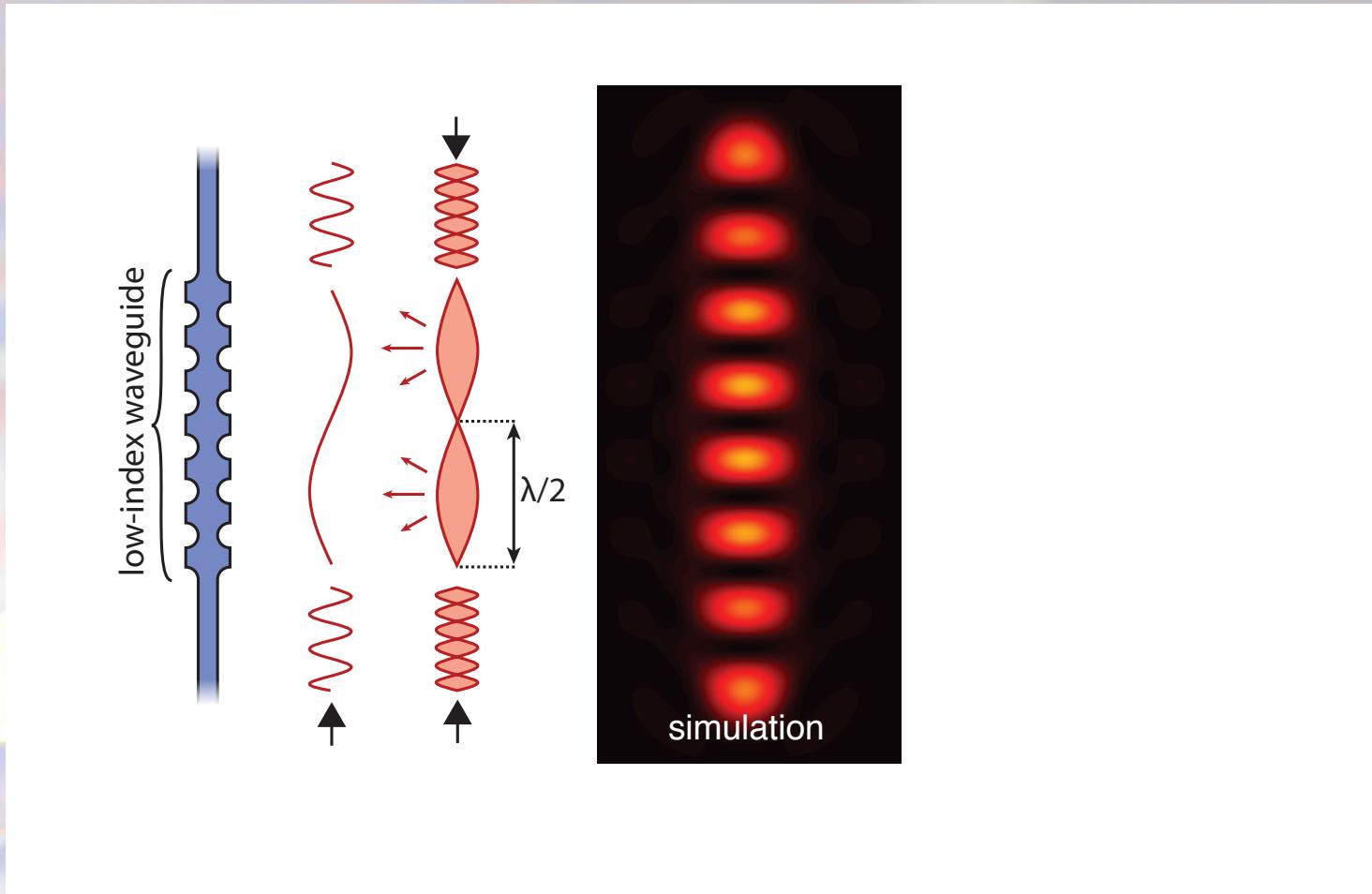


1 index

2 zero index

3 experiments

# look at standing waves

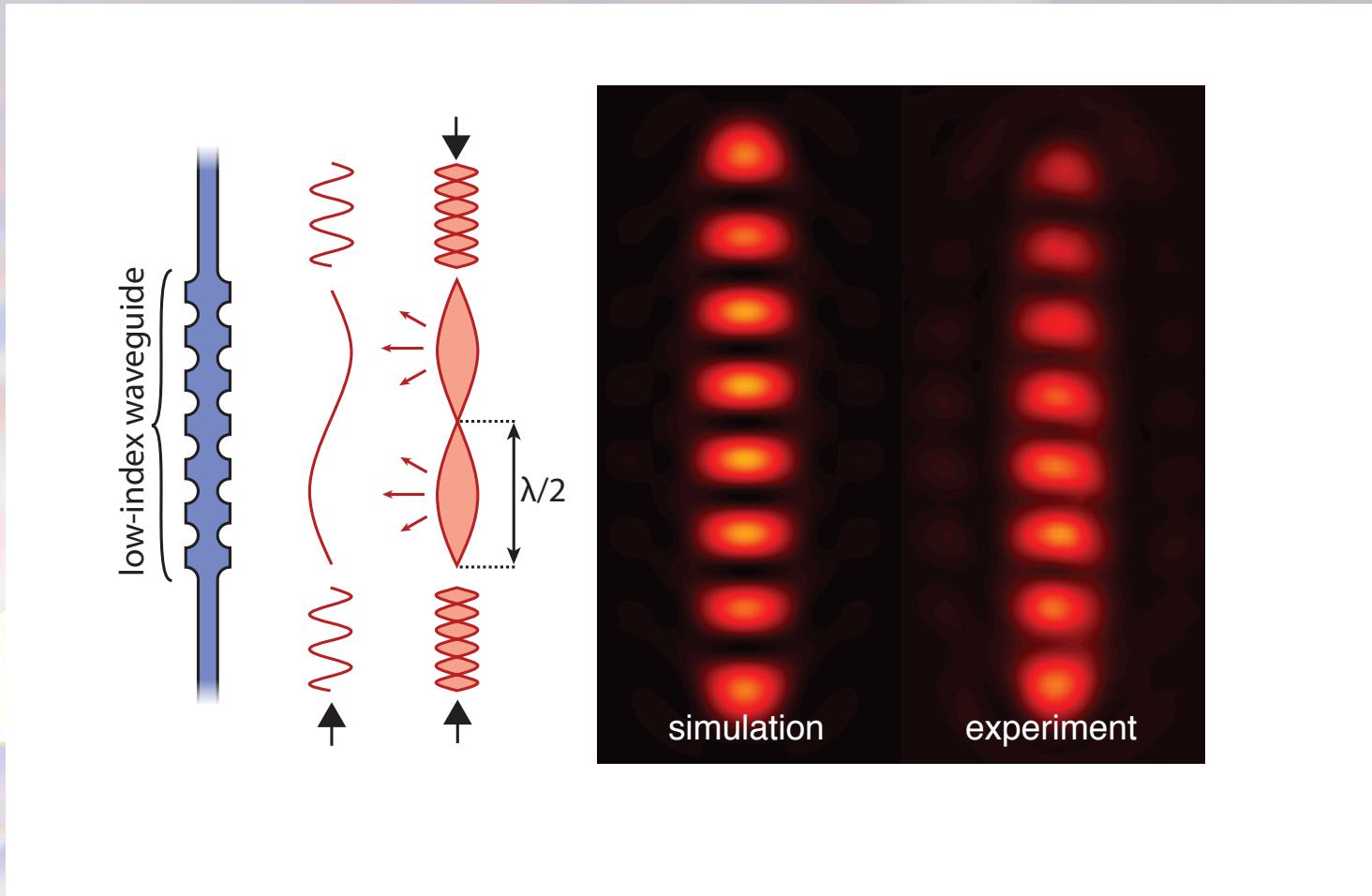


1 index

2 zero index

3 experiments

# look at standing waves

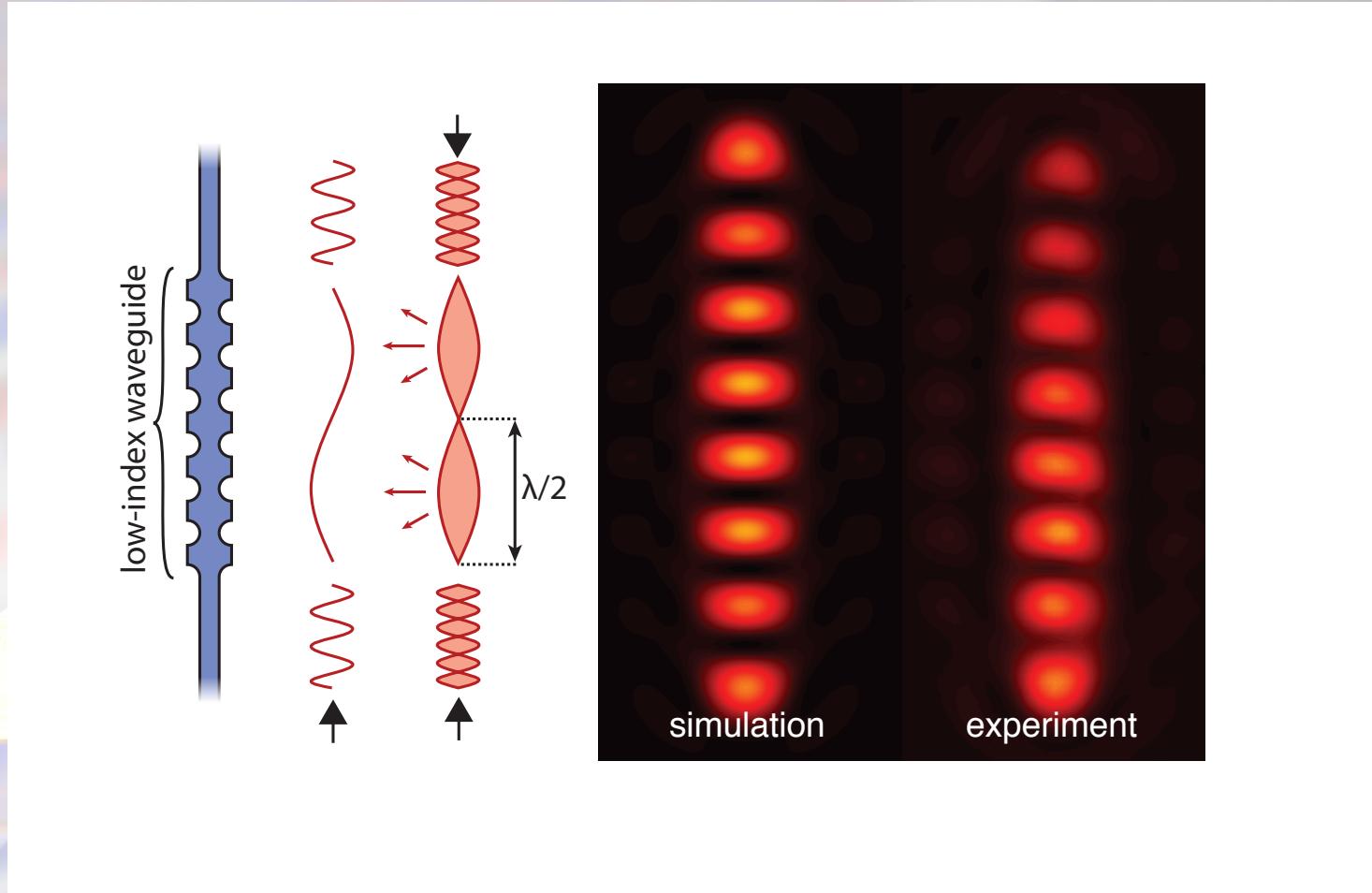


1 index

2 zero index

3 experiments

# *direct observation of effective wavelength!!*

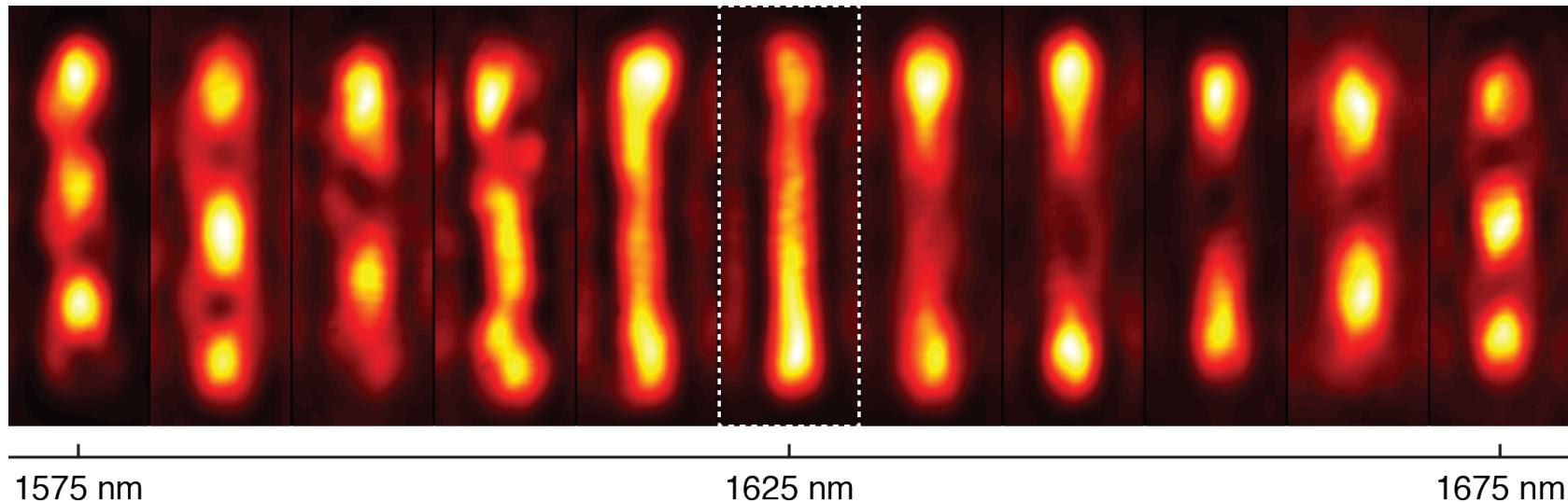


1 index

2 zero index

3 experiments

look at standing waves

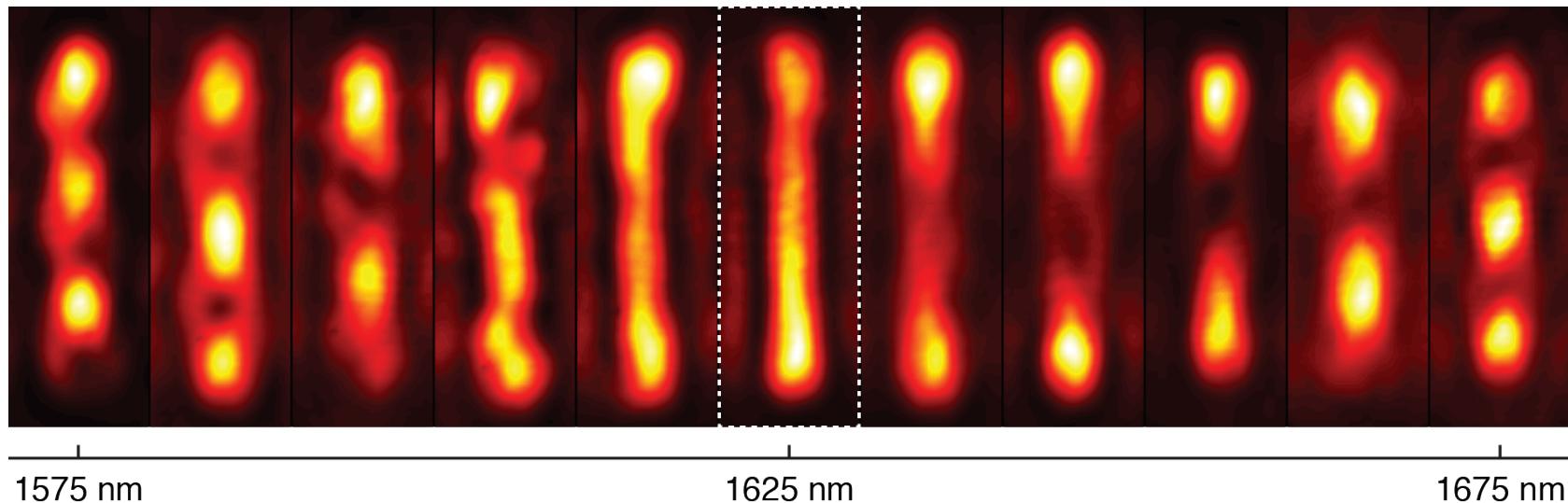


1 index

2 zero index

3 experiments

look at standing waves



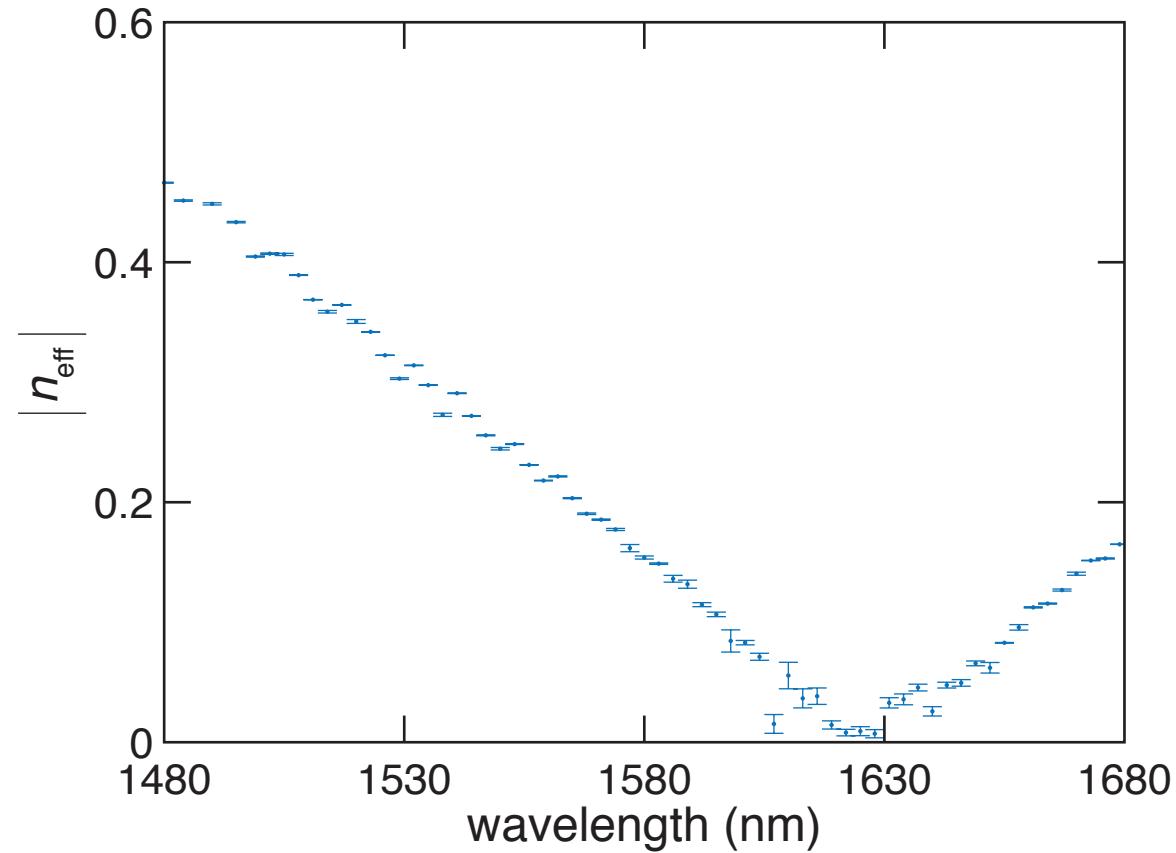
$$| n_{\text{eff}} | = \frac{\lambda_0}{\lambda_{\text{eff}}}$$

1 index

2 zero index

3 experiments

## comparison of experiment and simulation

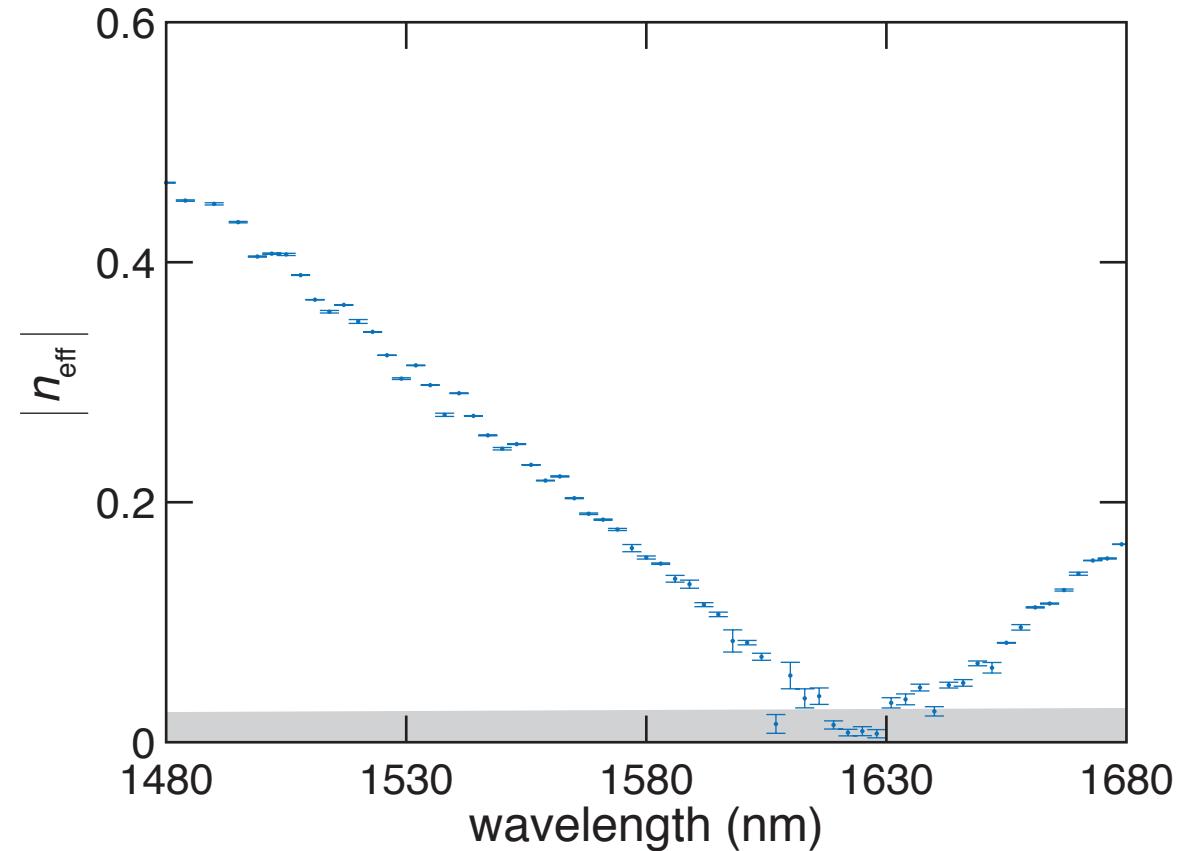


1 index

2 zero index

3 experiments

# comparison of experiment and simulation

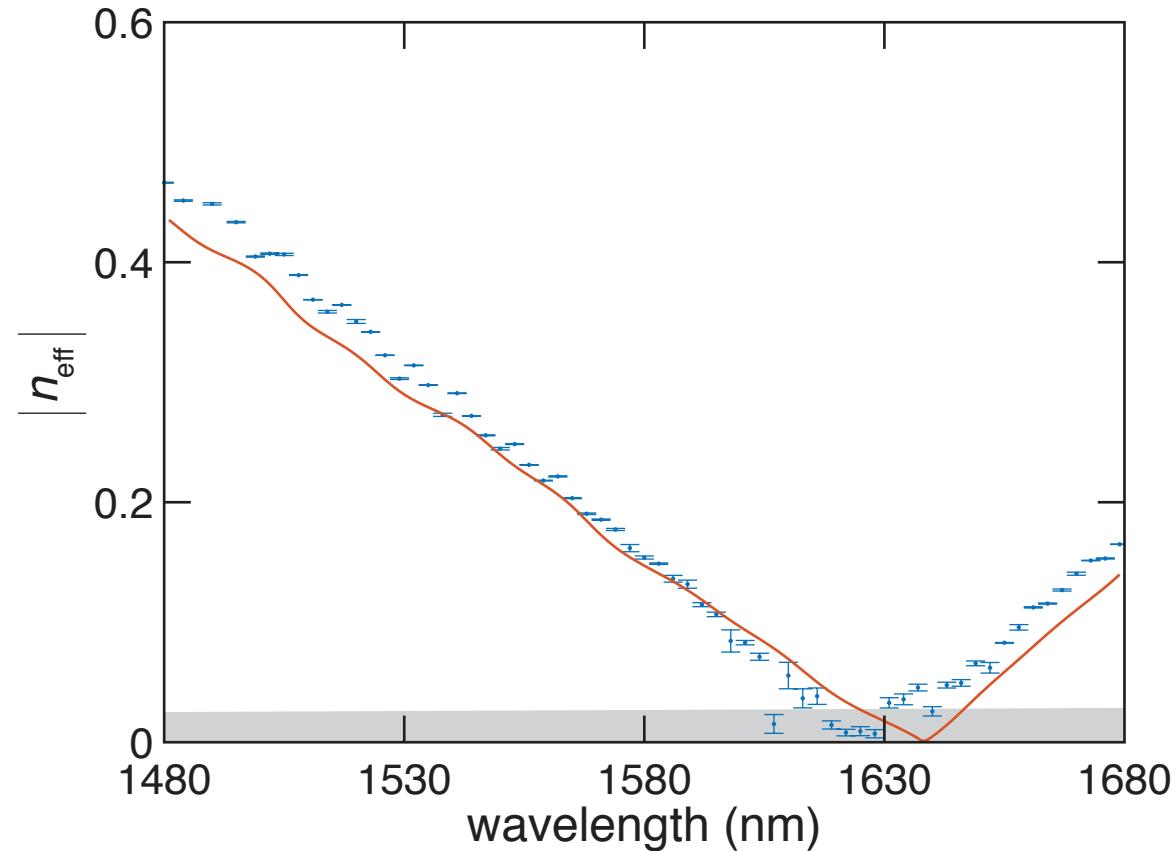


1 index

2 zero index

3 experiments

# comparison of experiment and simulation

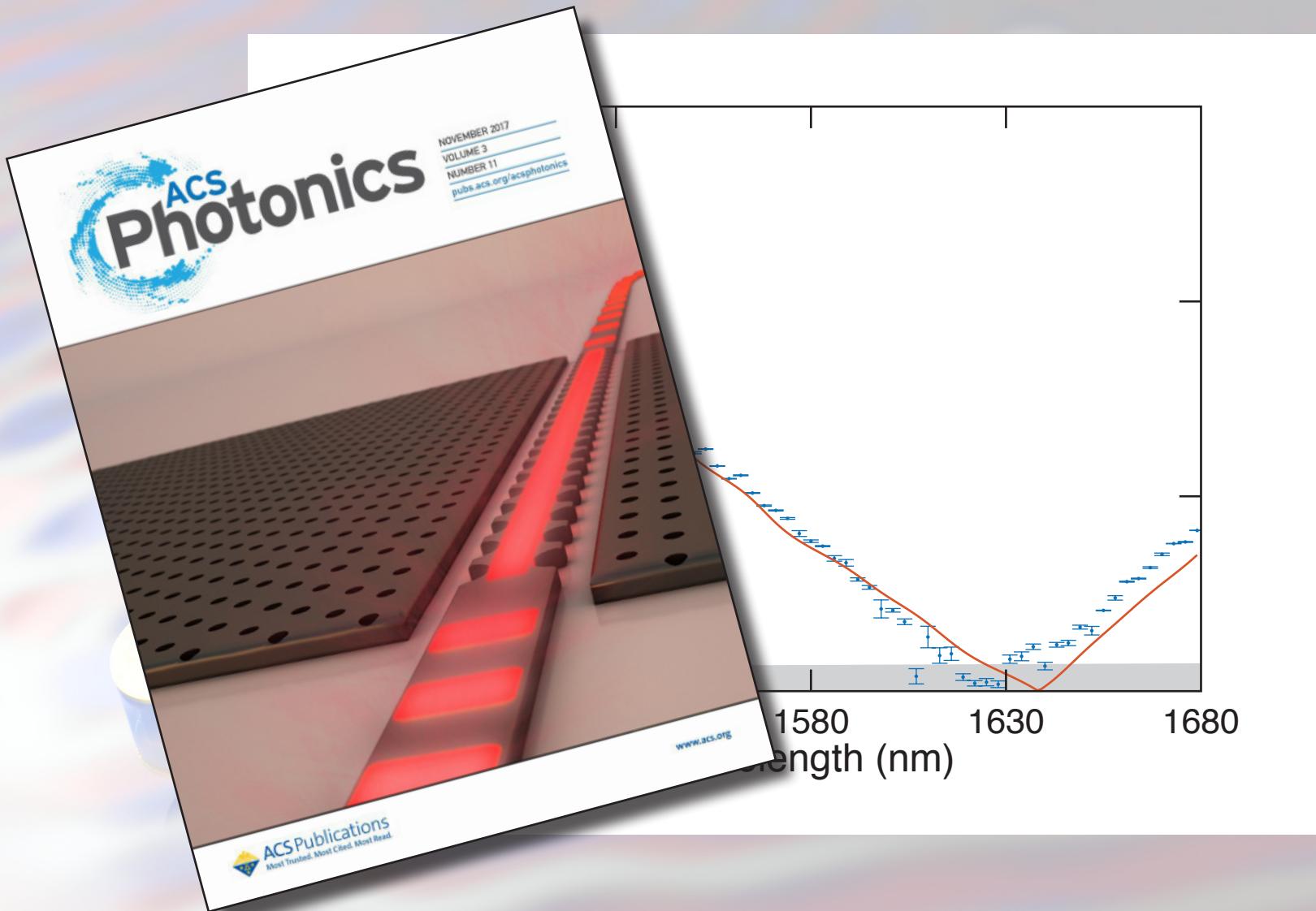


1 index

2 zero index

3 experiments

# comparison of experiment and simulation



1 index

2 zero index

3 experiments

Many exciting possibilities

$$n = 0$$

1 index

2 zero index

3 experiments

Many exciting possibilities

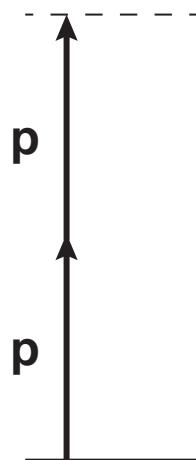
$$n \approx n_0 + \frac{\chi_R^{(3)}}{2n_0} |E(\omega)|^2$$

1 index

2 zero index

3 experiments

# four-wave mixing

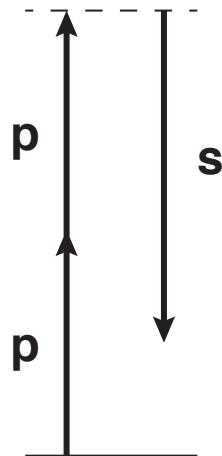


1 index

2 zero index

3 experiments

# four-wave mixing

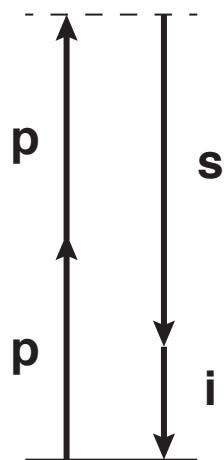


1 index

2 zero index

3 experiments

# four-wave mixing



1 index

2 zero index

3 experiments

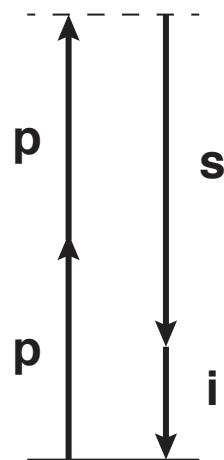
# four-wave mixing

energy  
conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$

momentum  
conservation

$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$



1 index

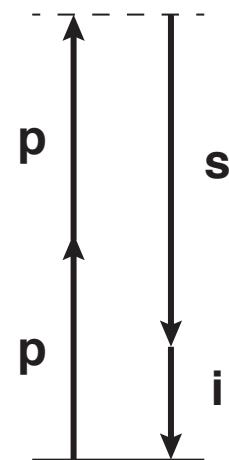
2 zero index

3 experiments

# four-wave mixing

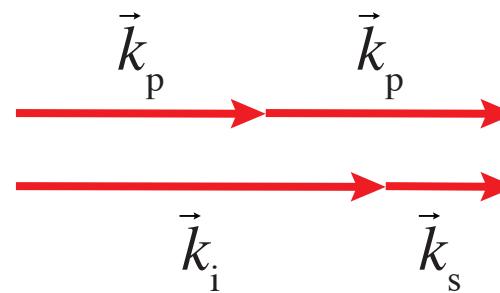
energy  
conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$



momentum  
conservation

$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$



phase matching

1 index

2 zero index

3 experiments

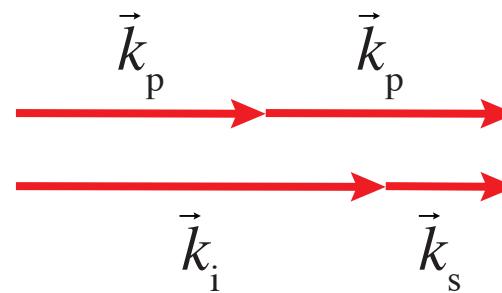
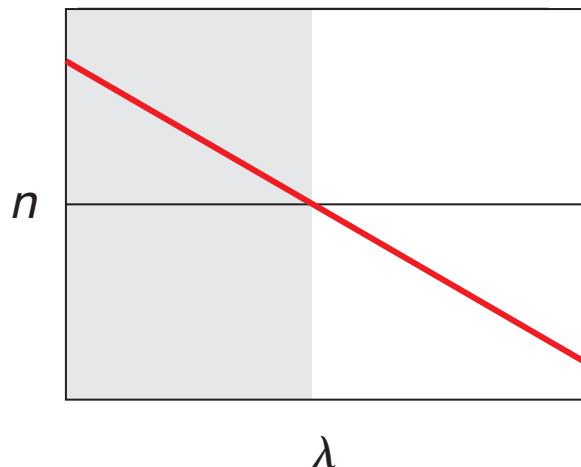
# four-wave mixing

energy  
conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$

momentum  
conservation

$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$



phase matching

1 index

2 zero index

3 experiments

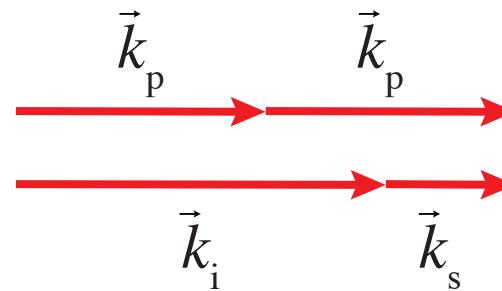
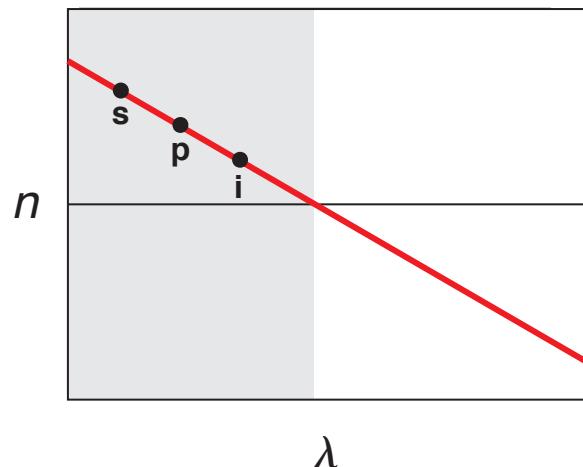
# four-wave mixing

energy  
conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$

momentum  
conservation

$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$



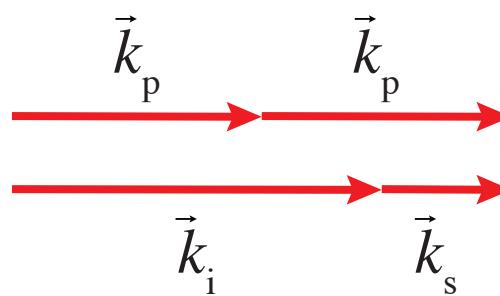
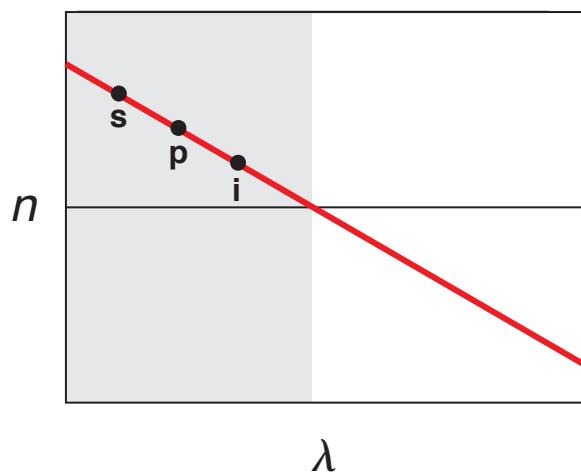
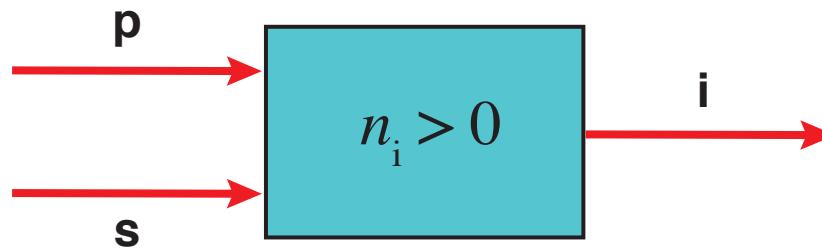
phase matching

1 index

2 zero index

3 experiments

# four-wave mixing



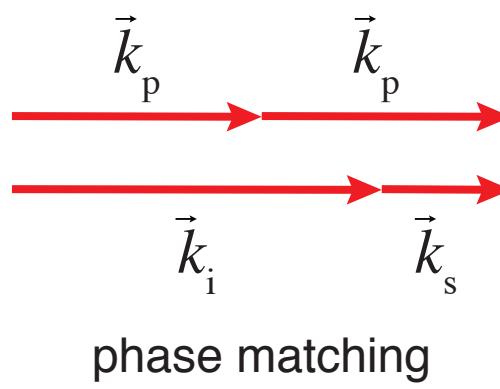
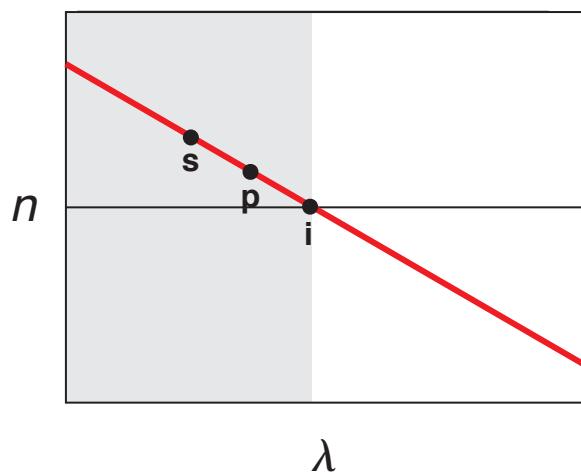
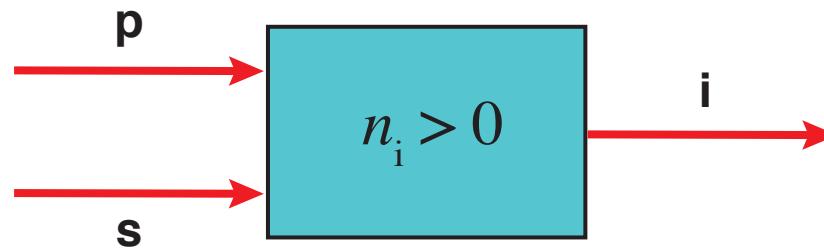
phase matching

1 index

2 zero index

3 experiments

# four-wave mixing

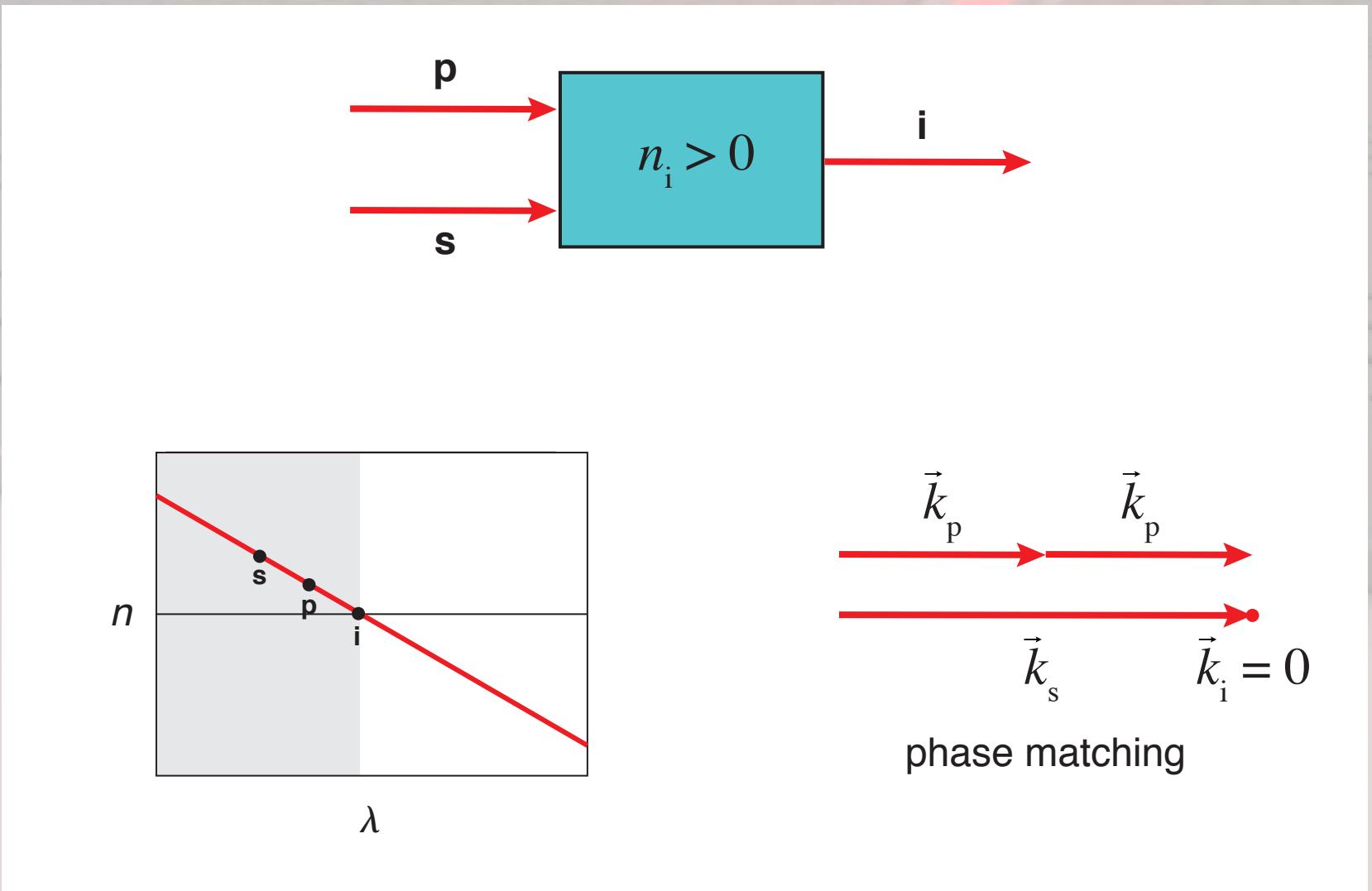


1 index

2 zero index

3 experiments

# four-wave mixing

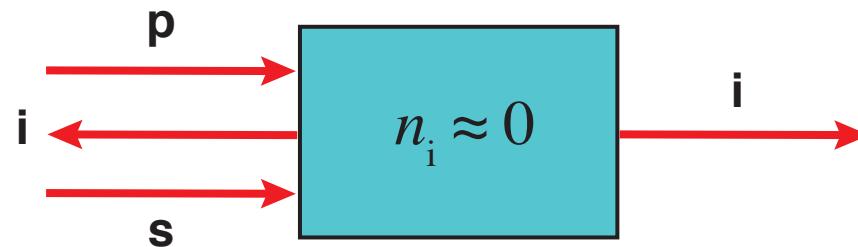


1 index

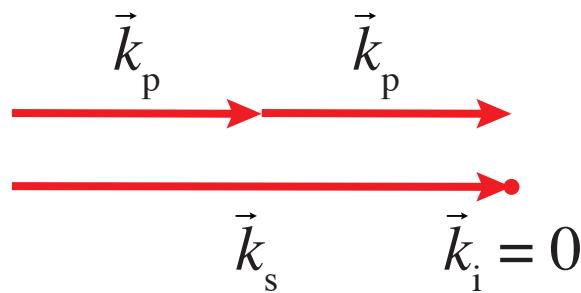
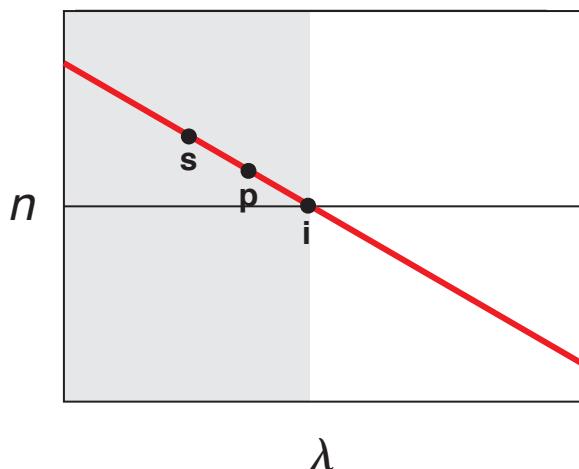
2 zero index

3 experiments

# four-wave mixing



forward and backward



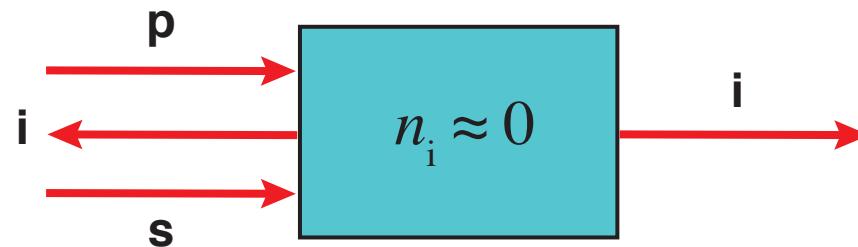
phase matching

1 index

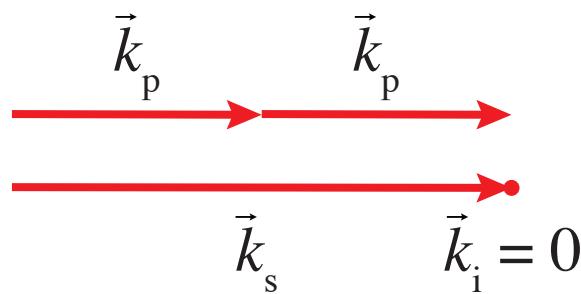
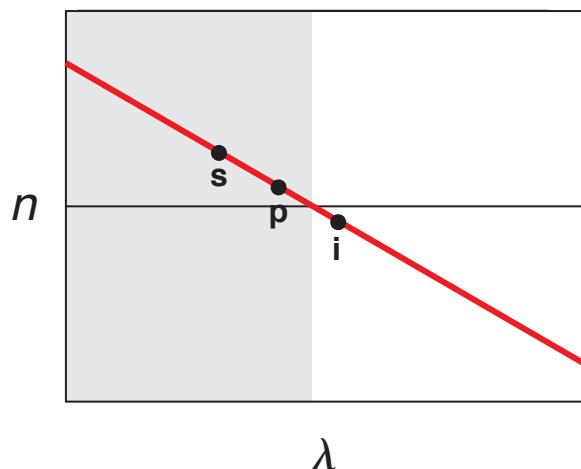
2 zero index

3 experiments

# four-wave mixing



forward and backward



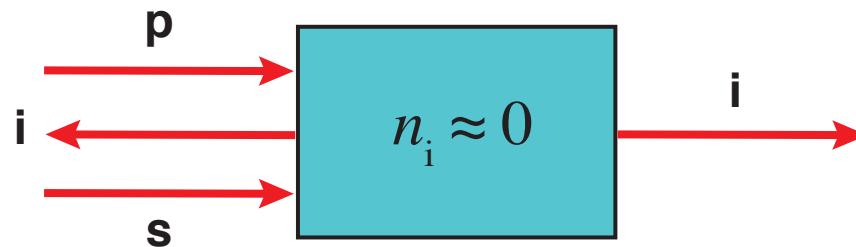
phase matching

1 index

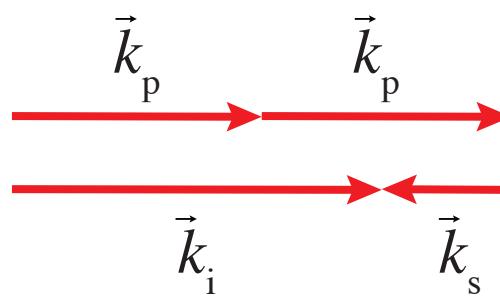
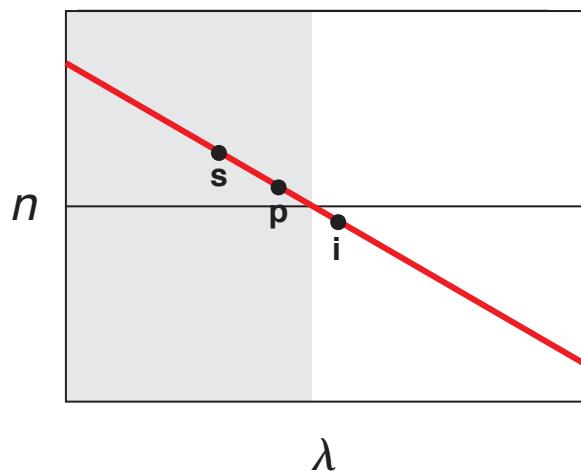
2 zero index

3 experiments

# four-wave mixing



forward and backward



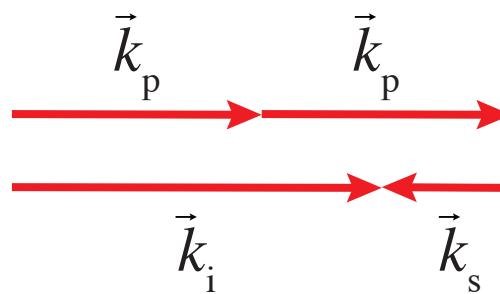
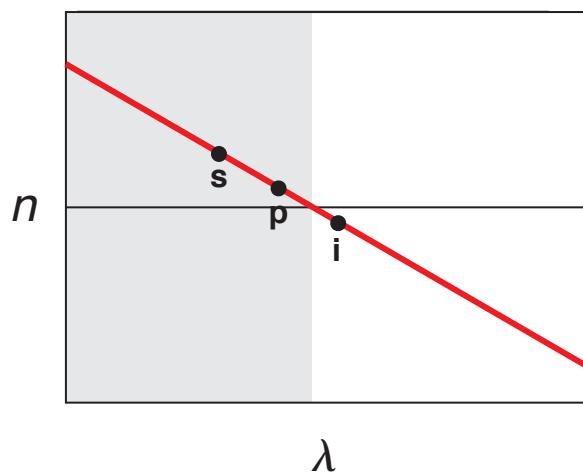
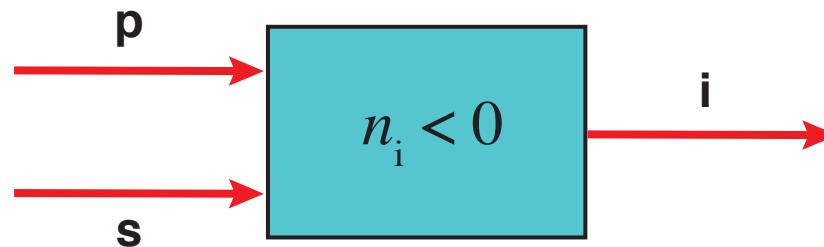
phase matching

1 index

2 zero index

3 experiments

# four-wave mixing

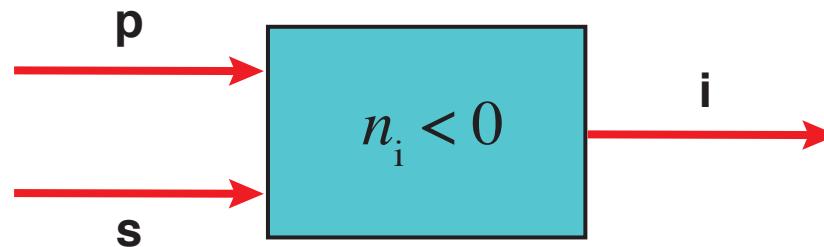


1 index

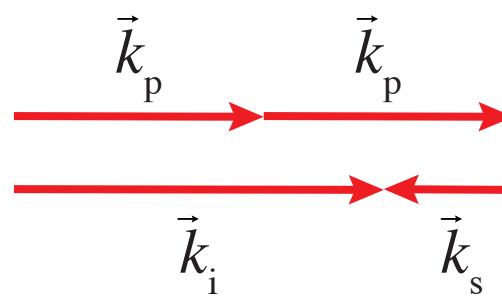
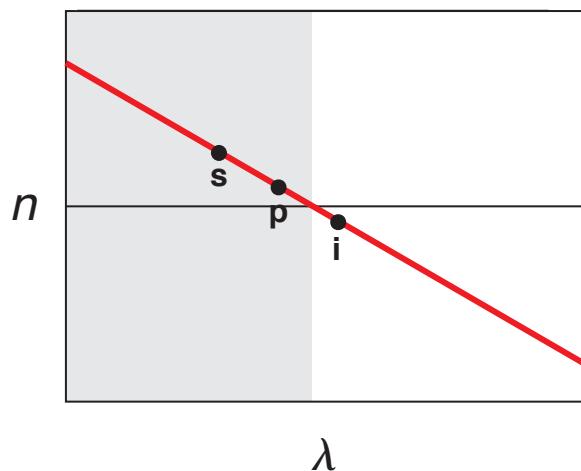
2 zero index

3 experiments

# four-wave mixing



forward only



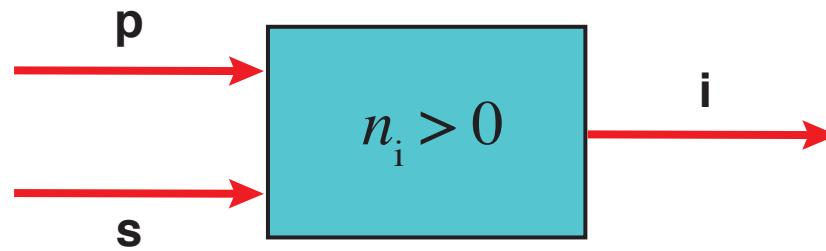
phase matching

1 index

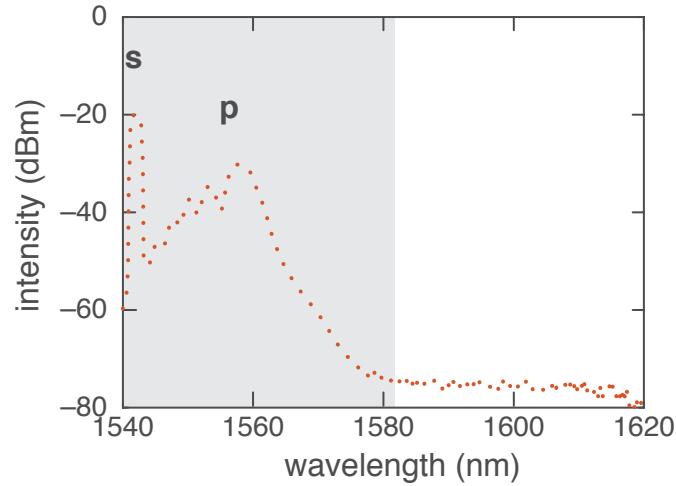
2 zero index

3 experiments

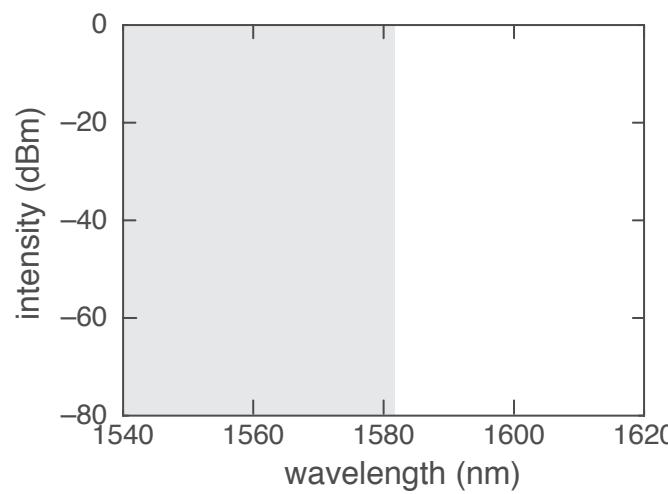
# four-wave mixing



backward



forward

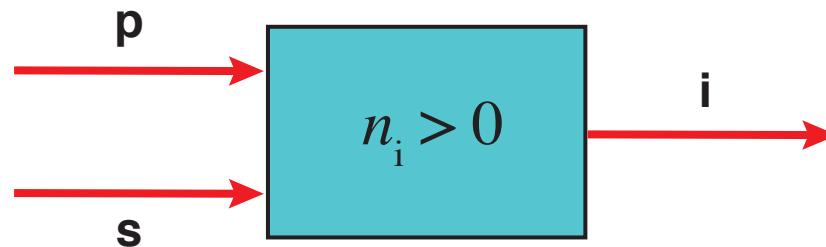


1 index

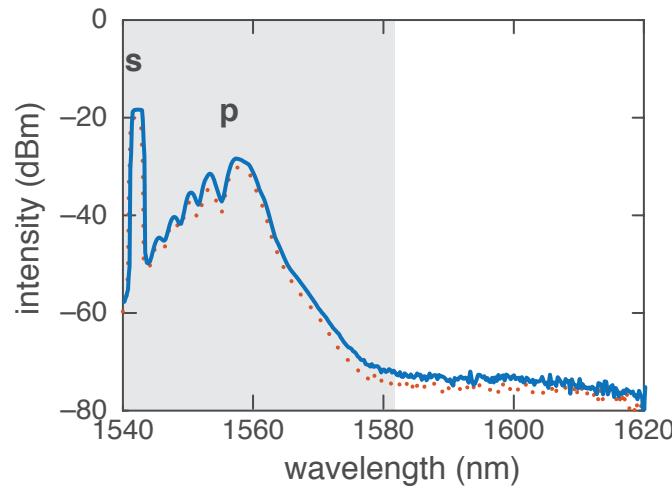
2 zero index

3 experiments

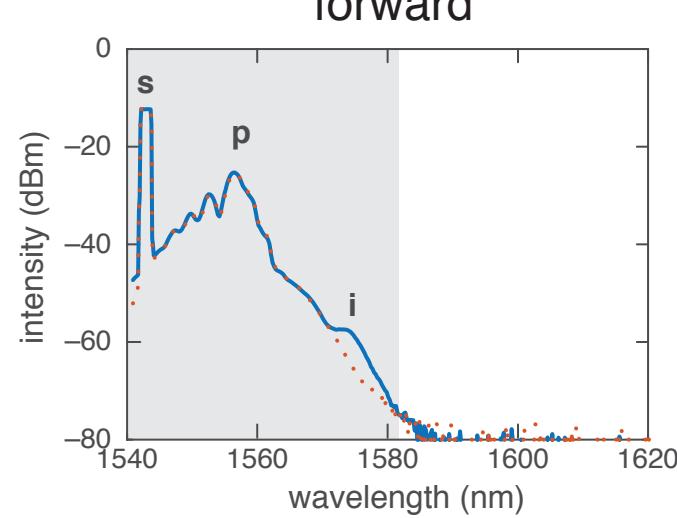
# four-wave mixing



backward



forward

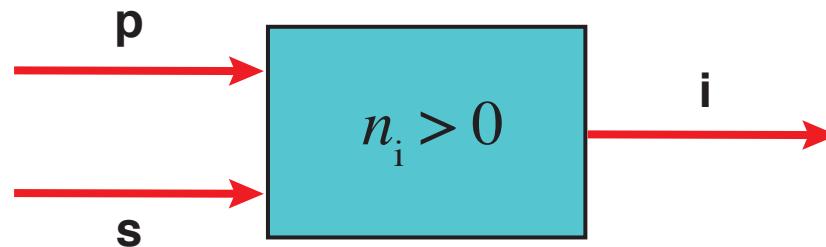


1 index

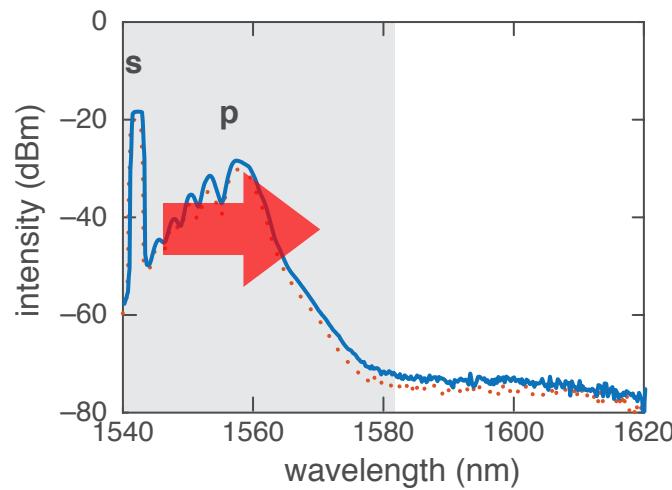
2 zero index

3 experiments

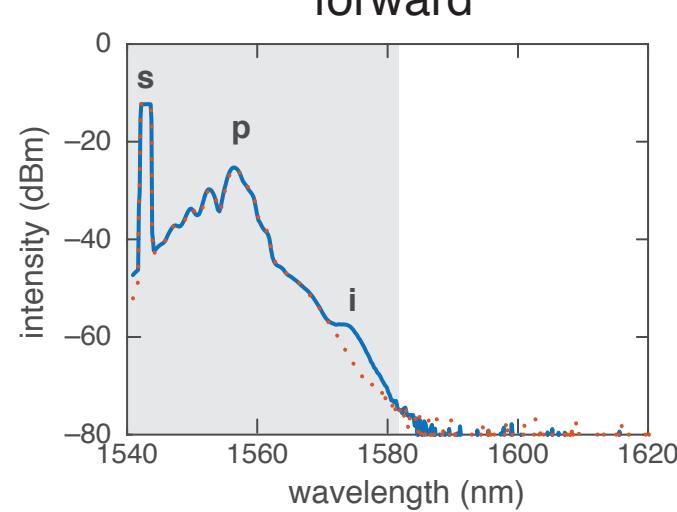
# four-wave mixing



backward



forward

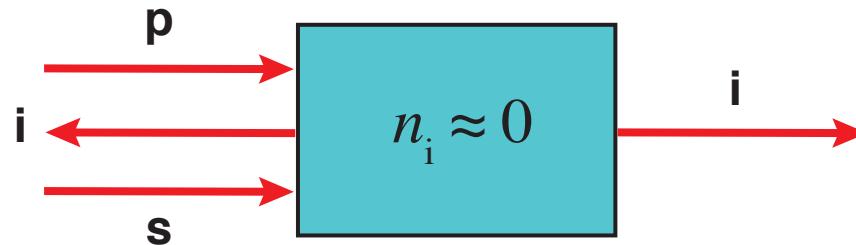


1 index

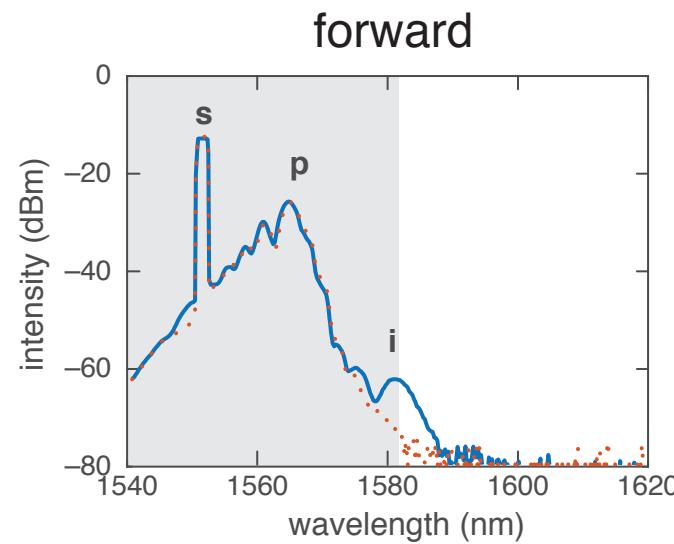
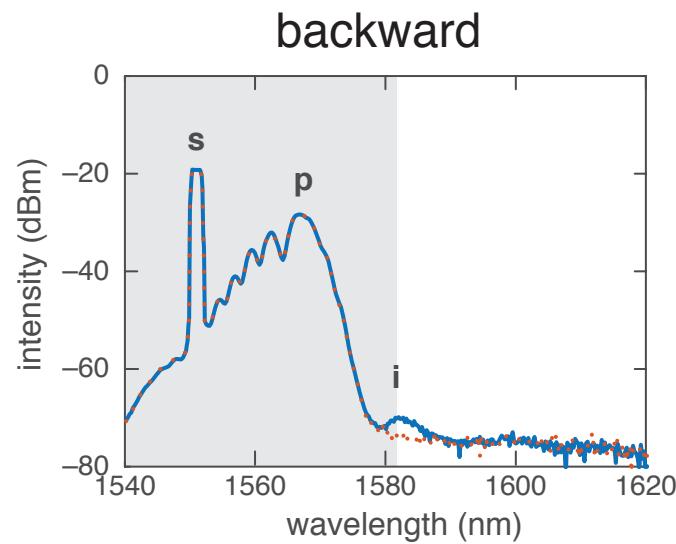
2 zero index

3 experiments

# four-wave mixing



forward and backward

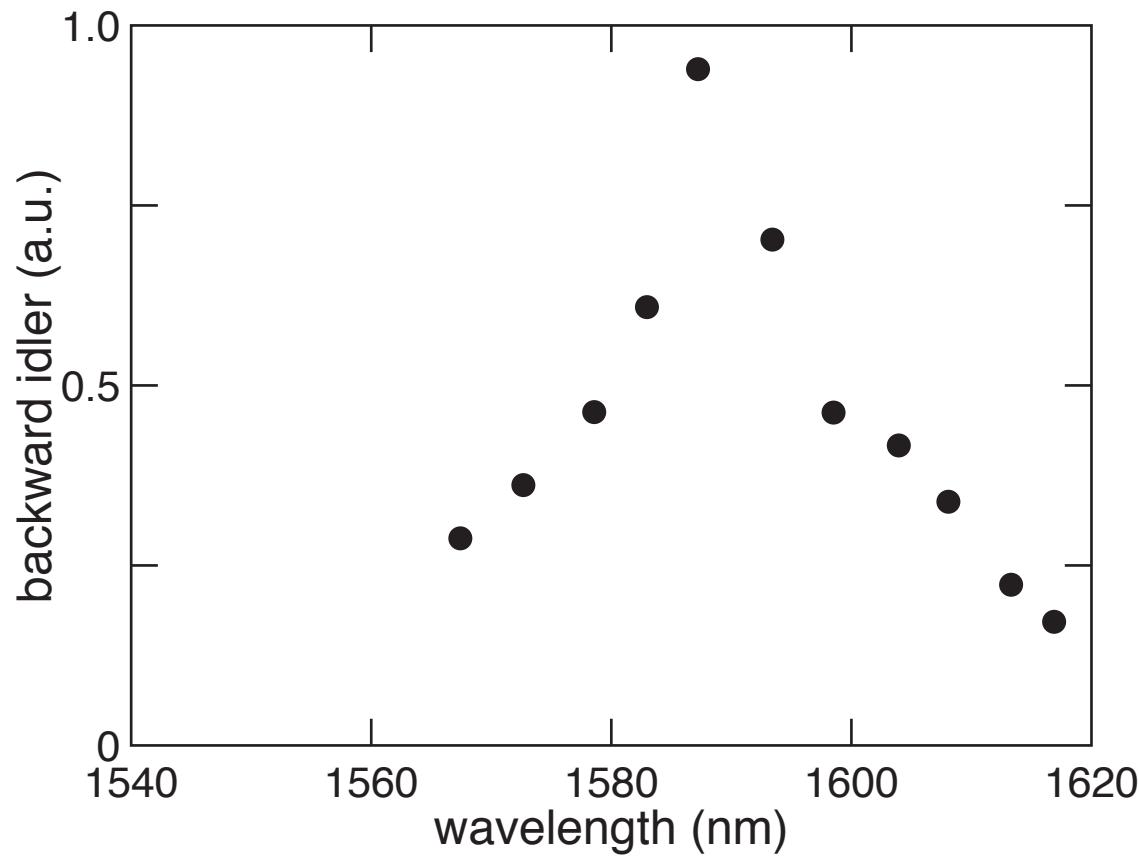


1 index

2 zero index

3 experiments

## backward idler intensity



1 index

2 zero index

3 experiments



Yang Li, Shota Kita, Phil Muñoz, Orad Reshef,  
Daryl Vulis, Mei Yin, Lysander Christakis, Zin Lin,  
Justin Gagnon, Olivia Mello, Haoning Tang, Marko Ločcar

Profs. Robert Boyd, Nader Engheta, and Alan Willner

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1 index

2 zero index

3 experiments