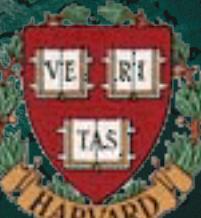


# On-Chip Zero-Index Metamaterials



Peking University  
Beijing, China, 18 December 2015



# On-Chip Zero-Index Metamaterials



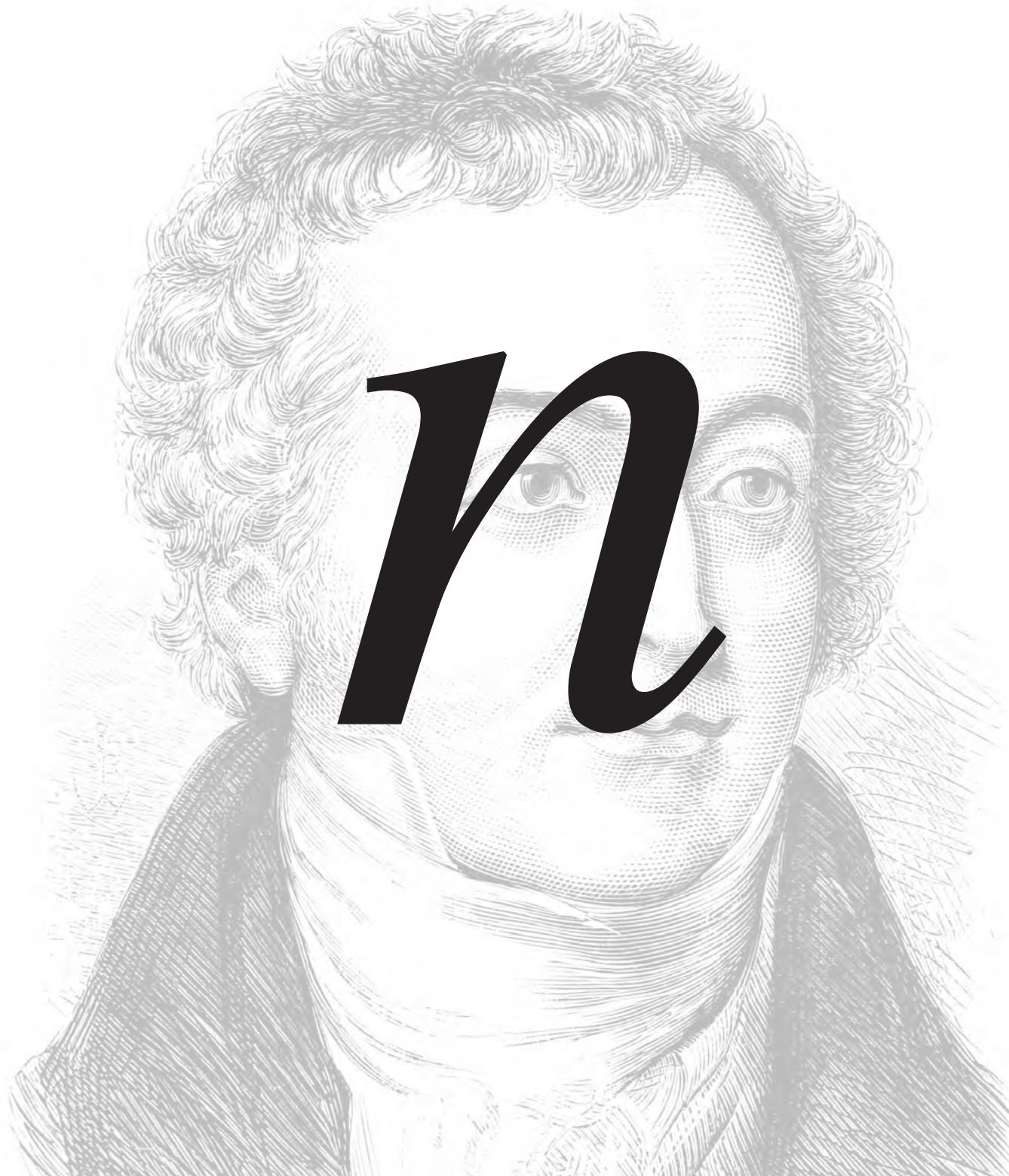
@eric\_mazur

Peking University  
Beijing, China, 18 December 2015





*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

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

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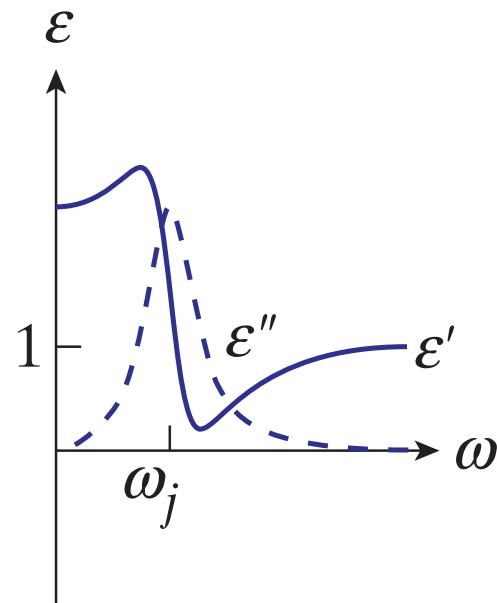
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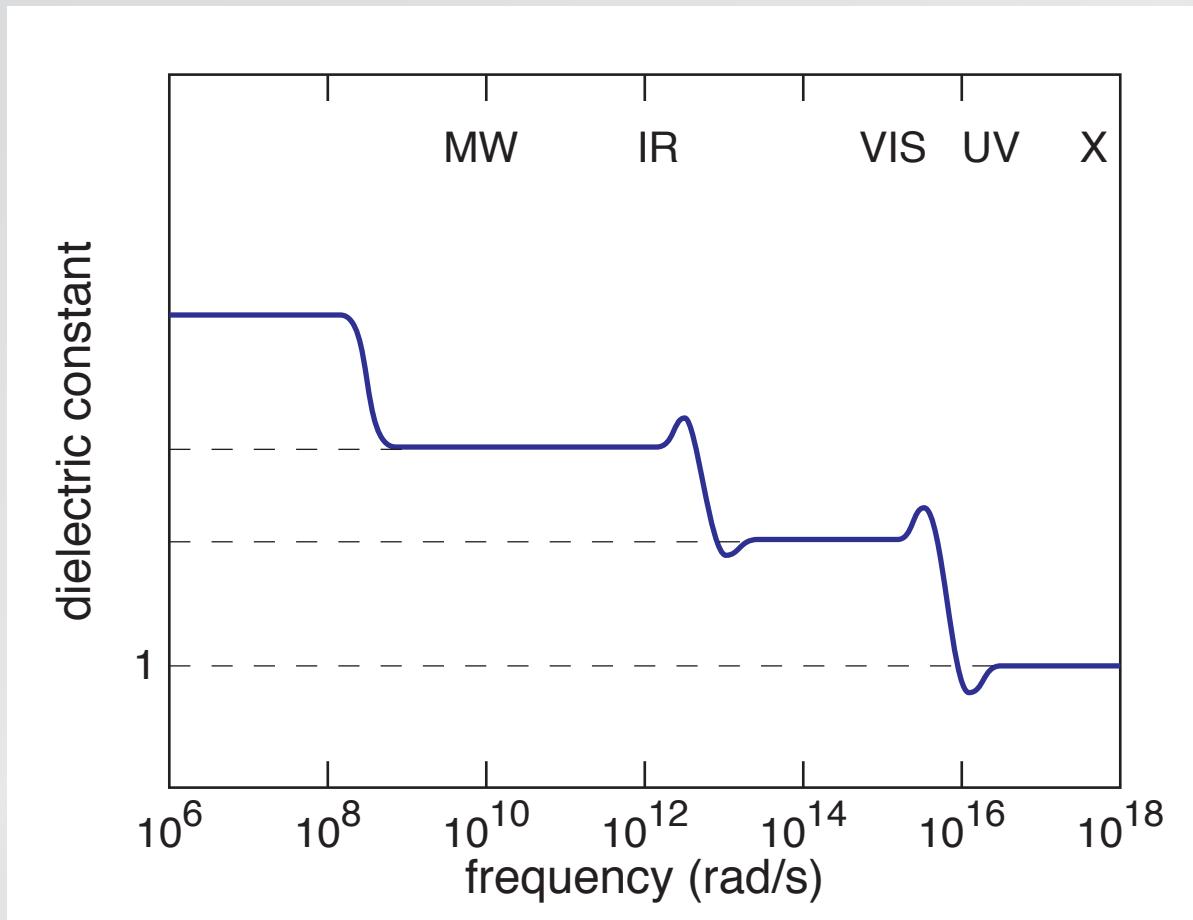
**In dispersive media**  $n = n(\omega)$  .

# Dielectric constant

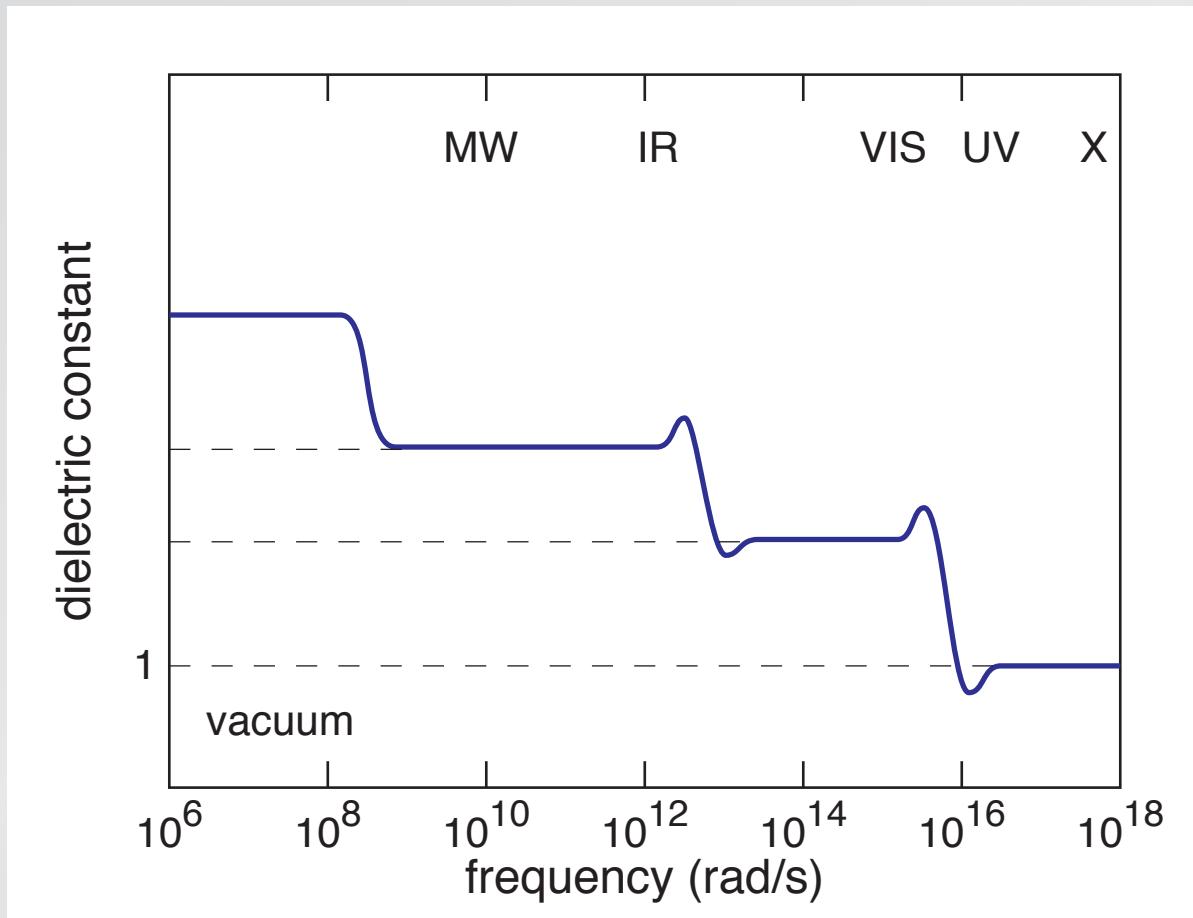
## Lorentz oscillator



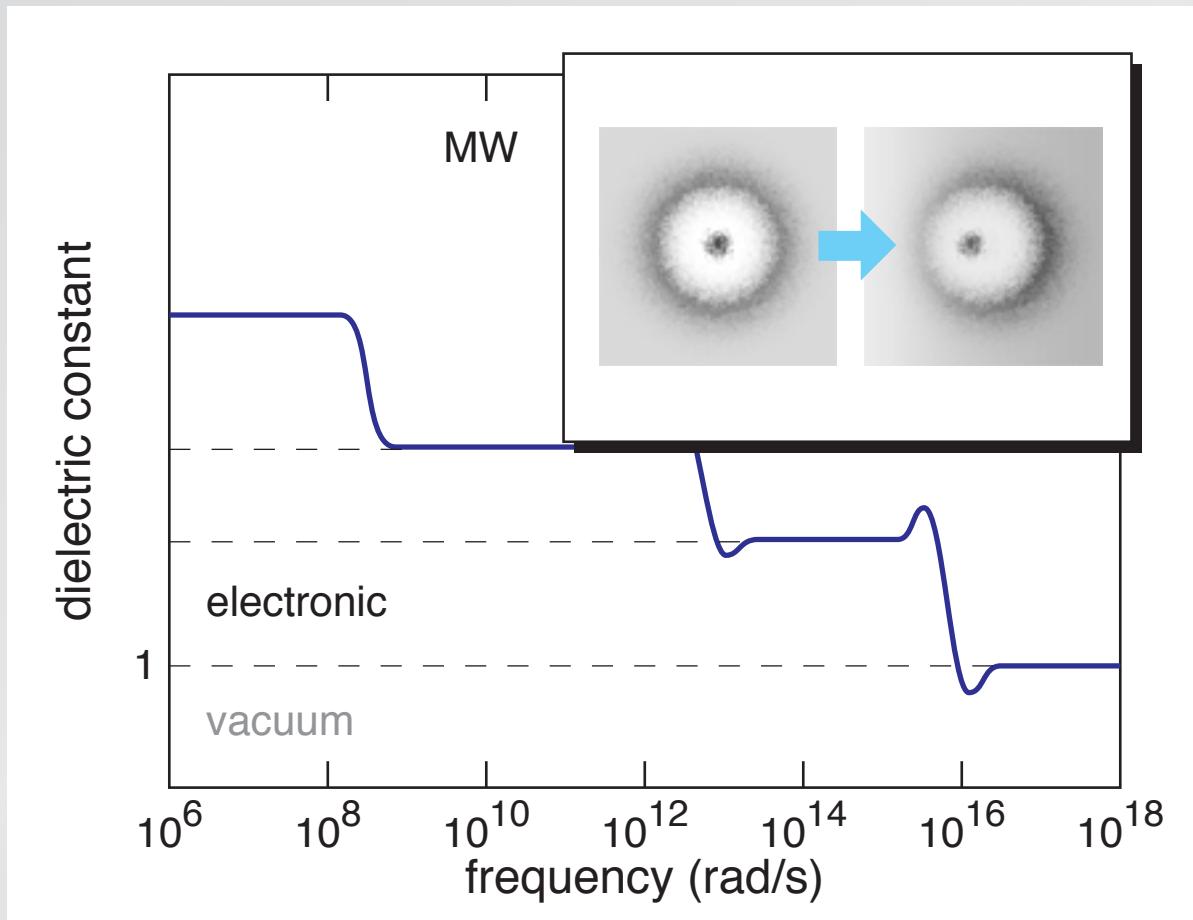
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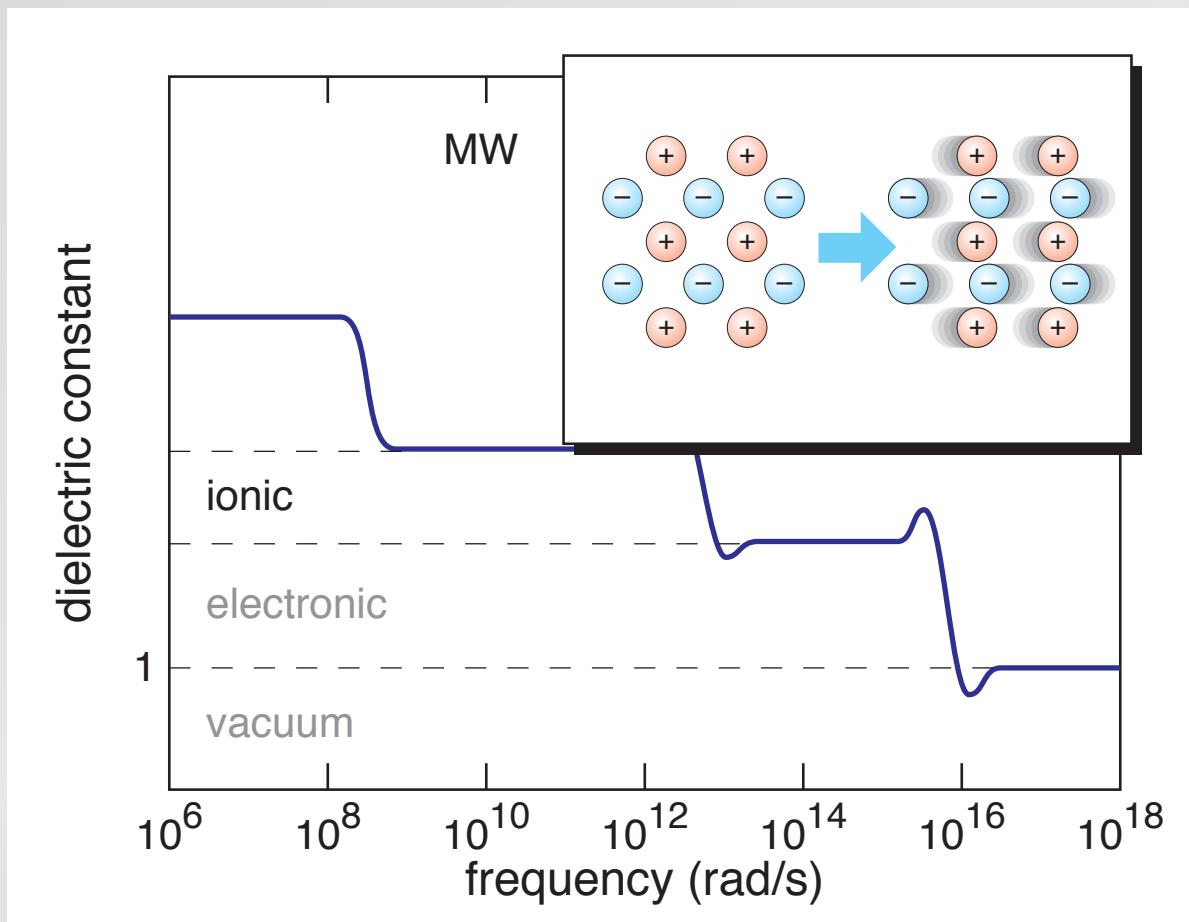
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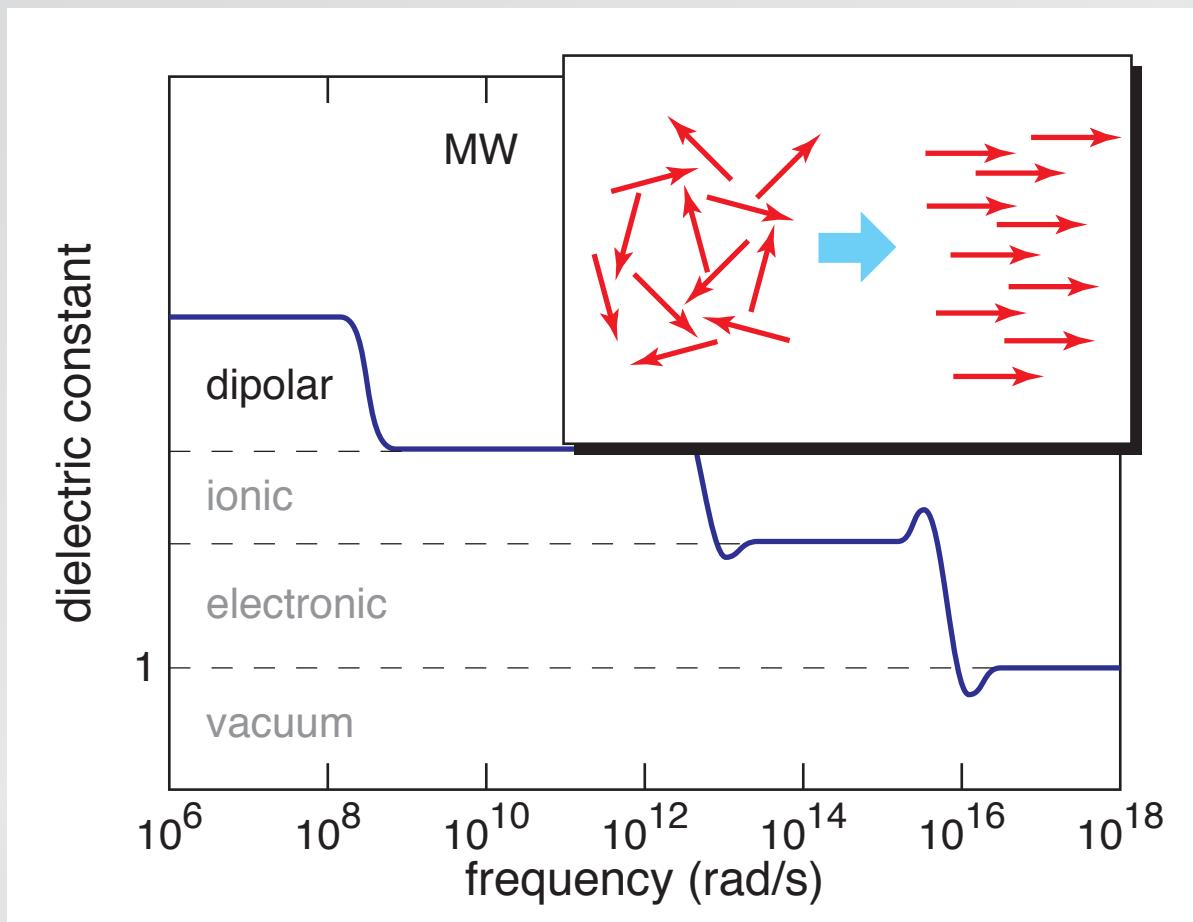
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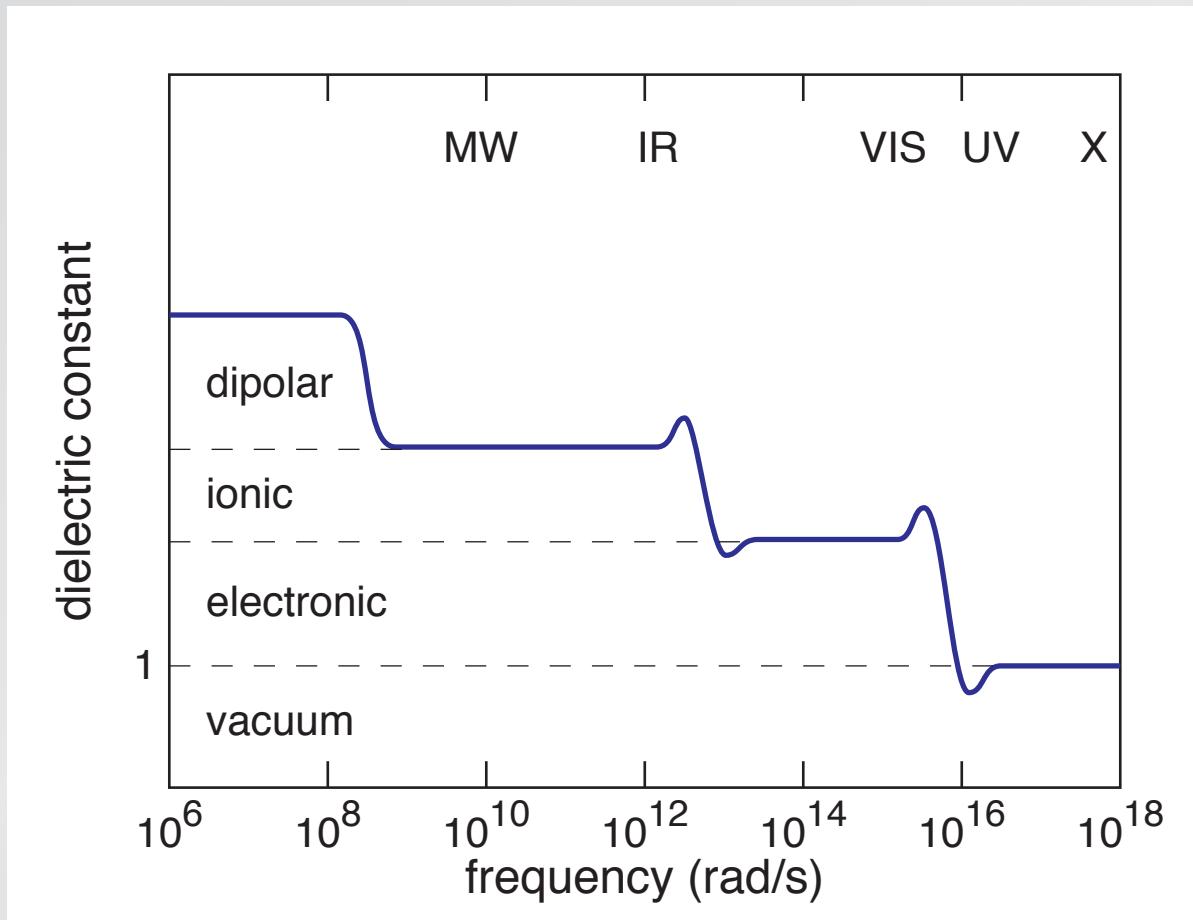
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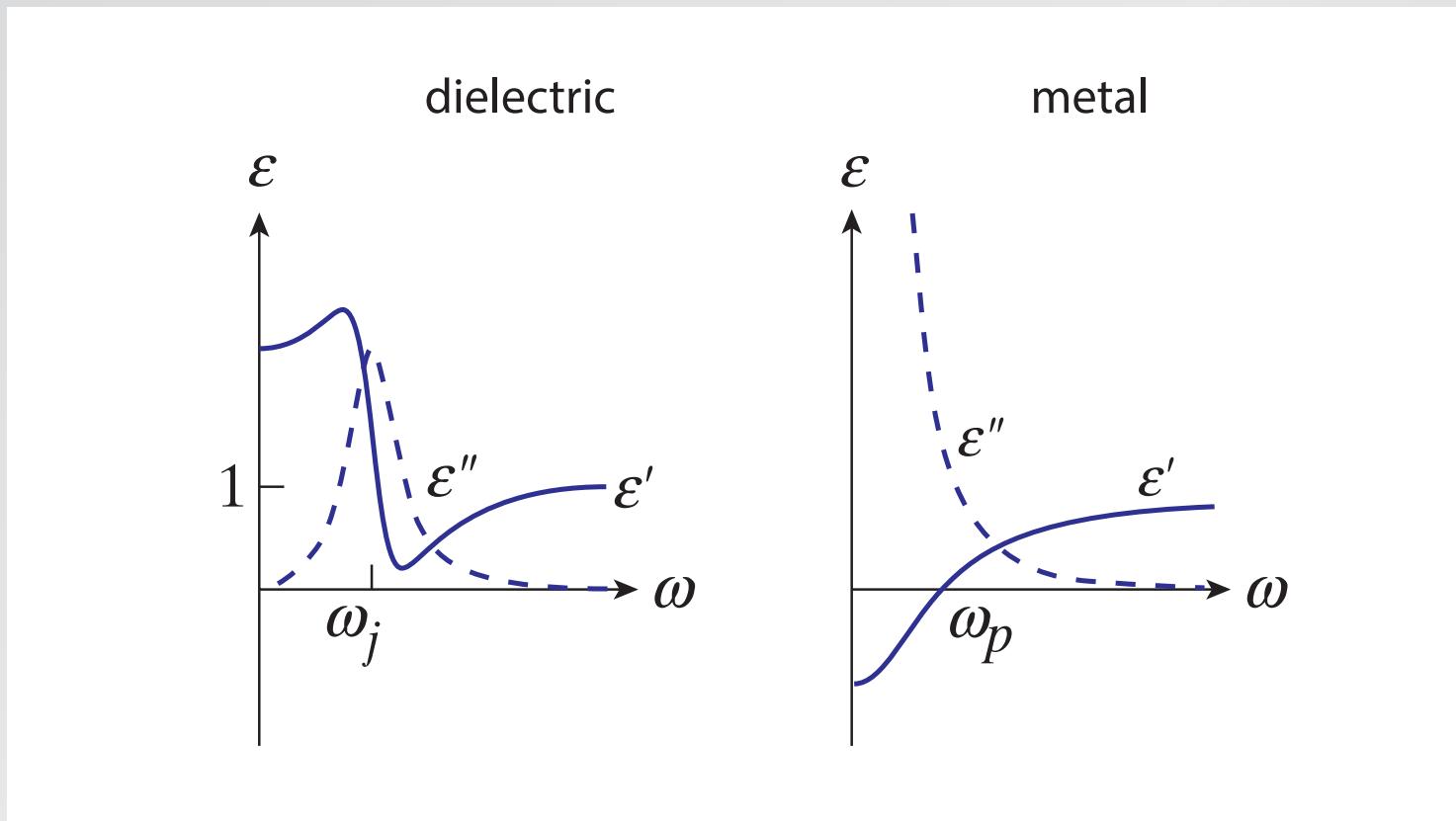
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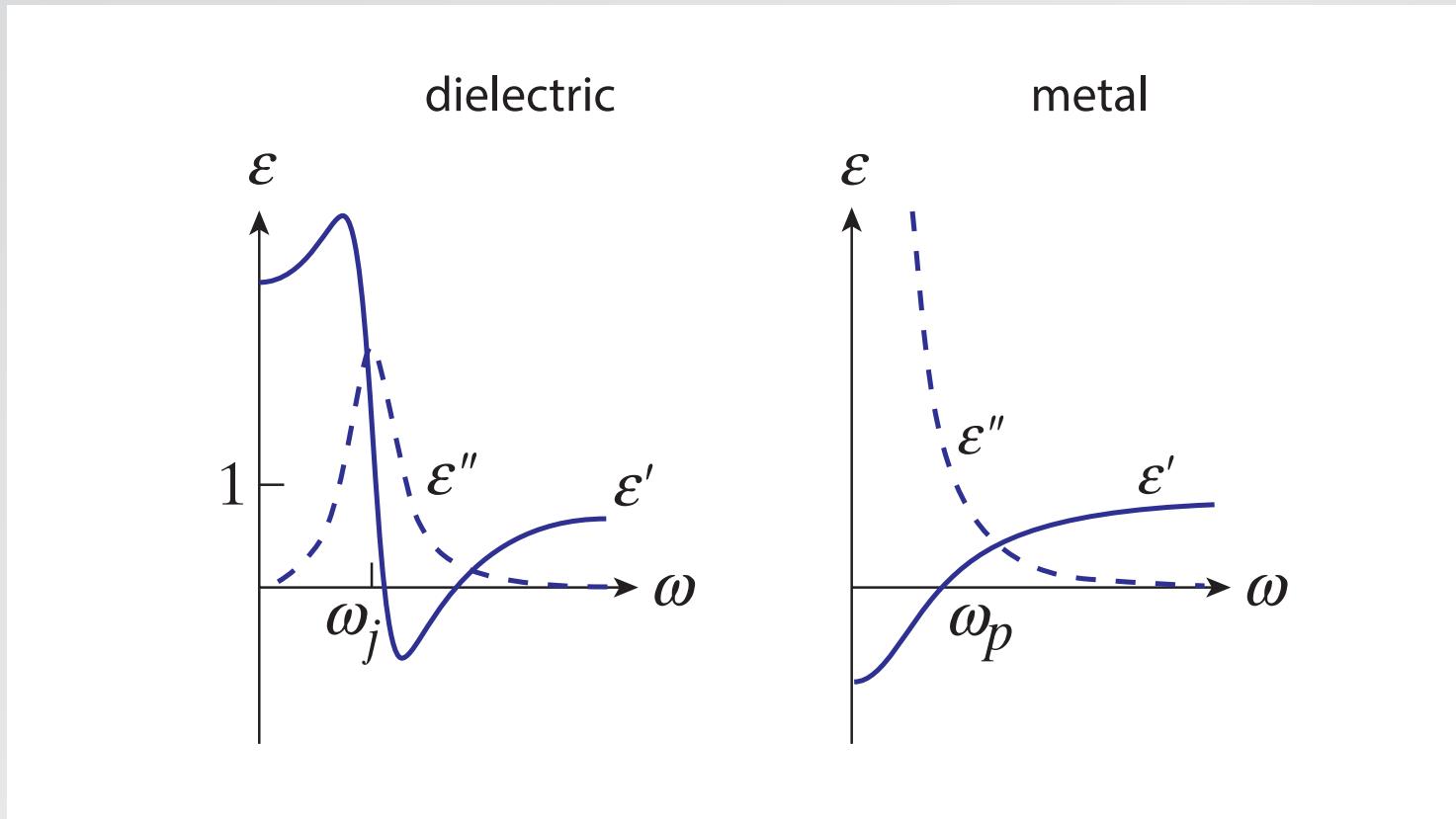


# Lorentz and Drude models



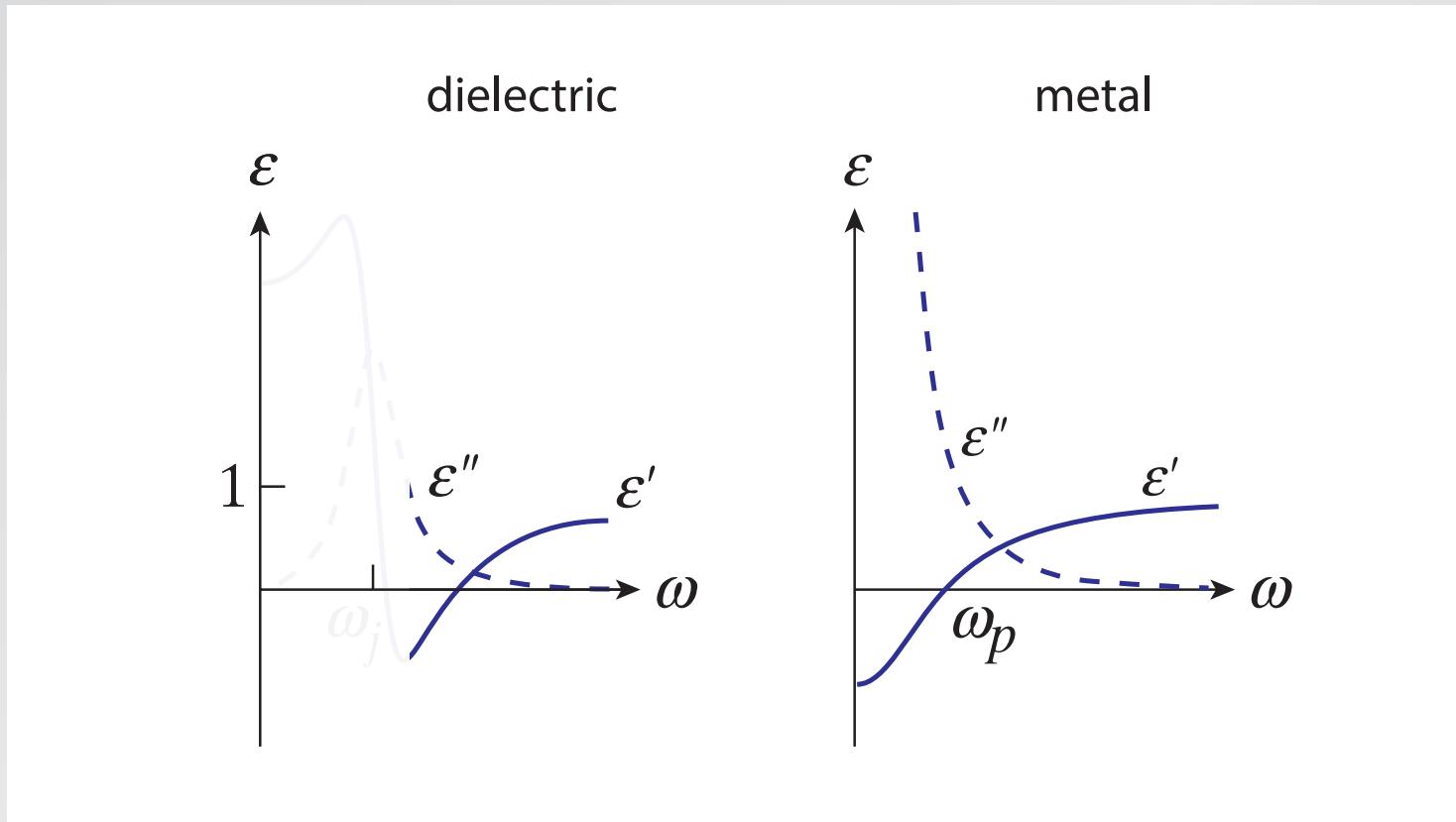
# Lorentz and Drude models

for a strong (dielectric) resonance  $\varepsilon$  can become negative



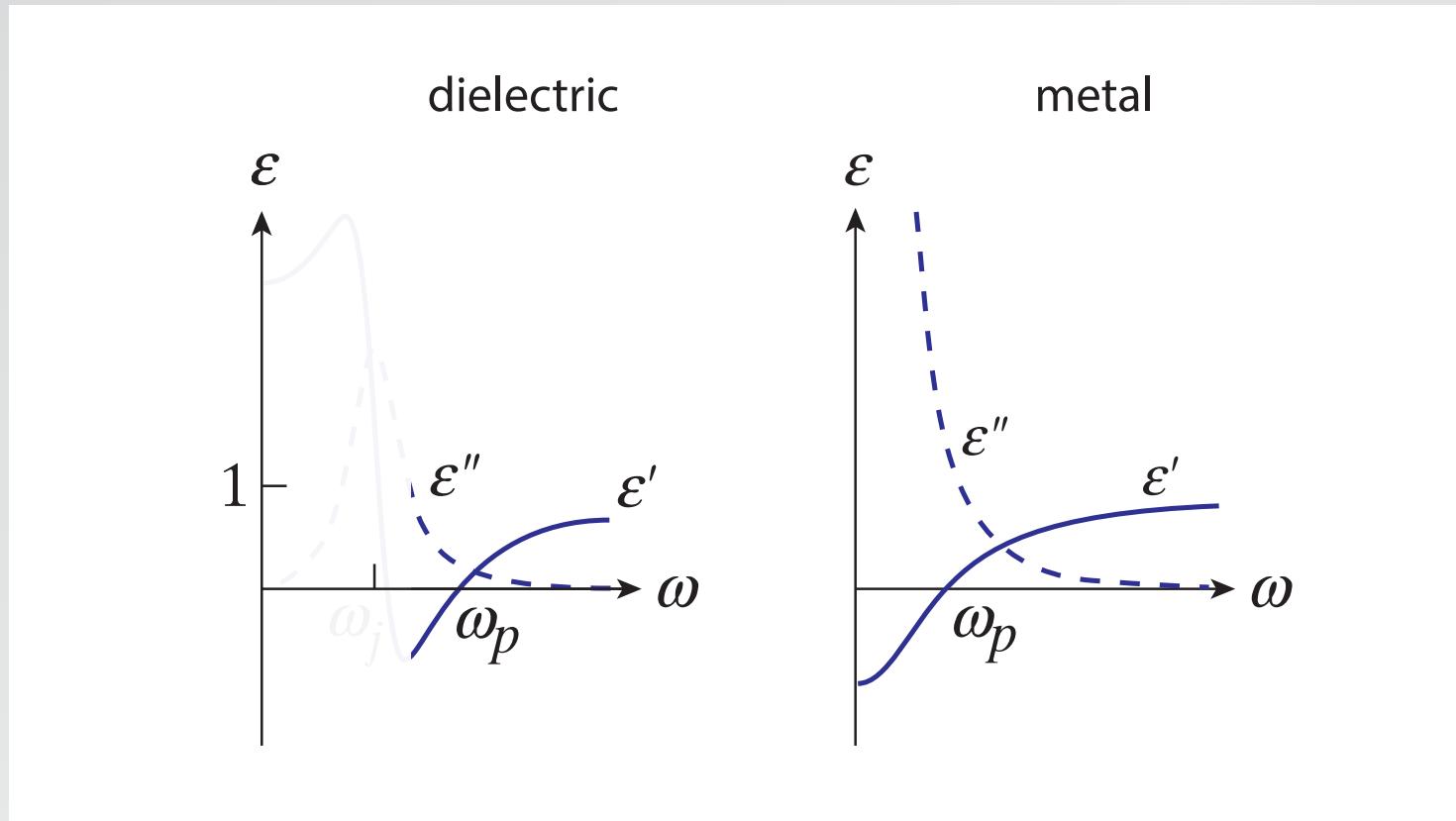
# Lorentz and Drude models

valence electrons in dielectric then behave like a plasma



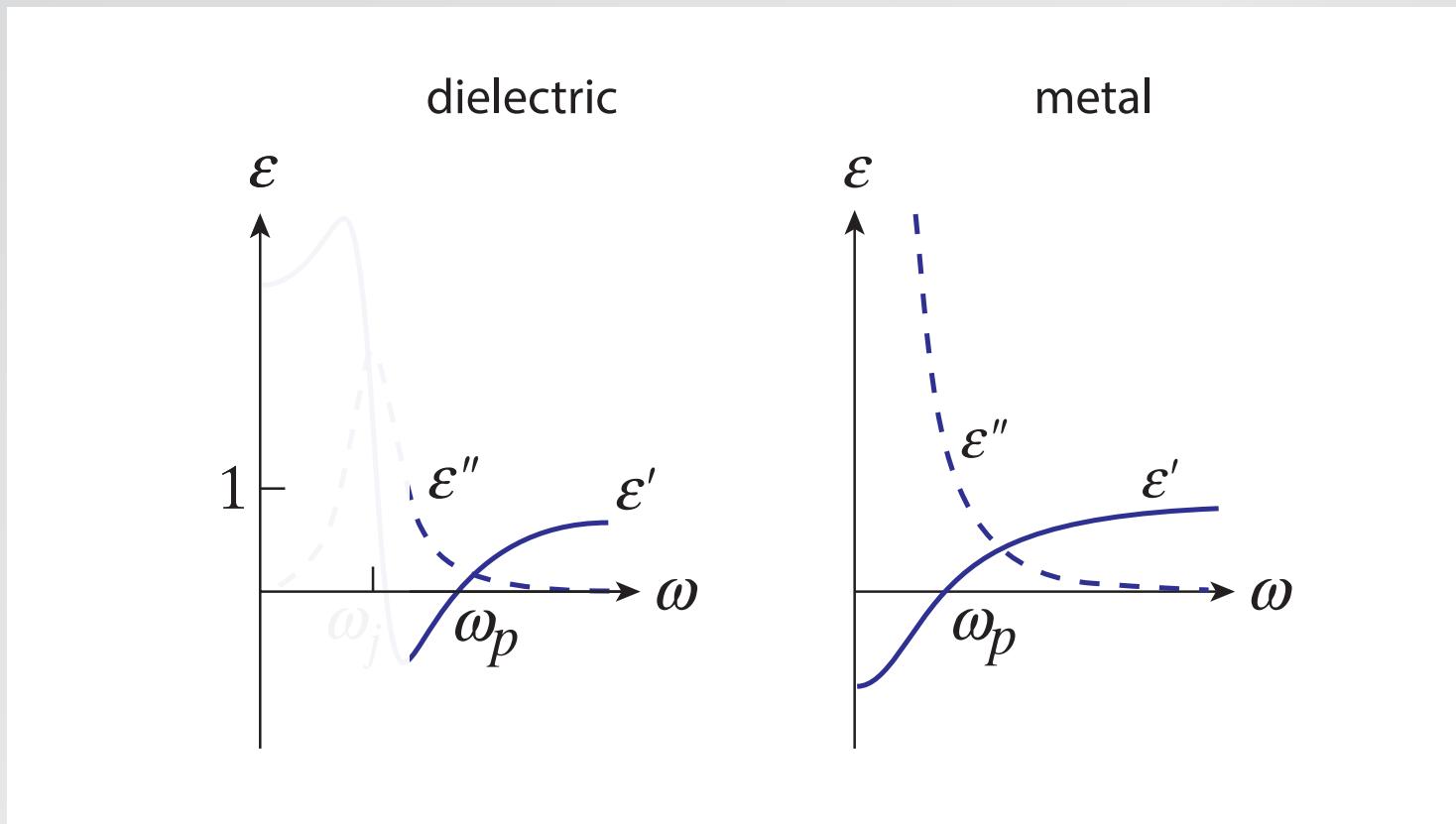
# Lorentz and Drude models

with plasma frequency above the resonance



# Lorentz and Drude models

(and far below the UV region)



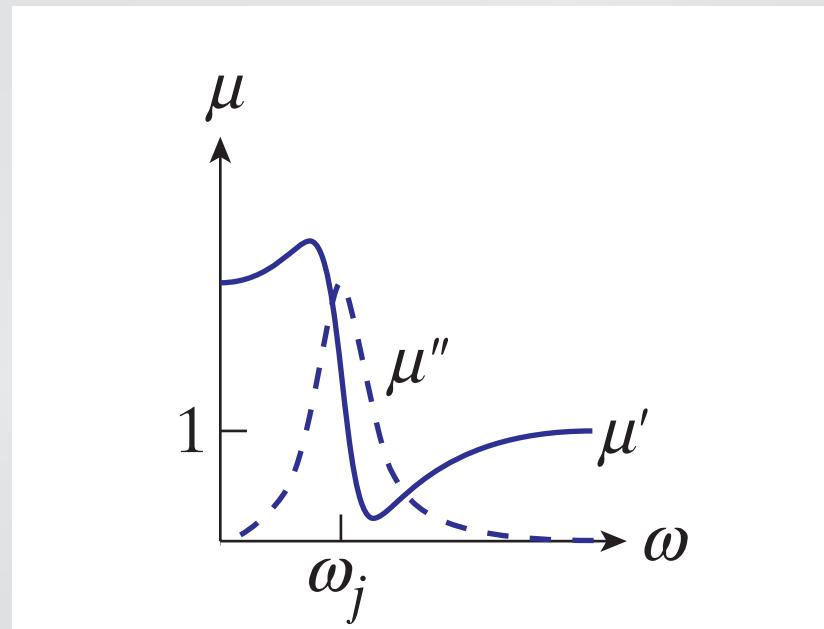
**Index also determined by magnetic response**

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

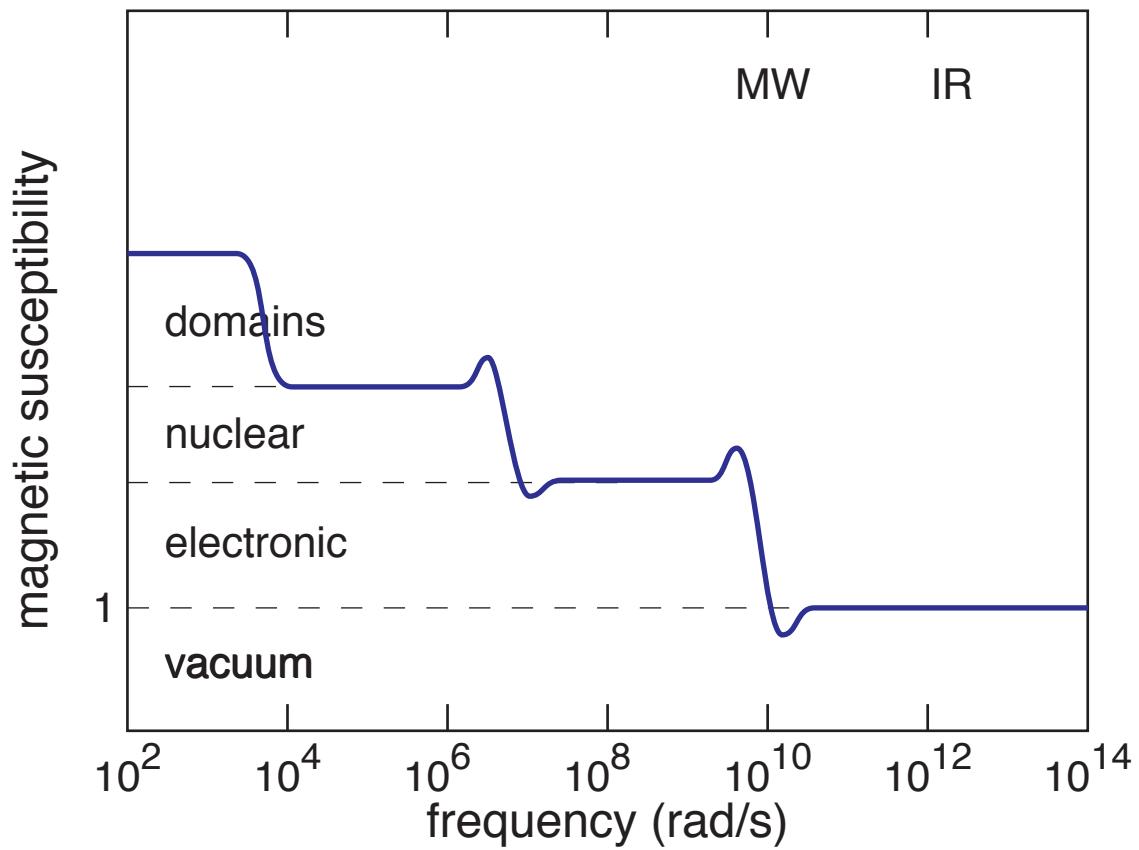
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**and magnetic response shows similar resonances**

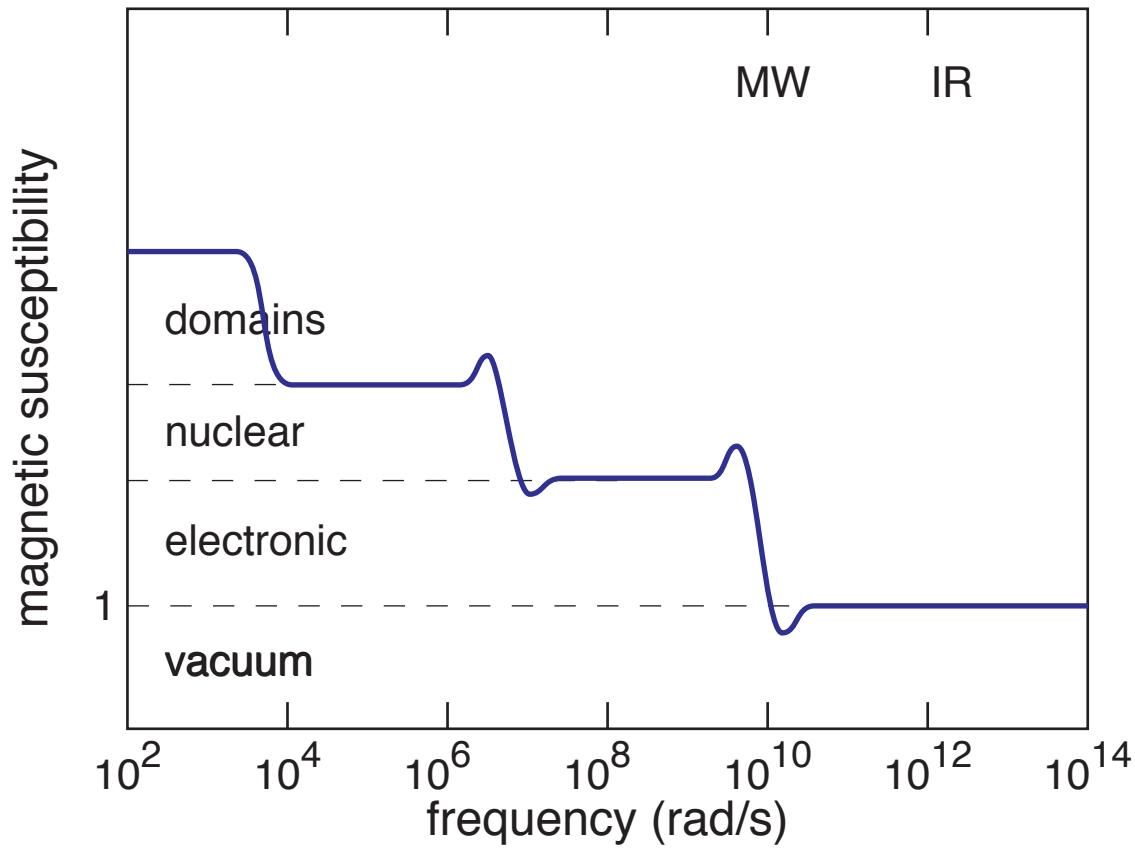


# Magnetic response



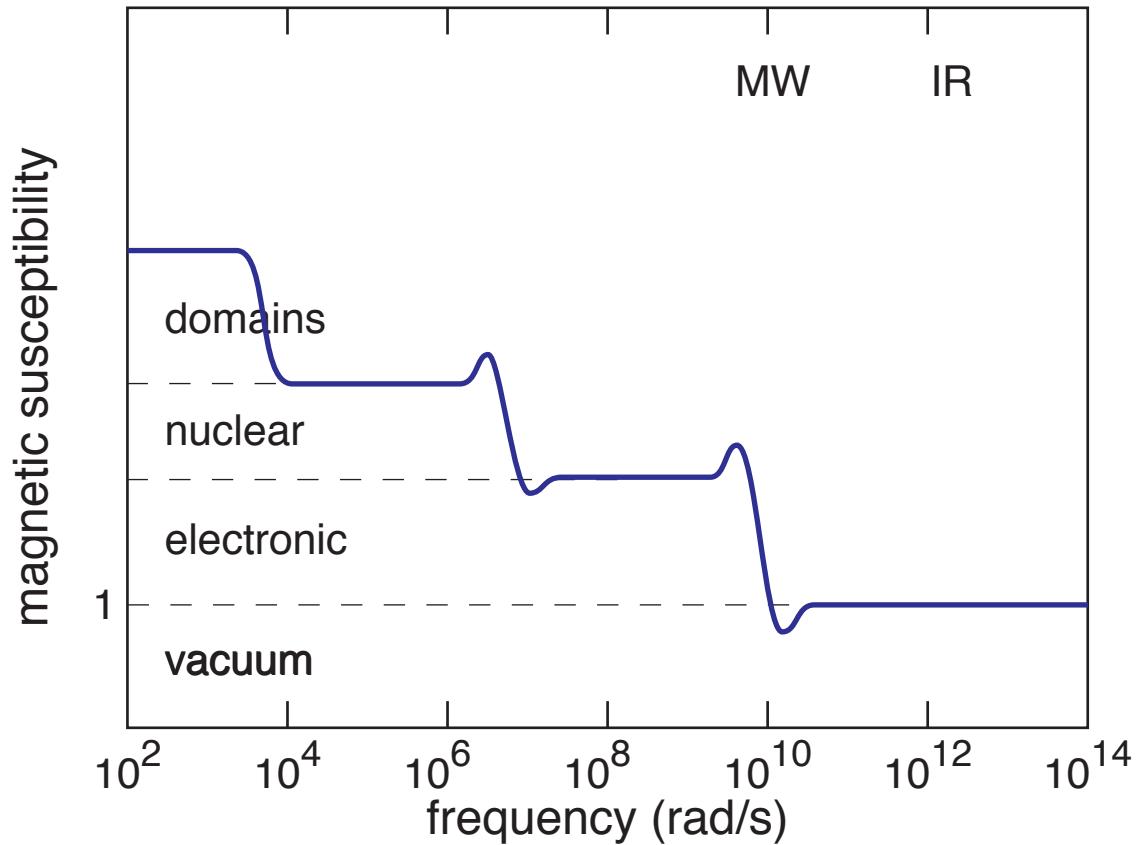
# Magnetic response

but magnetic resonances occur below optical frequencies



# Magnetic response

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



## Index of refraction

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

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

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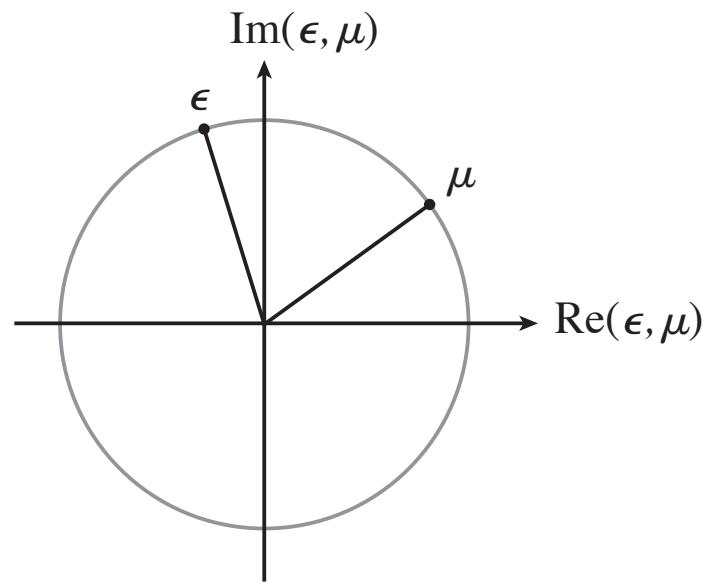
What happens when  $\text{Re}\epsilon$  and/or  $\text{Re}\mu$  is negative?

**Write complex quantities as**

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

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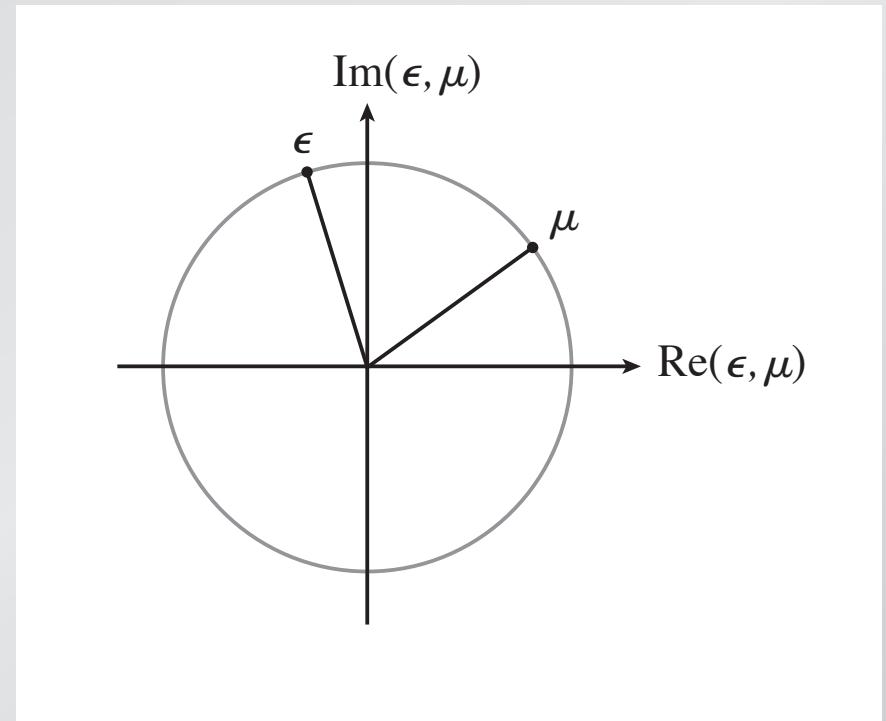


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**Index**

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

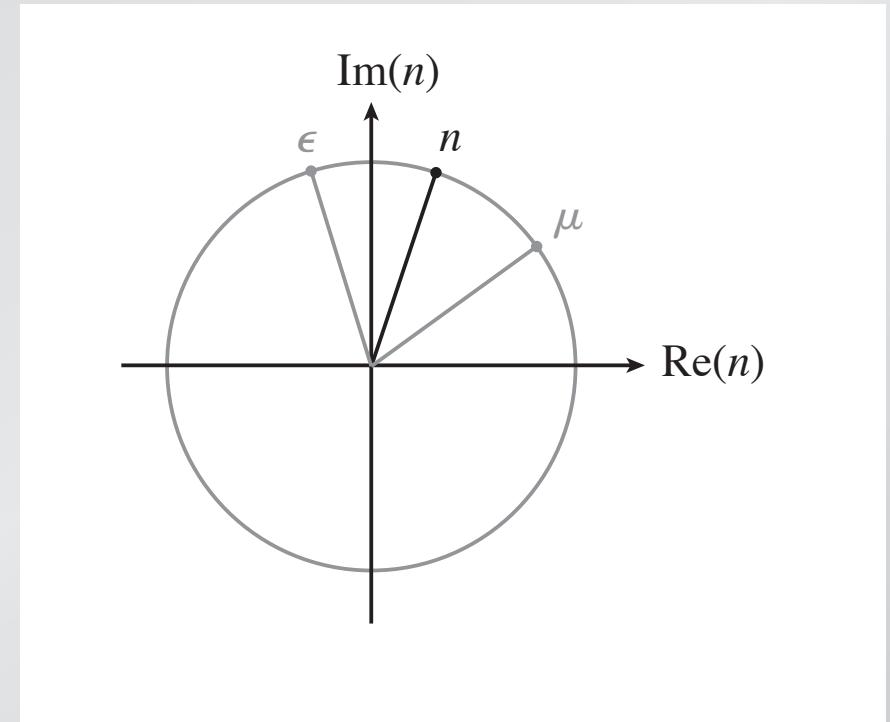


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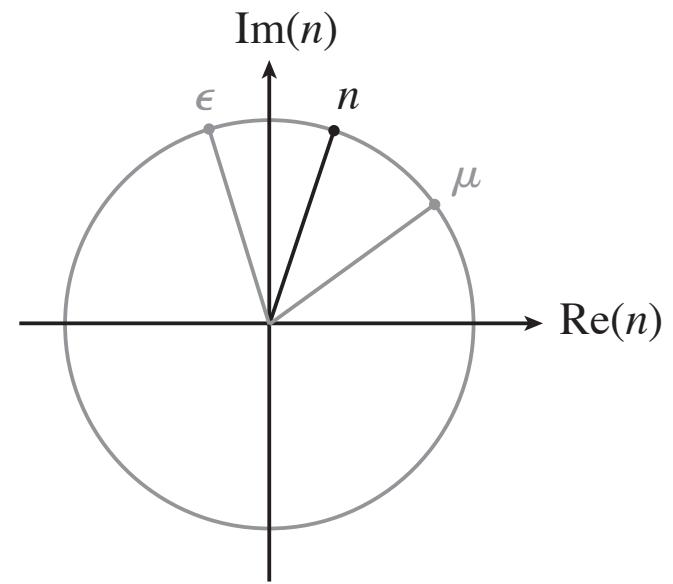
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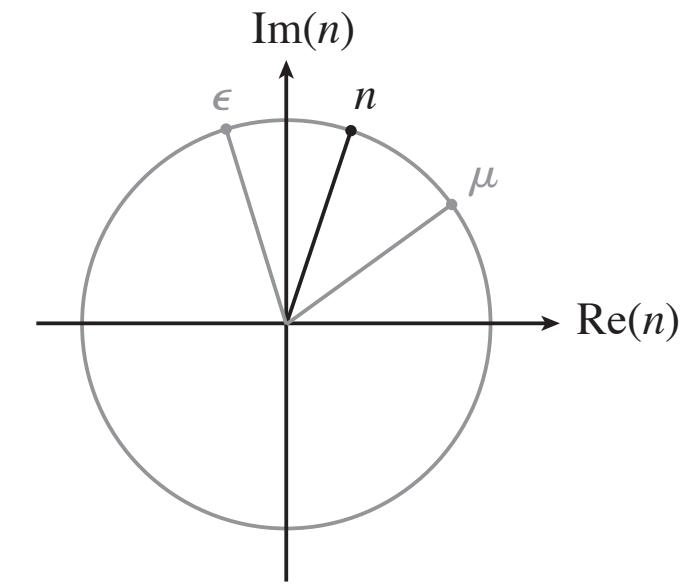


**Q: Is this the only possible solution?**

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



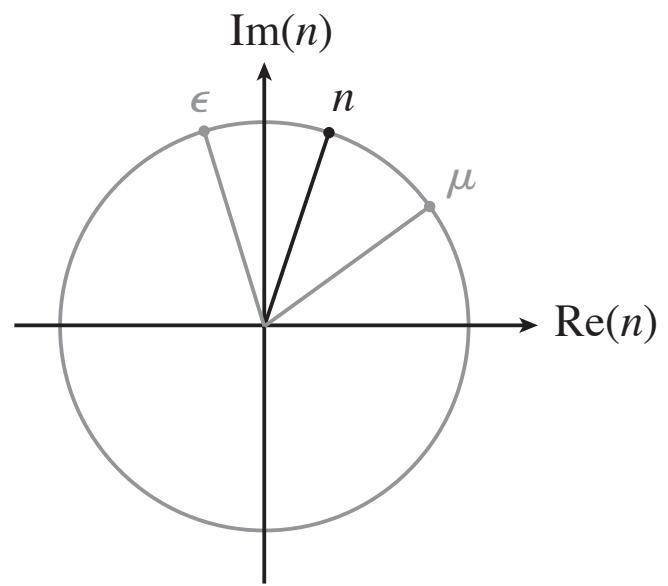
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**Can add  $2\pi$  to exponent**

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



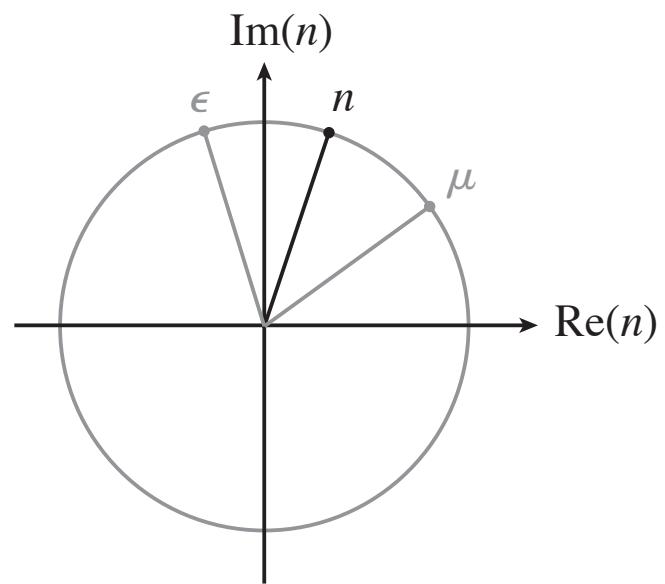
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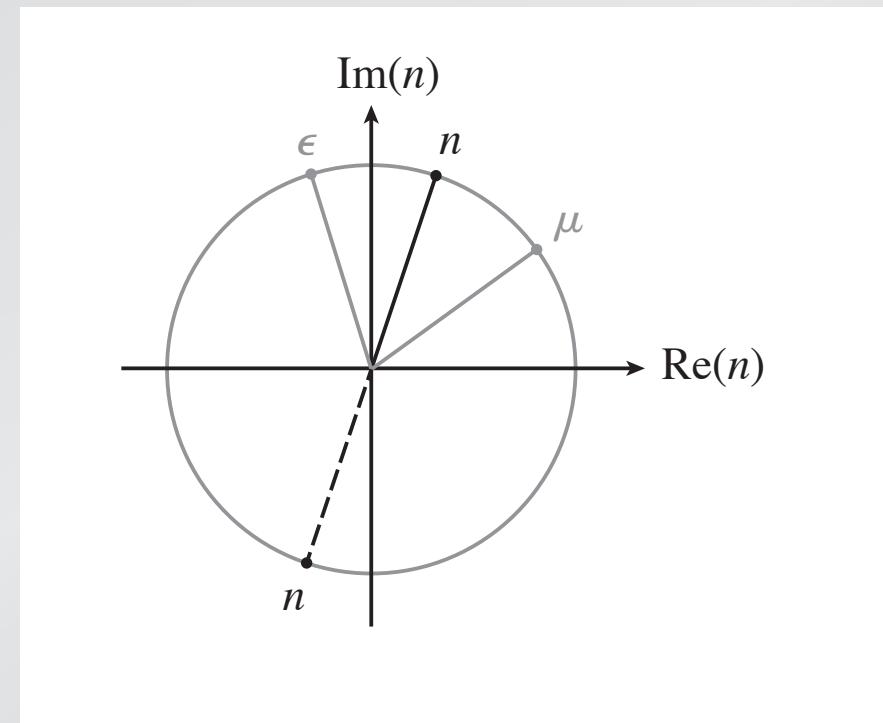
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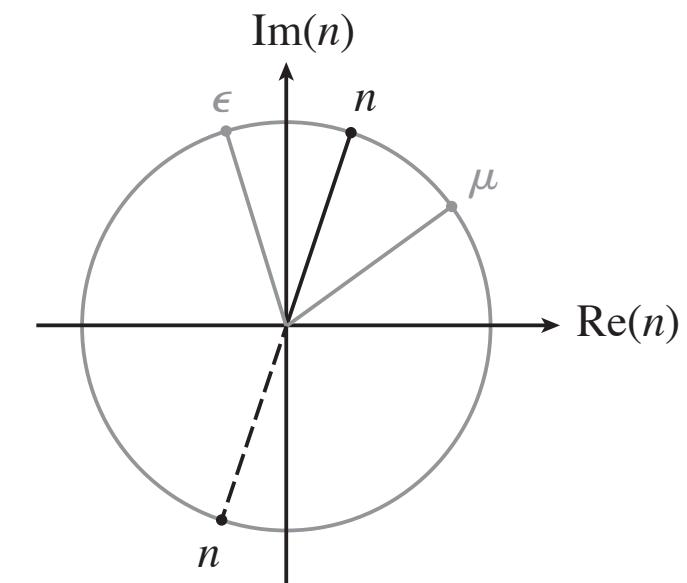
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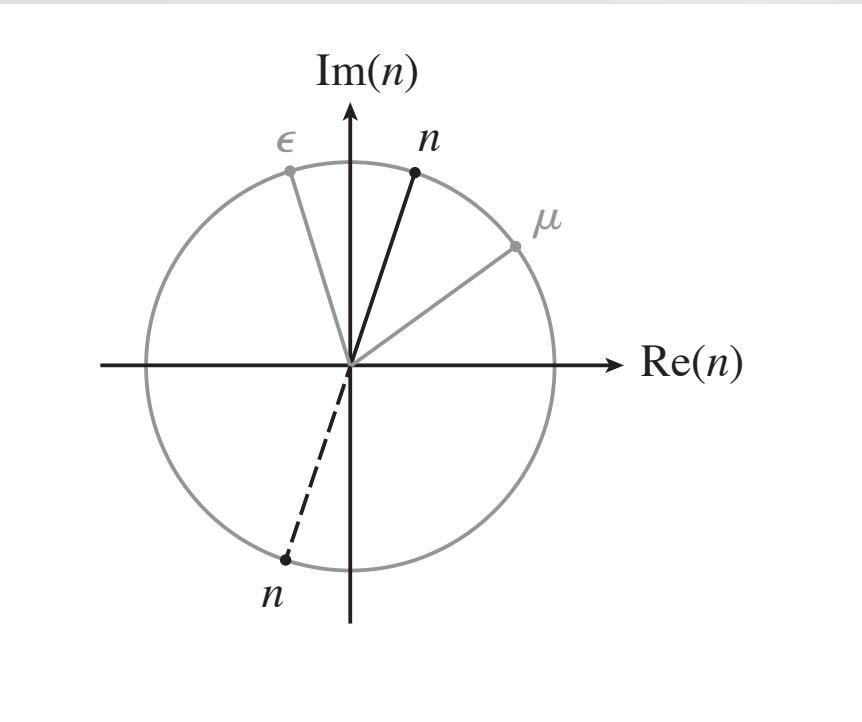
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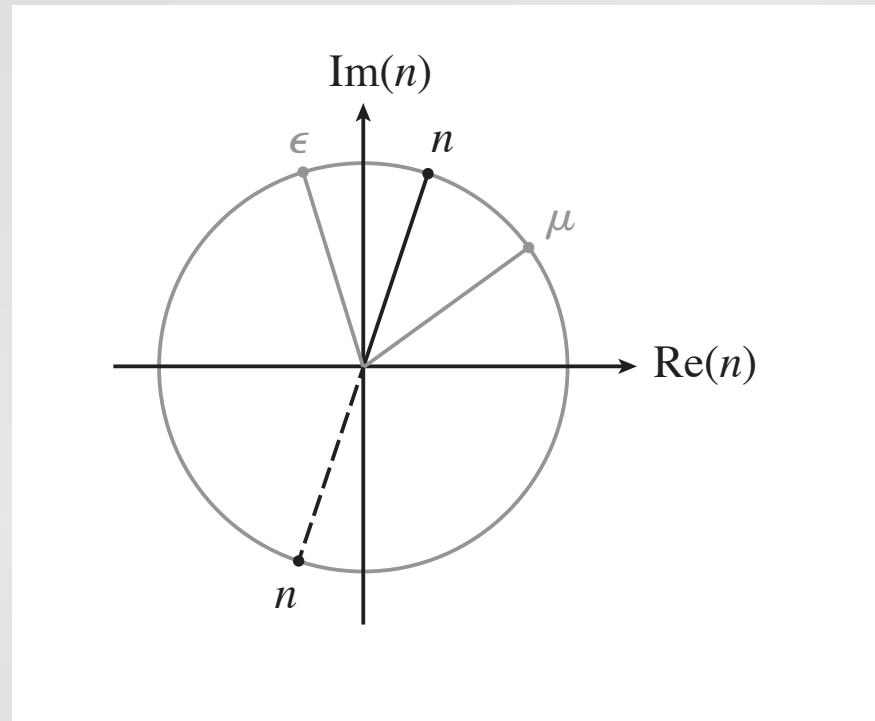
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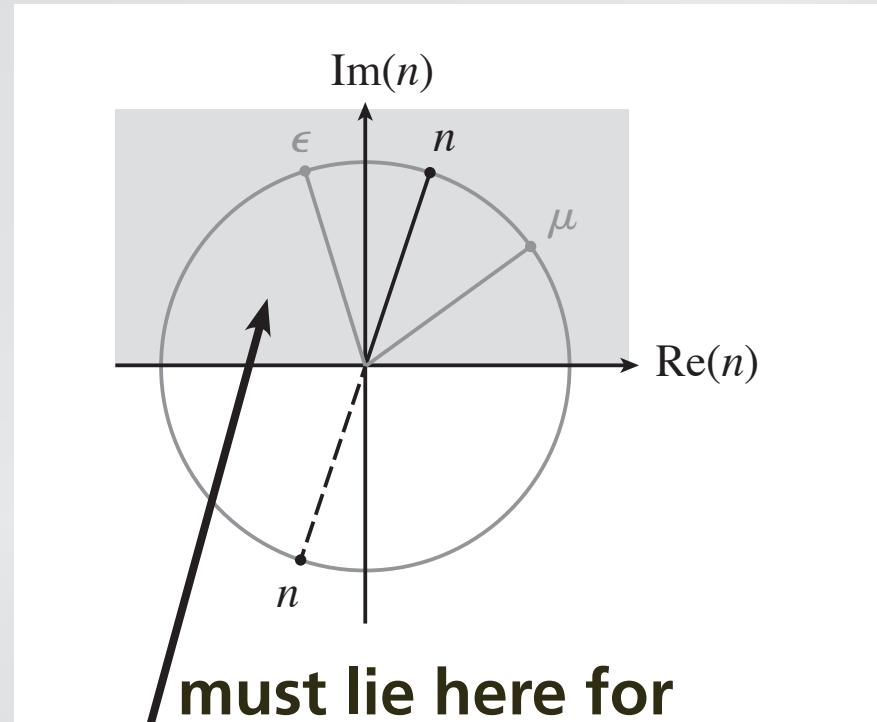
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**must lie here for  
passive material**

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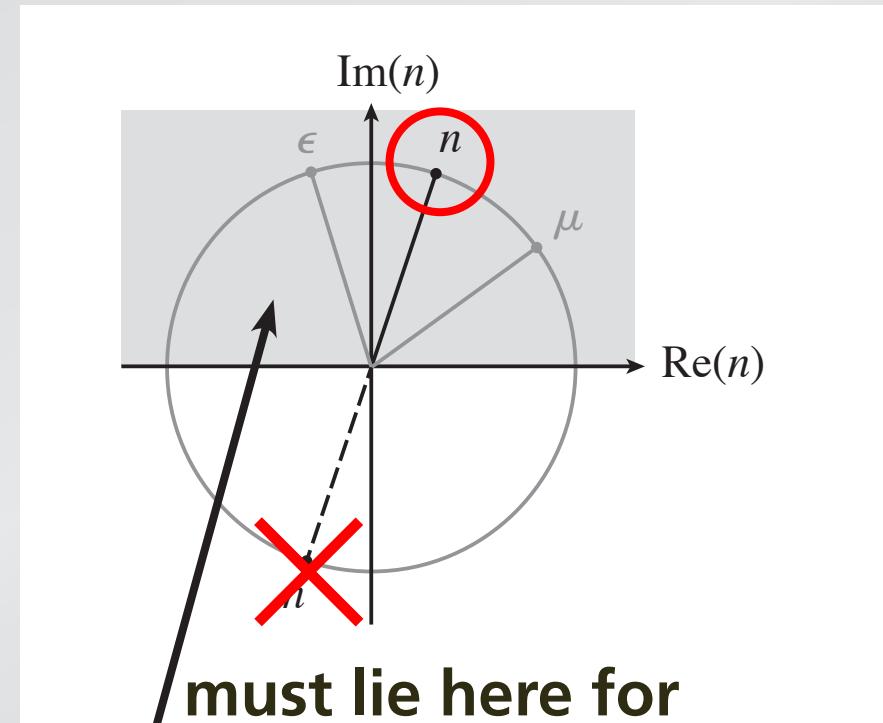
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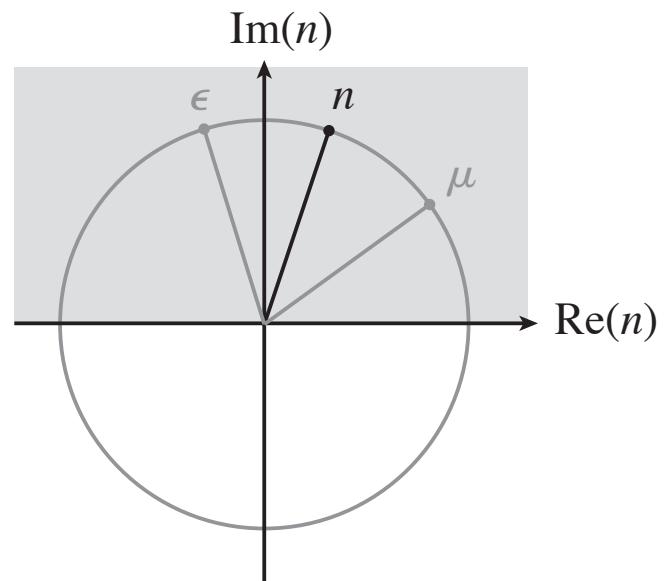
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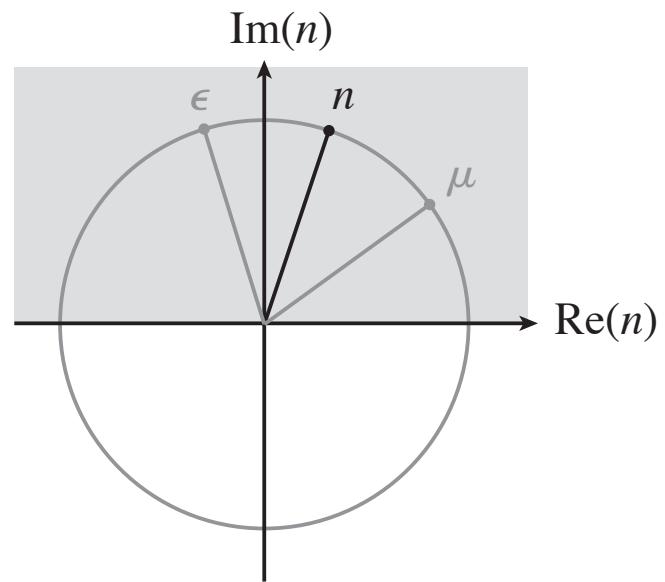
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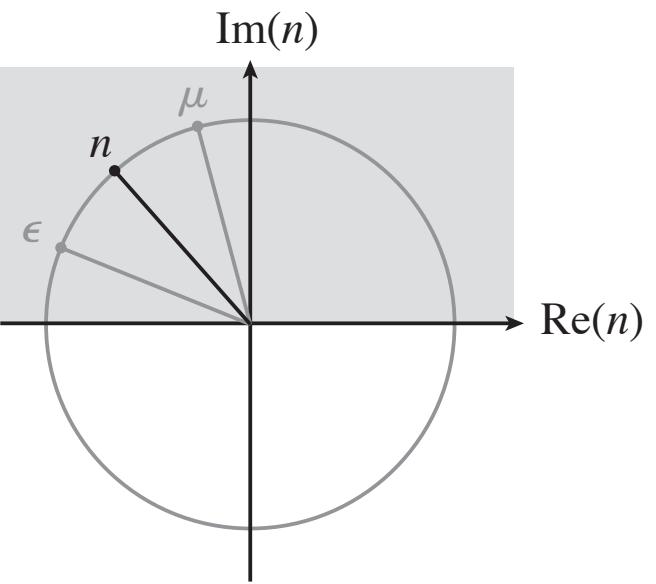


To find  $n$  (passive materials):

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

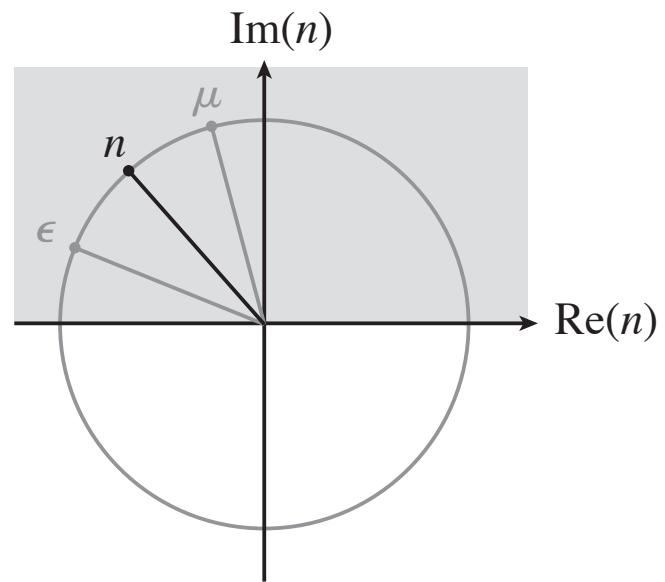


**For certain values of  $\epsilon$  and  $\mu$   
we can get a *negative*  $\text{Re}(n)$ !**



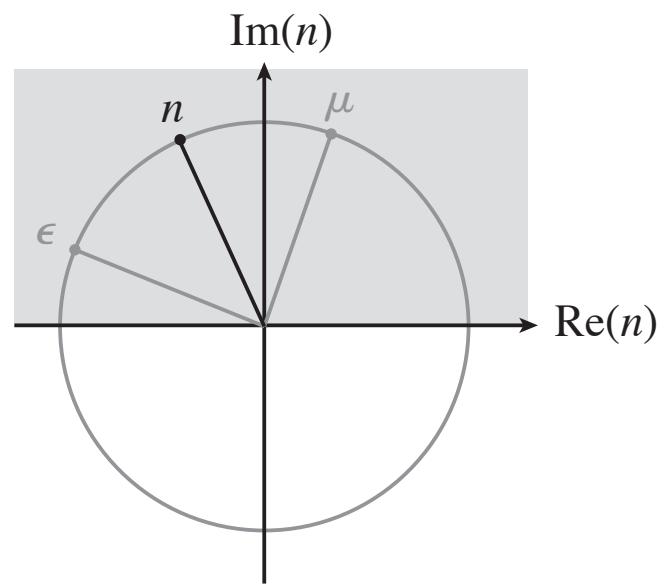
**Q: Must both  $\operatorname{Re}\epsilon < 0$  and  $\operatorname{Re}\mu < 0$  to get a negative index?**

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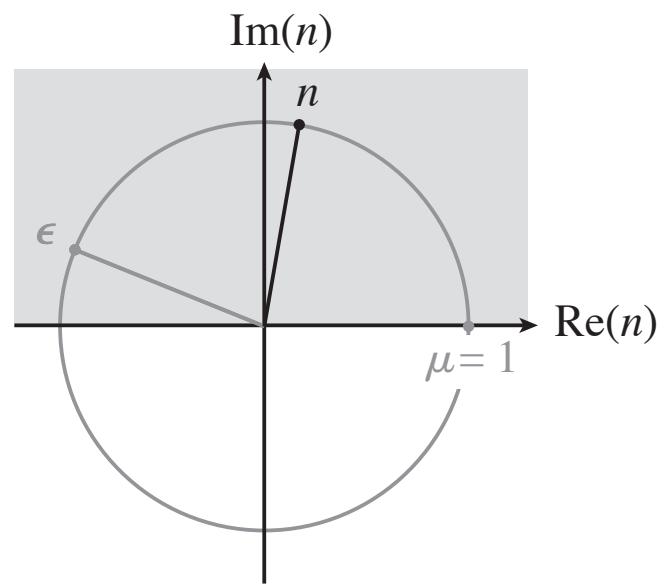


**Q: Must both  $\operatorname{Re}\epsilon < 0$  and  $\operatorname{Re}\mu < 0$  to get a negative index?**

1. yes
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**Note: need magnetic response  
to achieve  $n \leq 0$ !**



**Now remember**

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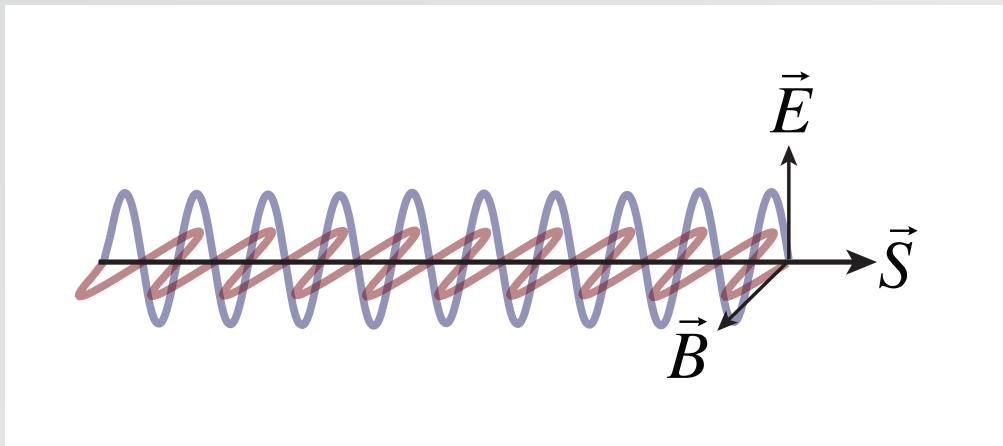
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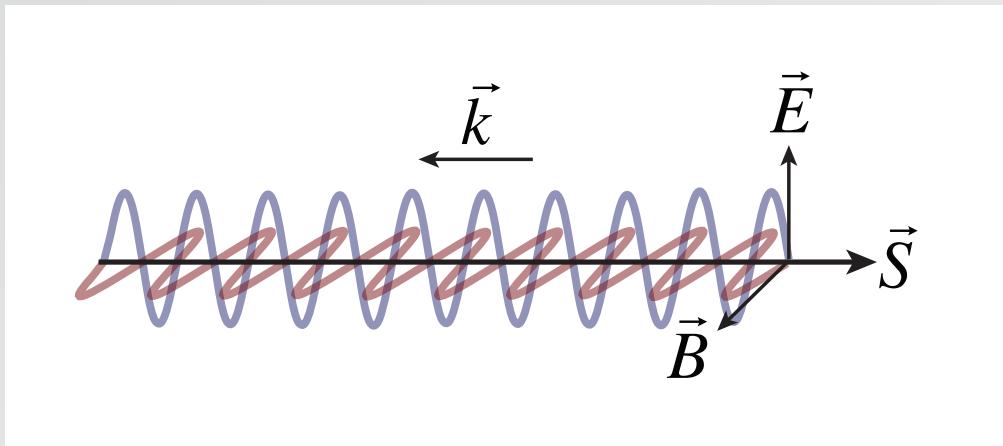
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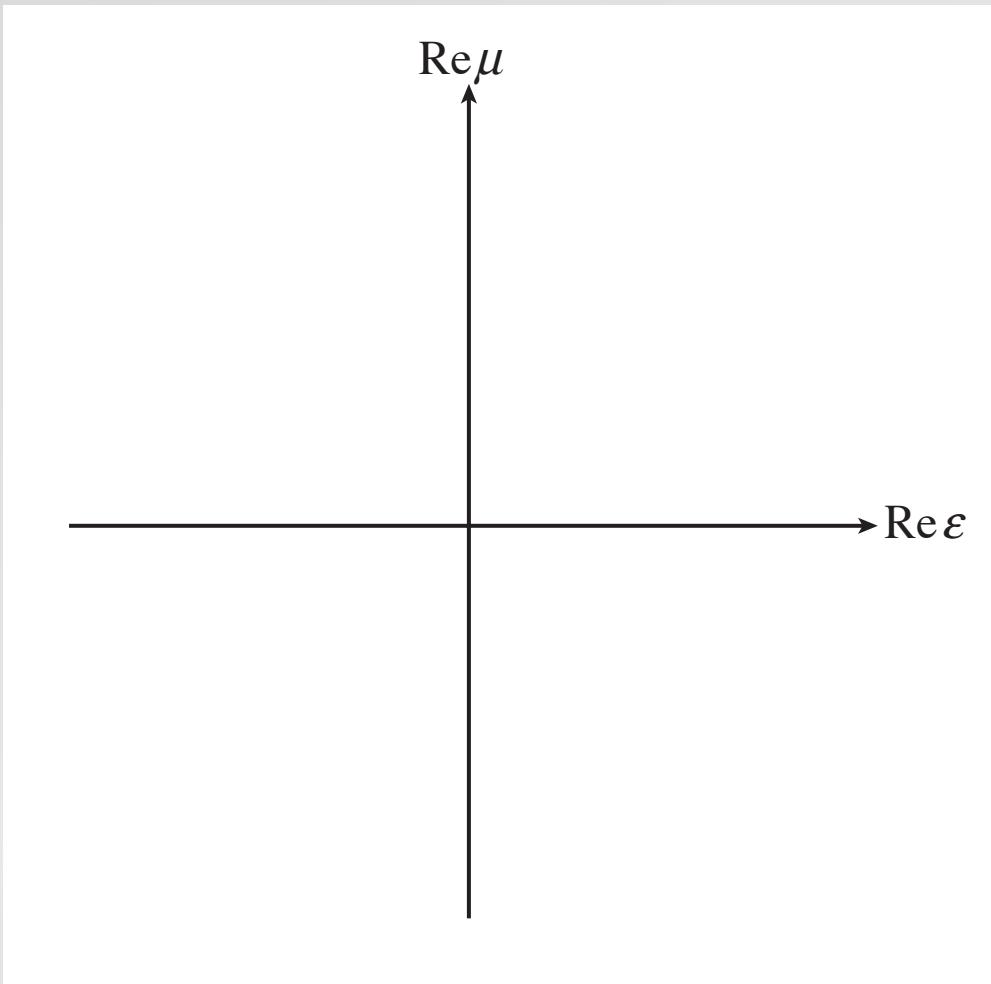


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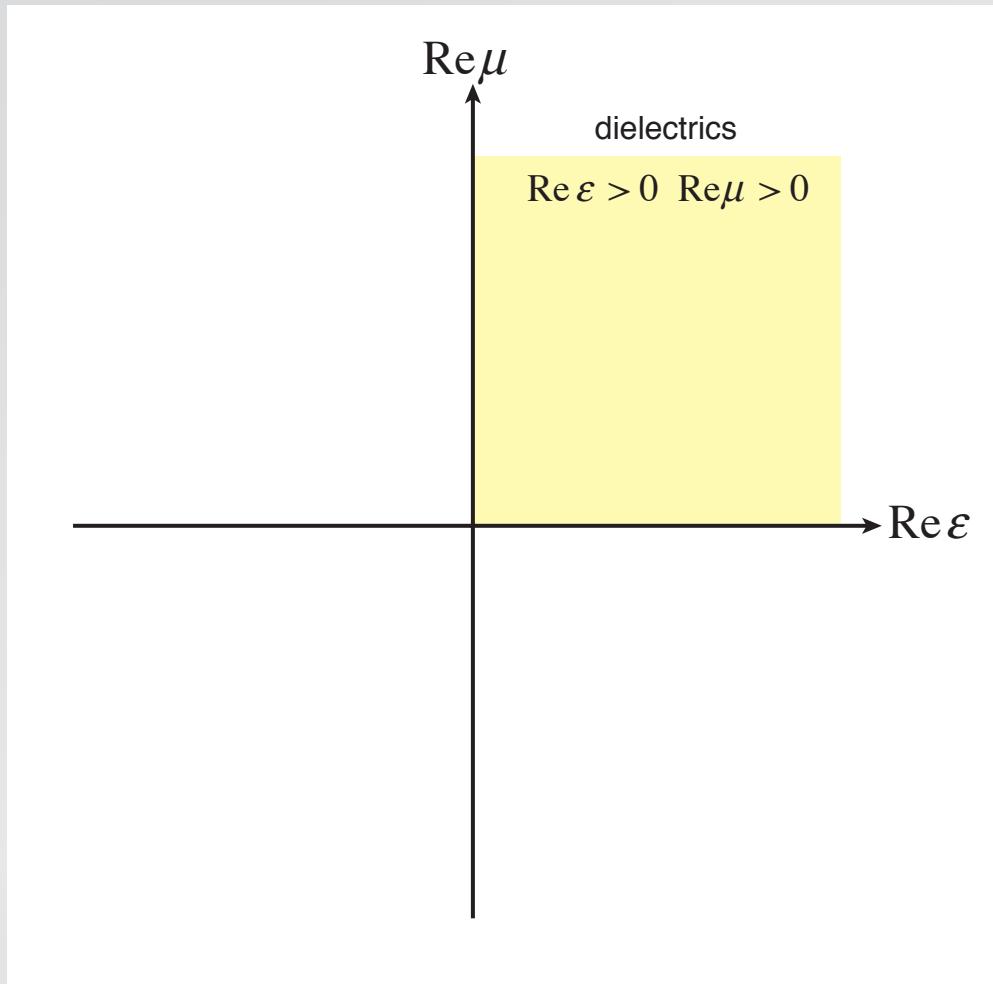


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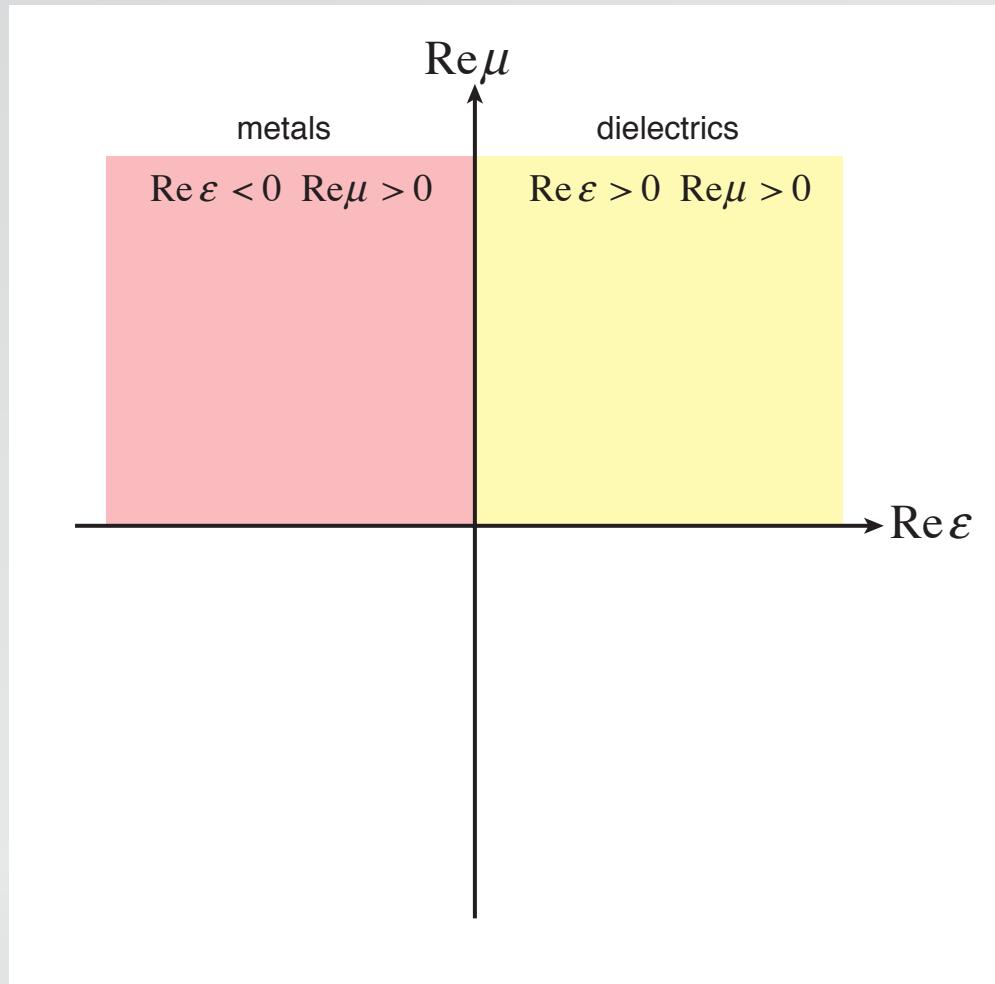
# classification of (non-lossy) materials



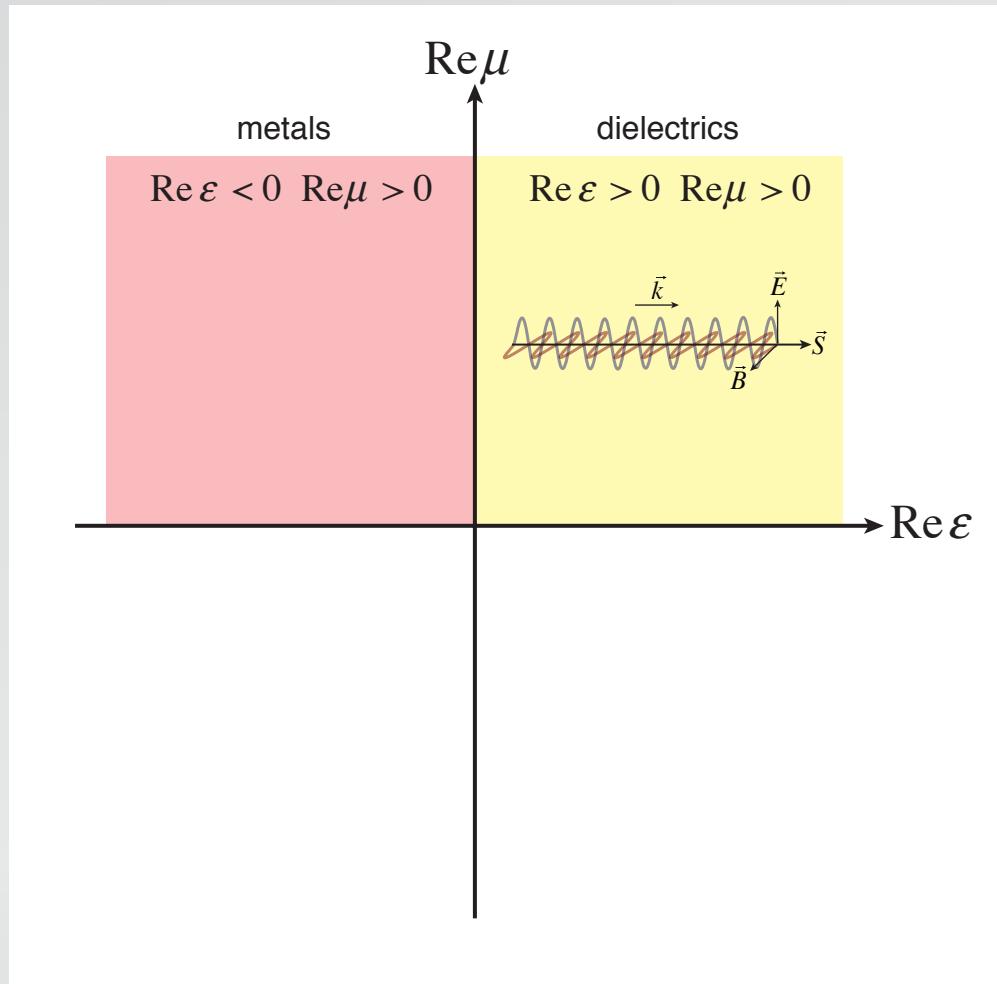
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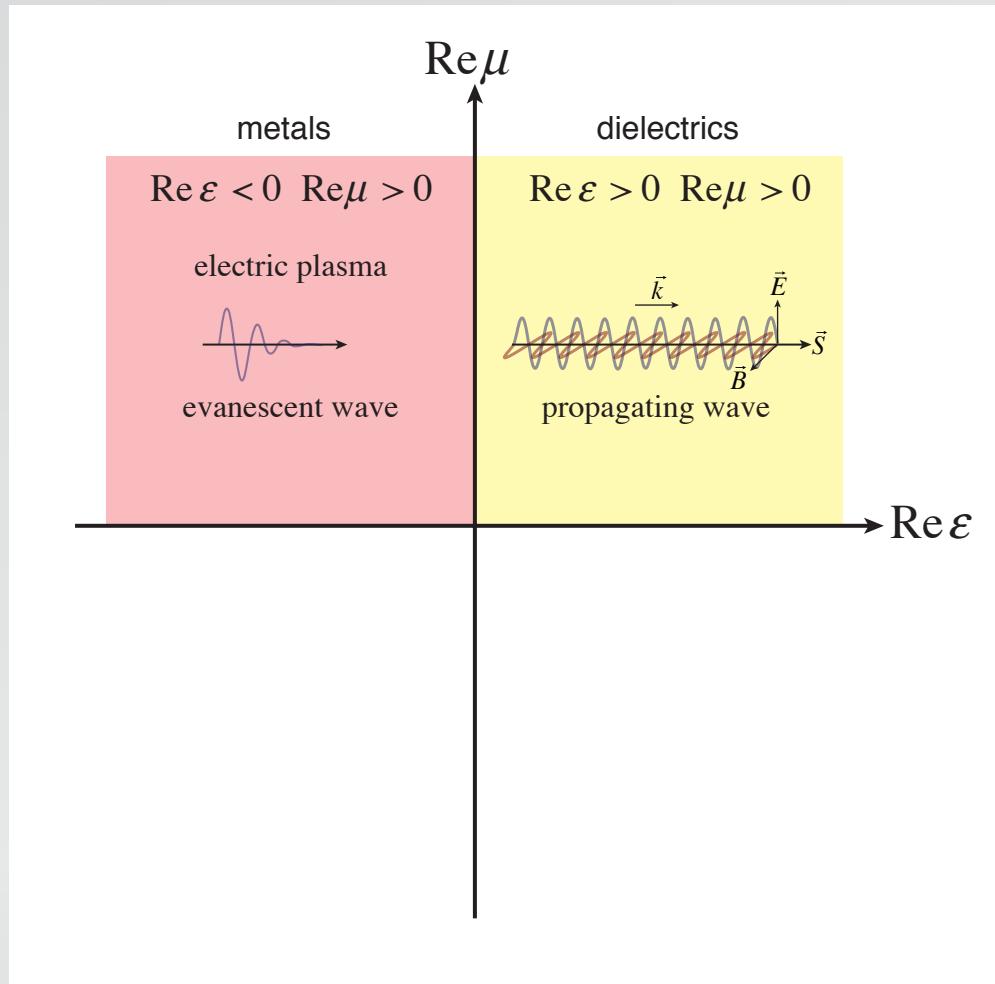
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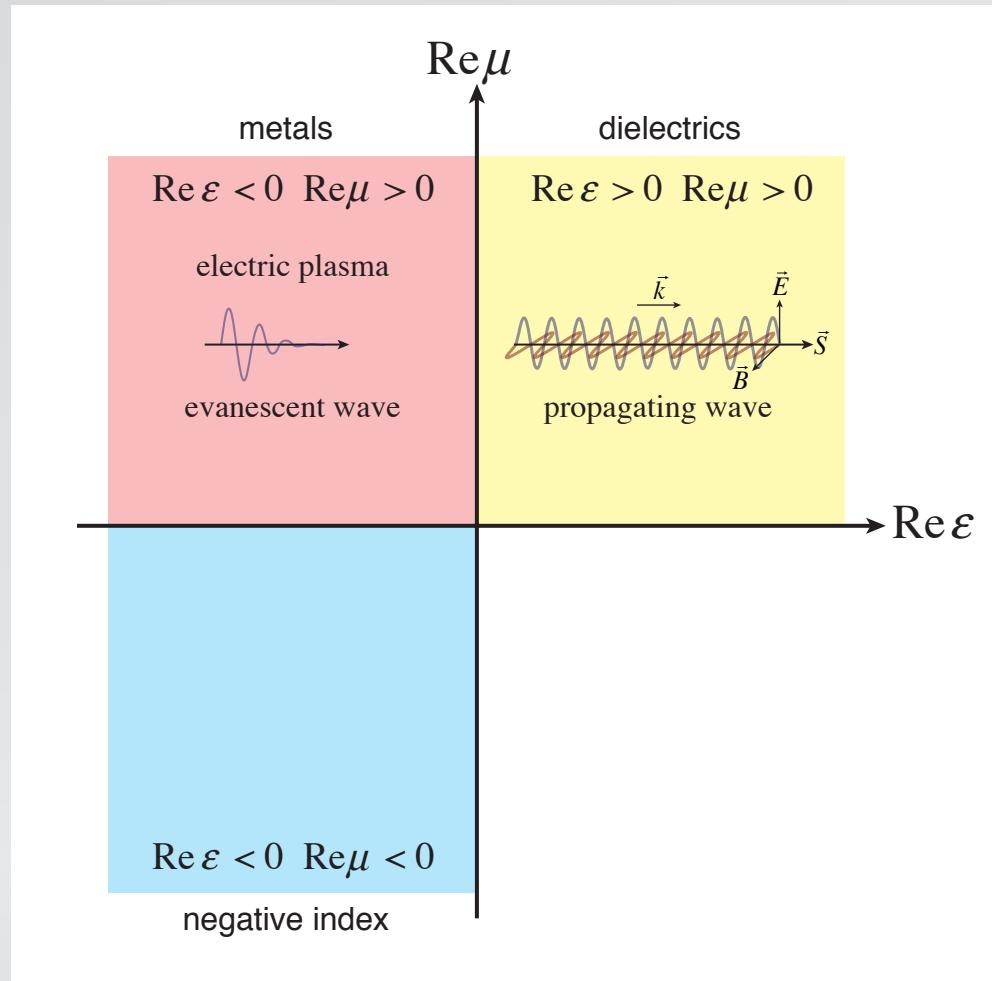
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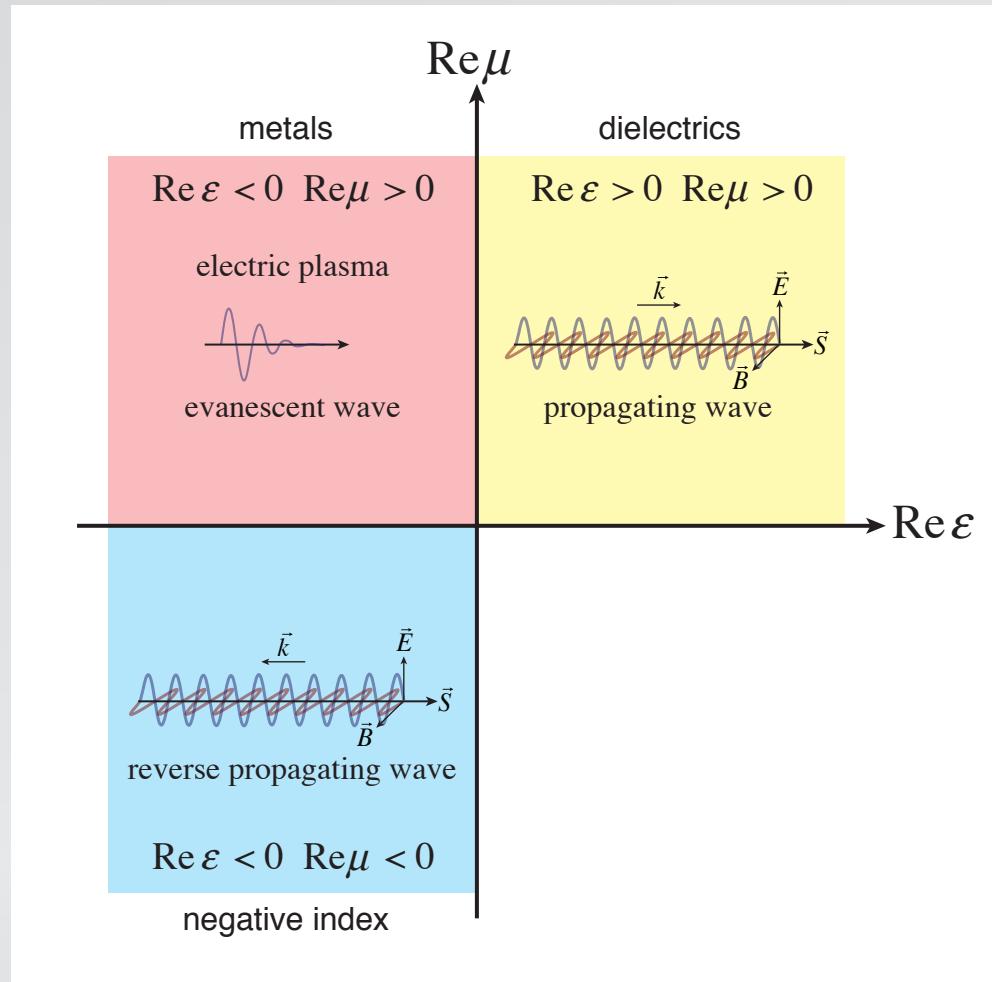
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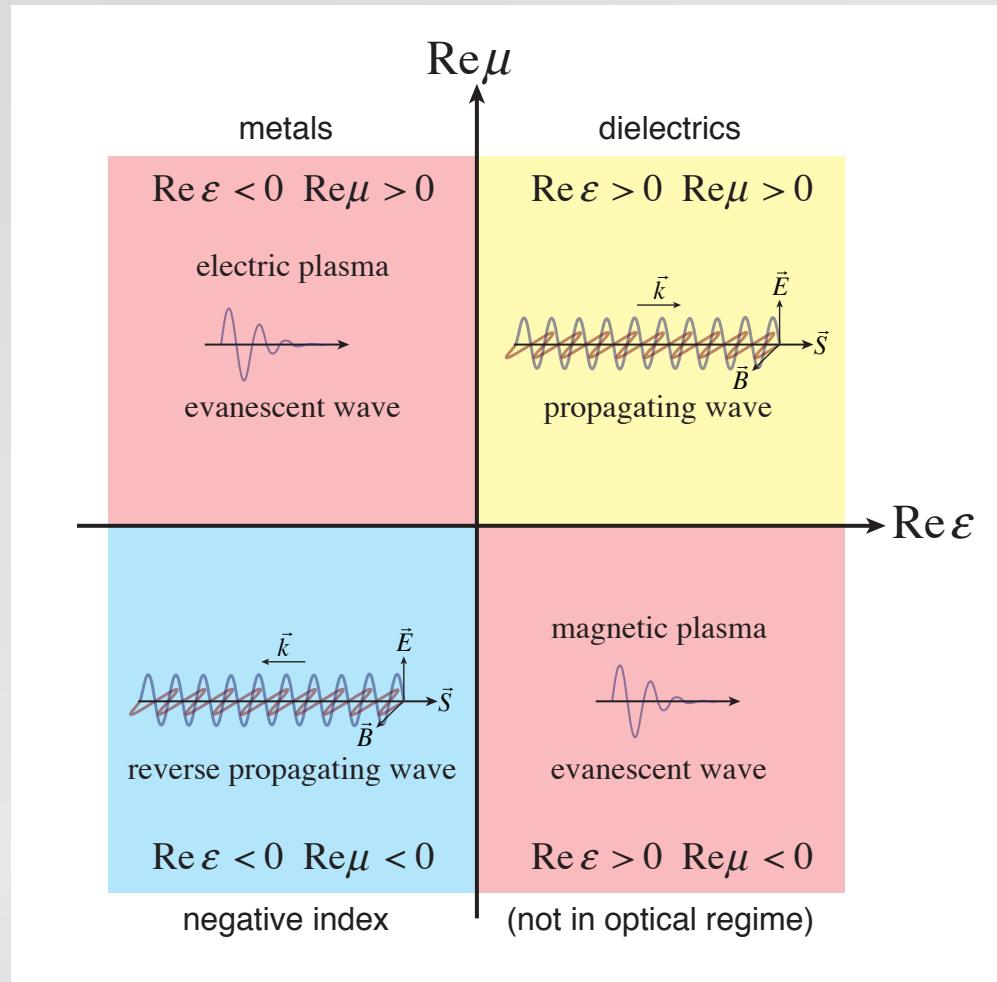
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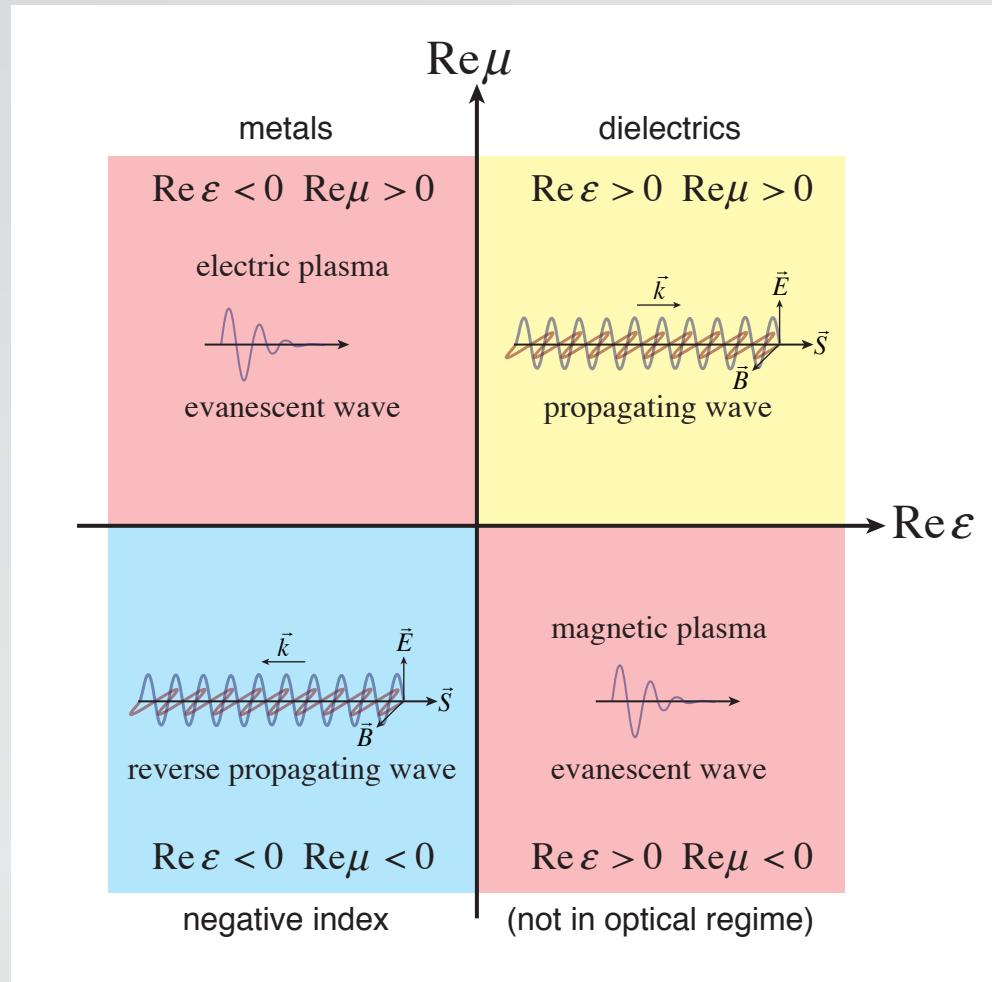
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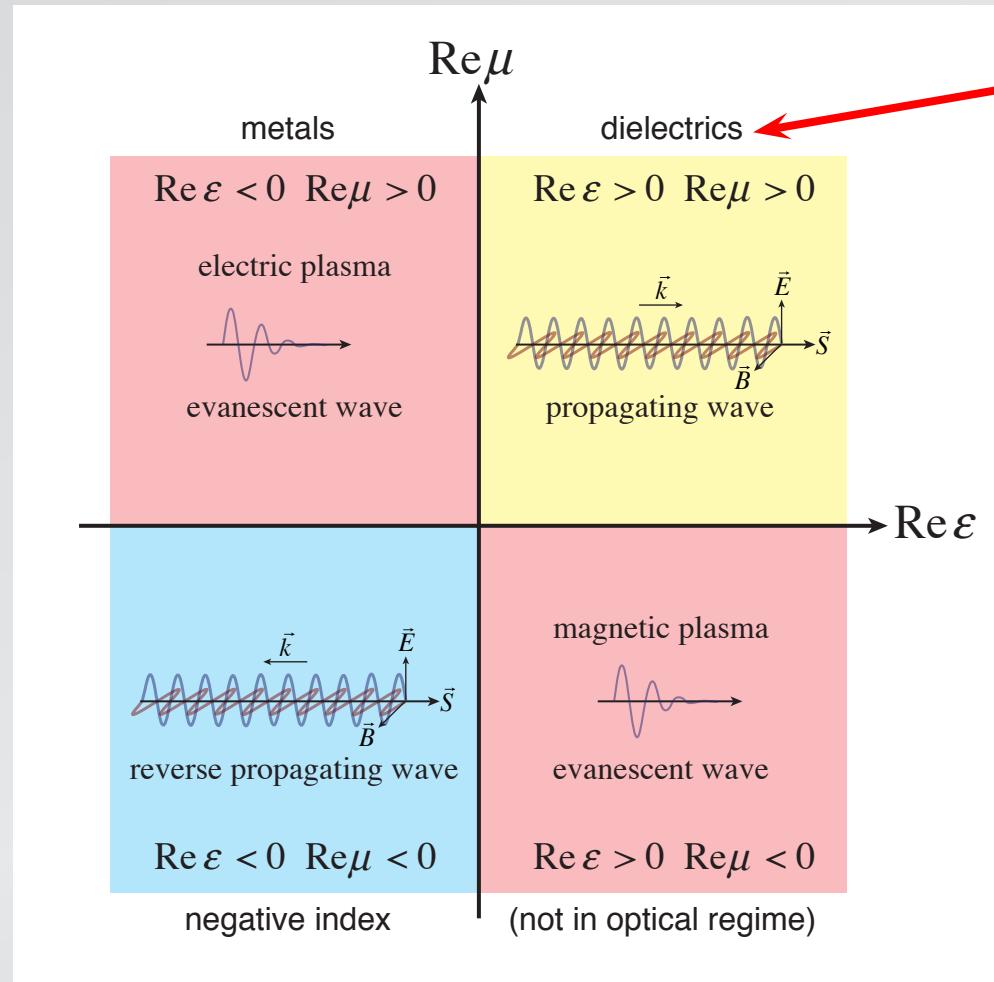
# classification of (non-lossy) materials



# common materials very limited



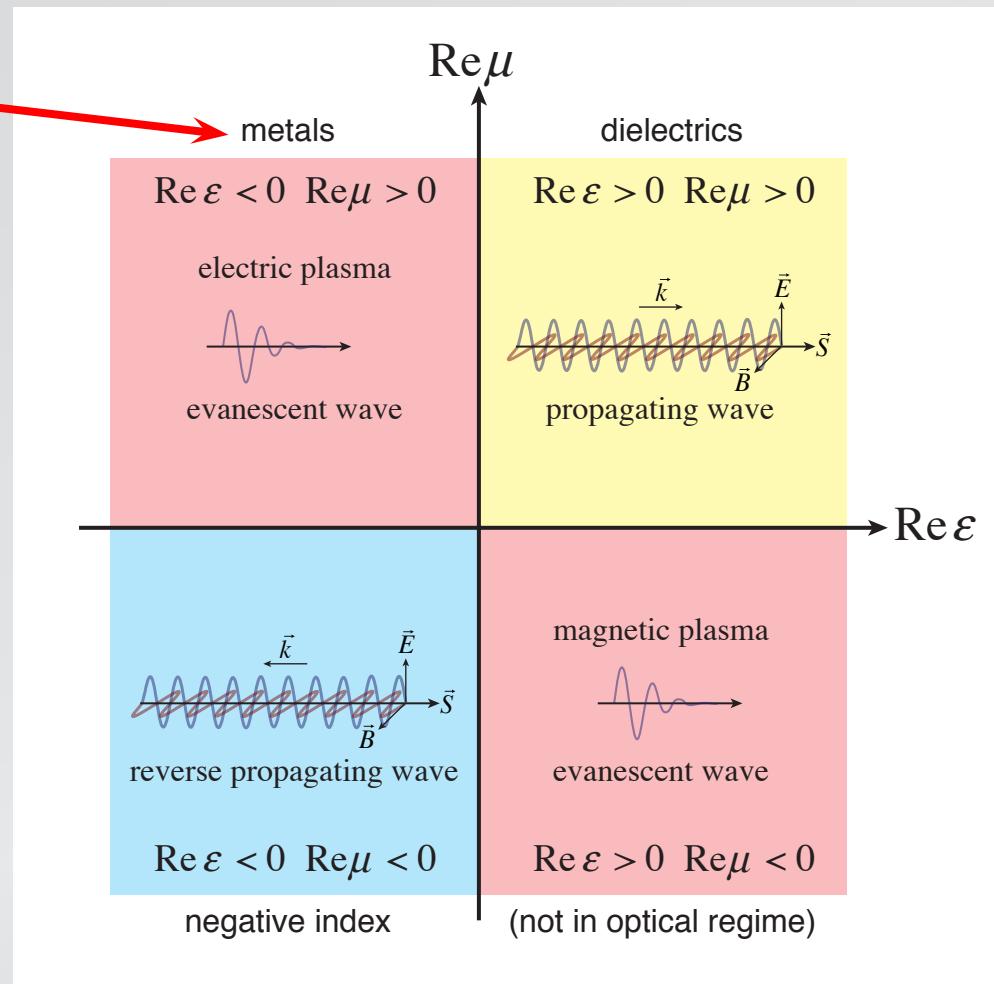
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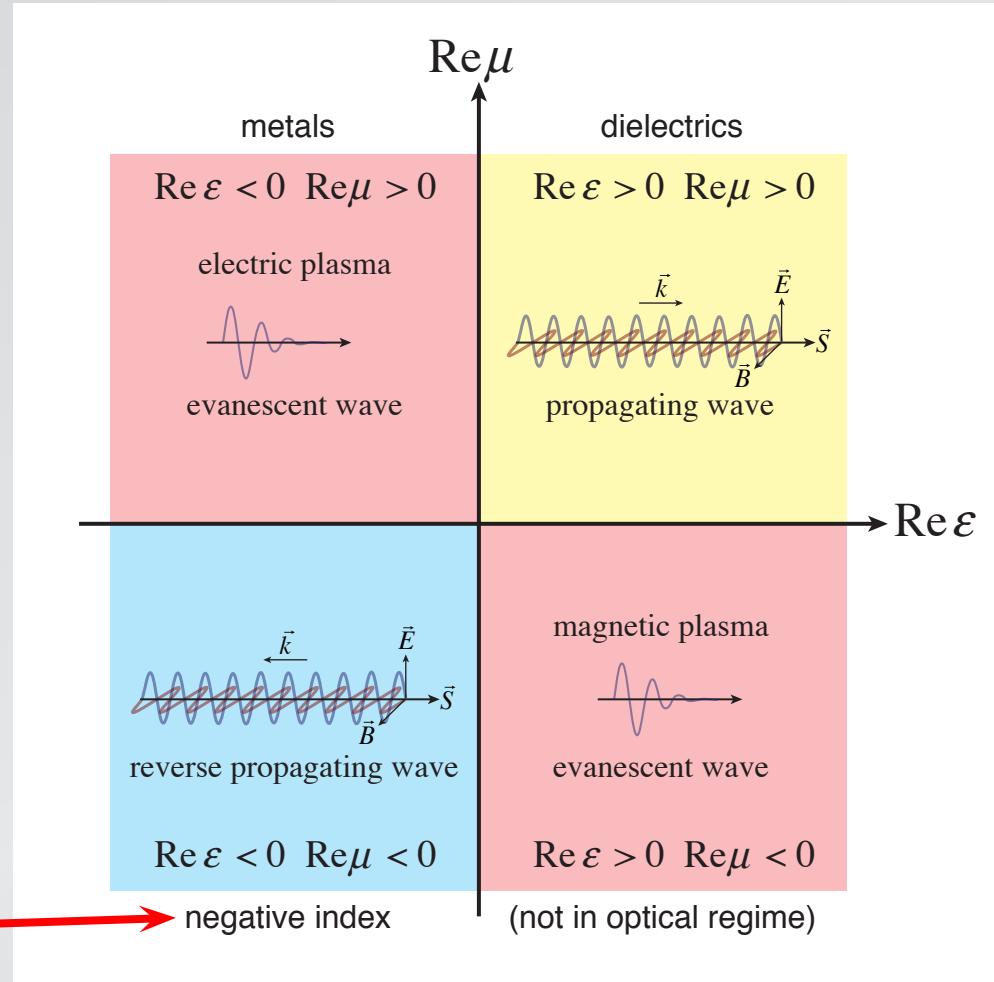
limited by  
diffraction

**common materials very limited**

**lossy & no propagation**

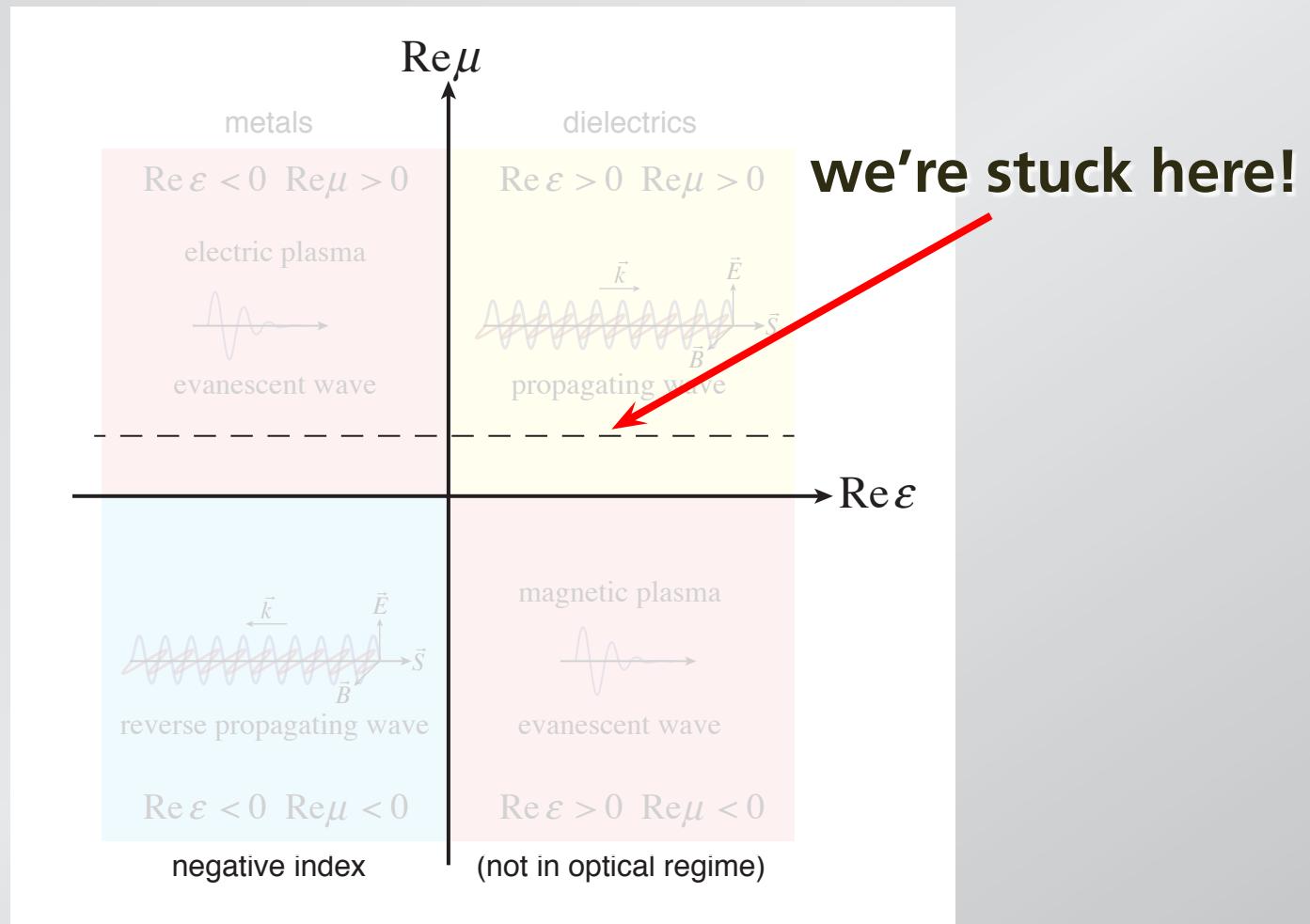


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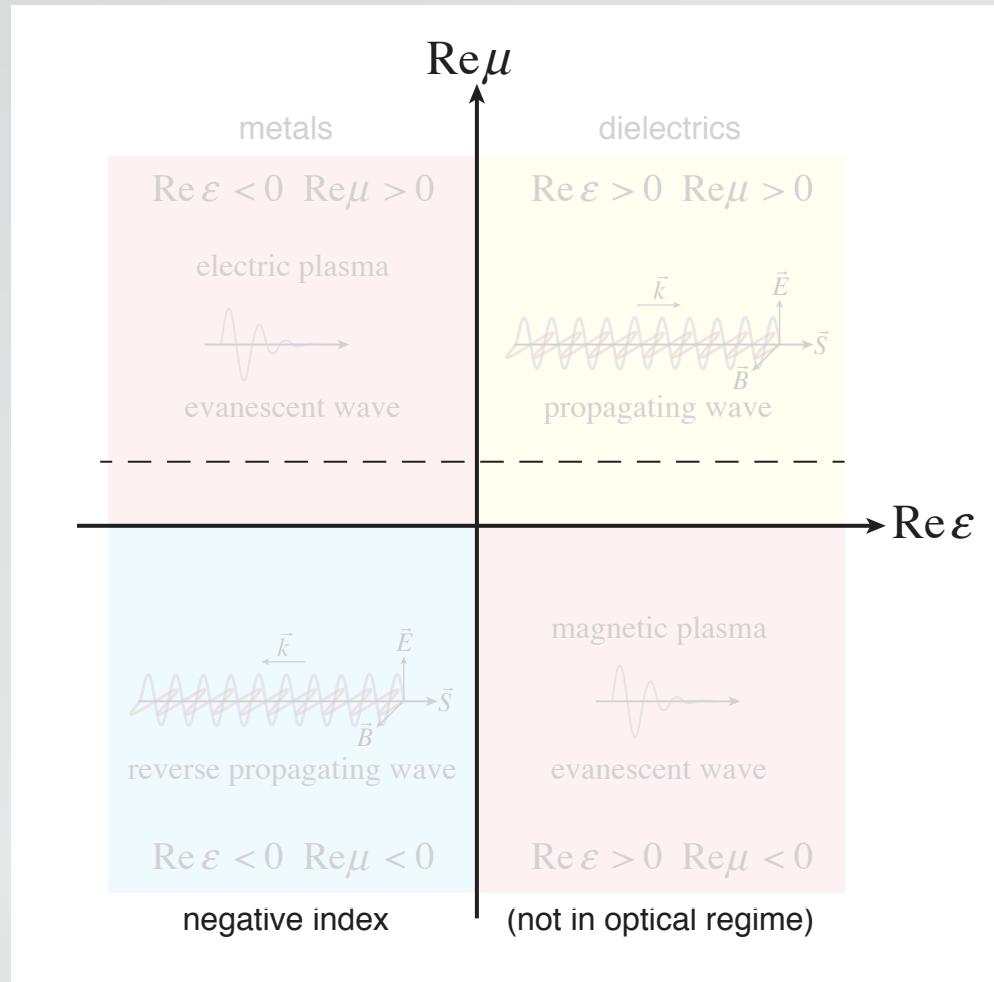


superlensing  
but...

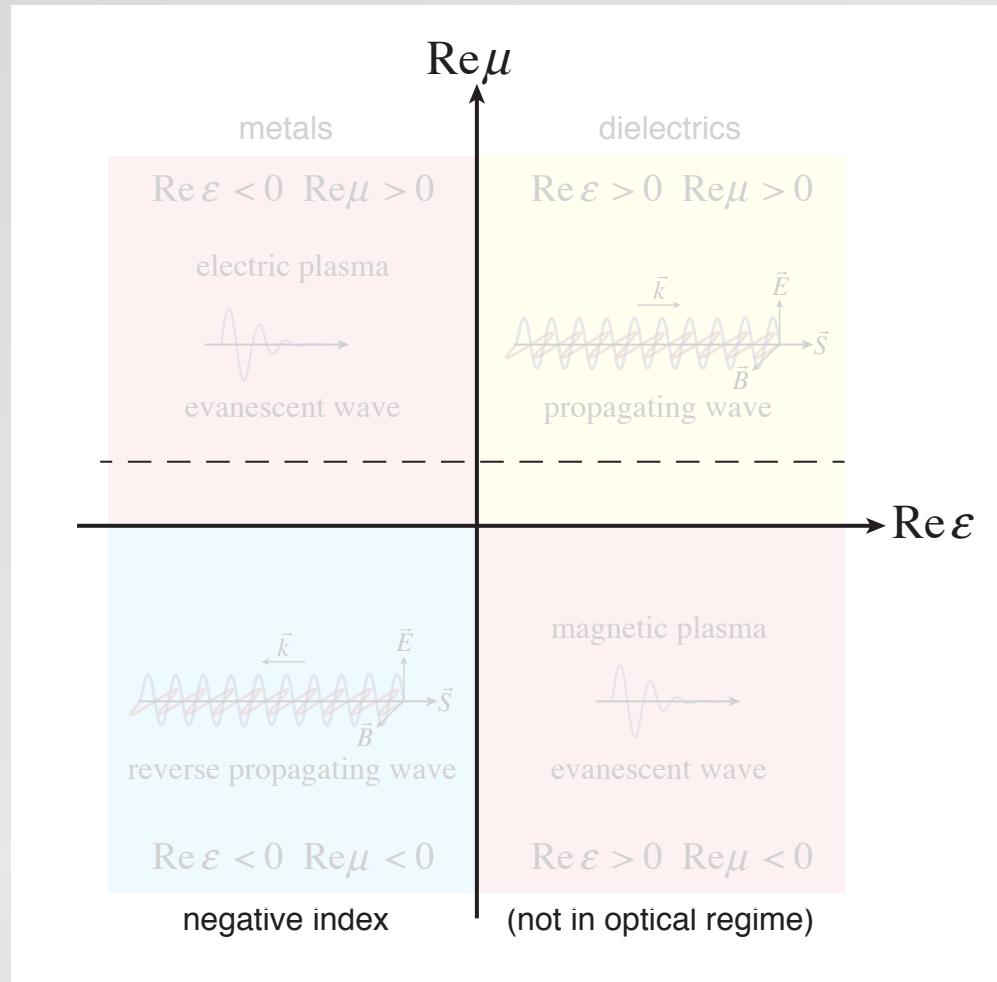
# common materials very limited



# What happens on the axes?



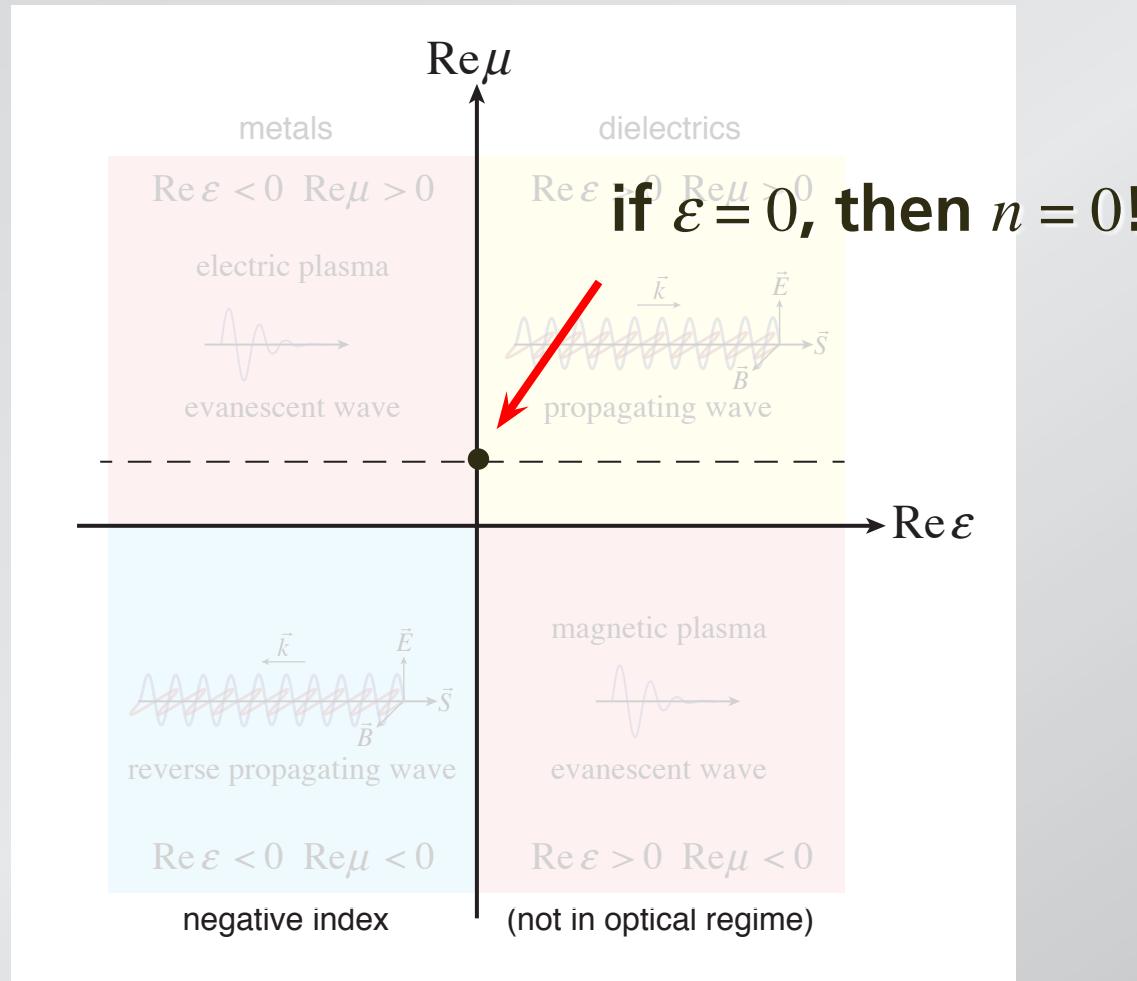
# what if we let $\varepsilon = 0$ ?



1 index

2 zero index

# what if we let $\varepsilon = 0$ ?



1 index

2 zero index

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

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

**1 index**

**2 zero index**

# wave equation

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

## solution

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

where

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

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## 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

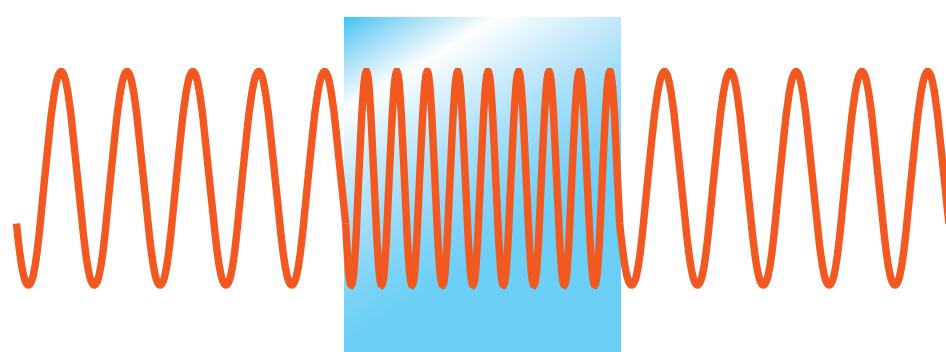
**Q: If  $n = 0$ , which of the following is true?**

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

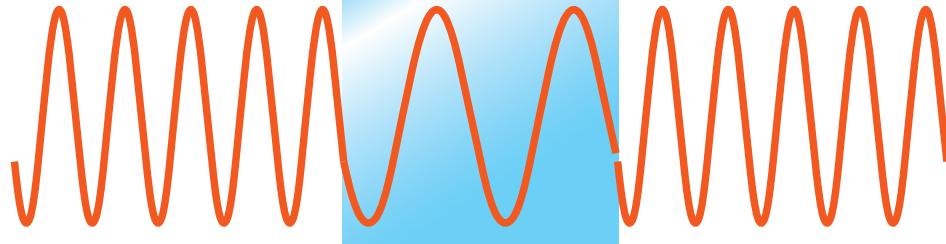
$n > 1$



1 index

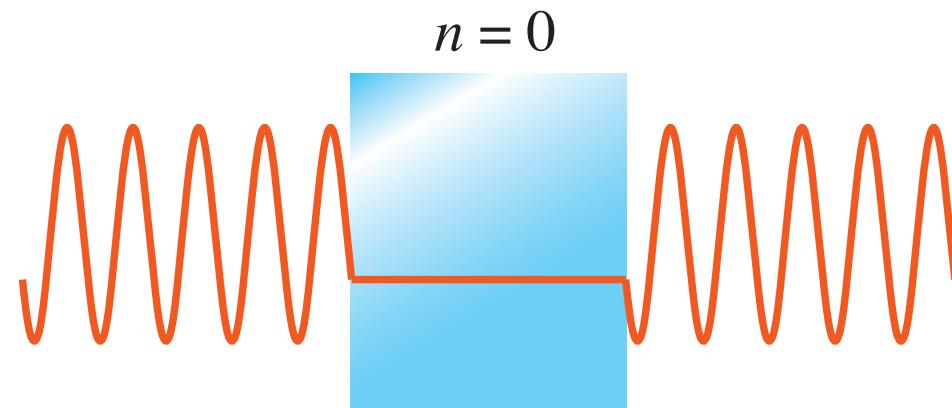
2 zero index

$$0 < n < 1$$



1 index

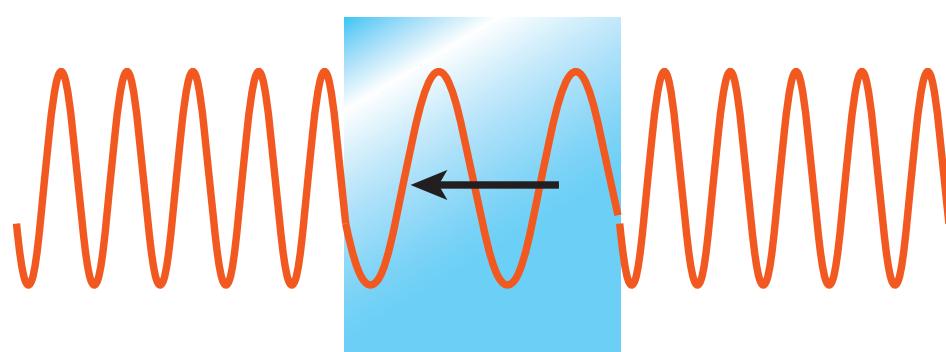
2 zero index



1 index

2 zero index

$n < 0$



1 index

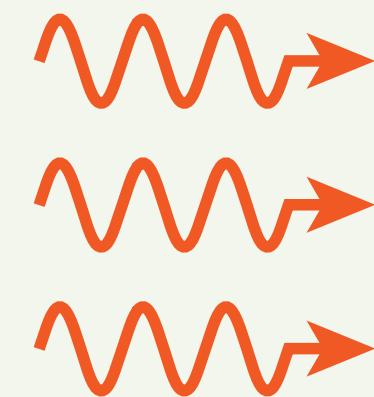
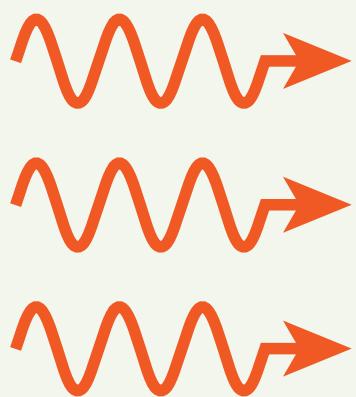
2 zero index



1 index

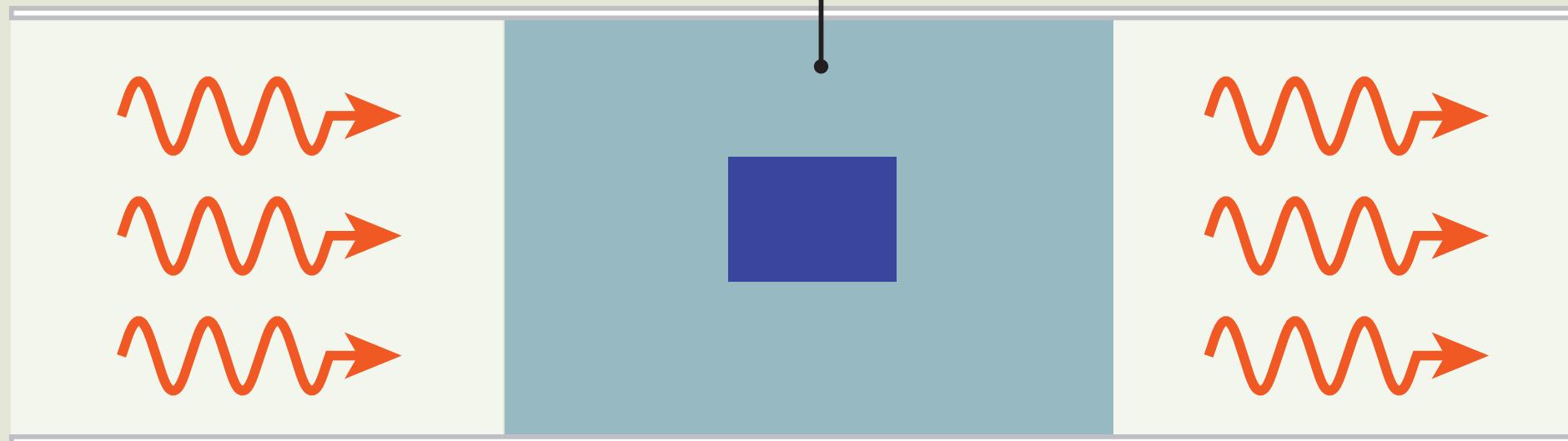
2 zero index

$n = 0$



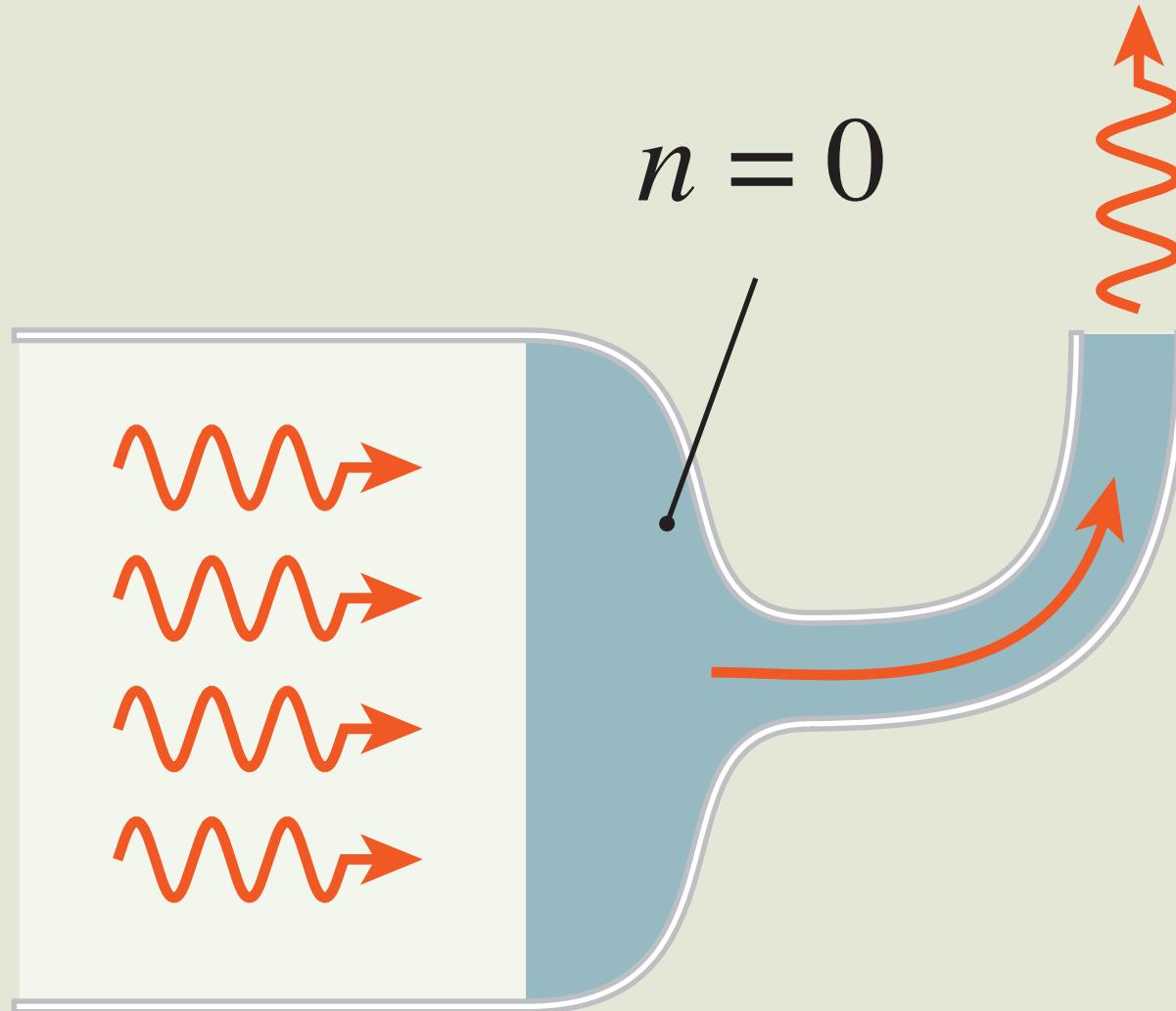
1 index

2 zero index

$n = 0$ 

1 index

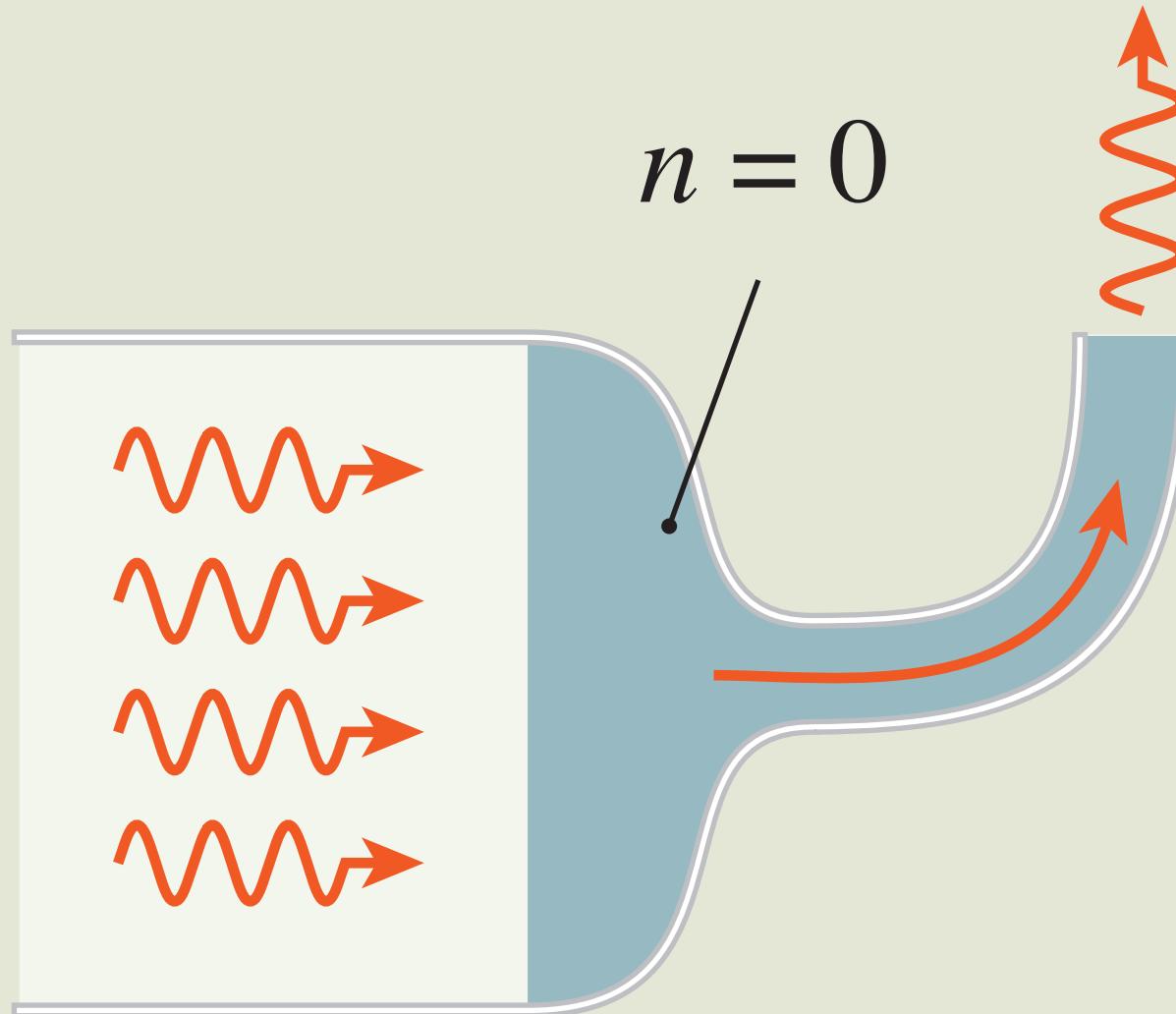
2 zero index



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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**1** index

**2** zero index

**how?**

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

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

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**where**

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

**1 index**

**2 zero index**

**how?**

$$\epsilon \rightarrow 0$$

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

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

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \rightarrow 1$$

**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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \rightarrow -1$$

**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**

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

**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



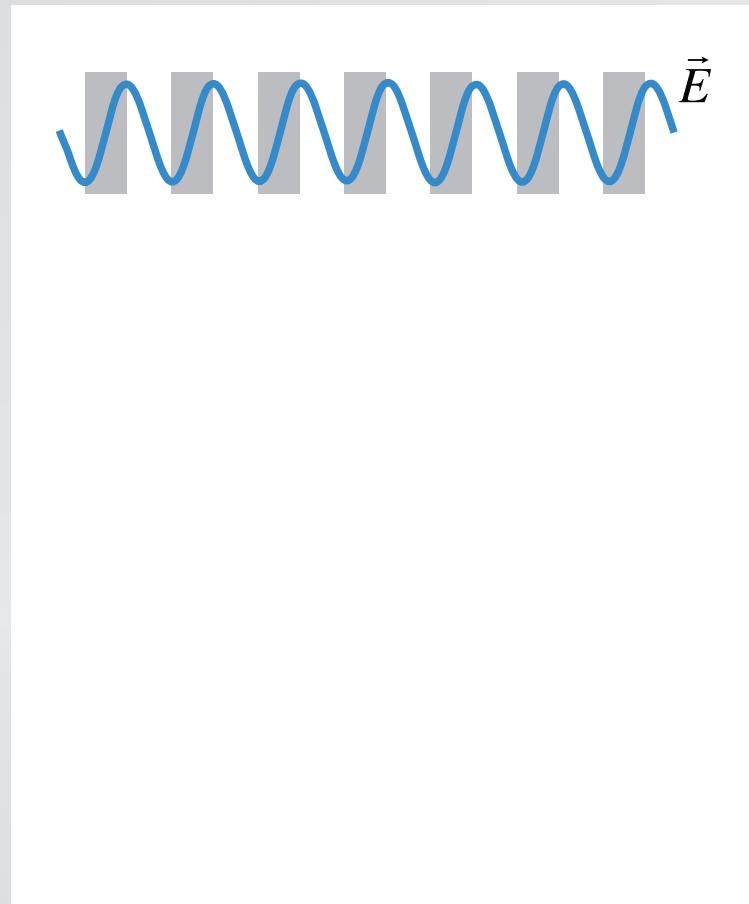
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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

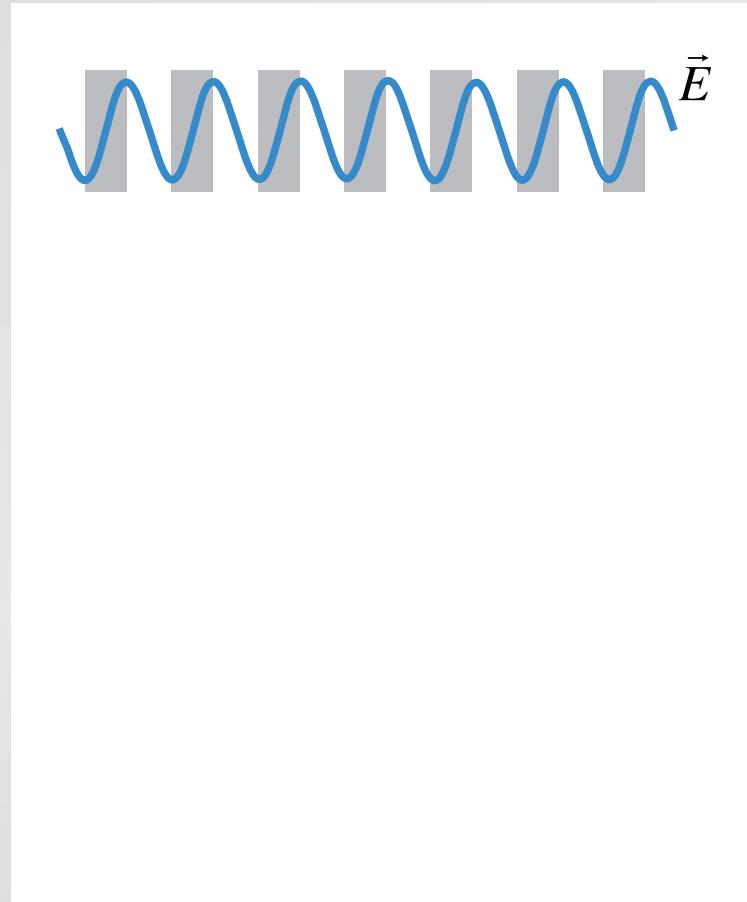


1 index

2 zero index

# Engineering a magnetic response

produces an electric response...



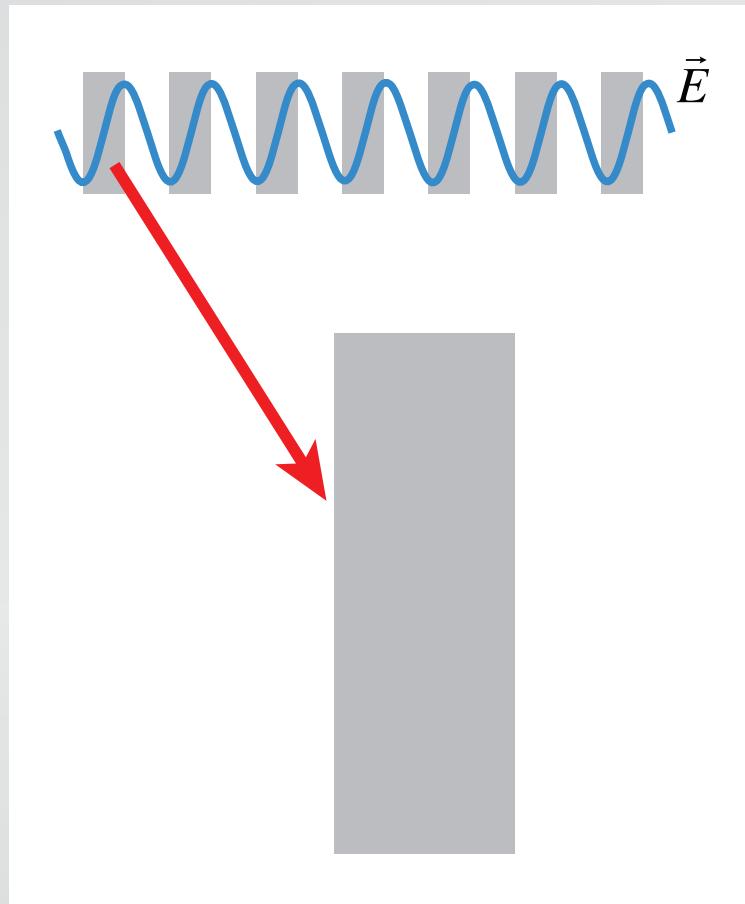
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



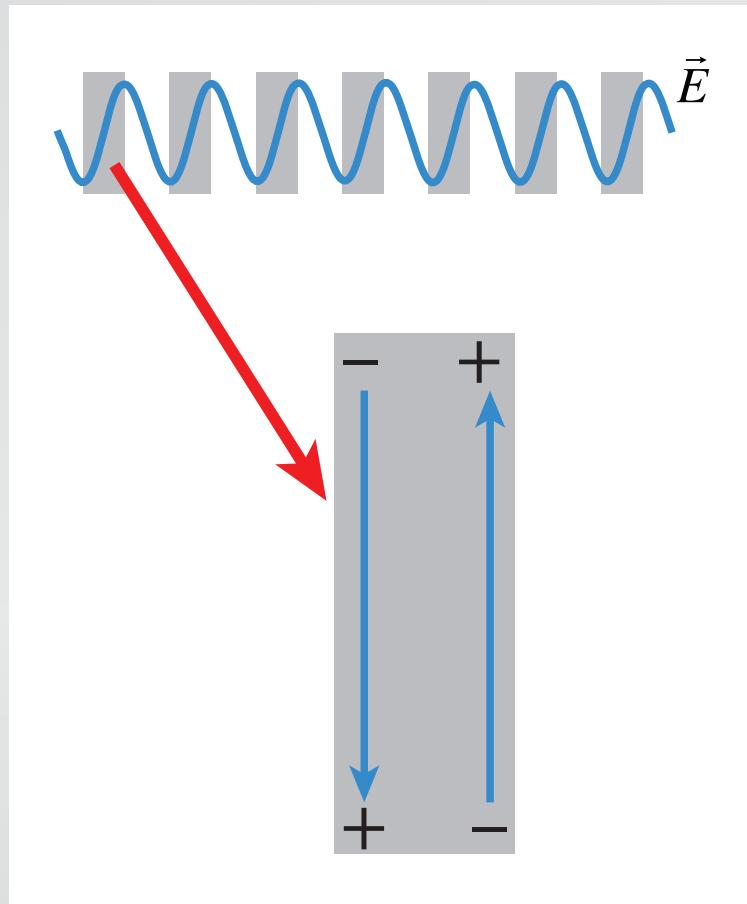
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



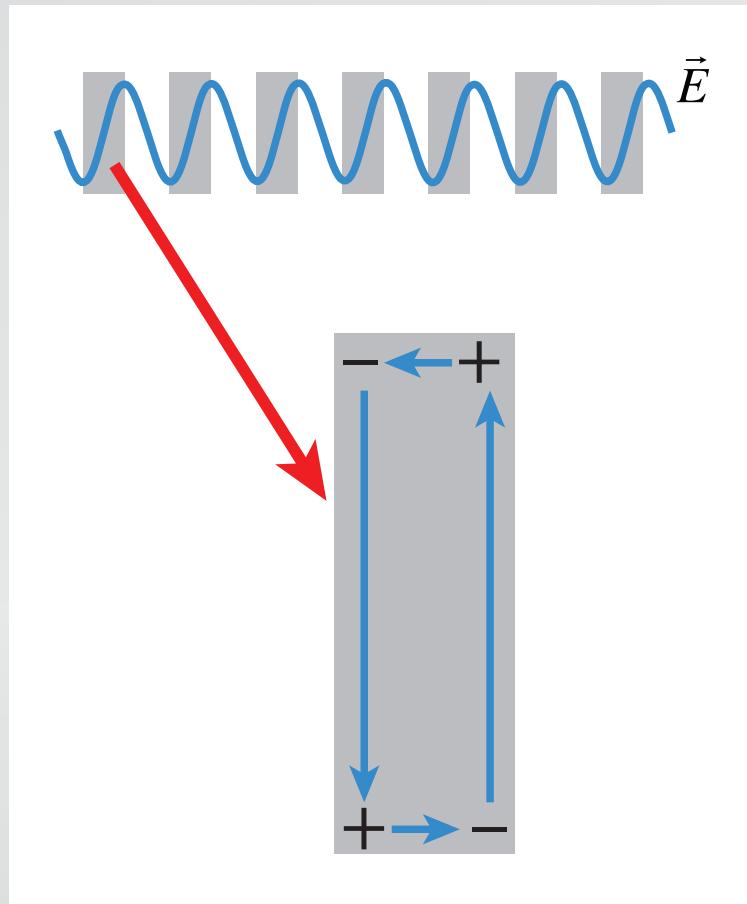
1 index

2 zero index

3 experiments

# Engineering a magnetic response

...causing a current loop...



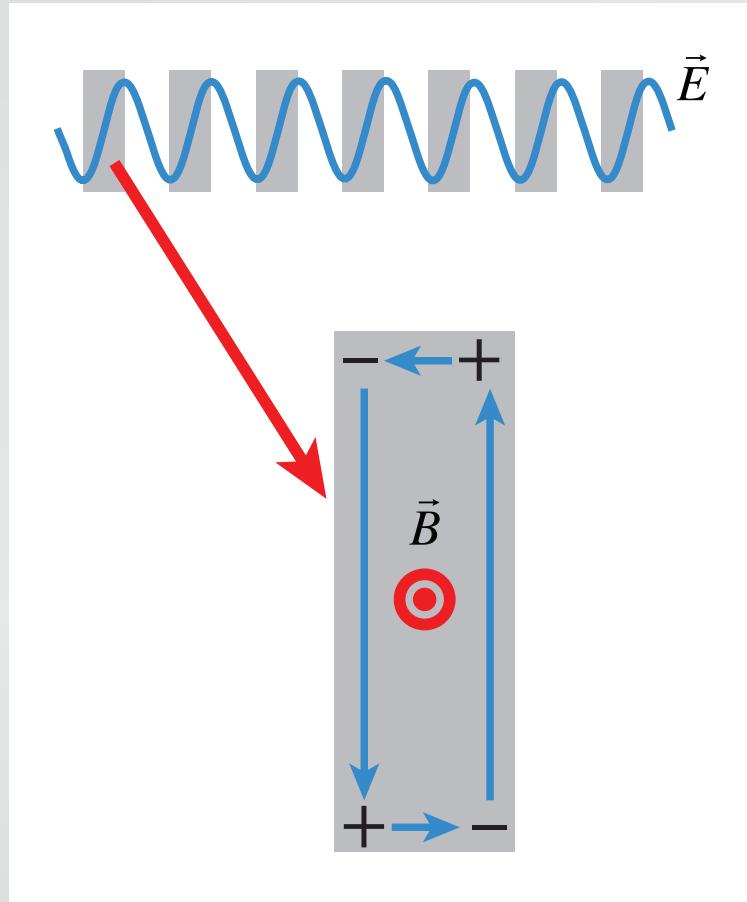
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



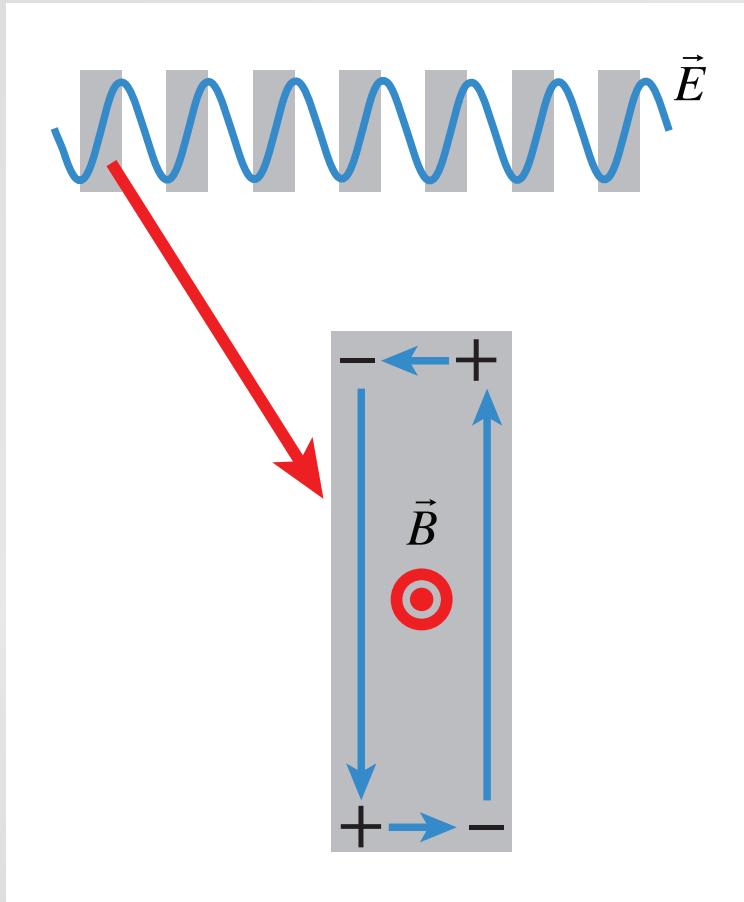
1 index

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



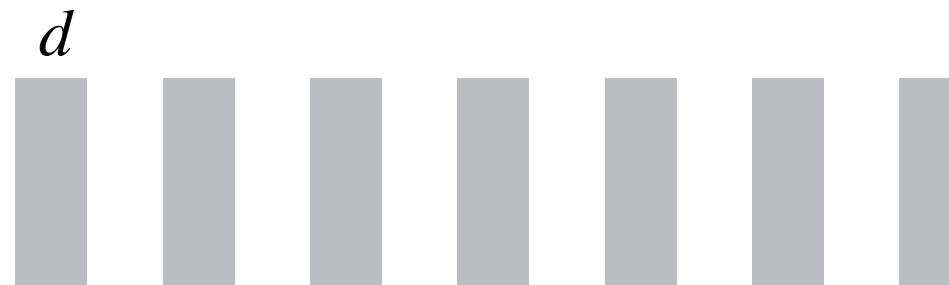
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



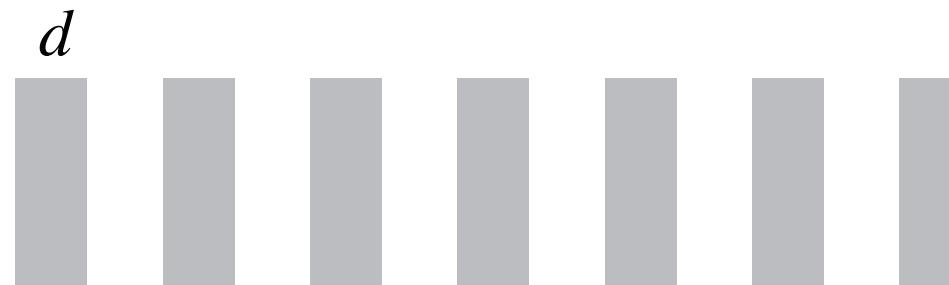
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



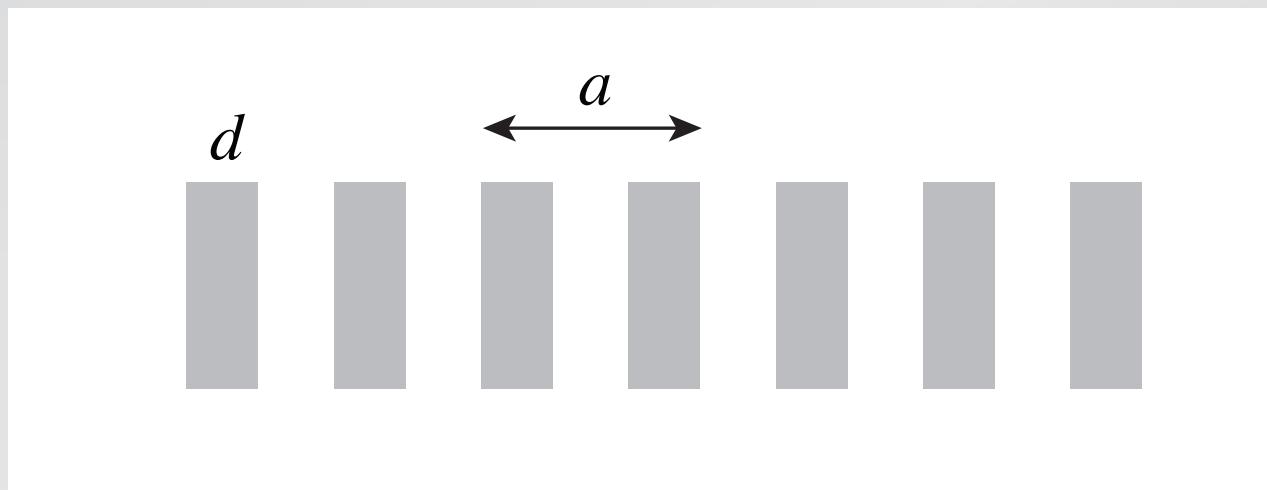
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



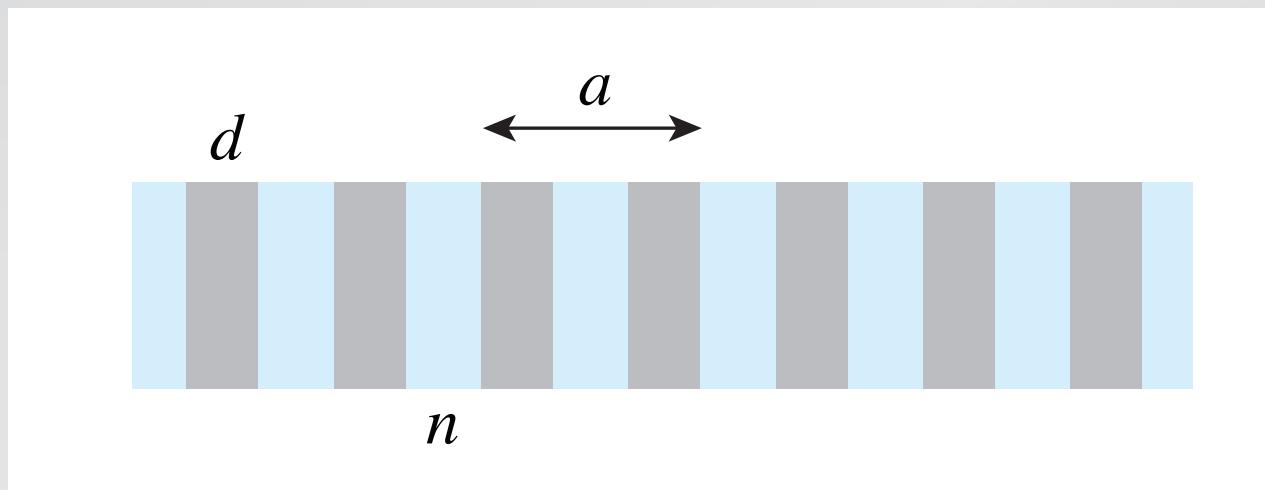
1 index

2 zero index

3 experiments

# Engineering a magnetic response

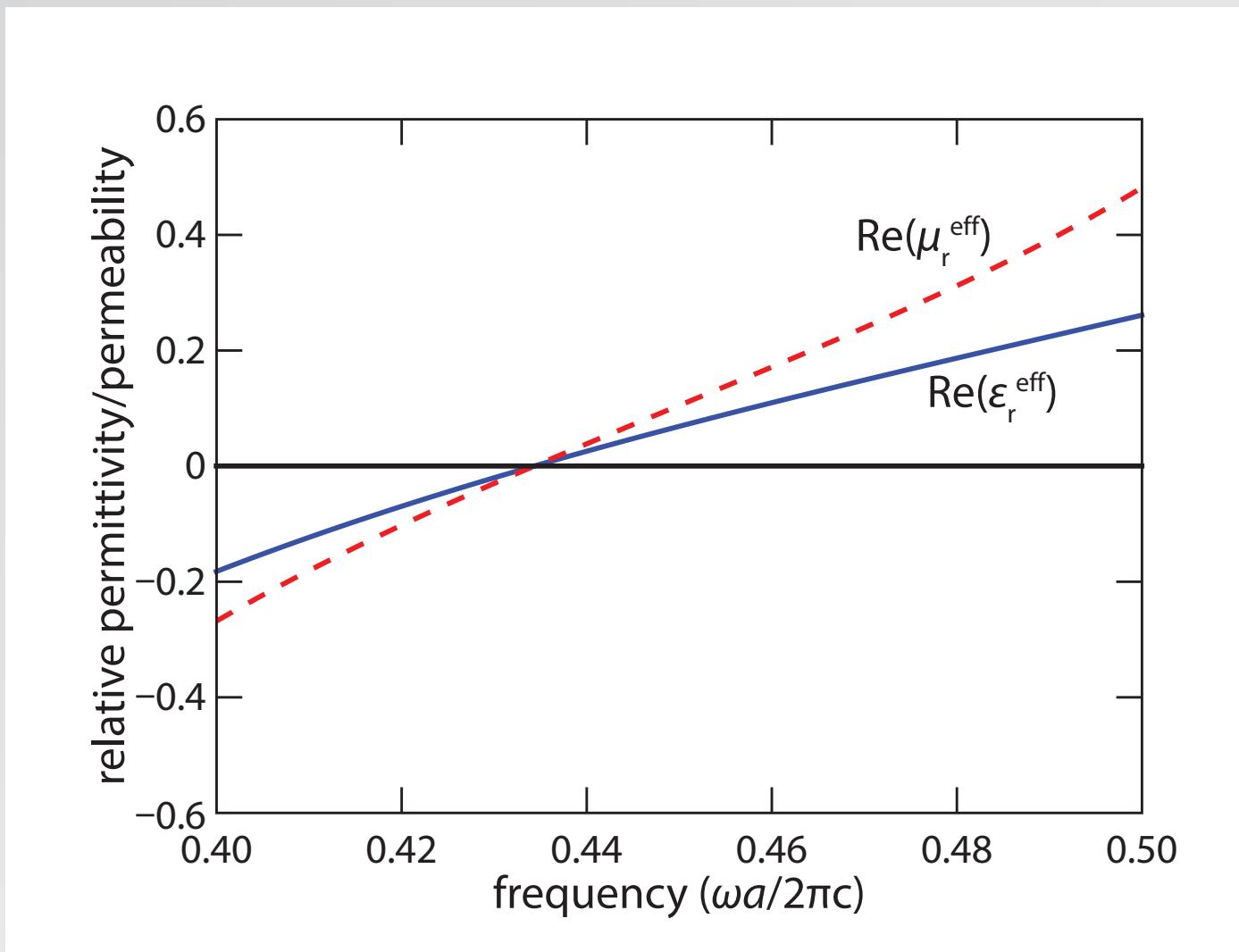
adjustable parameters



1 index

2 zero index

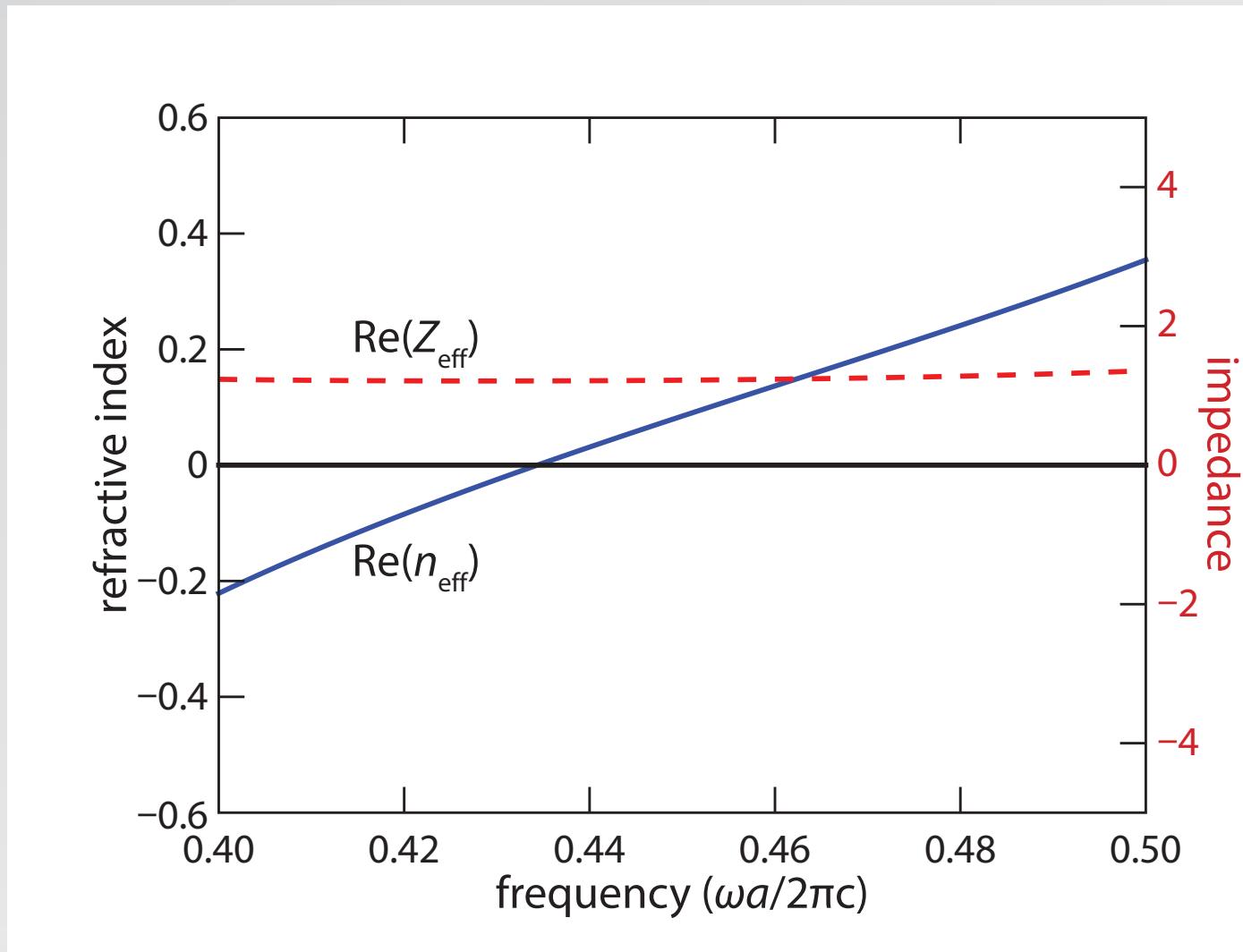
3 experiments



1 index

2 zero index

3 experiments

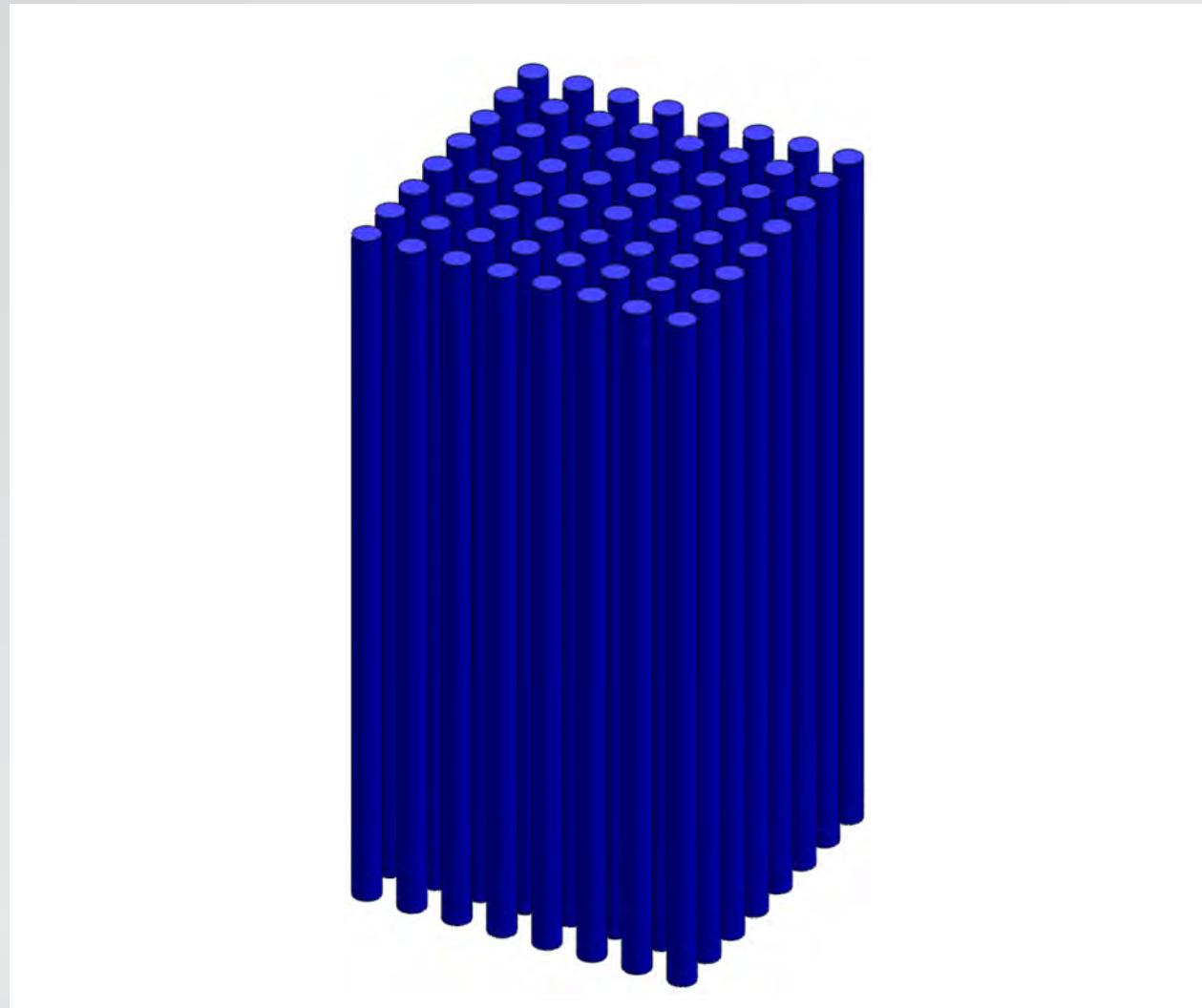


1 index

2 zero index

3 experiments

# How to fabricate?



1 index

2 zero index

3 experiments

# On-chip zero-index fabrication

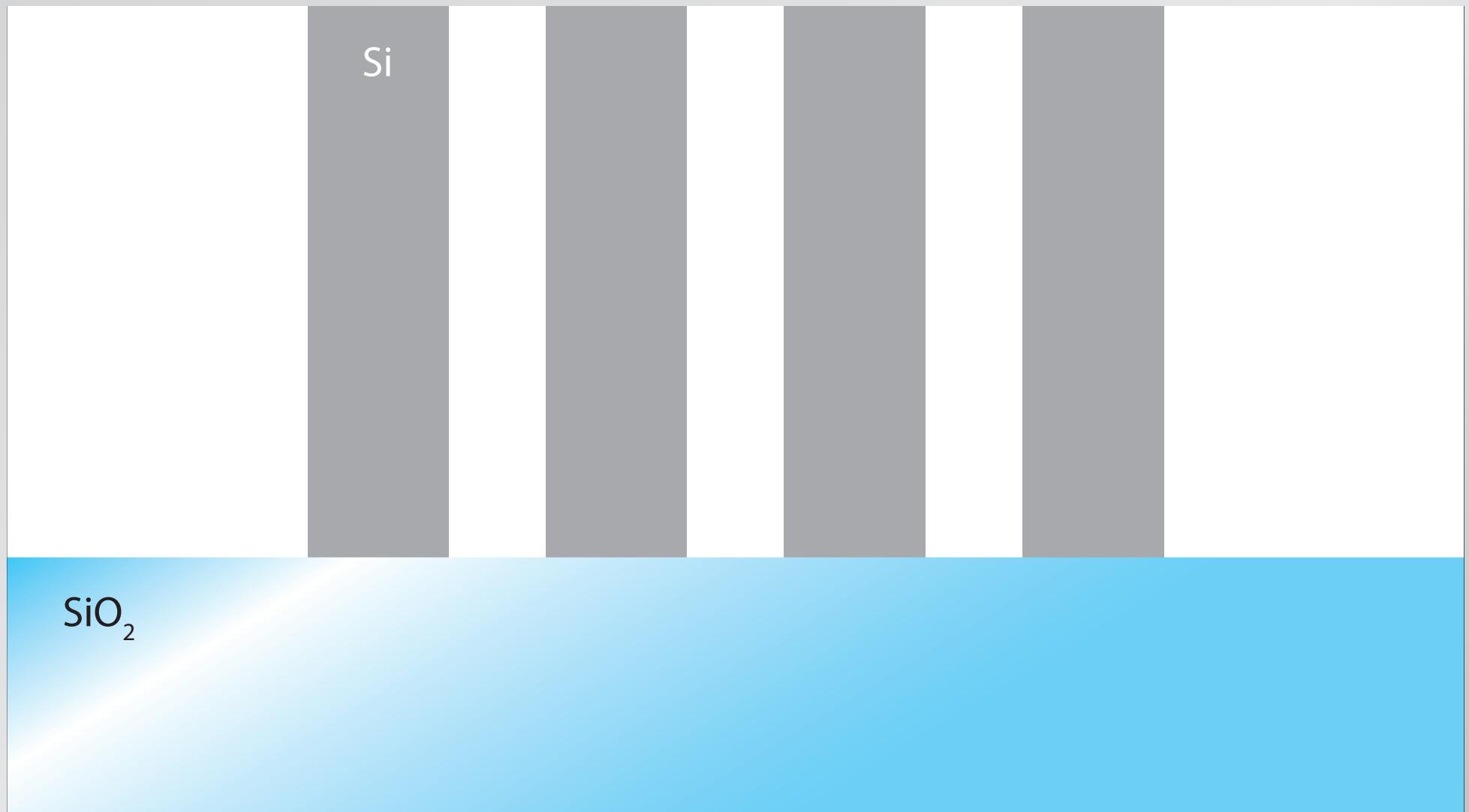


1 index

2 zero index

3 experiments

# On-chip zero-index fabrication

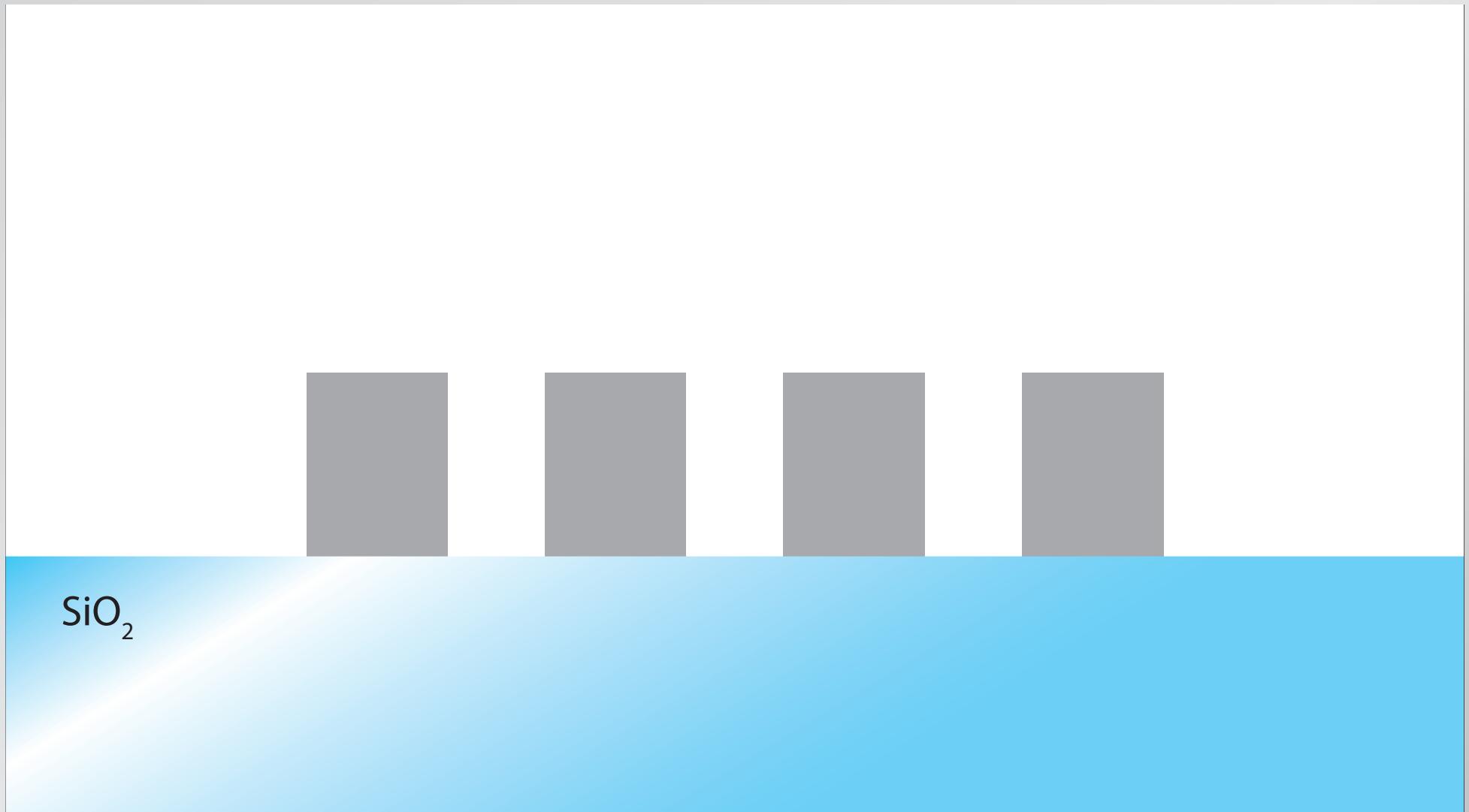


1 index

2 zero index

3 experiments

# On-chip zero-index fabrication

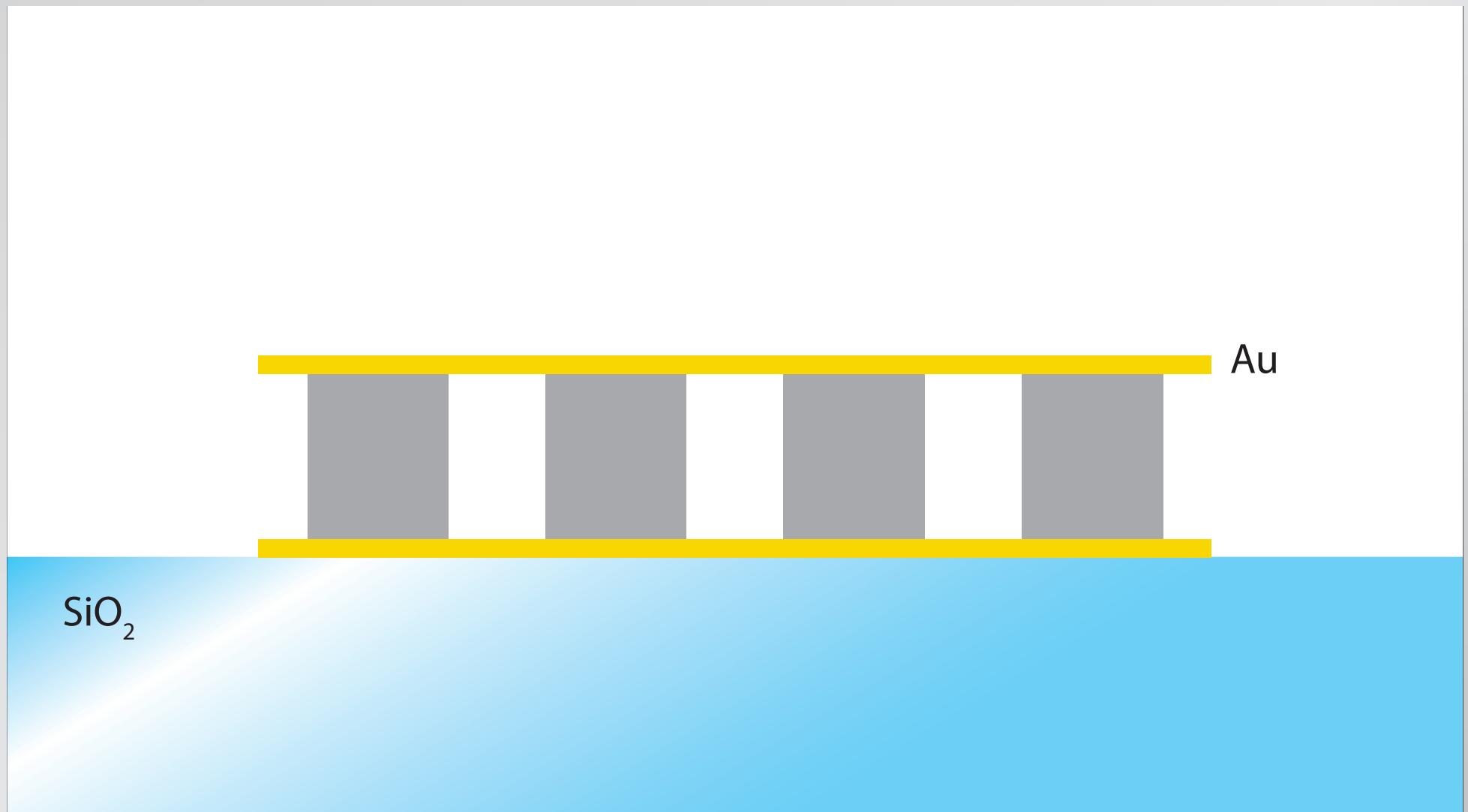


1 index

2 zero index

3 experiments

# On-chip zero-index fabrication

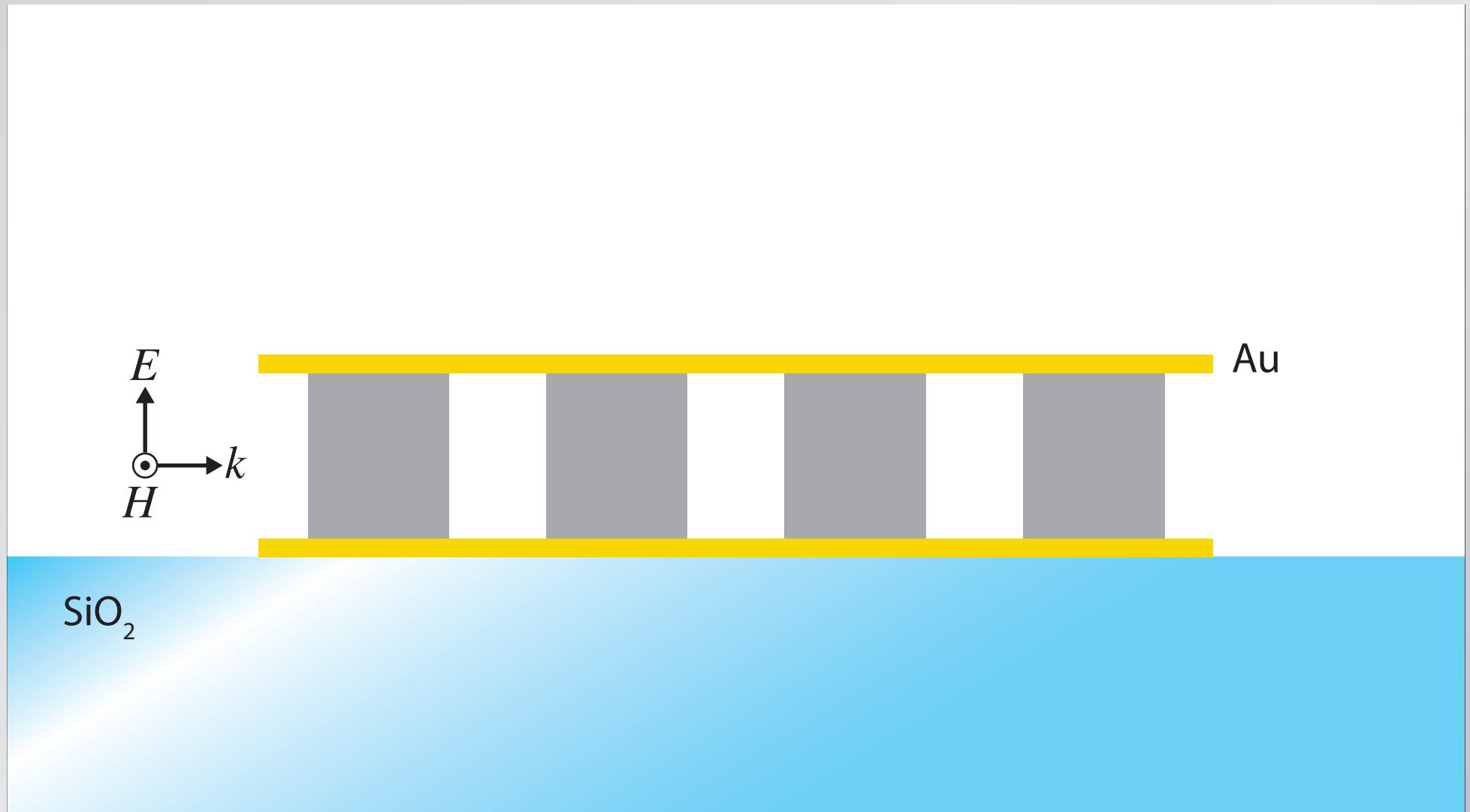


1 index

2 zero index

3 experiments

# On-chip zero-index fabrication

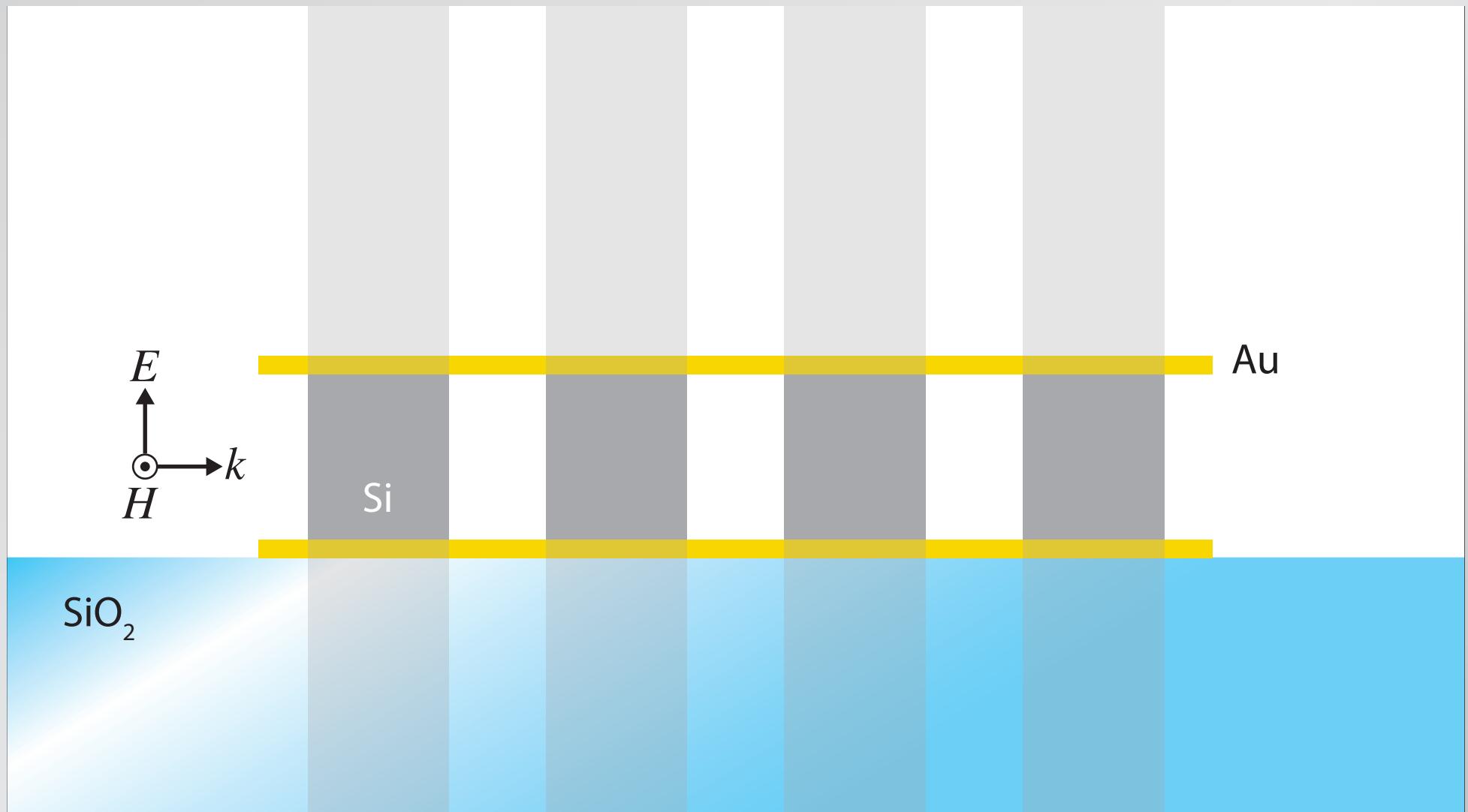


1 index

2 zero index

3 experiments

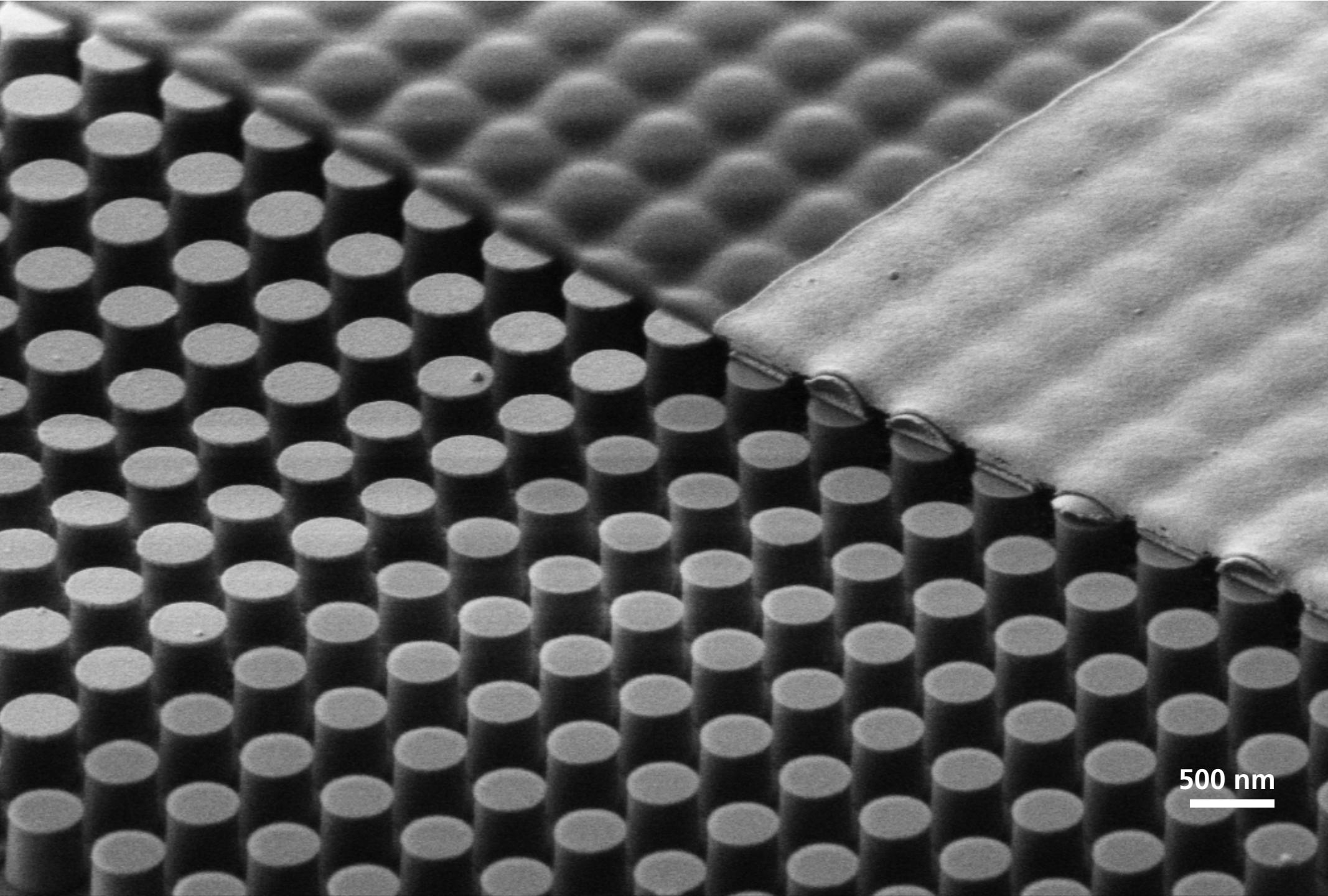
# On-chip zero-index fabrication



1 index

2 zero index

3 experiments

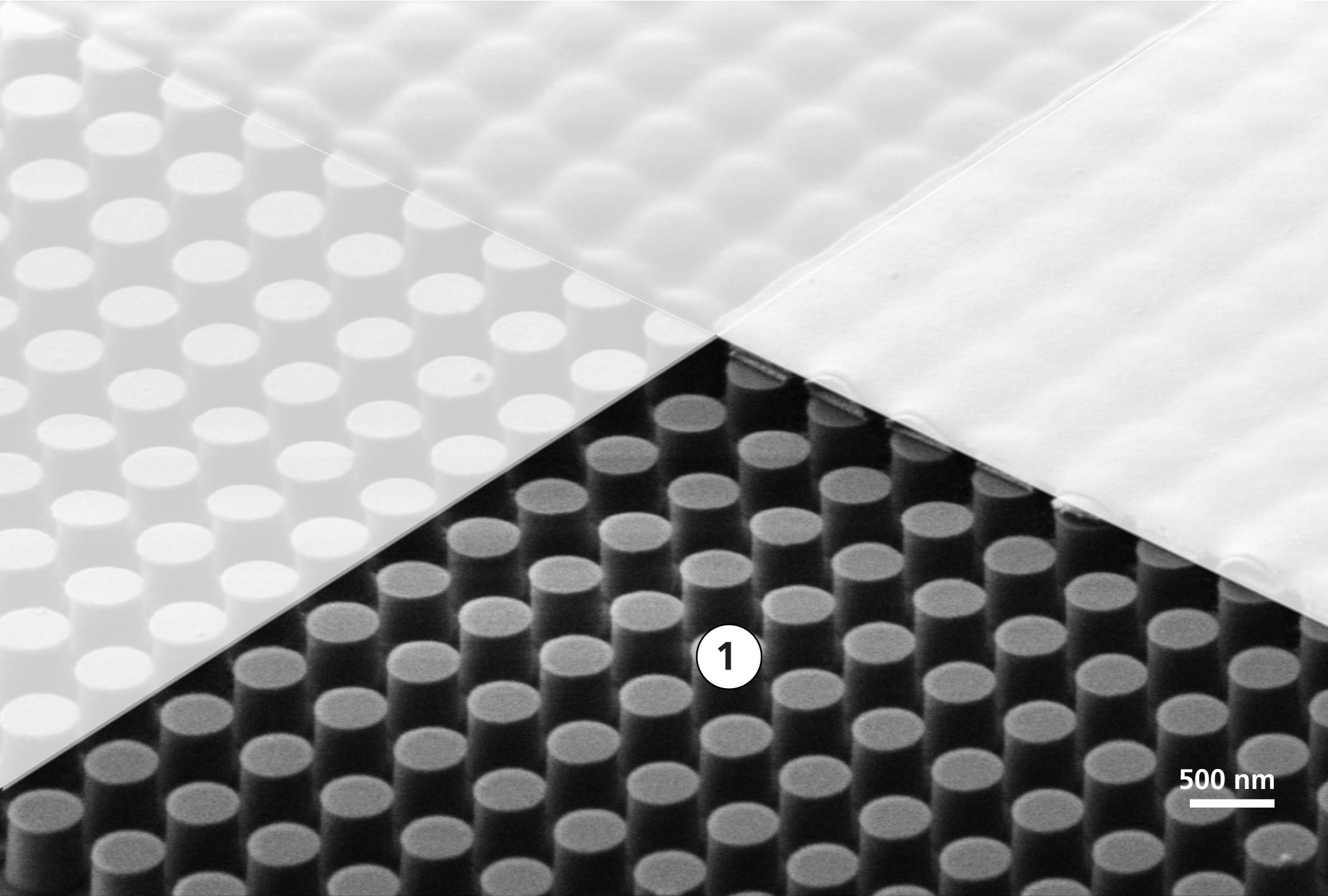


1 index

2 zero index

3 experiments

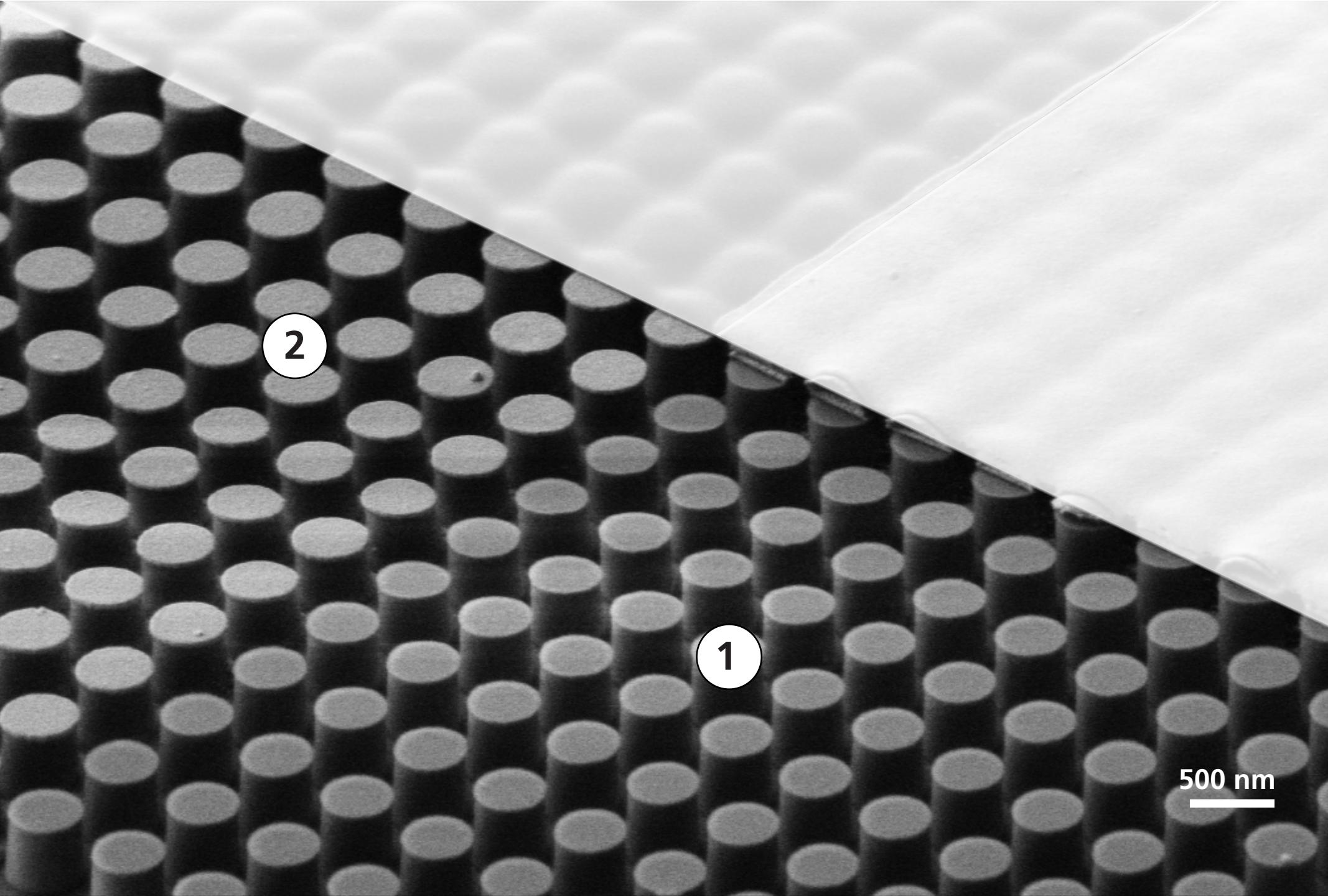
500 nm



1 index

2 zero index

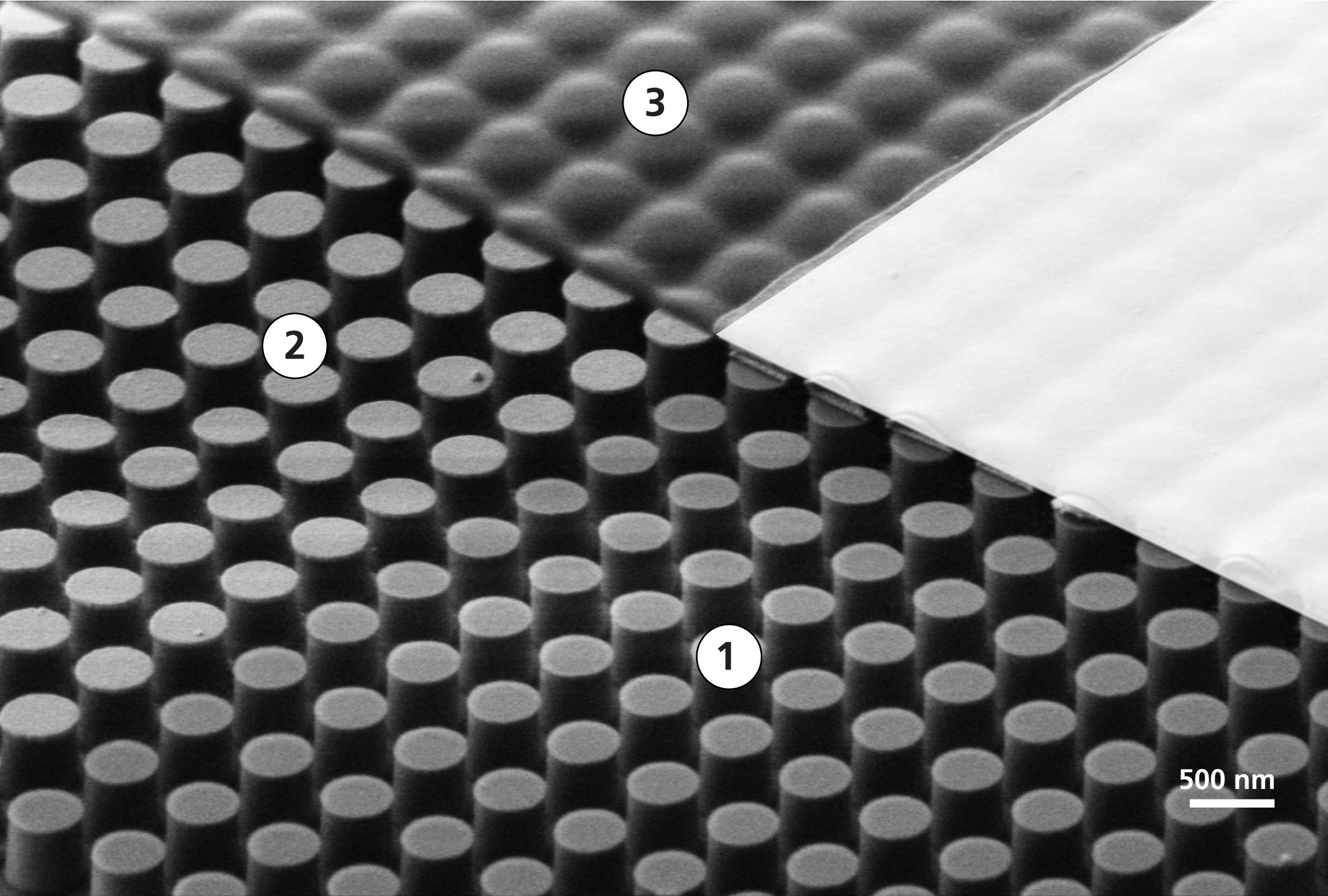
3 experiments



1 index

2 zero index

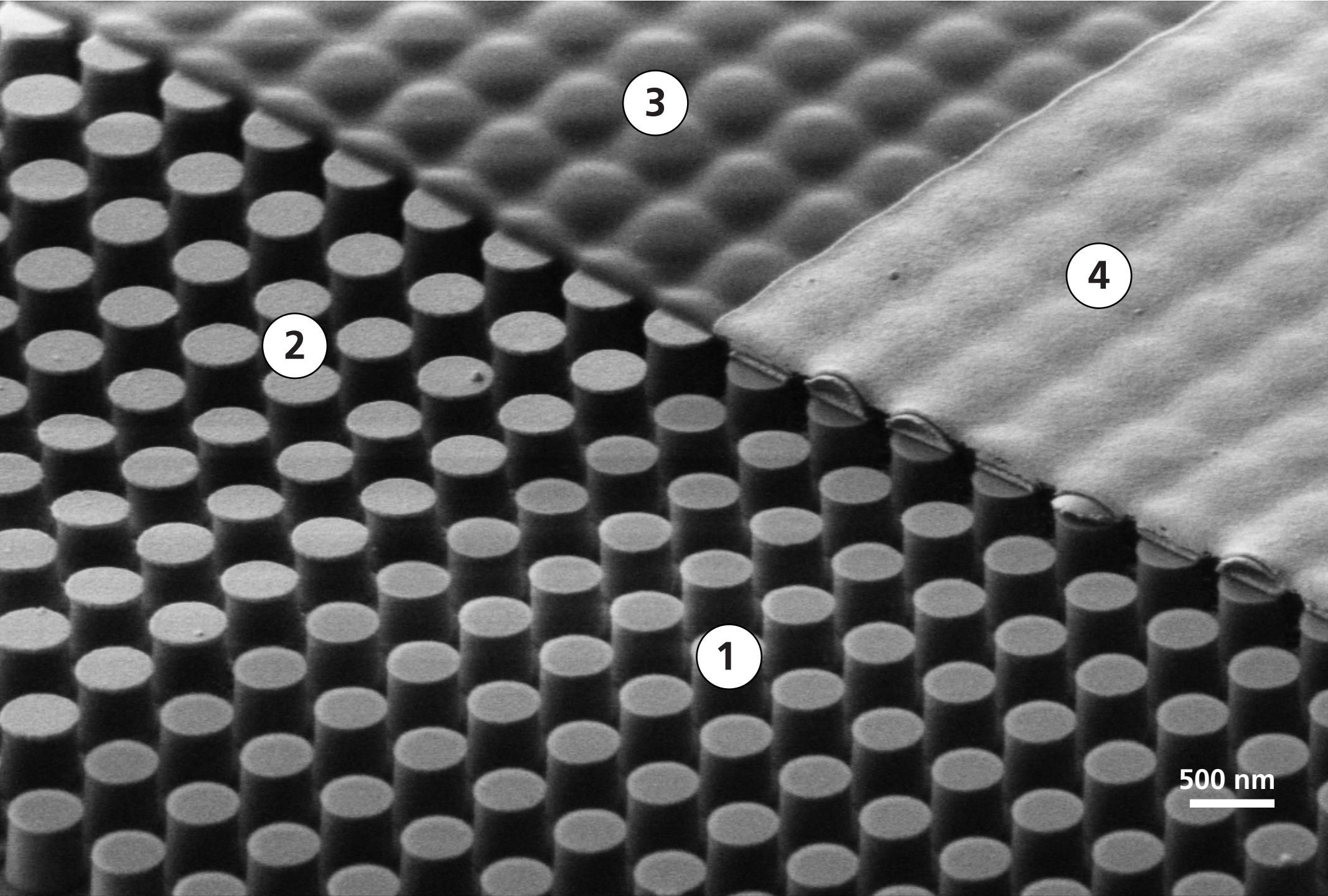
3 experiments



1 index

2 zero index

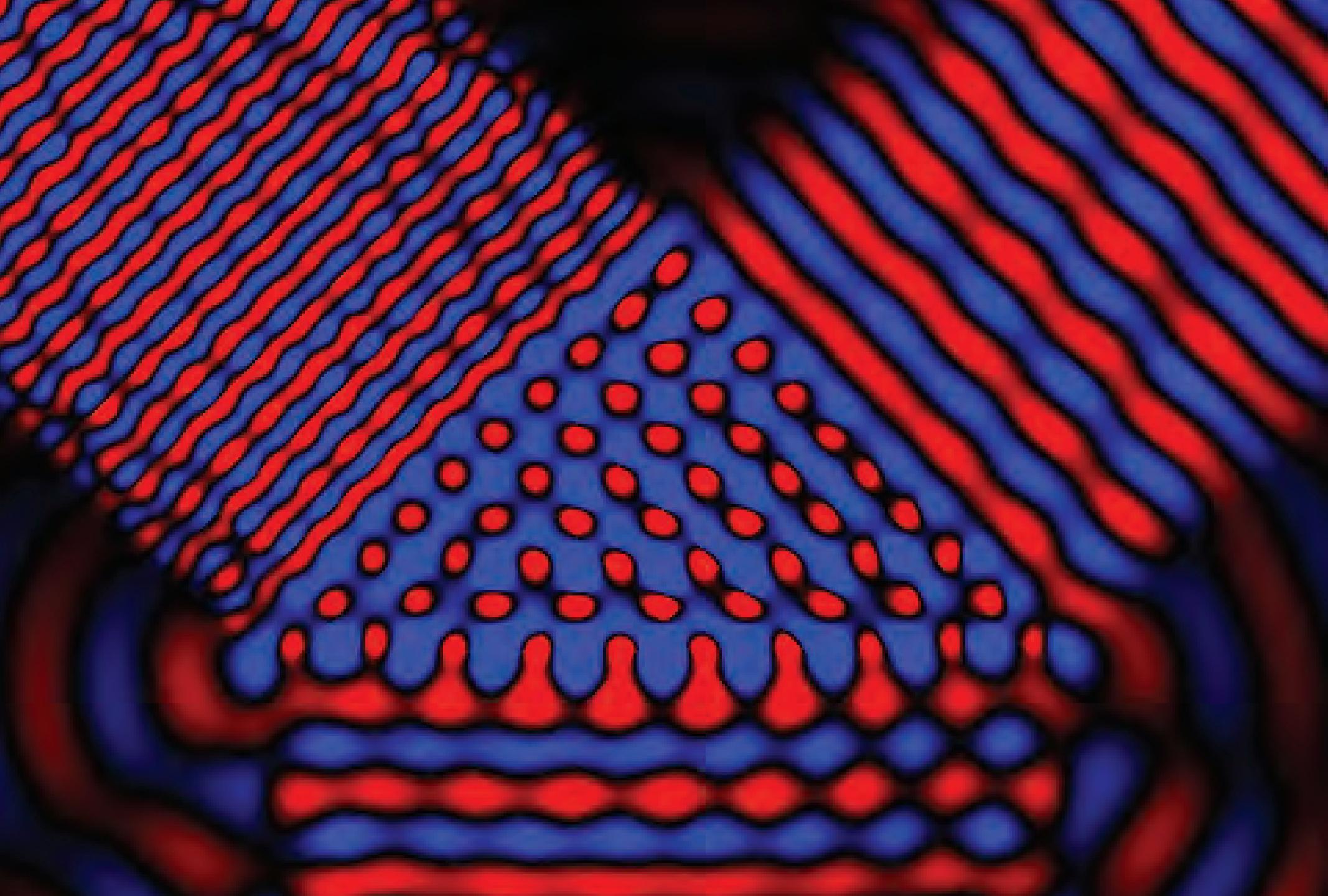
3 experiments



1 index

2 zero index

3 experiments



1 index

2 zero index

3 experiments

# On-chip zero-index prism

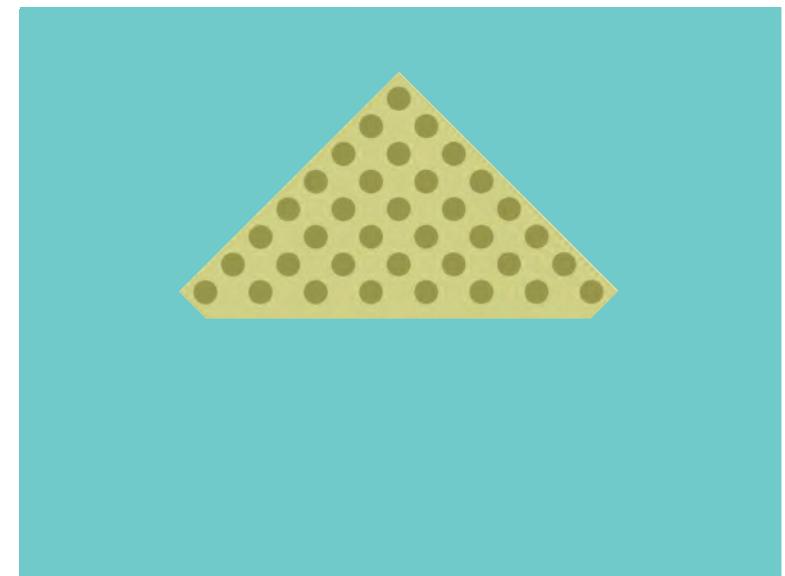


1 index

2 zero index

3 experiments

# On-chip zero-index prism

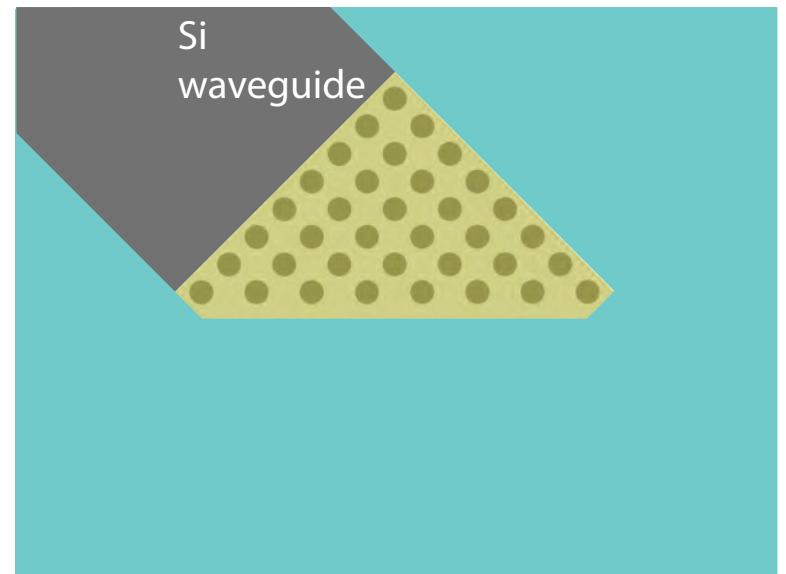


1 index

2 zero index

3 experiments

# On-chip zero-index prism

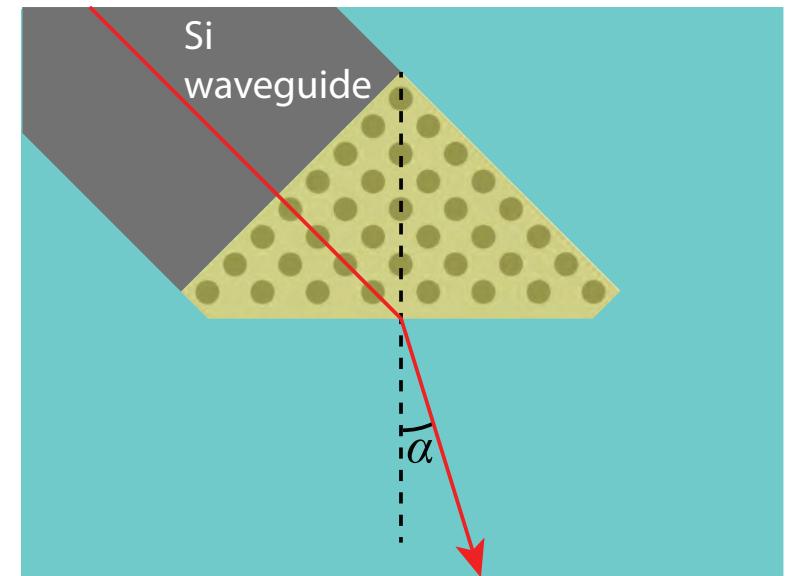


1 index

2 zero index

3 experiments

# On-chip zero-index prism

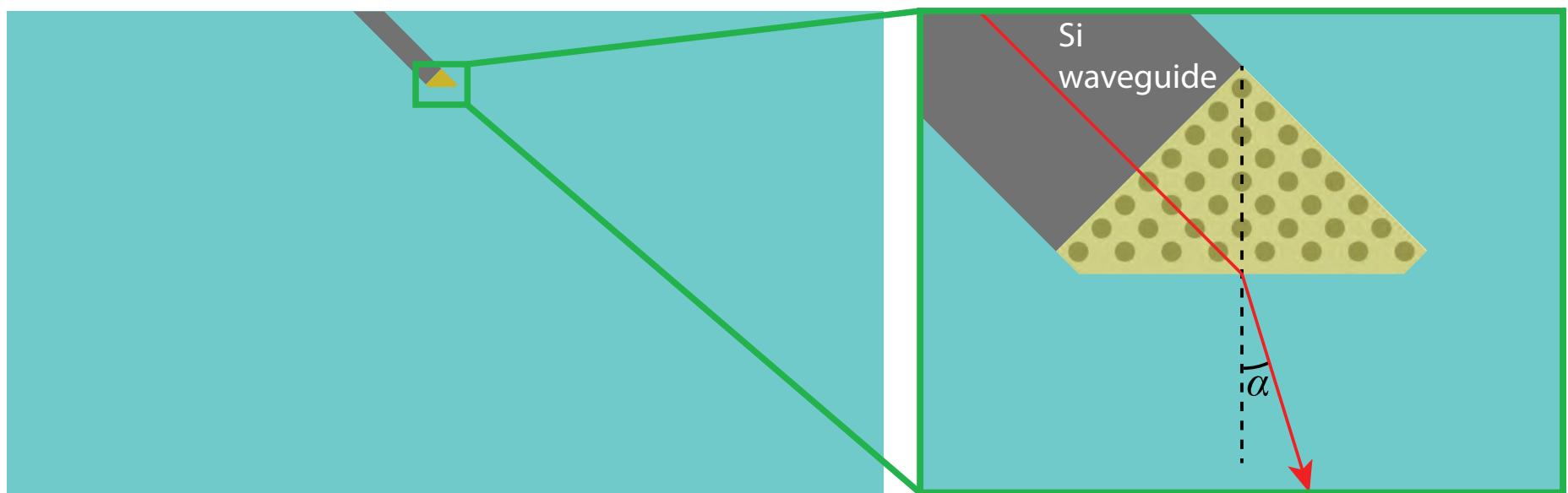


1 index

2 zero index

3 experiments

# On-chip zero-index prism

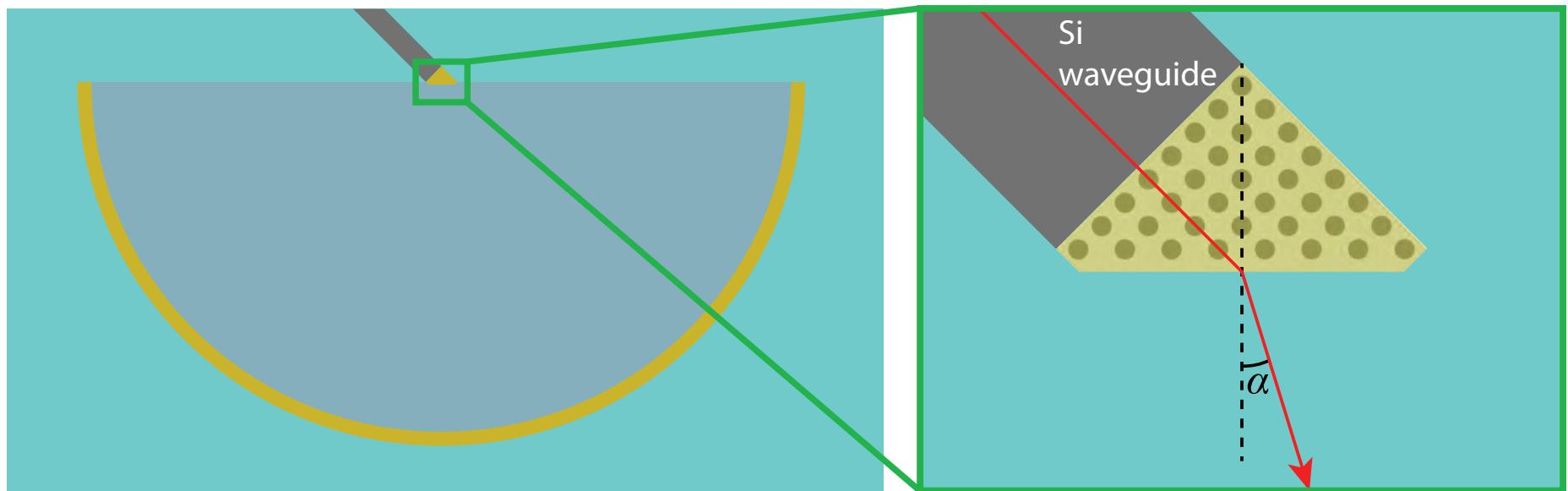


1 index

2 zero index

3 experiments

# On-chip zero-index prism

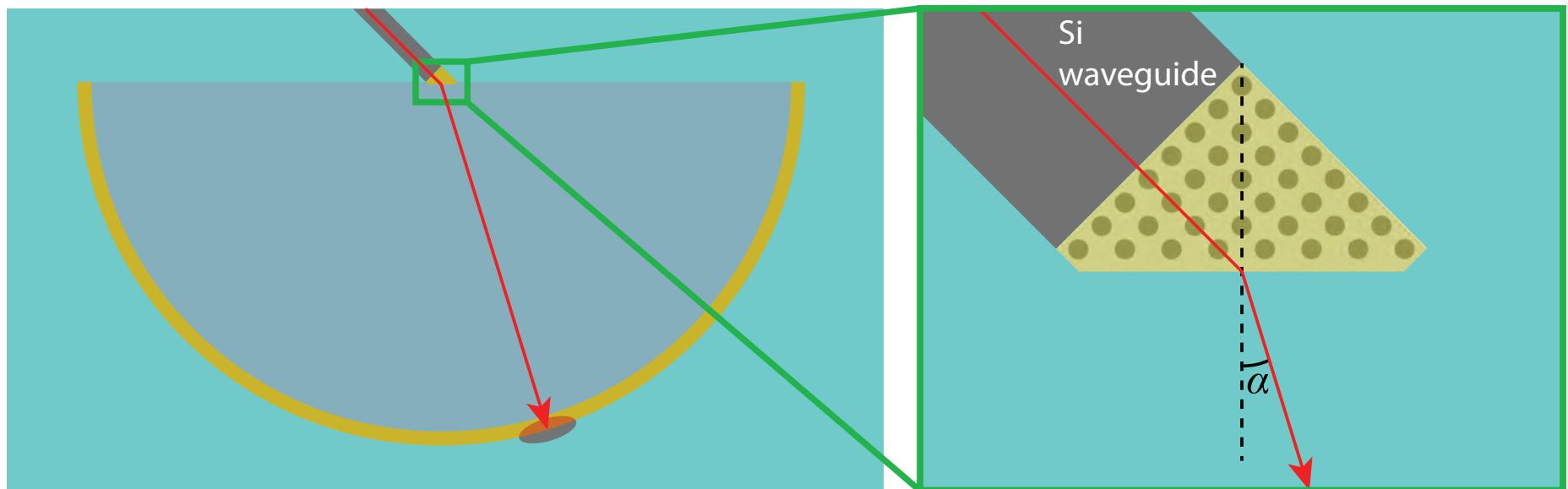


1 index

2 zero index

3 experiments

# On-chip zero-index prism

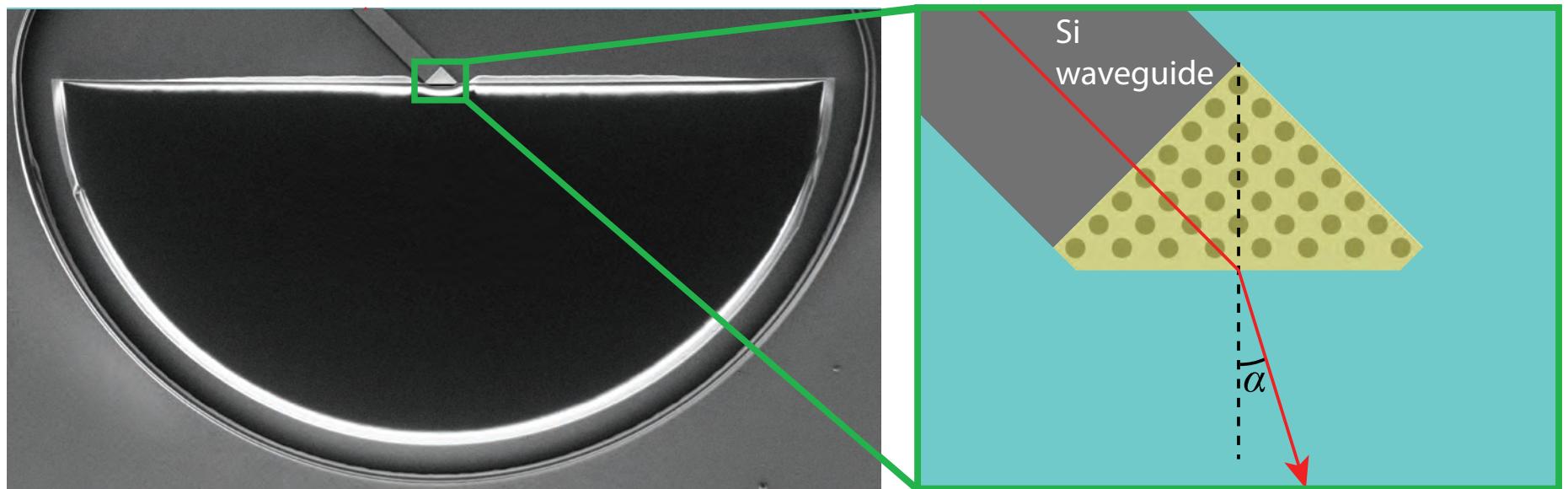


1 index

2 zero index

3 experiments

# On-chip zero-index prism

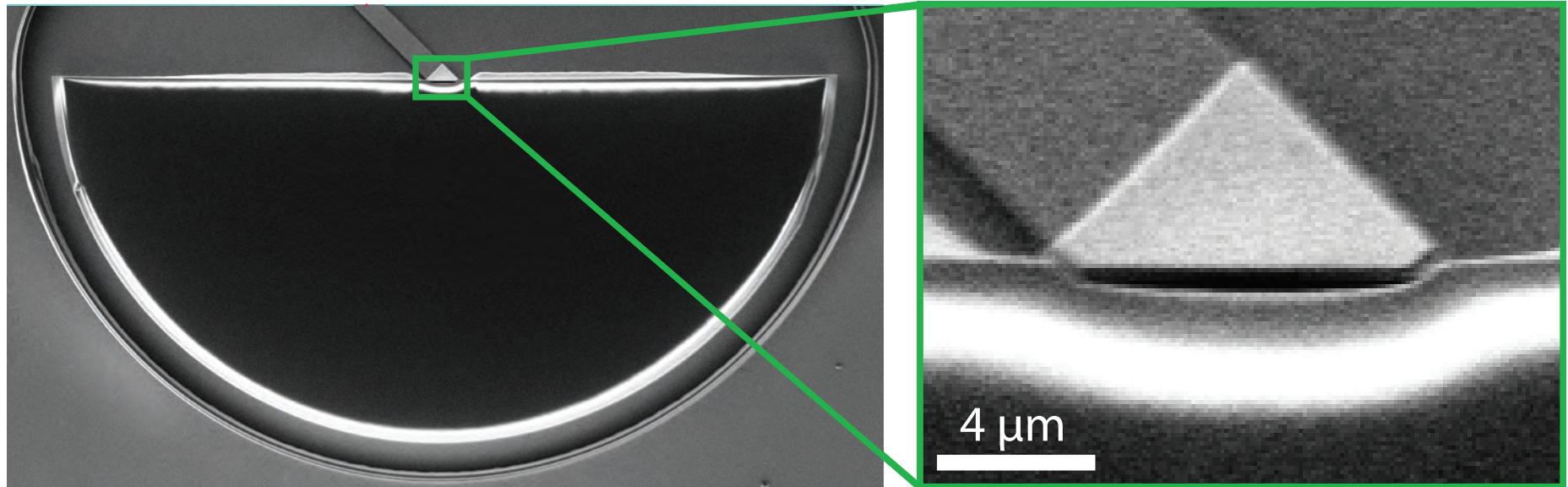


1 index

2 zero index

3 experiments

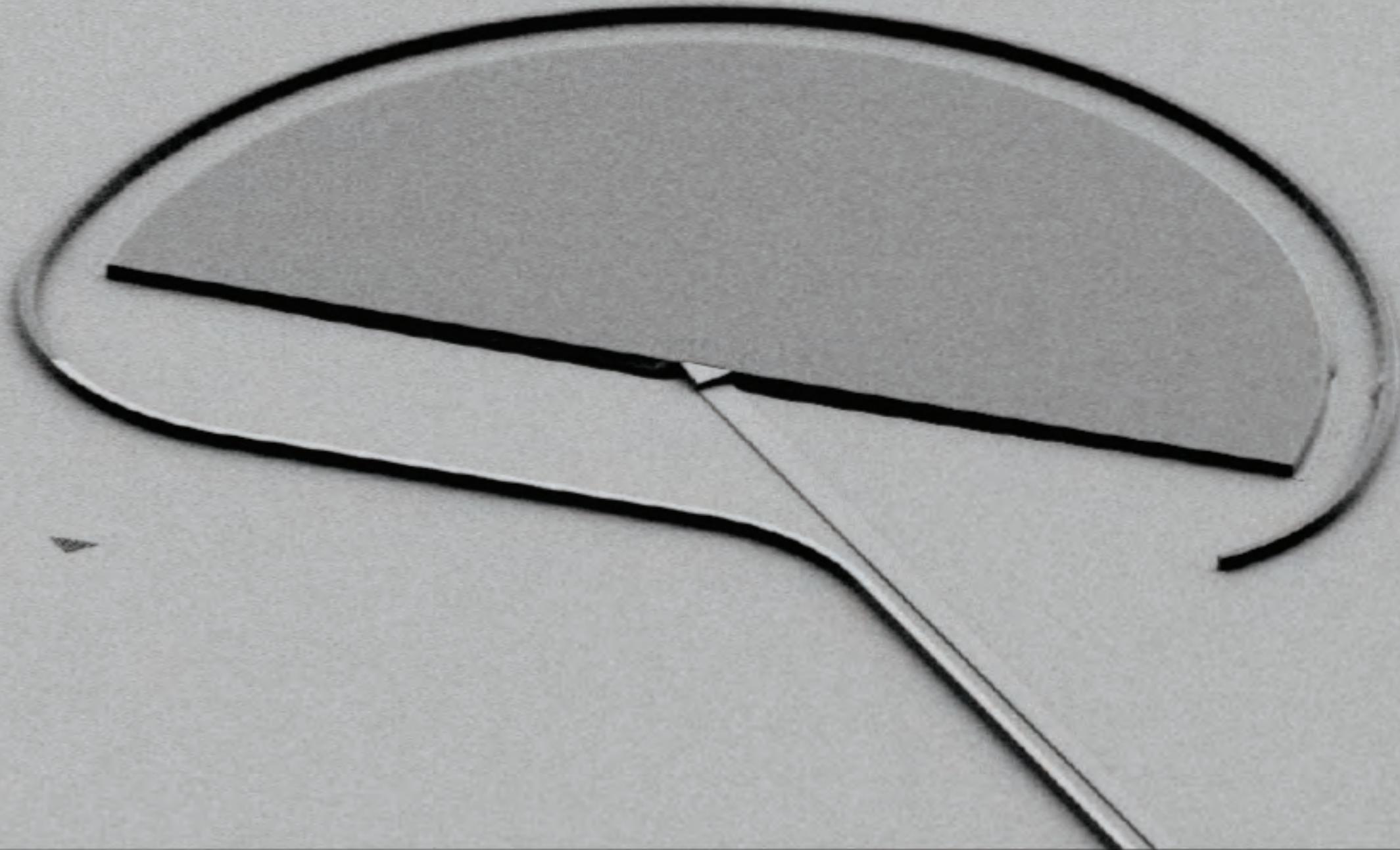
# On-chip zero-index prism



1 index

2 zero index

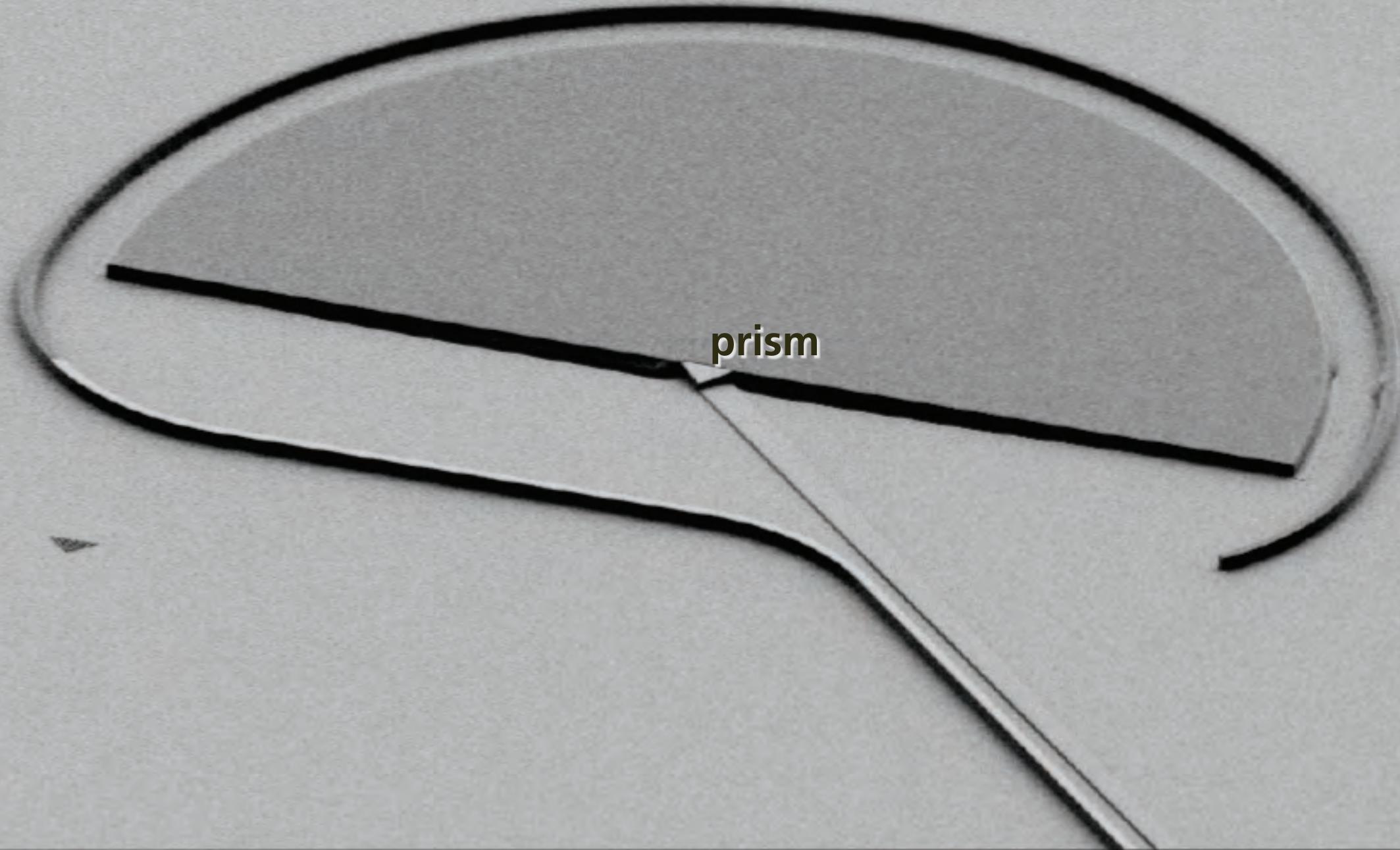
3 experiments



1 index

2 zero index

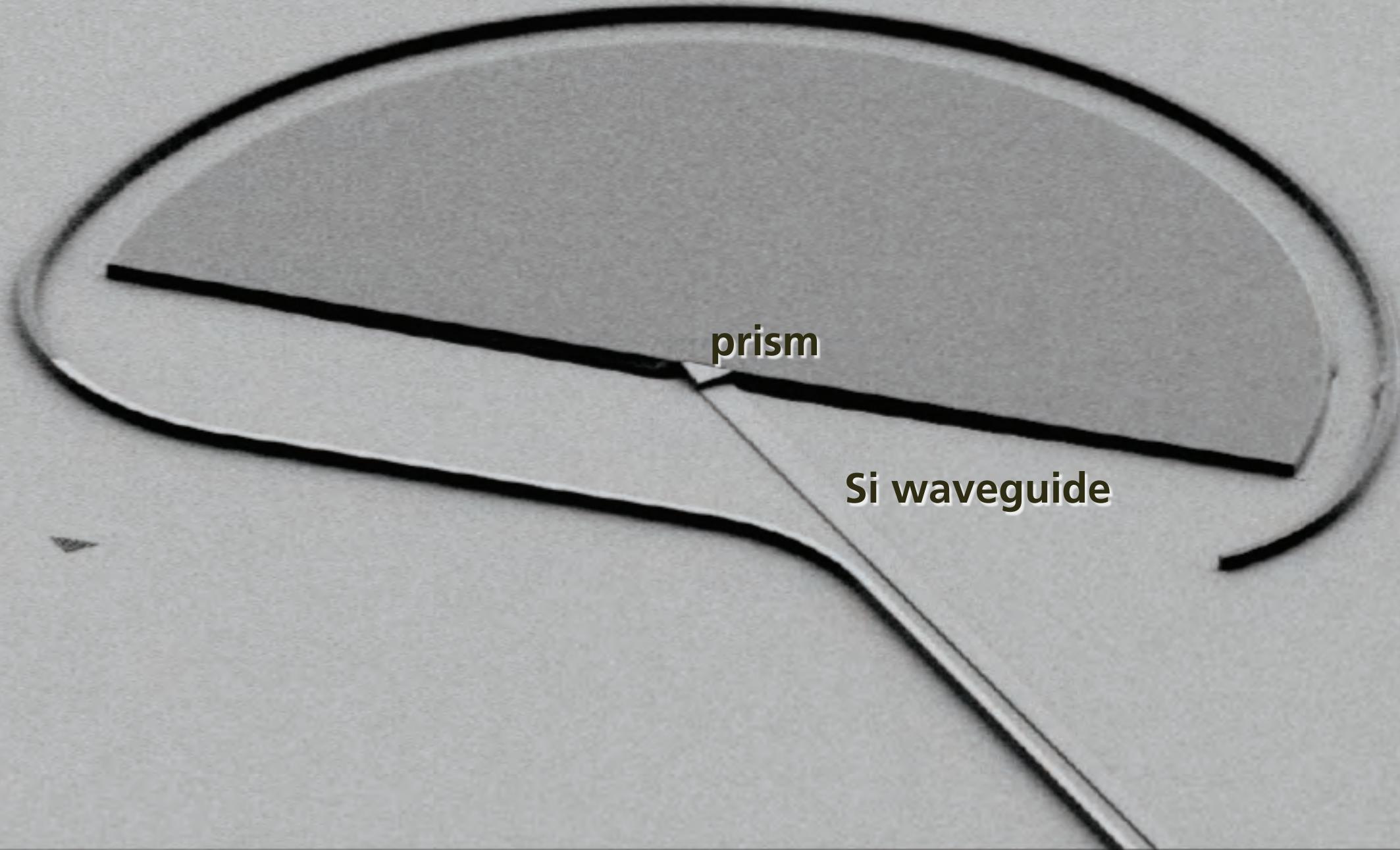
3 experiments



1 index

2 zero index

3 experiments



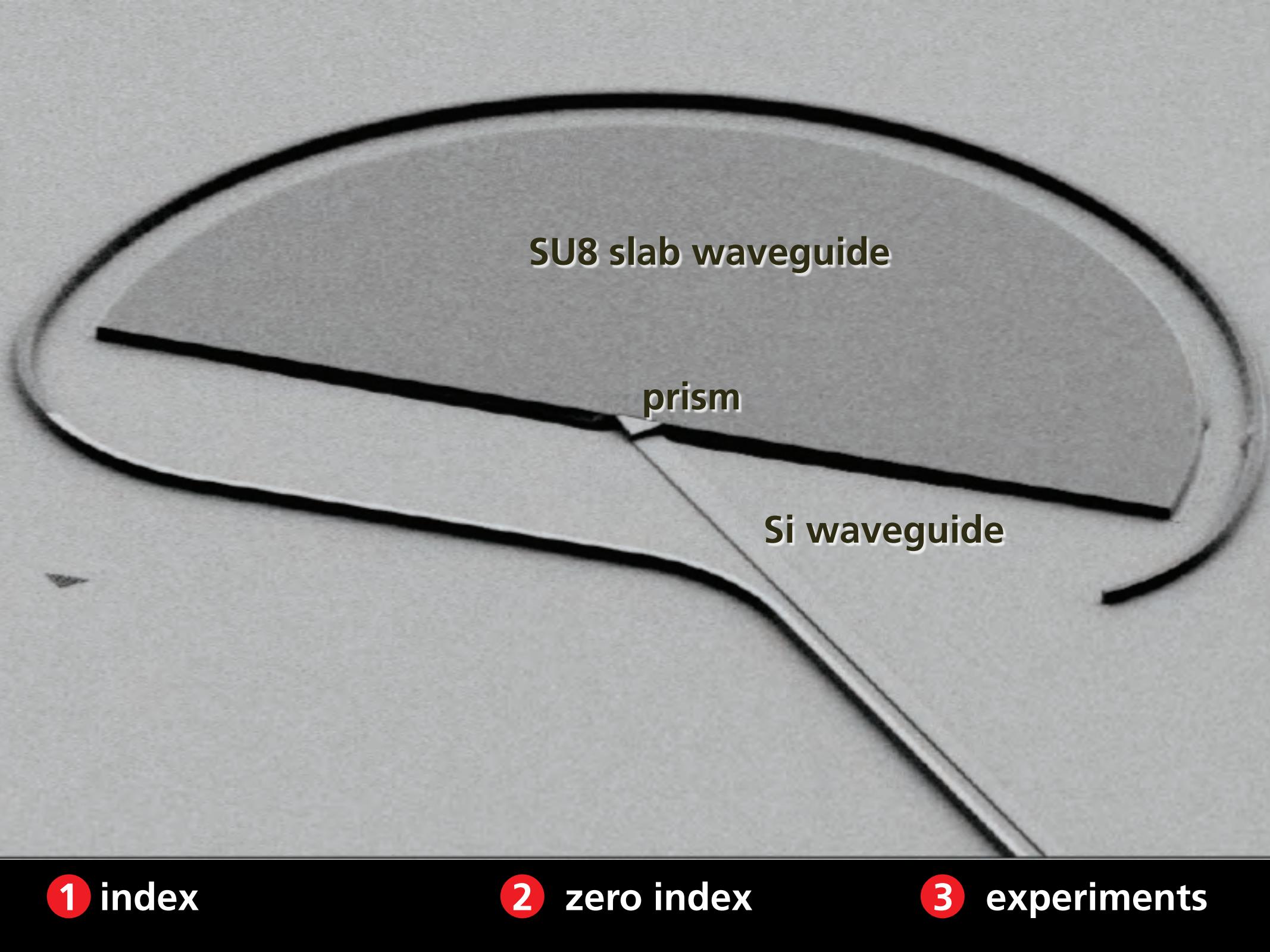
prism

Si waveguide

1 index

2 zero index

3 experiments

A scanning electron micrograph (SEM) showing a waveguide structure. It features a large, circular SU8 slab waveguide at the top. A smaller, rectangular Si waveguide is positioned below it, partially embedded in the SU8. A triangular prism is placed between the two waveguides. The entire structure is set against a dark background.

SU8 slab waveguide

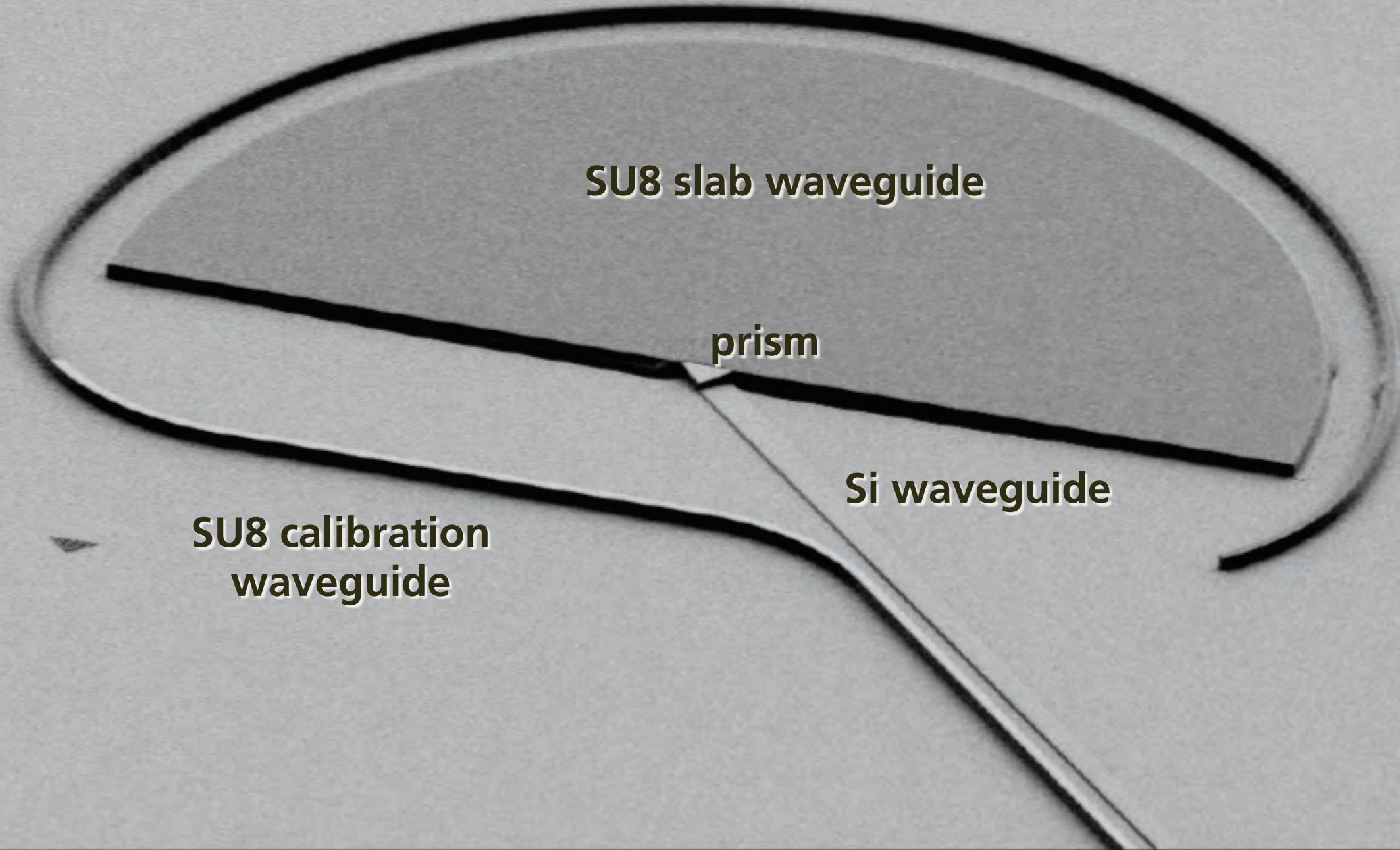
prism

Si waveguide

1 index

2 zero index

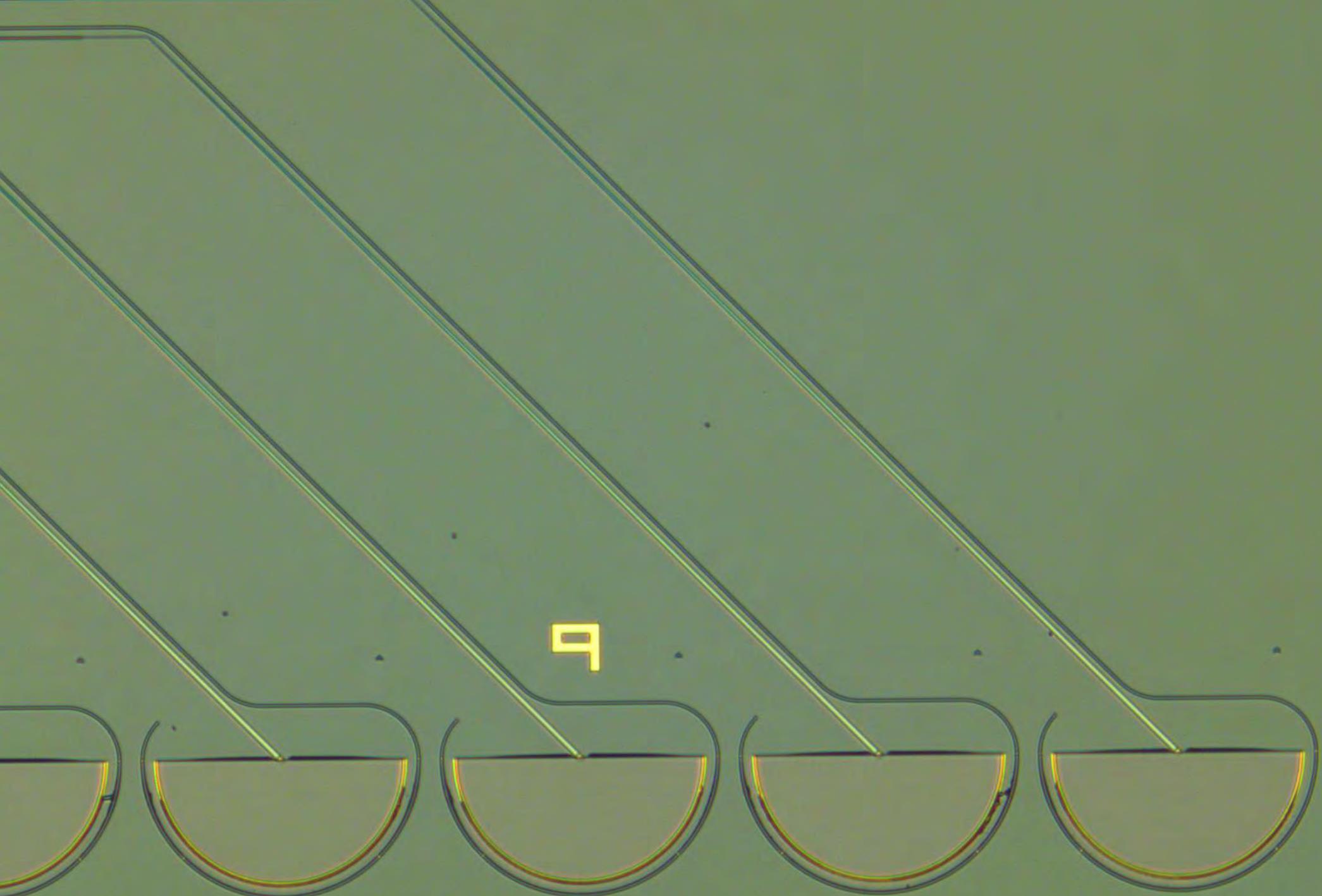
3 experiments



**1** index

**2** zero index

**3** experiments

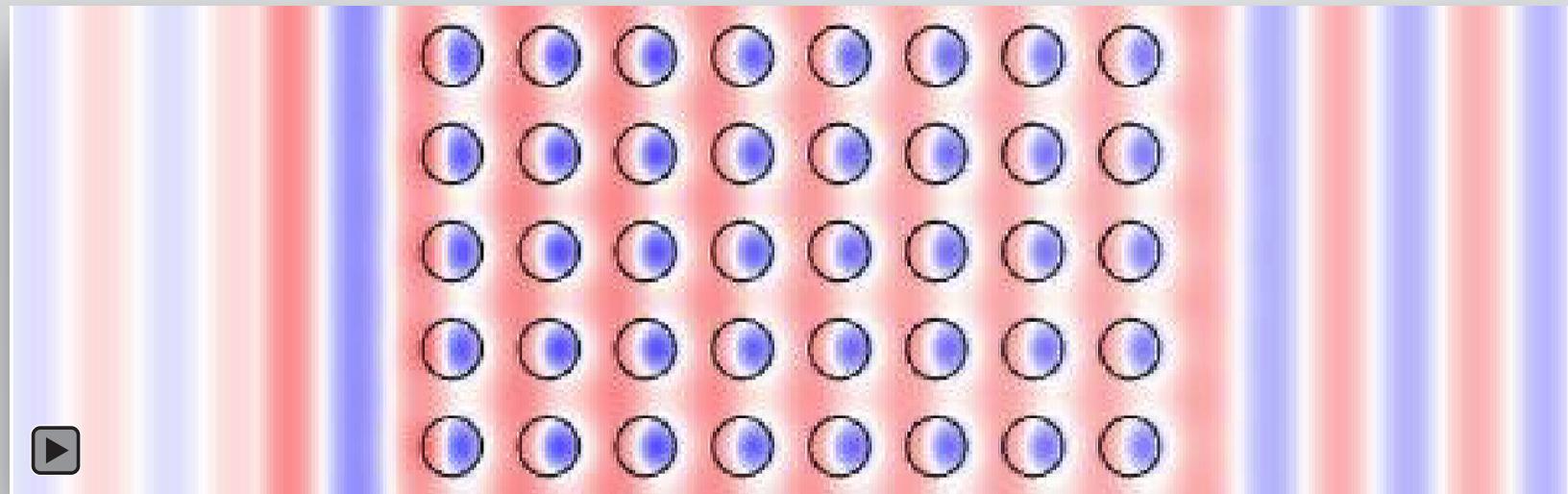


1 index

2 zero index

3 experiments

at design wavelength (1590 nm)

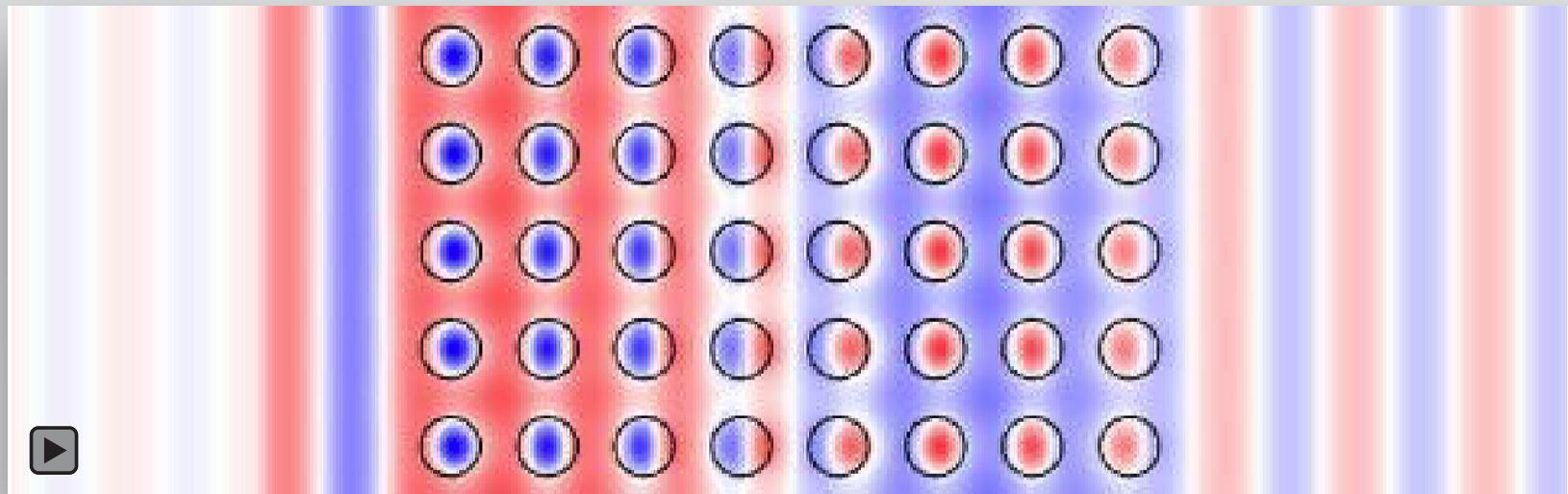


1 index

2 zero index

3 experiments

**below design wavelength (1530 nm)**

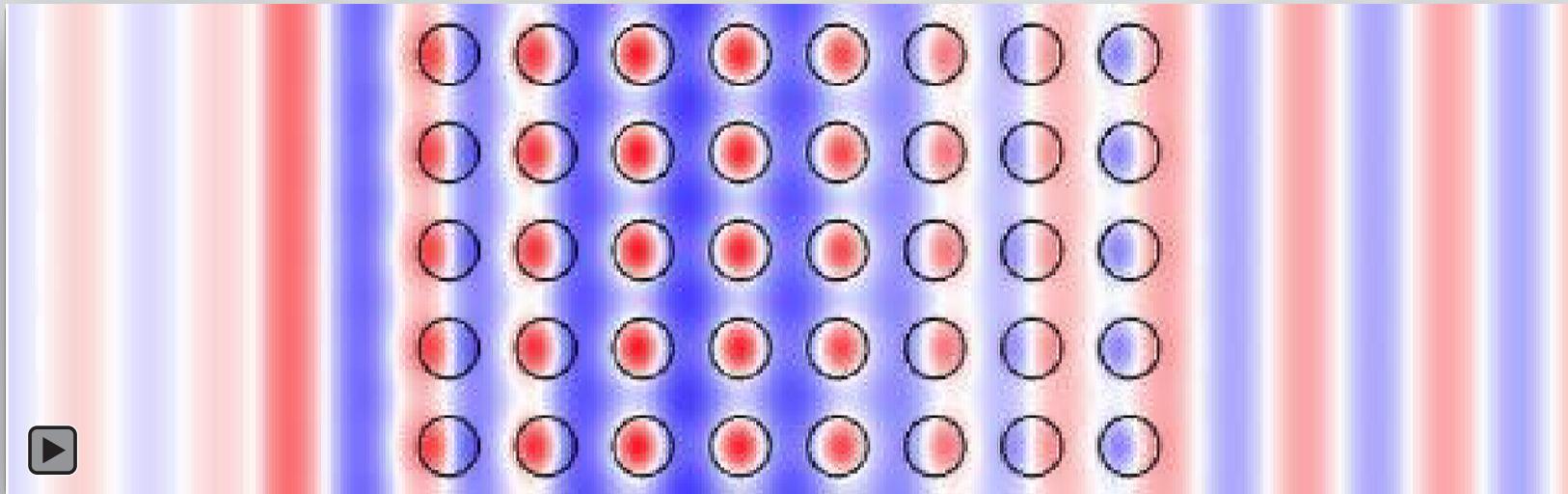


**1** index

**2** zero index

**3** experiments

**above design wavelength (1650 nm)**

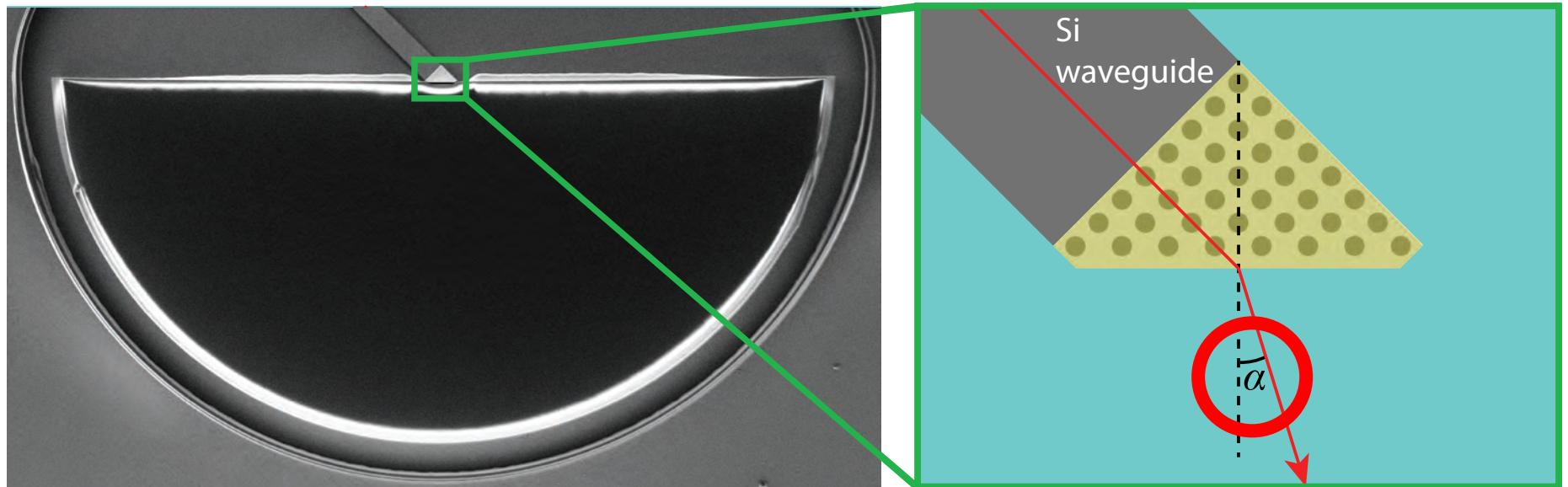


**1** index

**2** zero index

**3** experiments

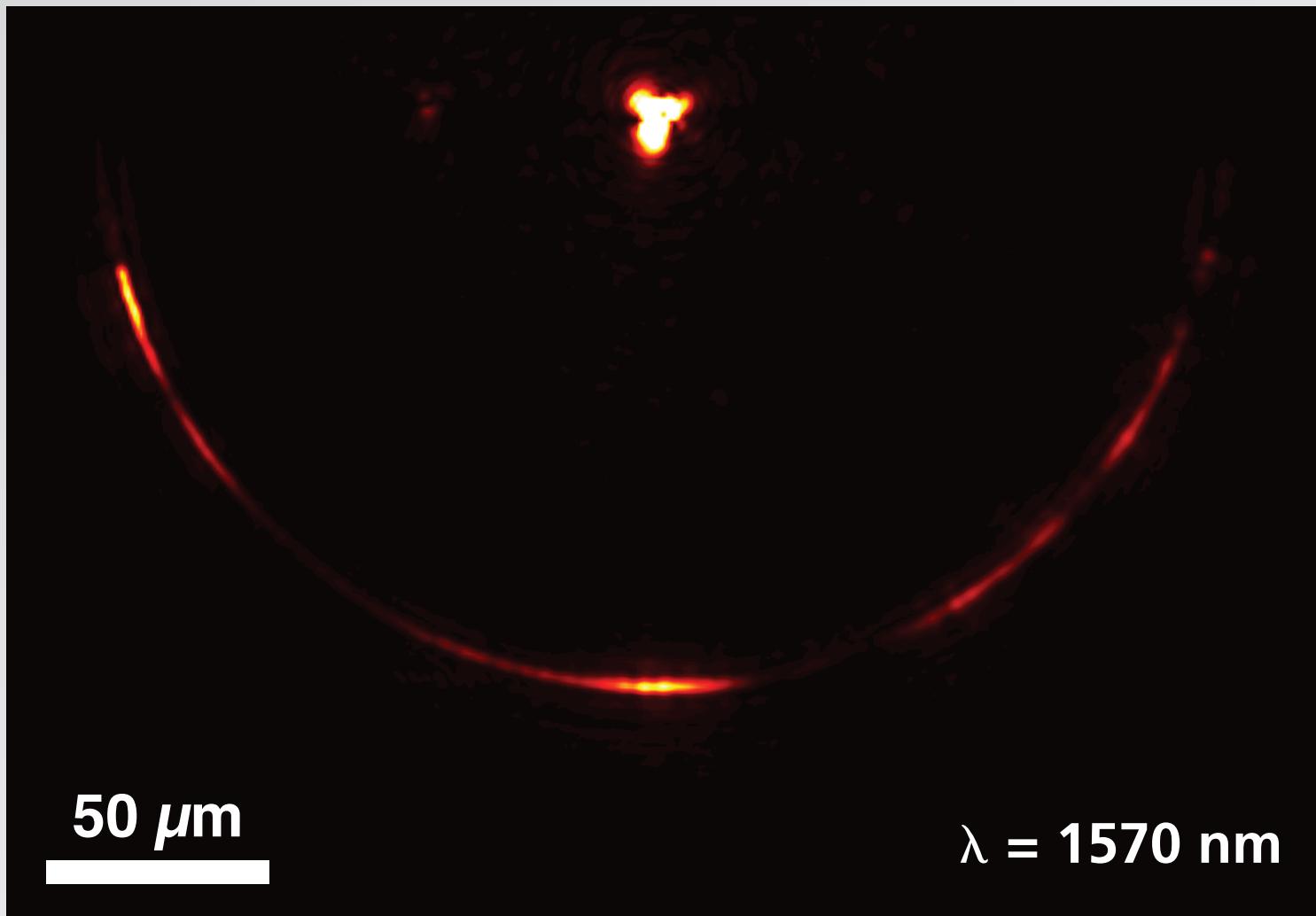
# On-chip zero-index prism



1 index

2 zero index

3 experiments



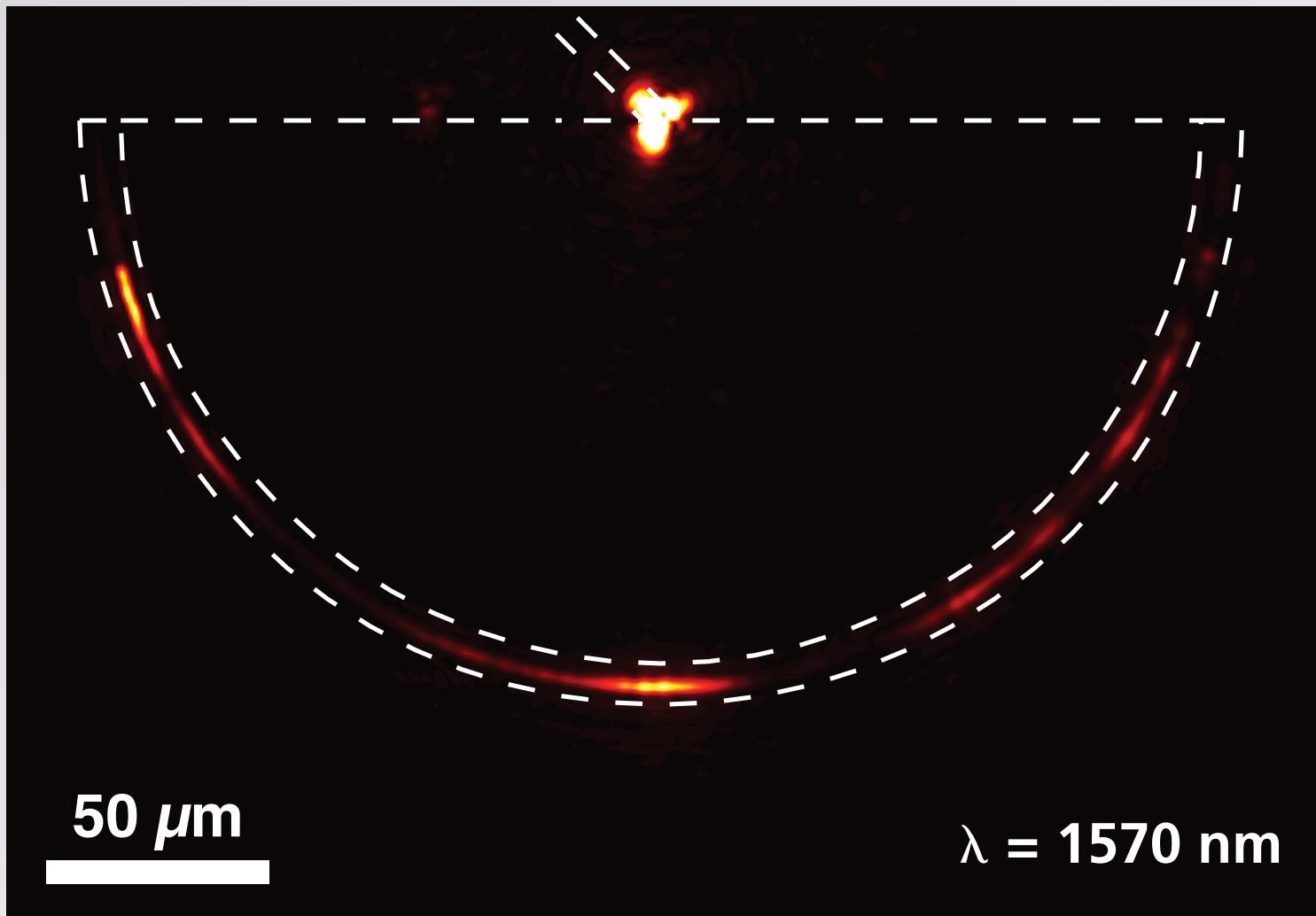
50  $\mu\text{m}$

$\lambda = 1570 \text{ nm}$

1 index

2 zero index

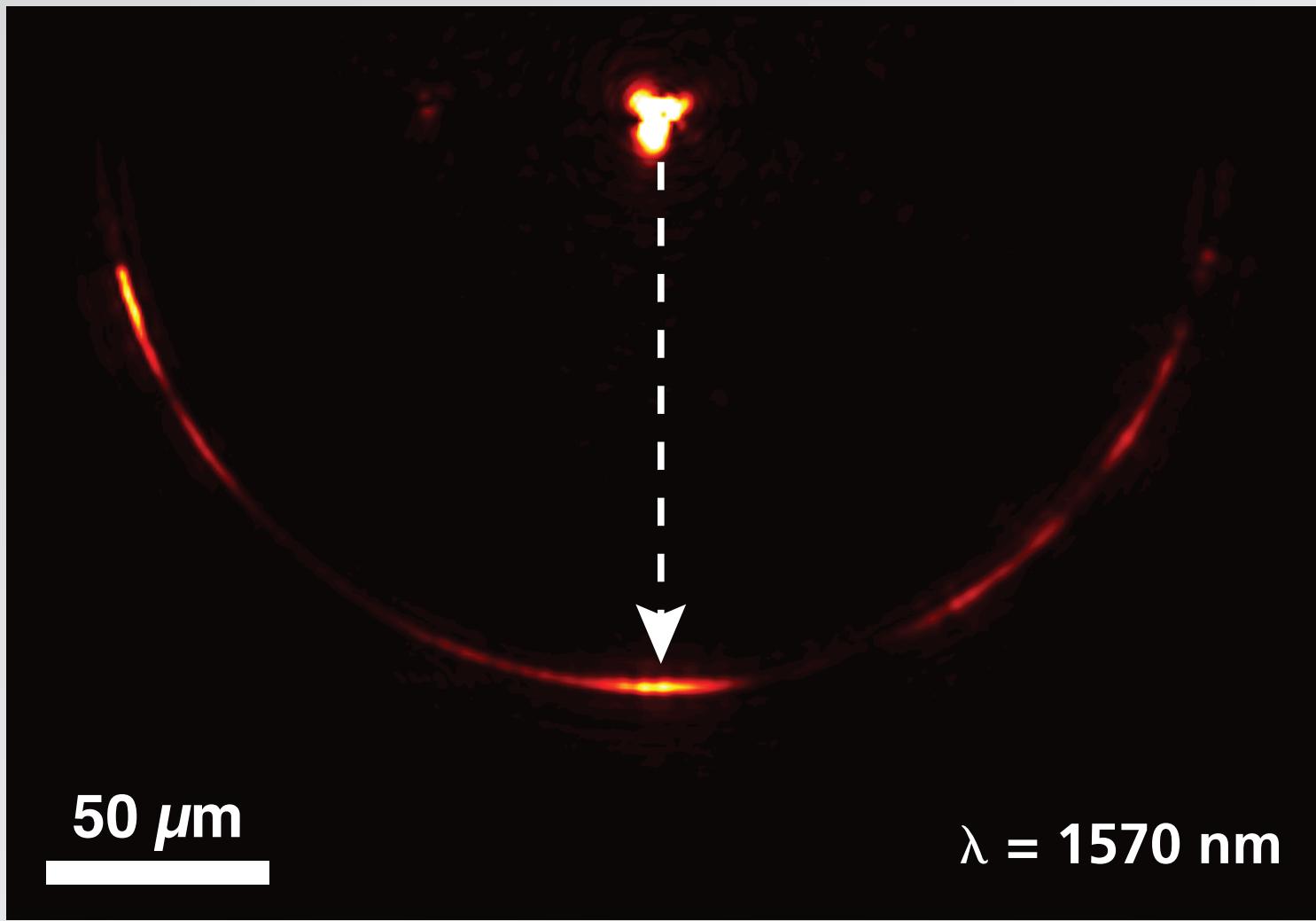
3 experiments



1 index

2 zero index

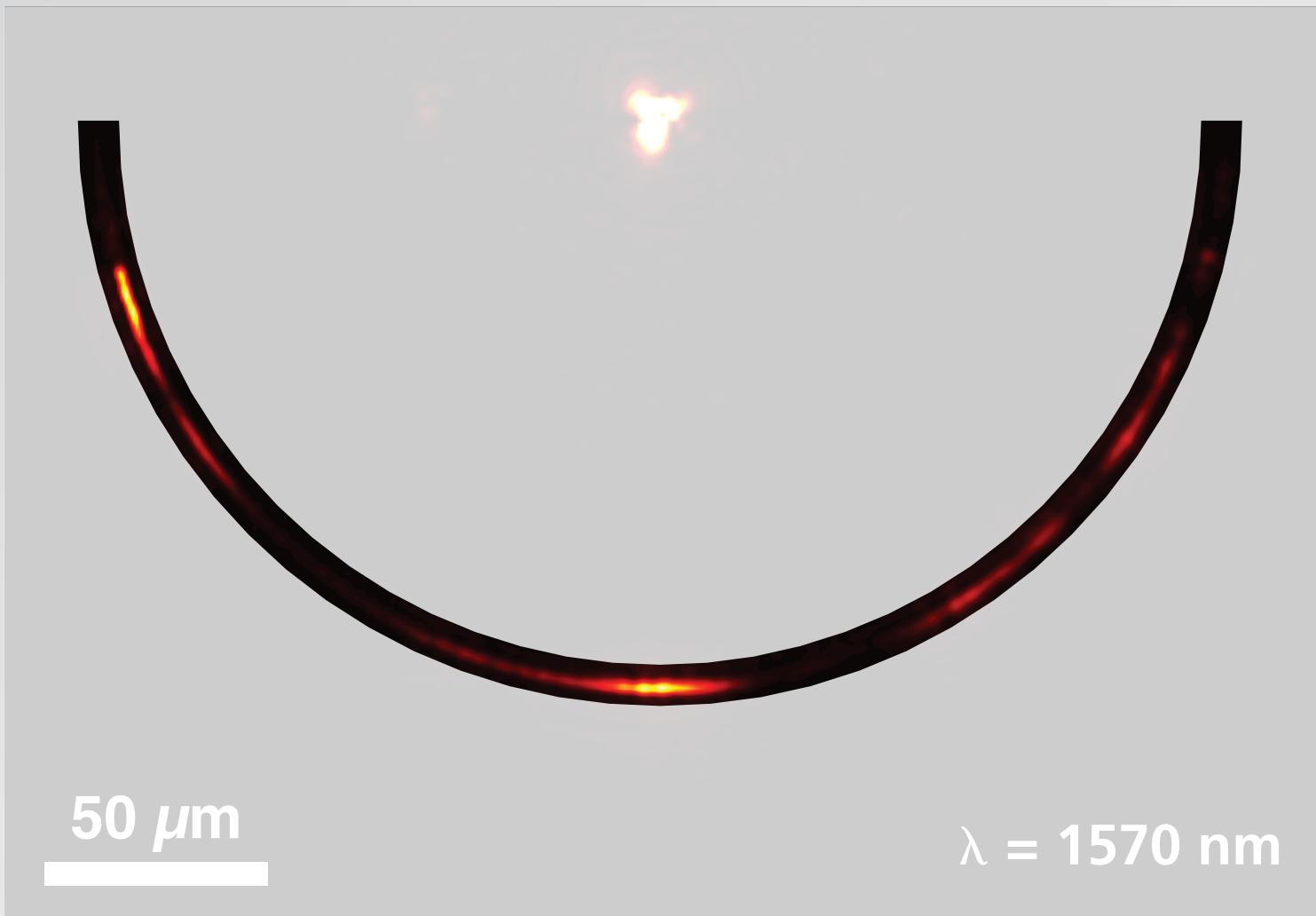
3 experiments



1 index

2 zero index

3 experiments

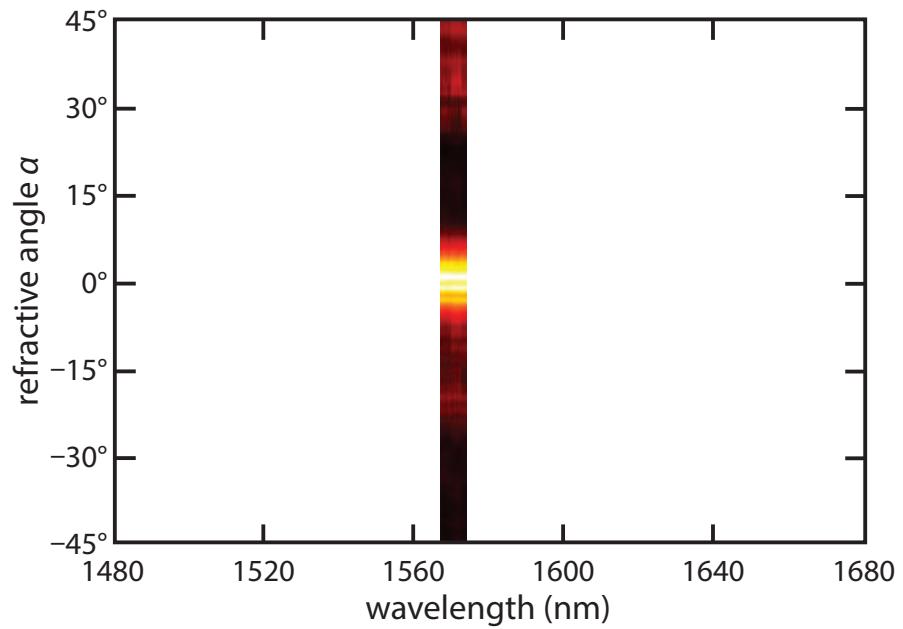


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

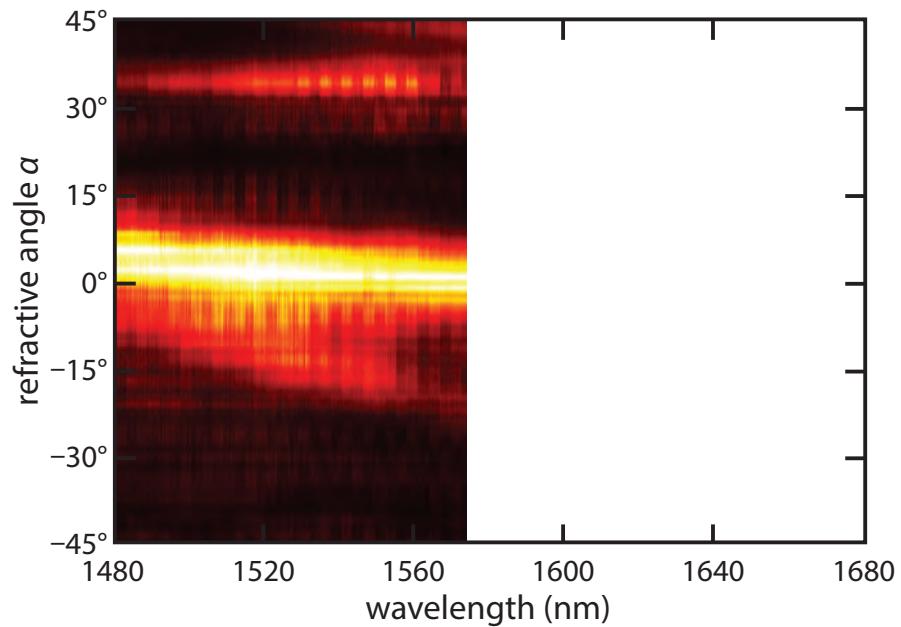


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

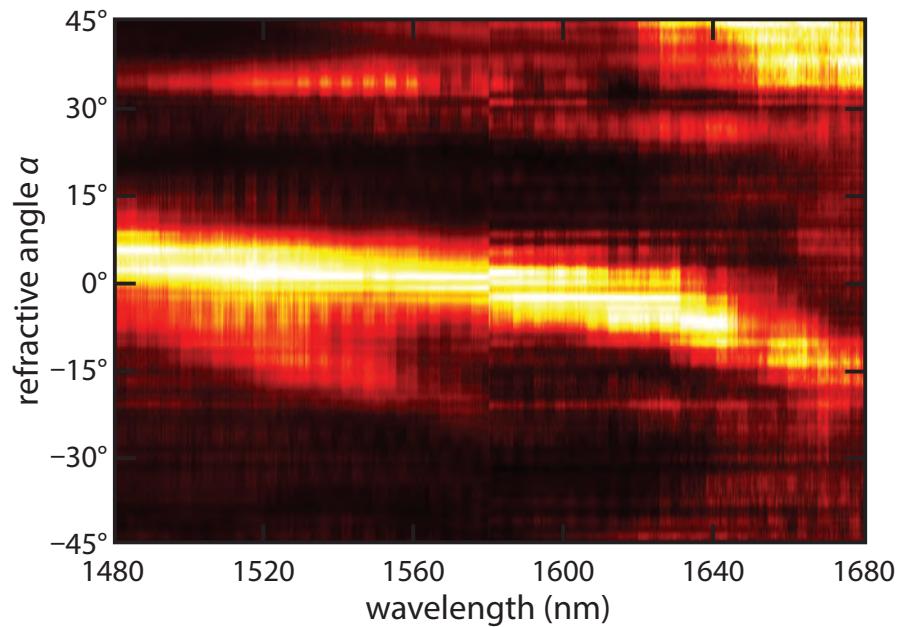


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

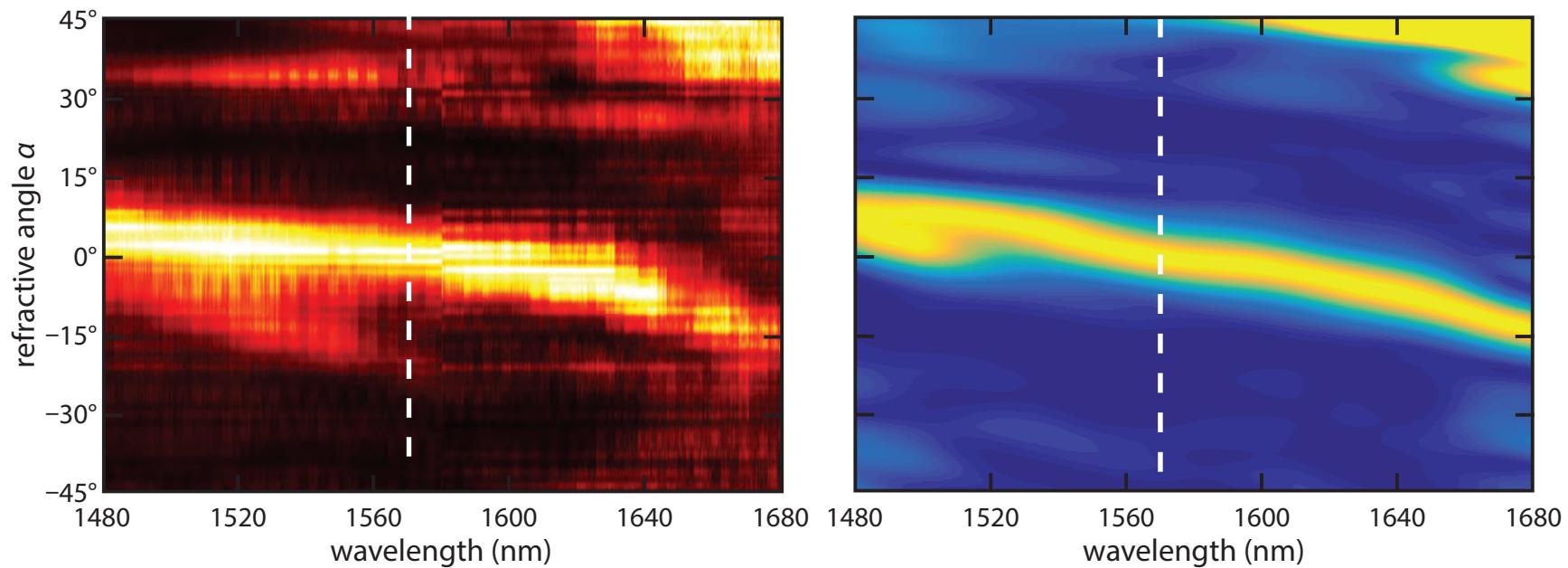


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

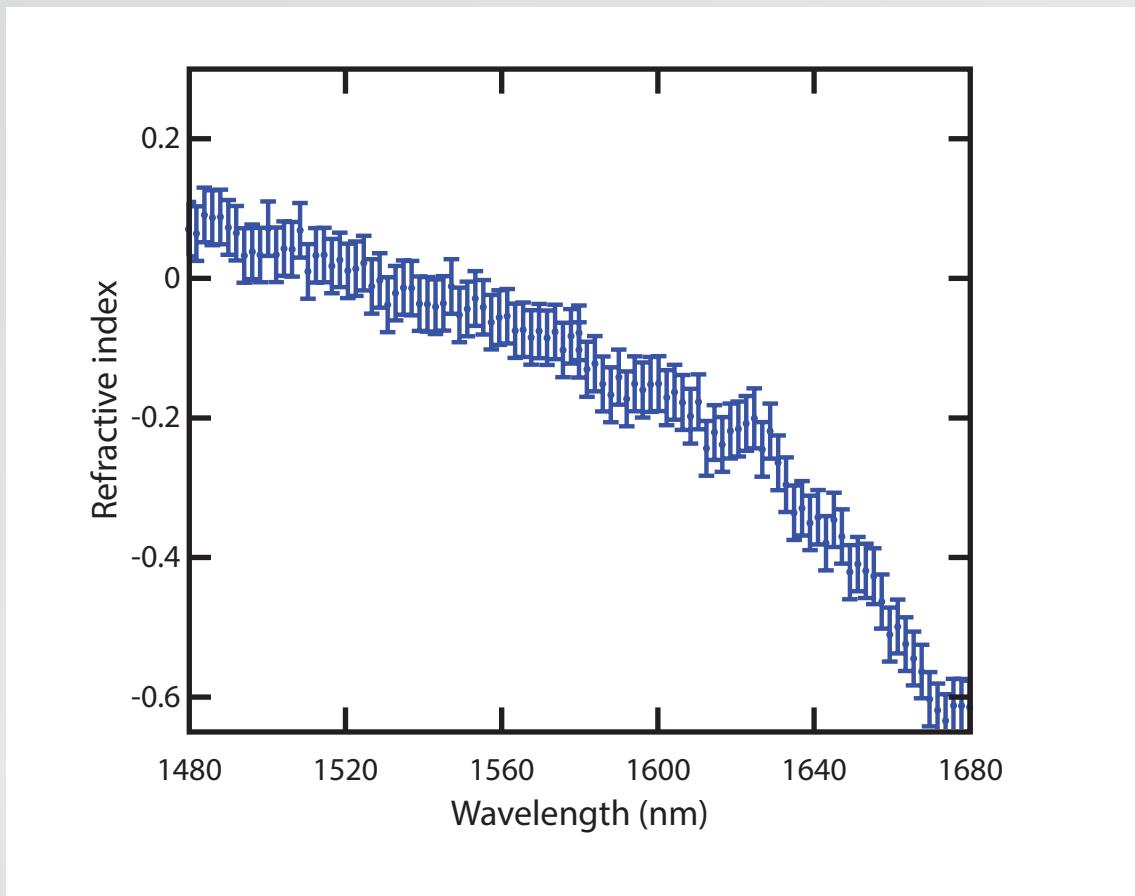


1 index

2 zero index

3 experiments

# Wavelength dependence of index

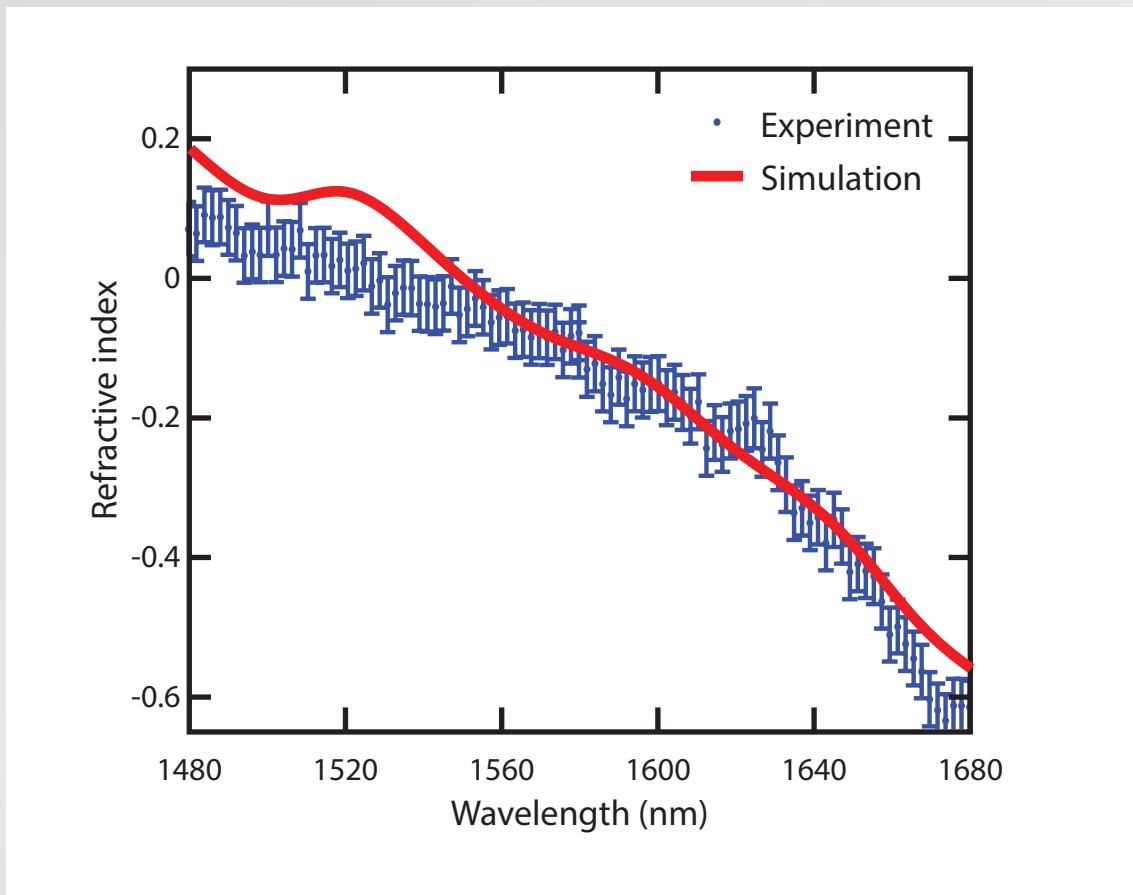


1 index

2 zero index

3 experiments

# Wavelength dependence of index



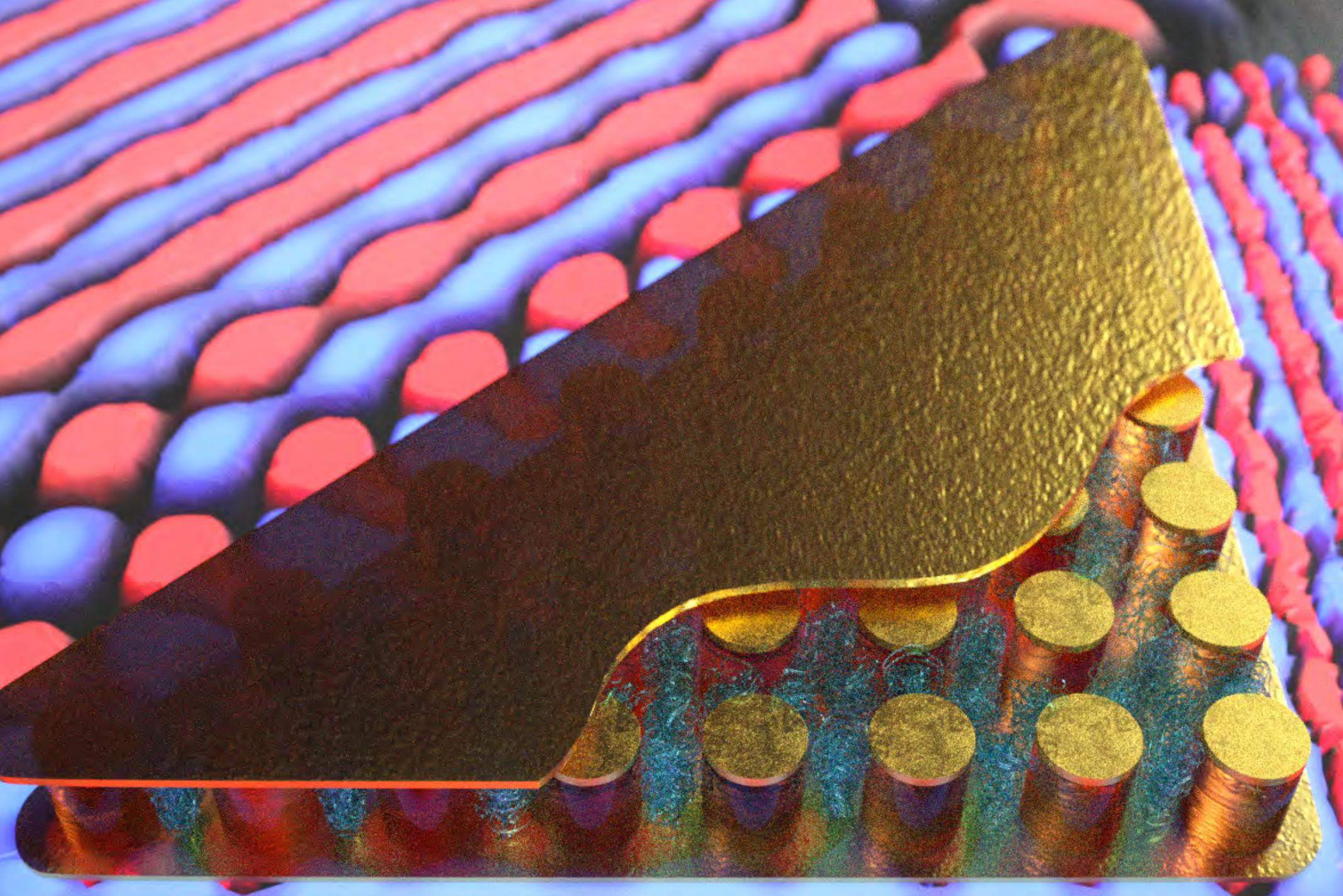
1 index

2 zero index

3 experiments

## More extreme optics

- suppressing losses
- beam steering & supercoupling
- nonlinear optics
- quantum optics



1 index

2 zero index

3 experiments

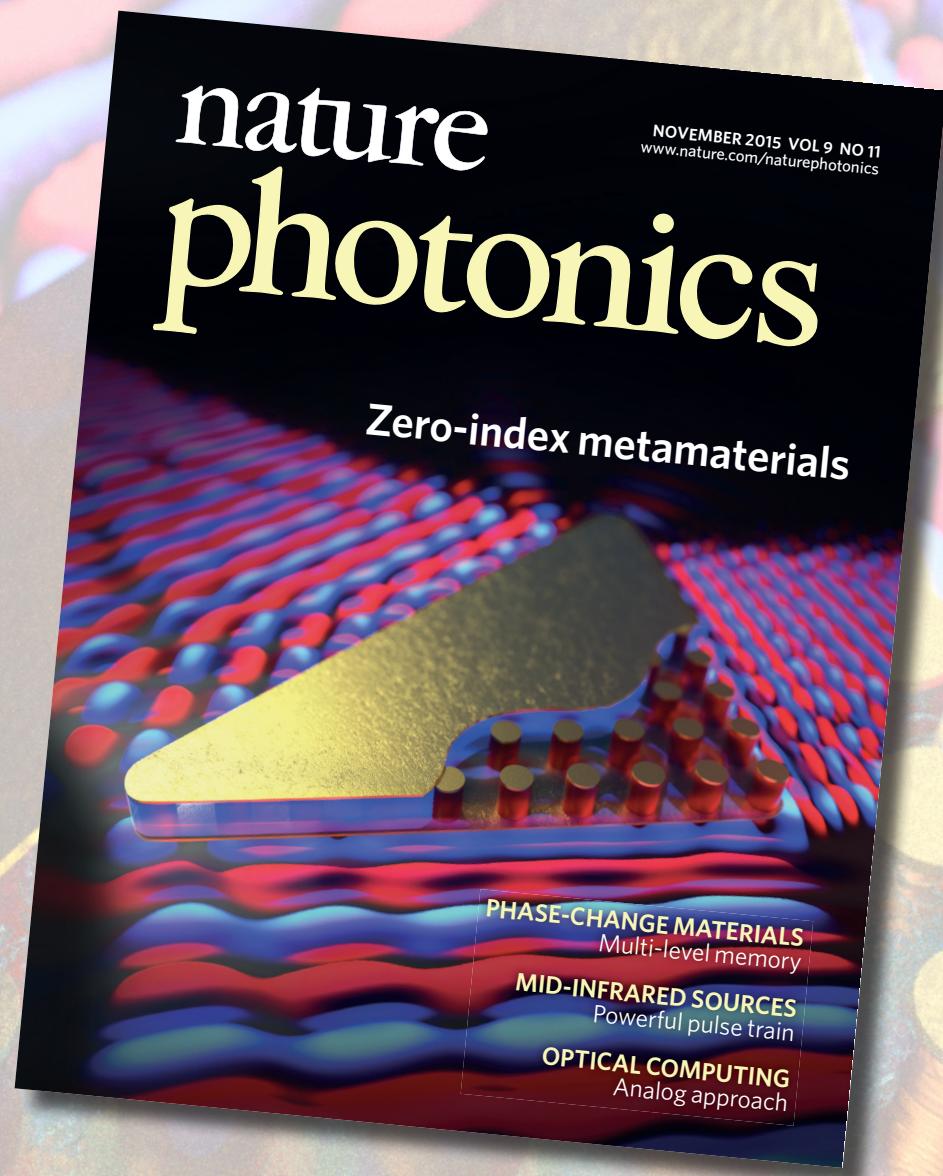
- on-chip zero-index material
- uniform field inside material (infinite wavelength)
- many exciting applications ahead!

1 index

2 zero index

3 experiments

More info: download paper!



1 index

2 zero index

3 experiments

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