

# Less is more: Extreme optics with zero refractive index



Physical Society of the Republic of China  
Annual Meeting 2016  
Kaohsiung, Republic of China, 16 January 2016





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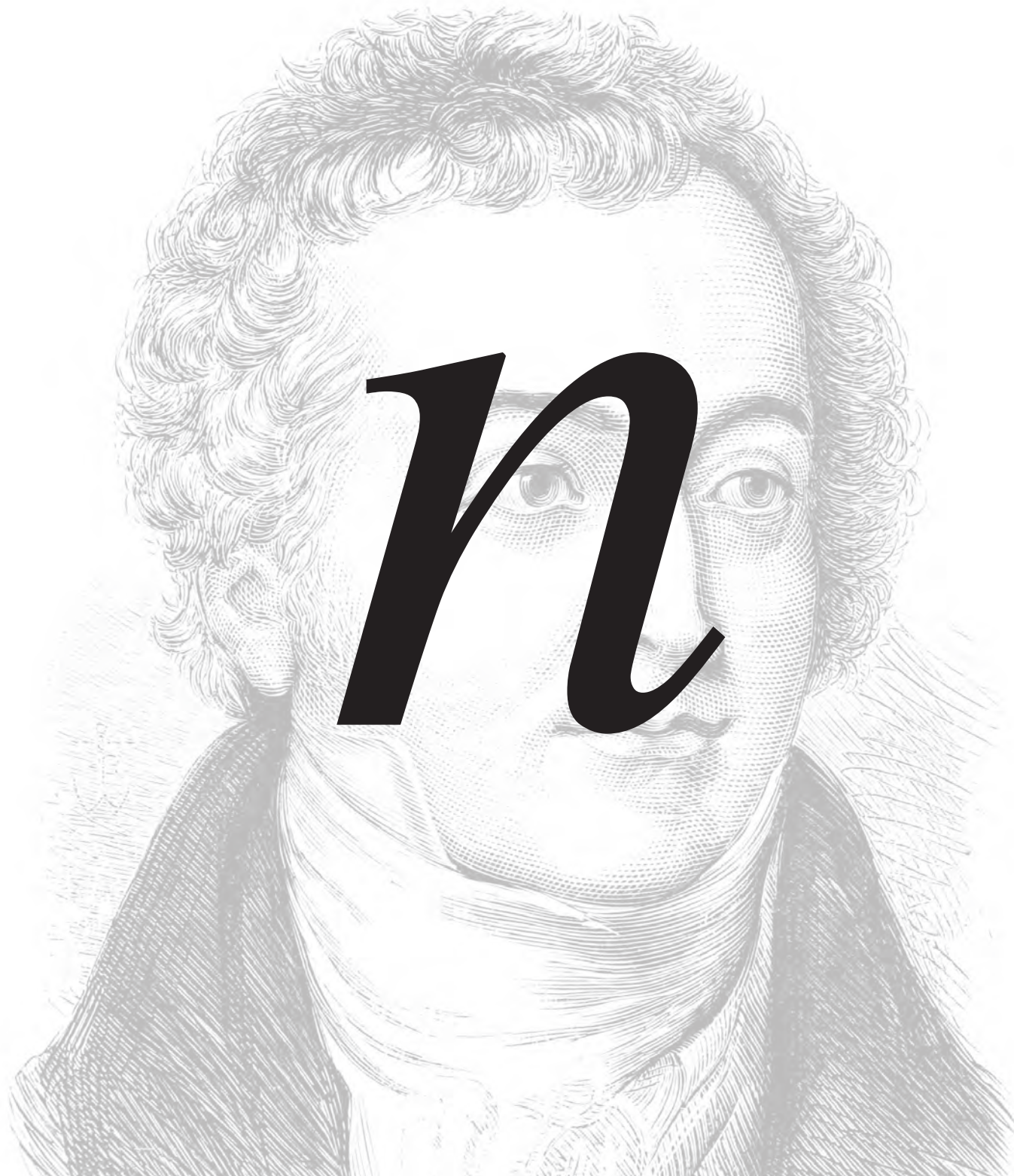
@eric\_mazur

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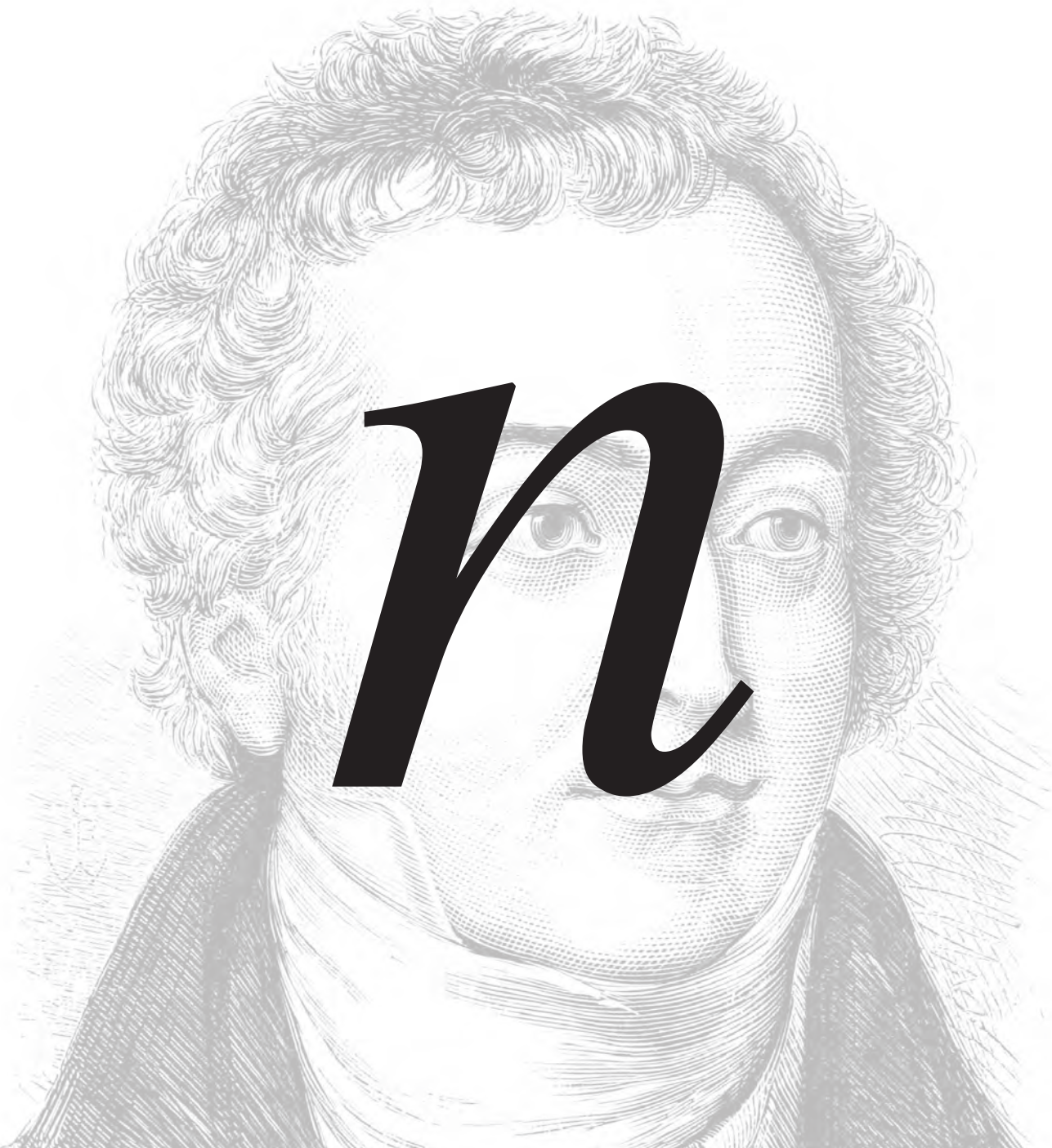




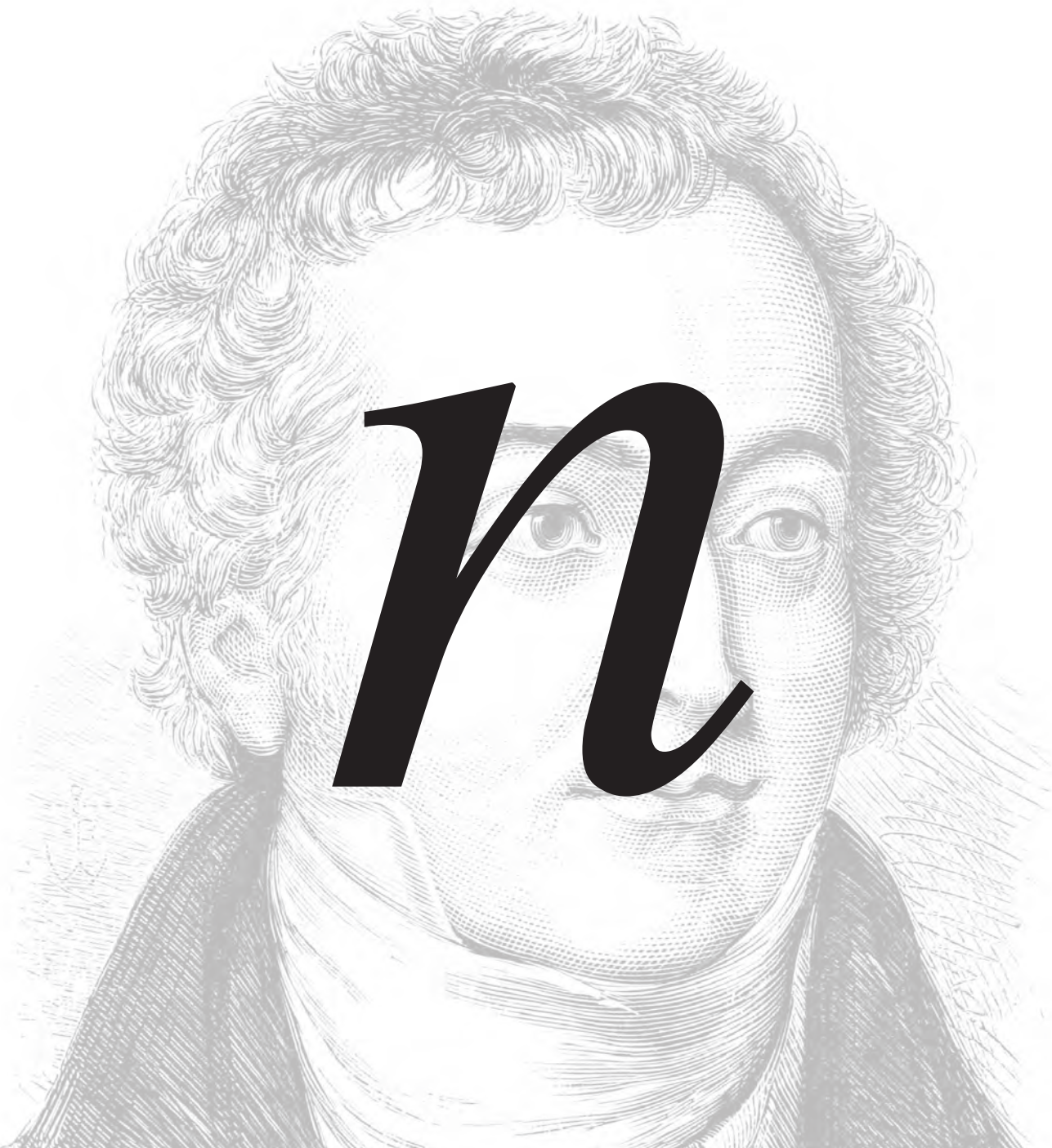








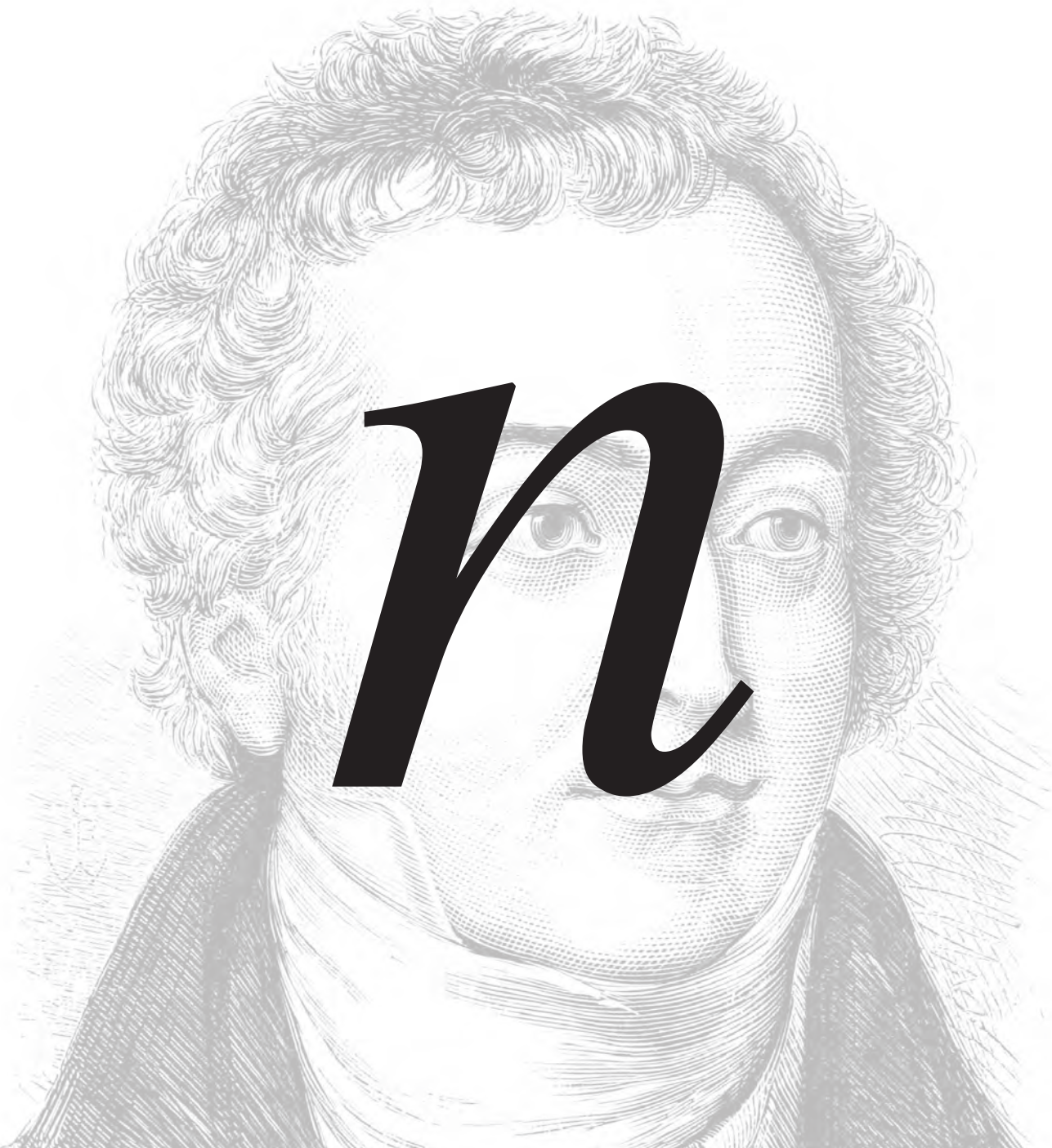




1 index

2 zero index





**1** index

**2** zero index

**3** experiments



# Propagation of EM wave



# Propagation of EM wave

governed by wave equation

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



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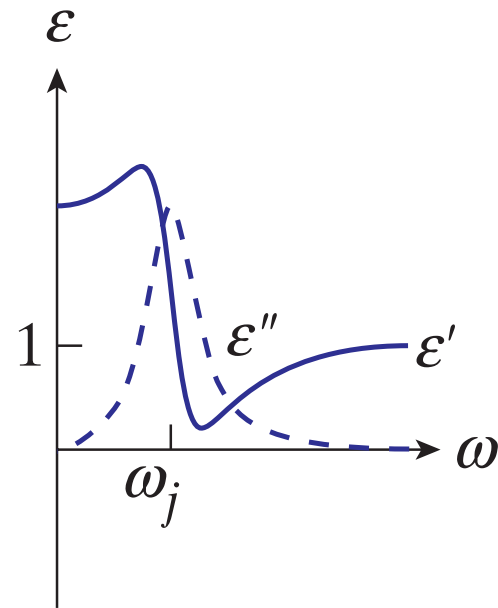
and

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

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

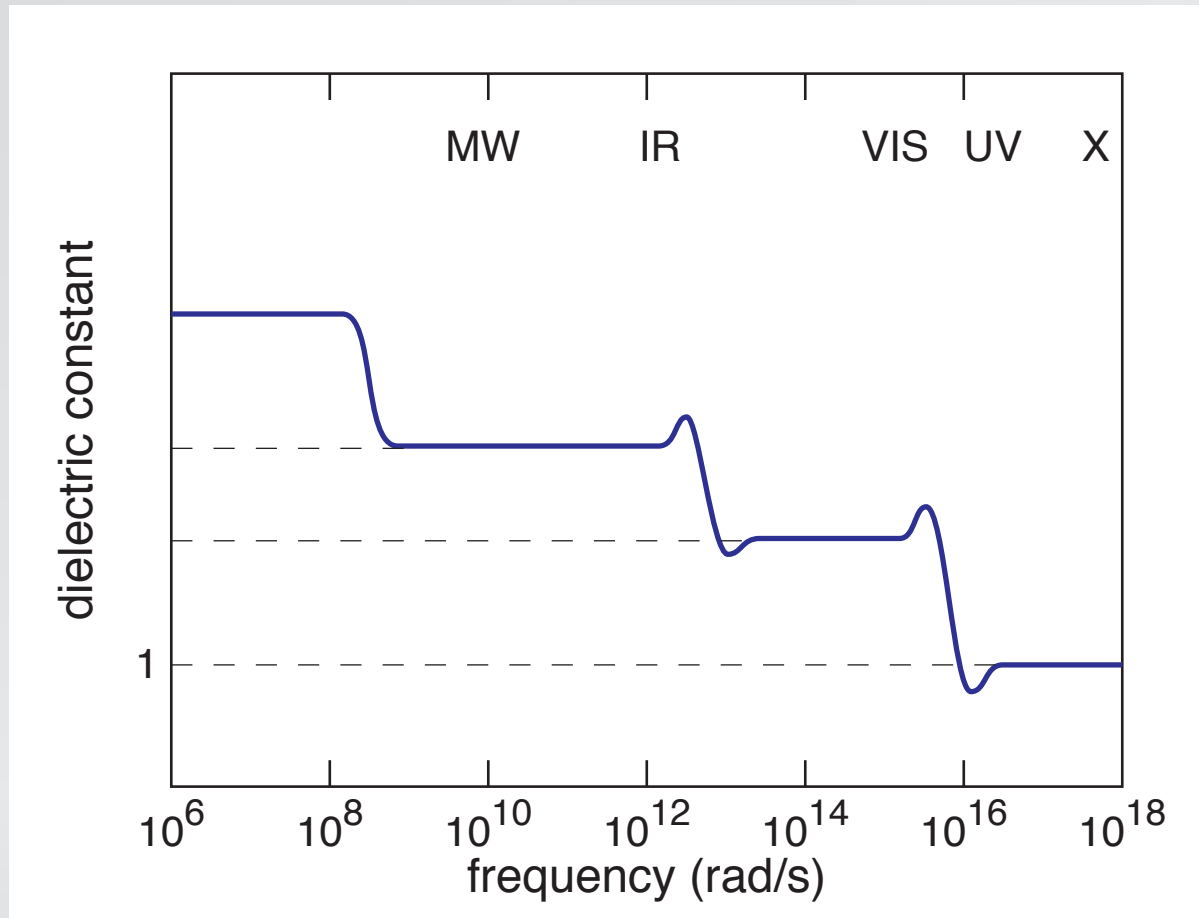
# Dielectric constant

## Lorentz oscillator

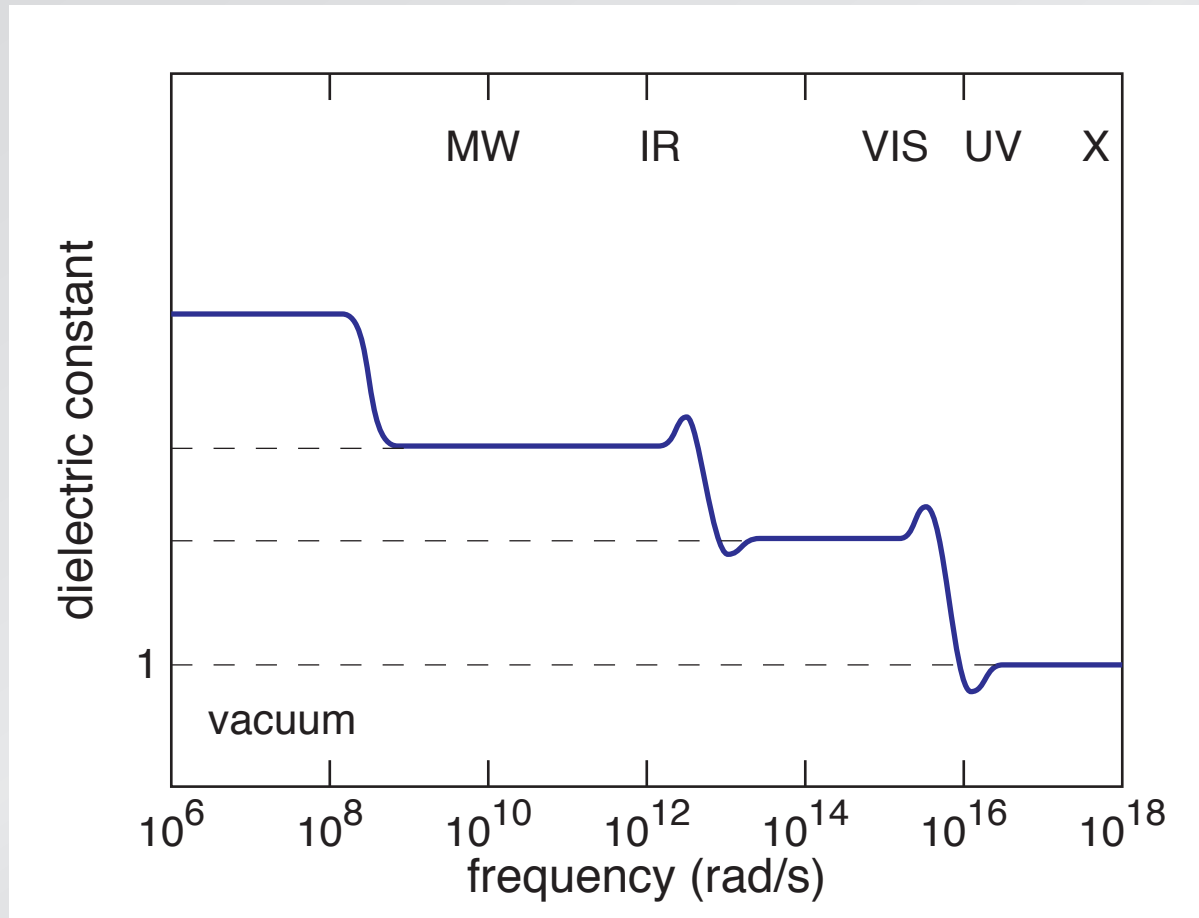




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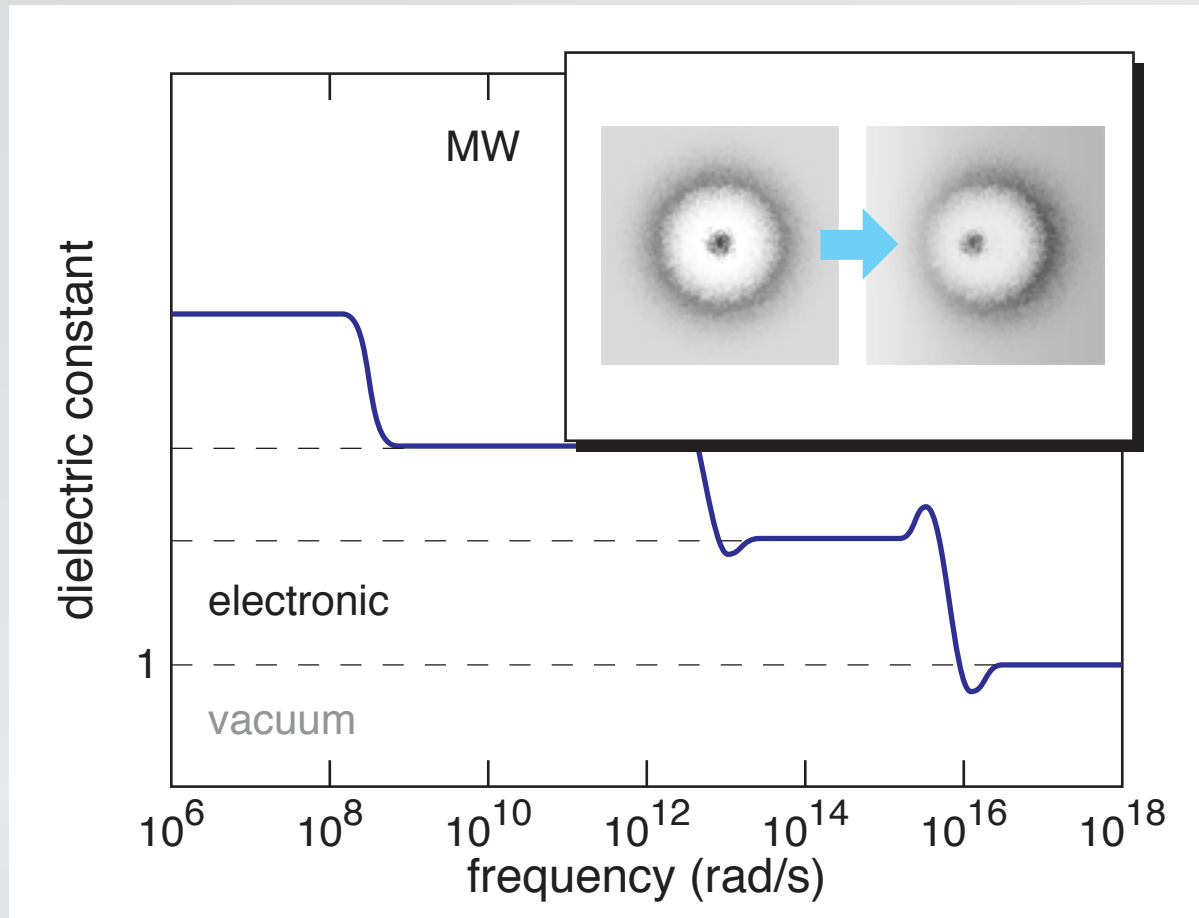


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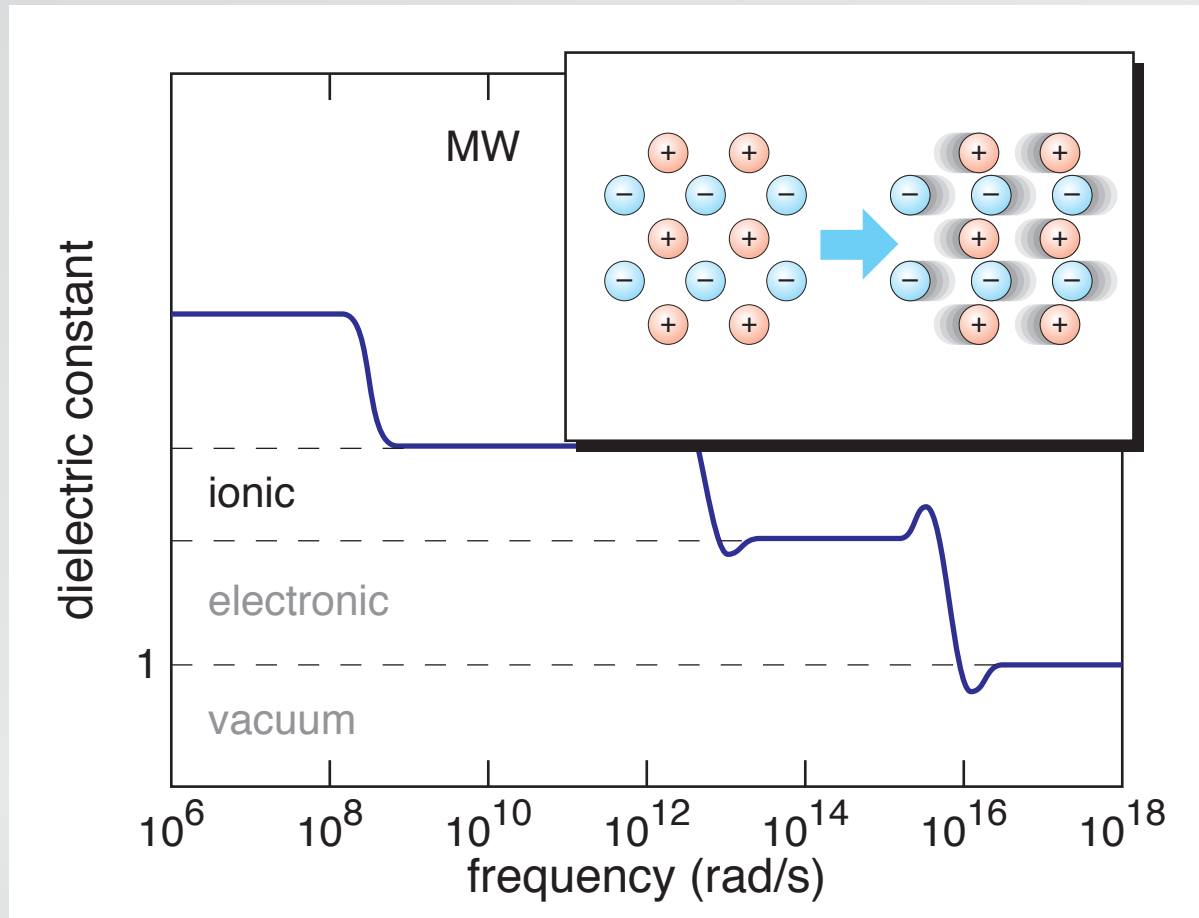




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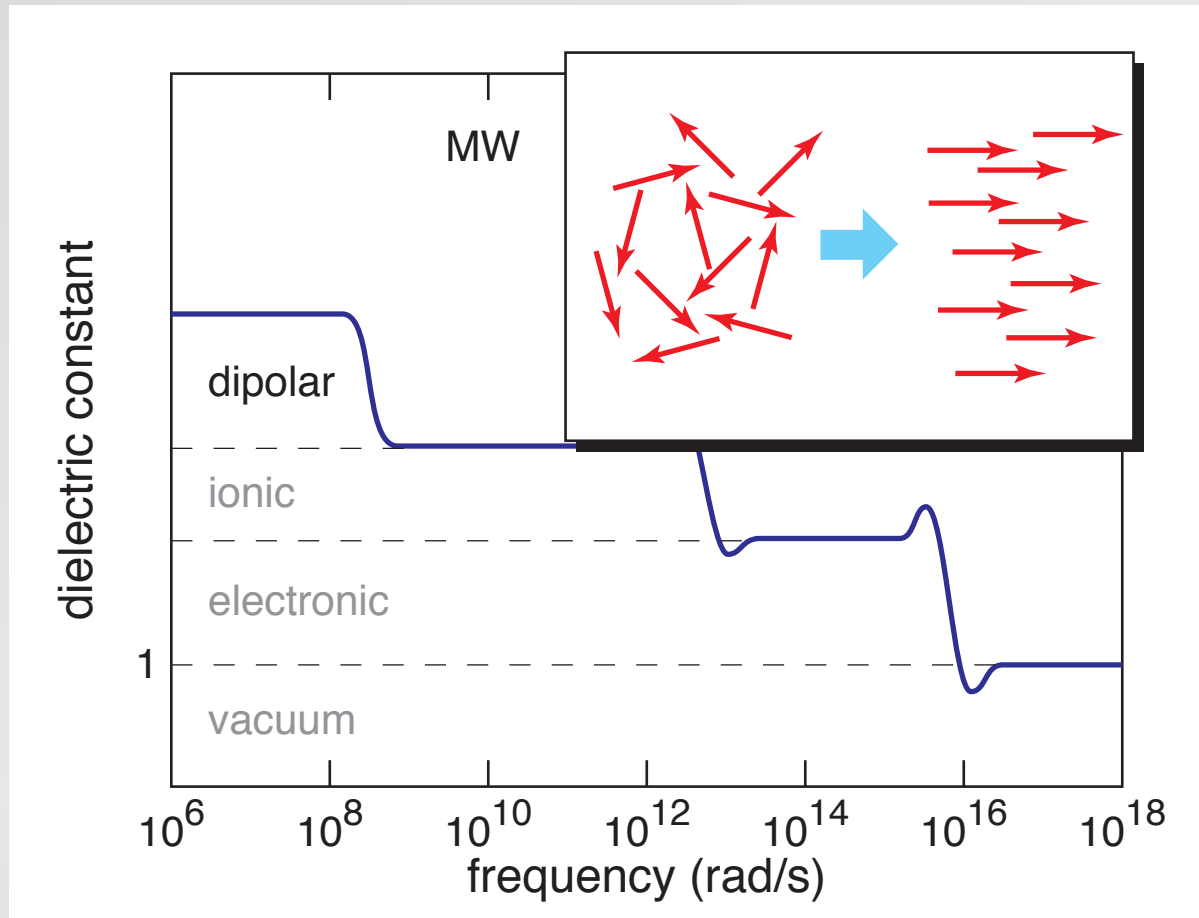


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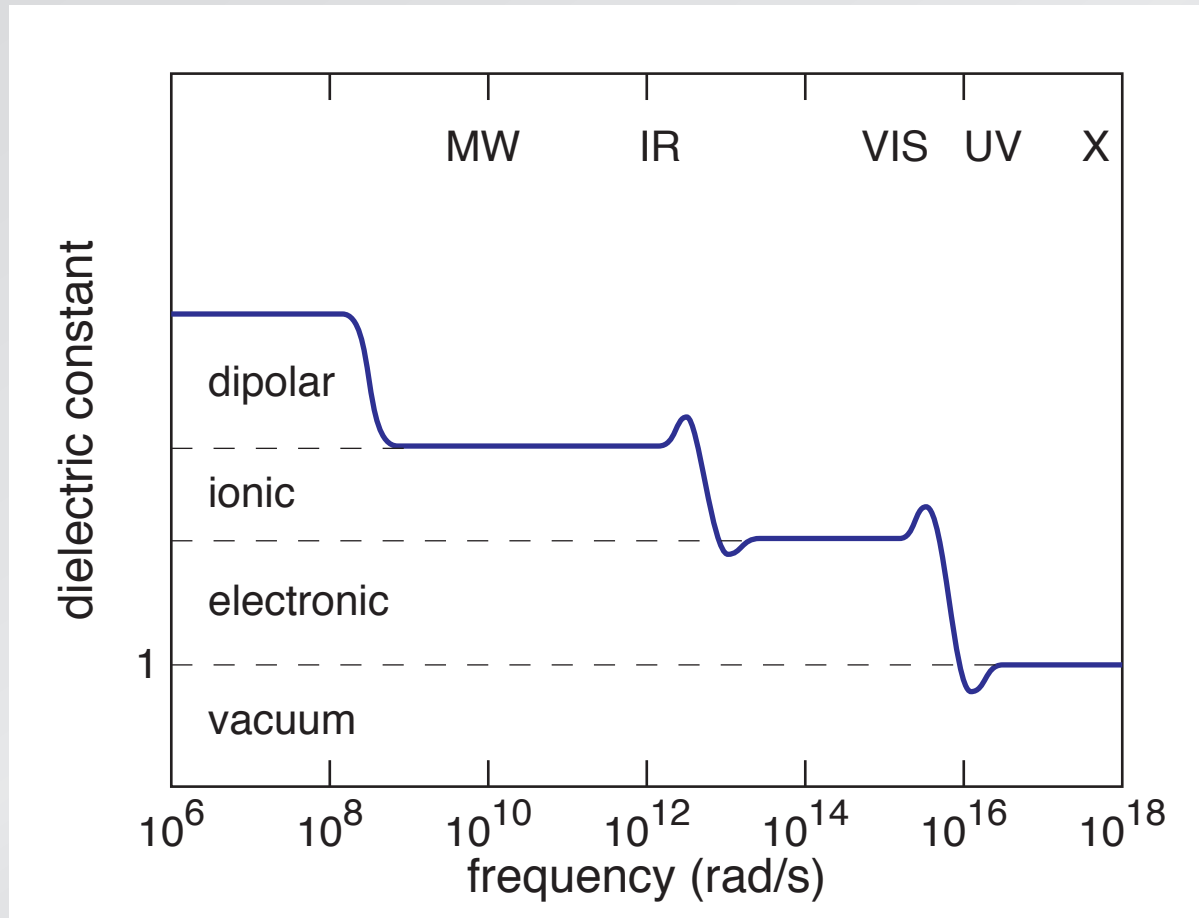




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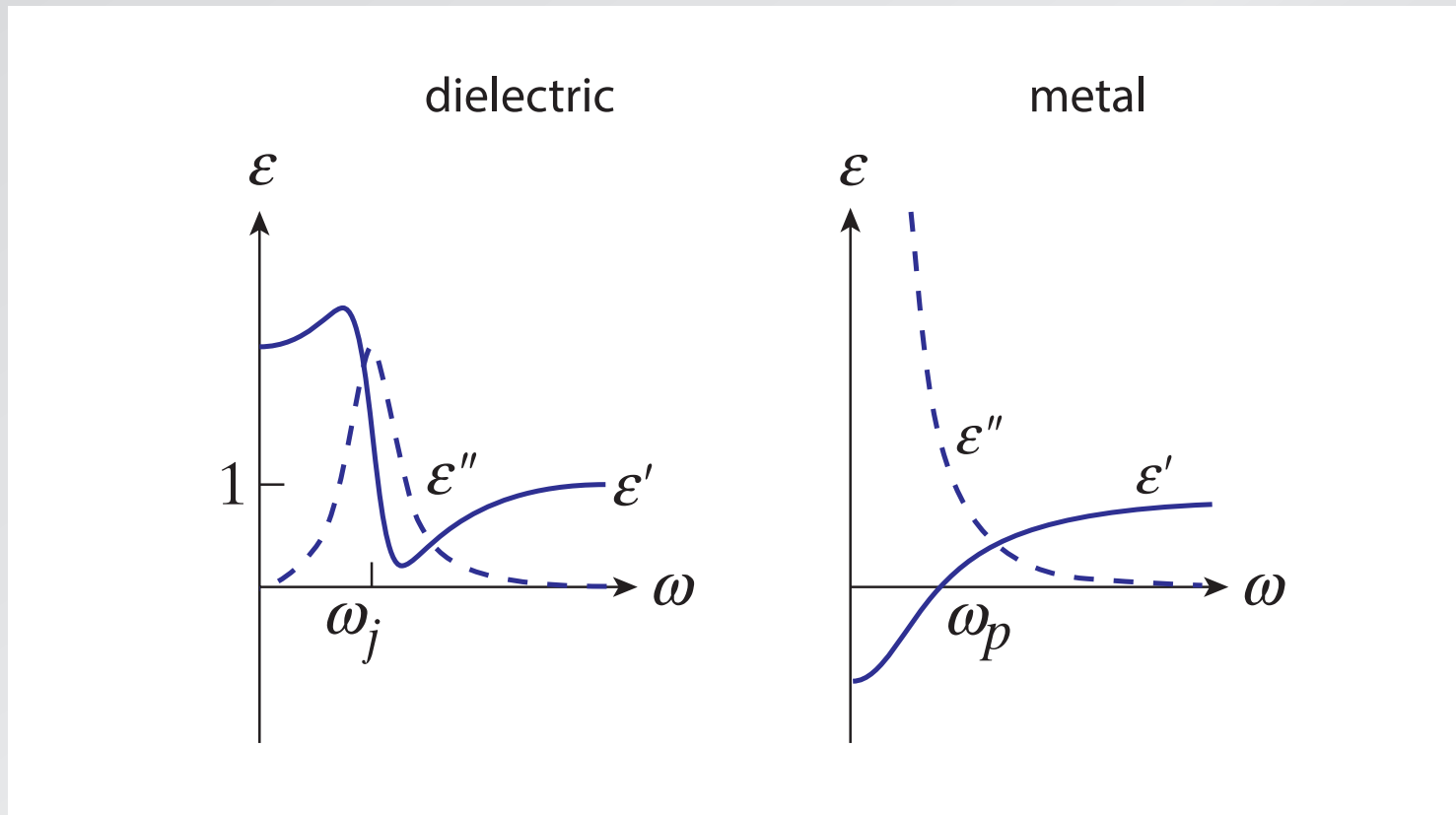


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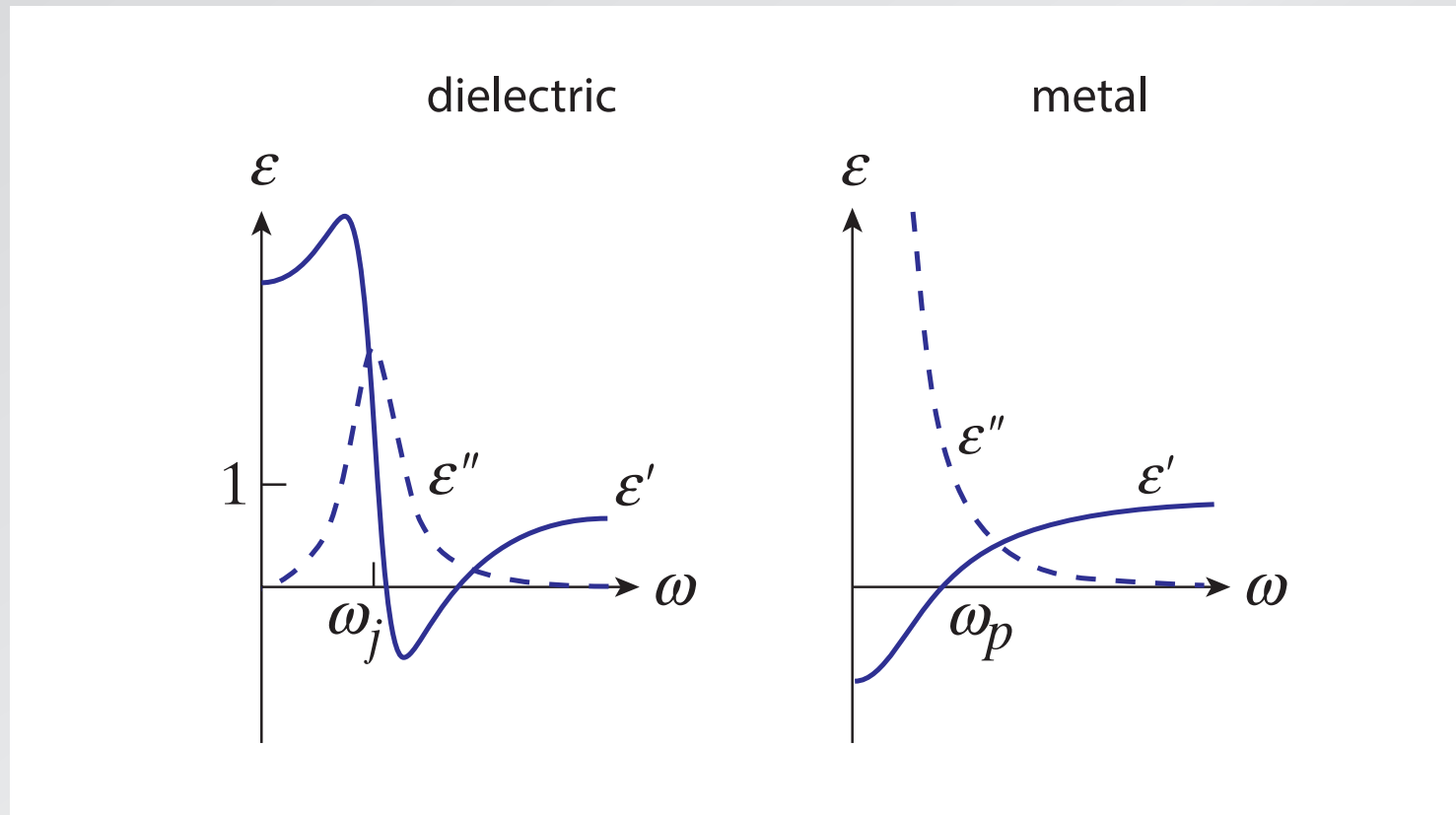


# Lorentz and Drude models



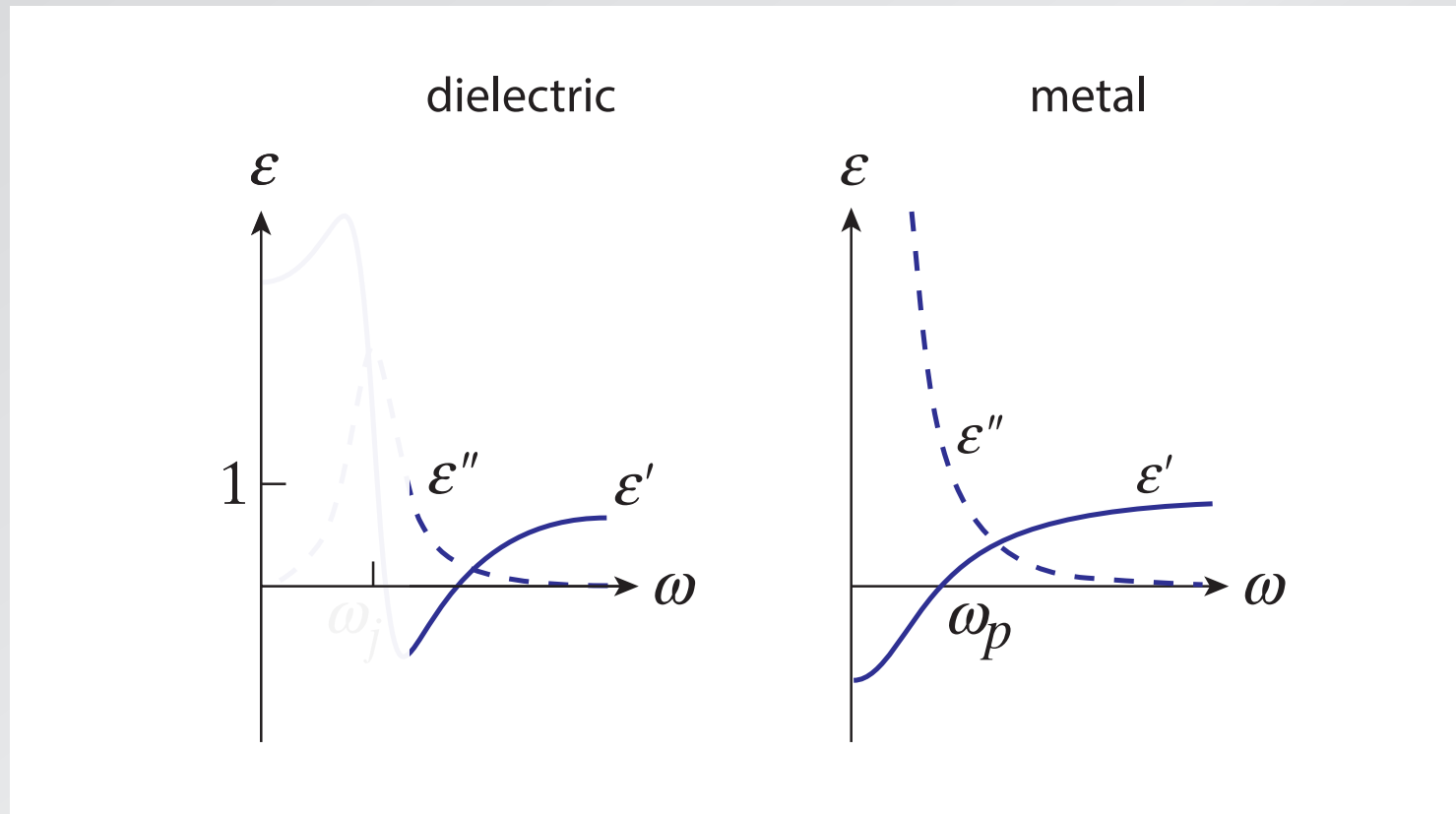
# Lorentz and Drude models

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



# Lorentz and Drude models

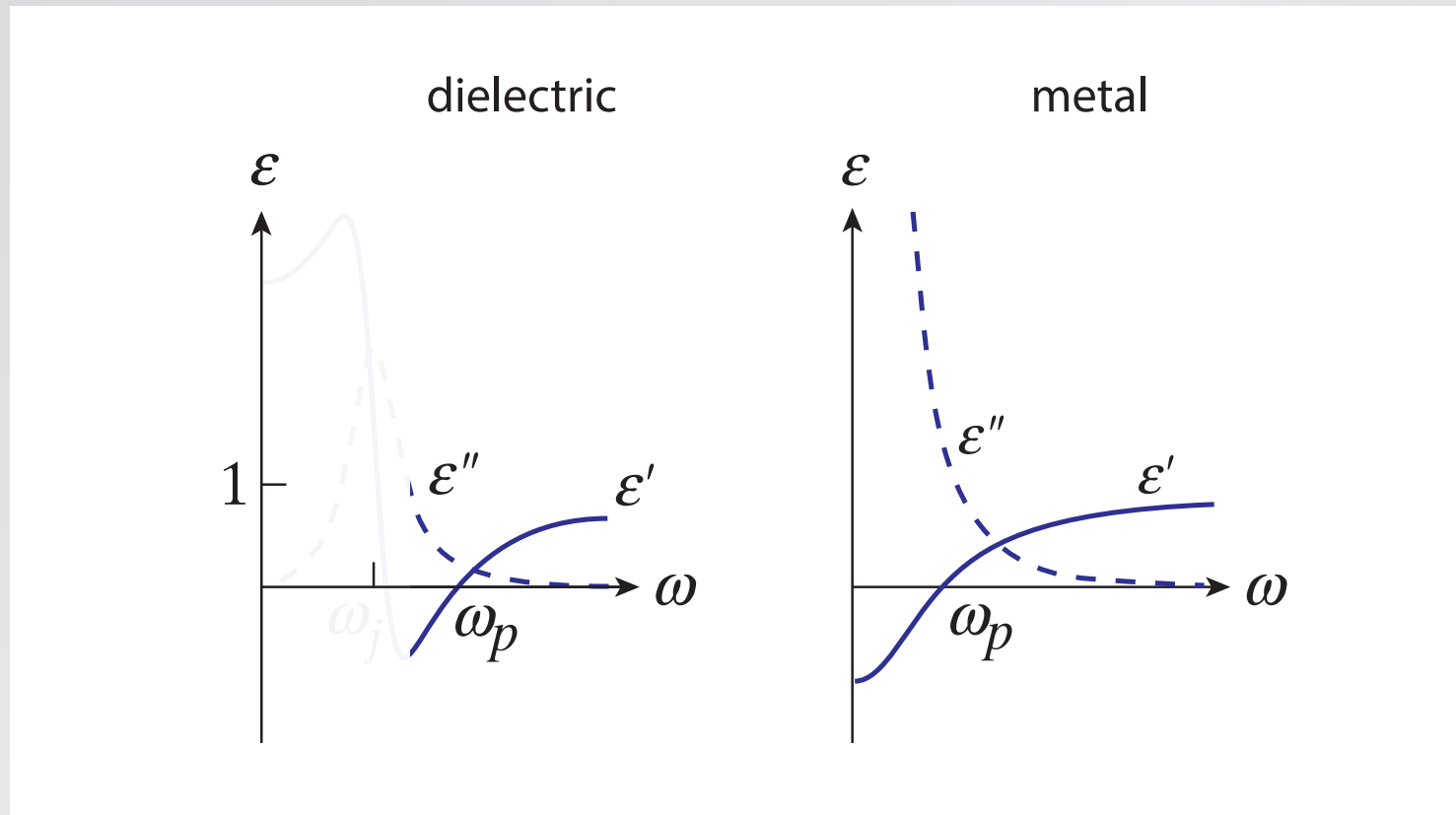
valence electrons in dielectric then behave like a plasma





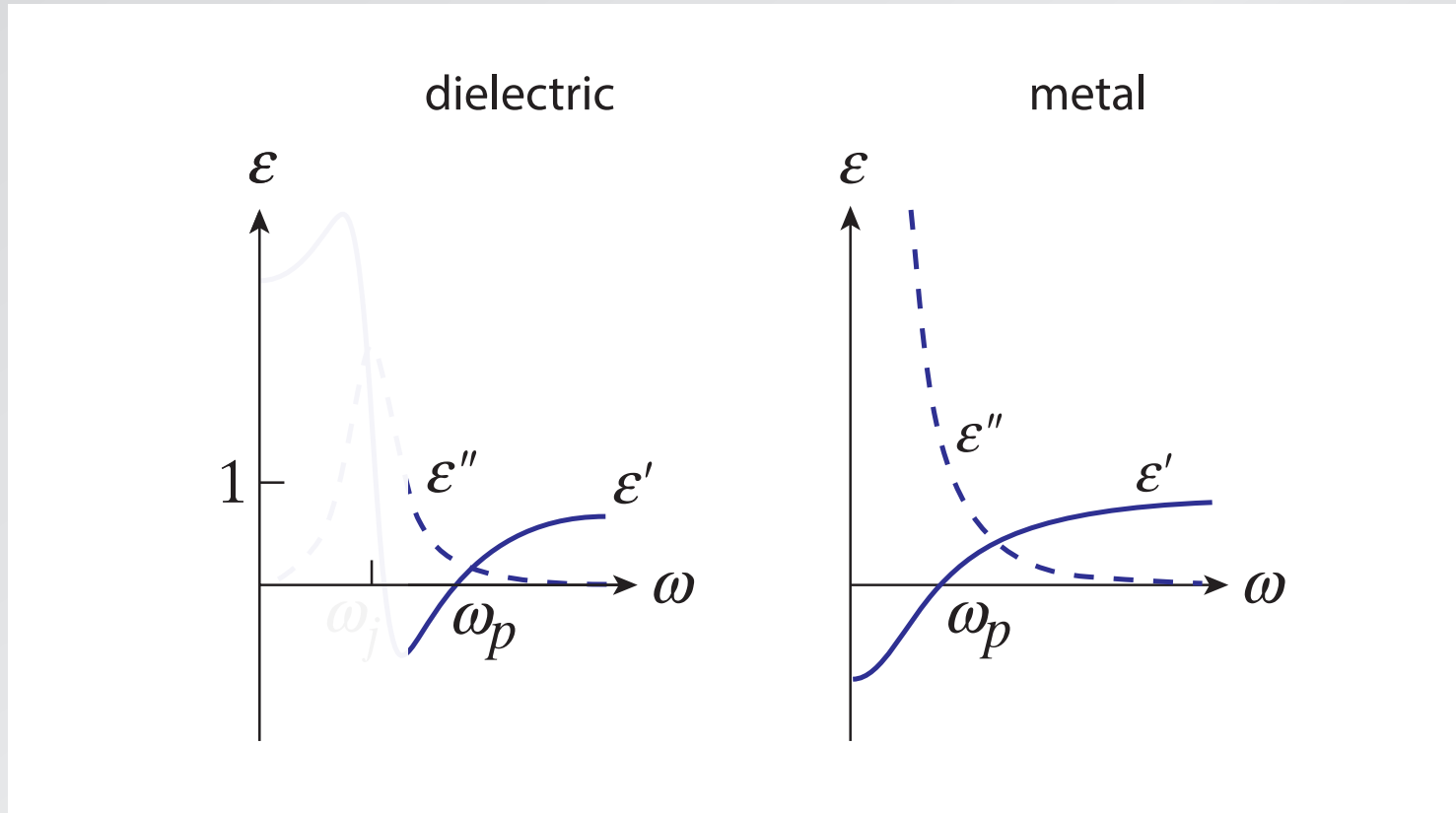
# Lorentz and Drude models

with plasma frequency above the resonance



# Lorentz and Drude models

(and far below the UV region)



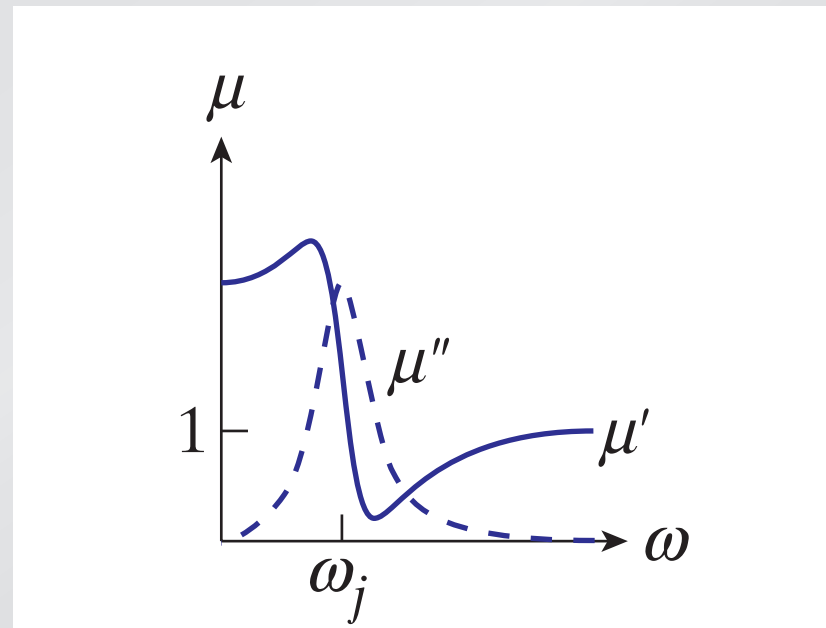
Index also determined by magnetic response

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

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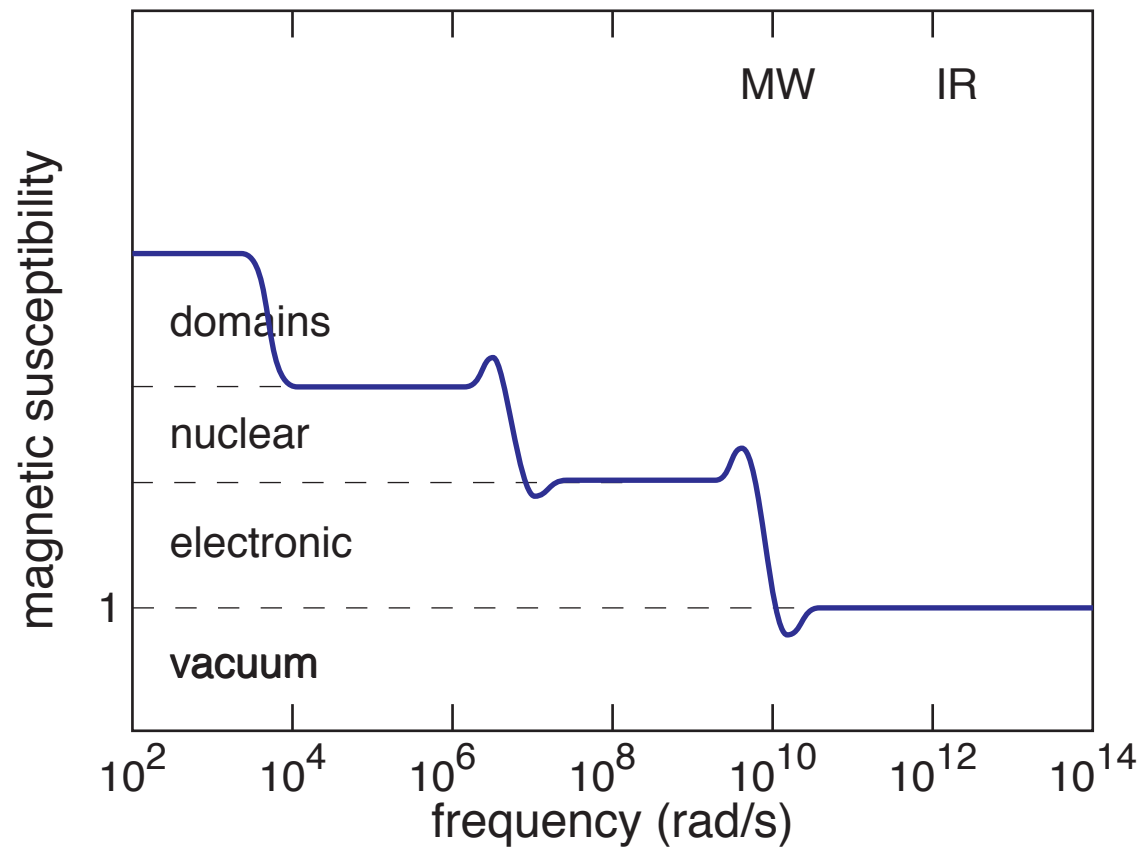
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and magnetic response shows similar resonances



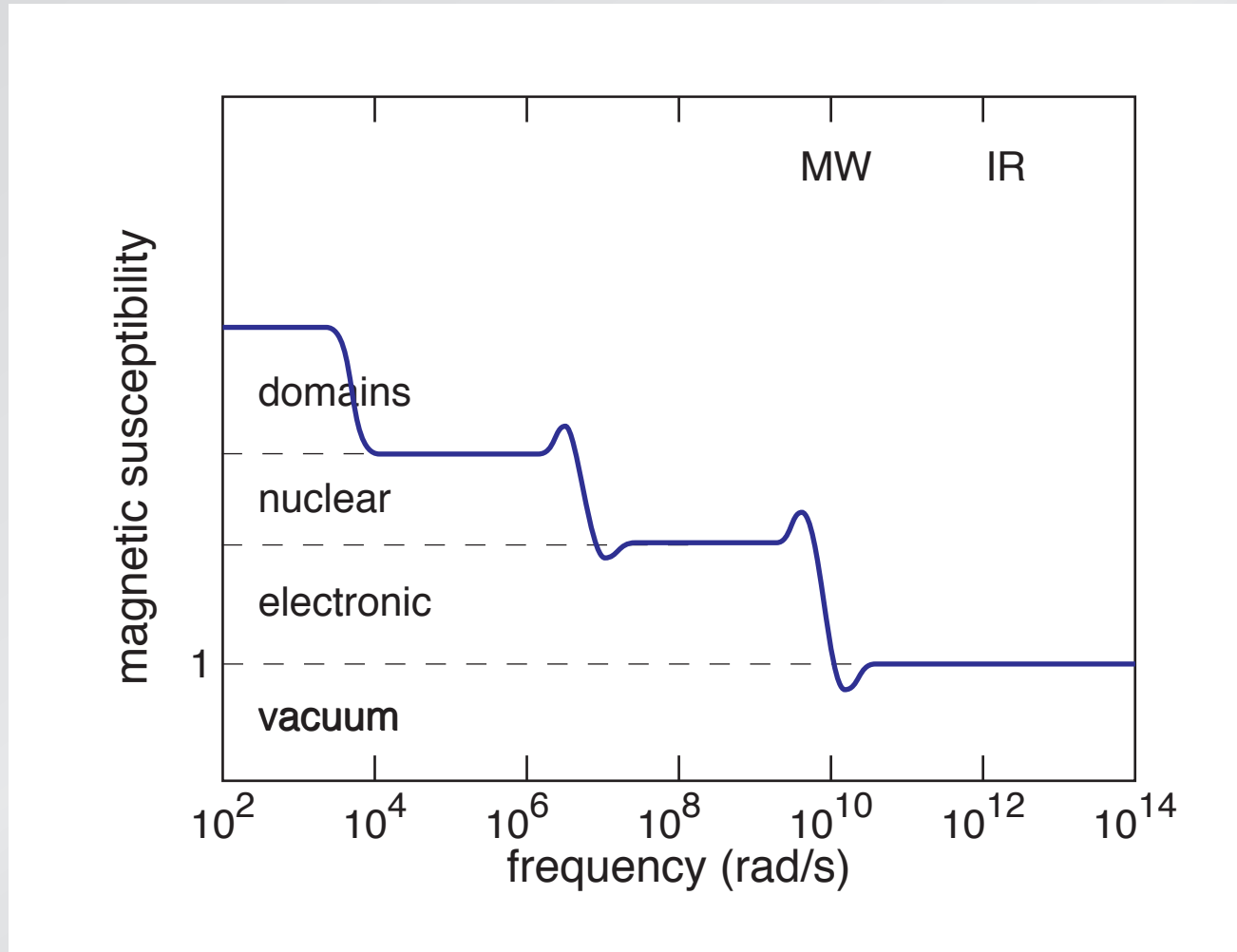


# Magnetic response



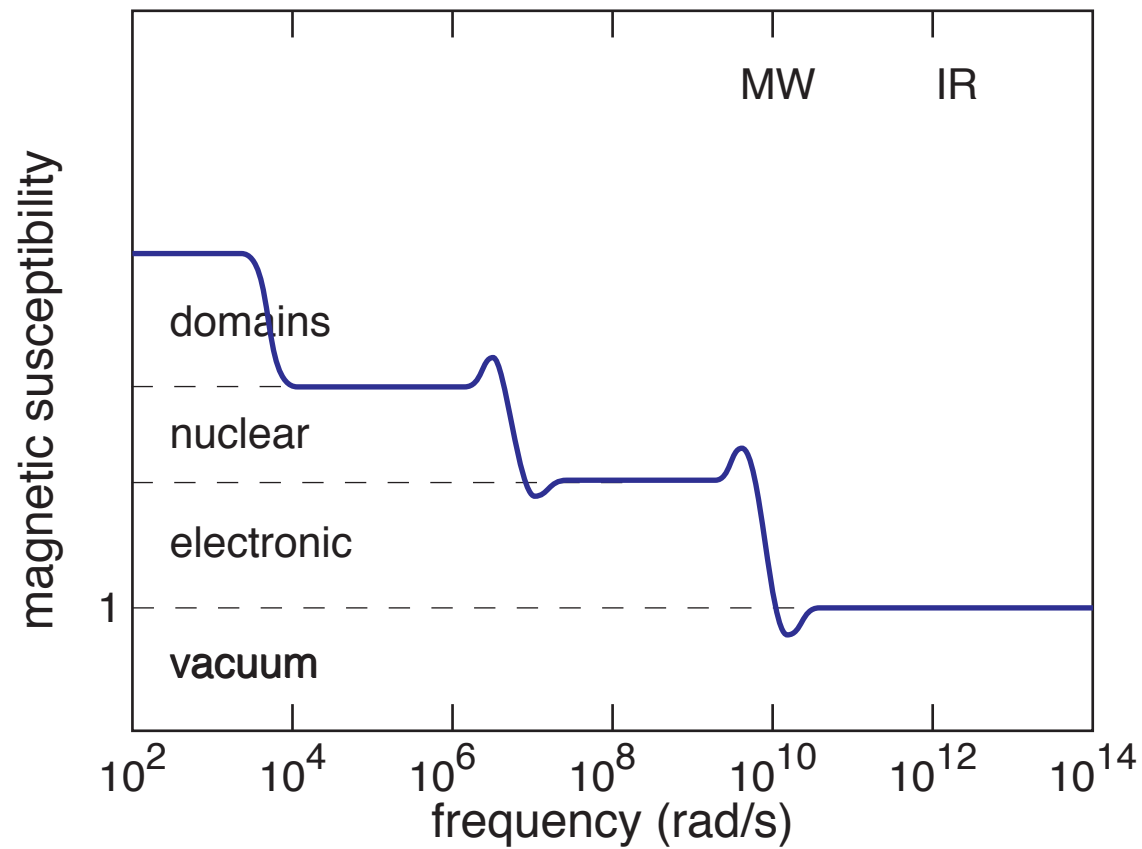
# Magnetic response

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

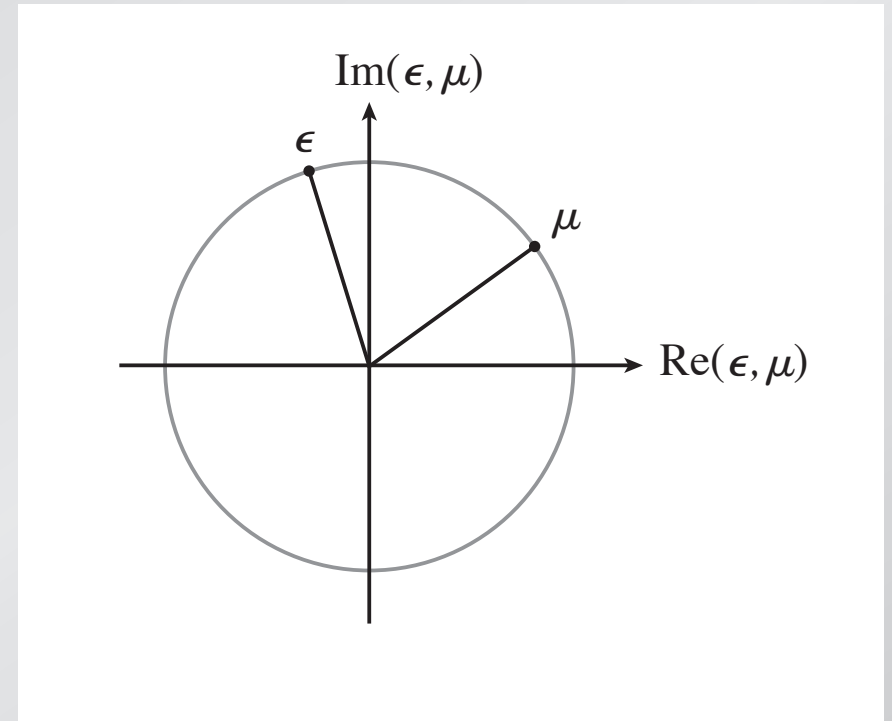
What happens when  $\text{Re}\epsilon$  and/or  $\text{Re}\mu$  is negative?

Write complex quantities as

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

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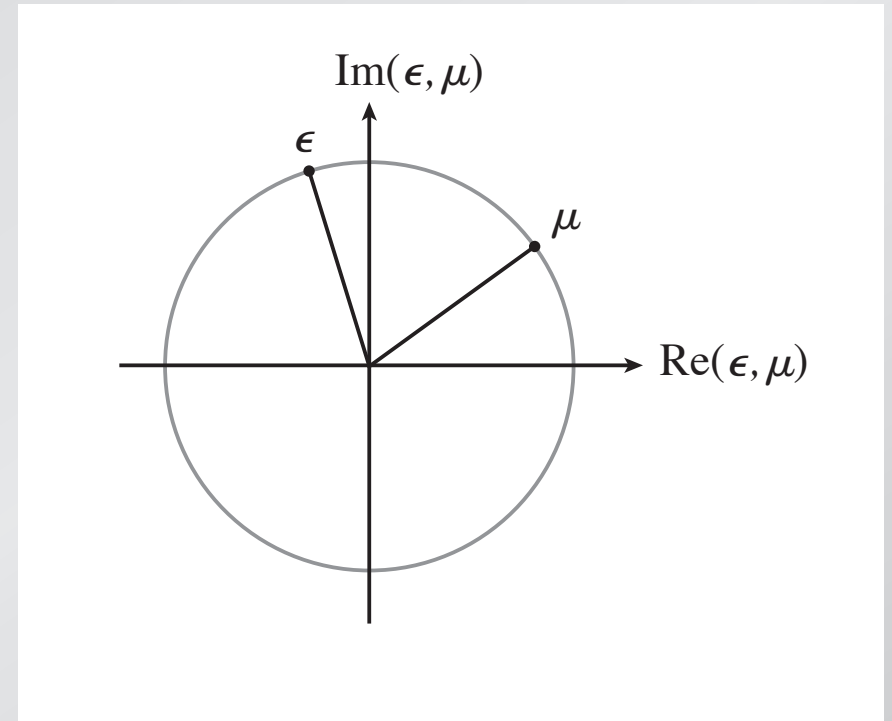


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Index

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



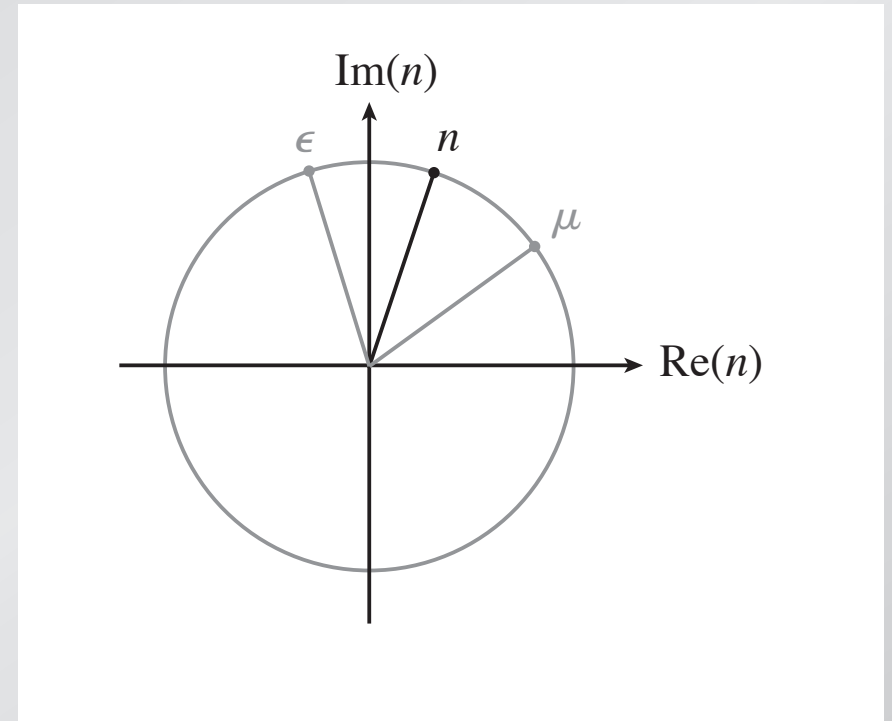


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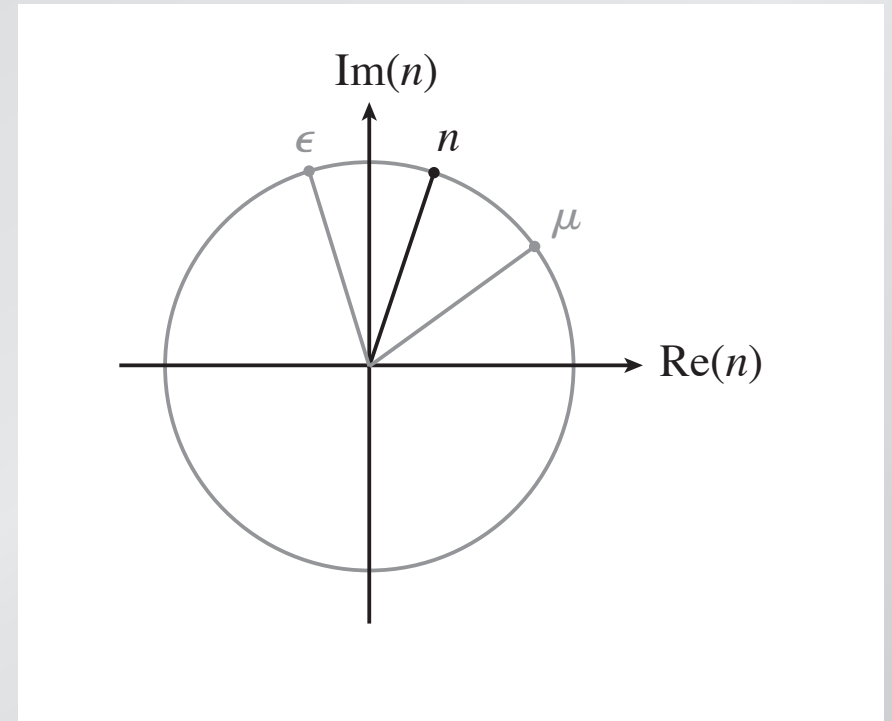
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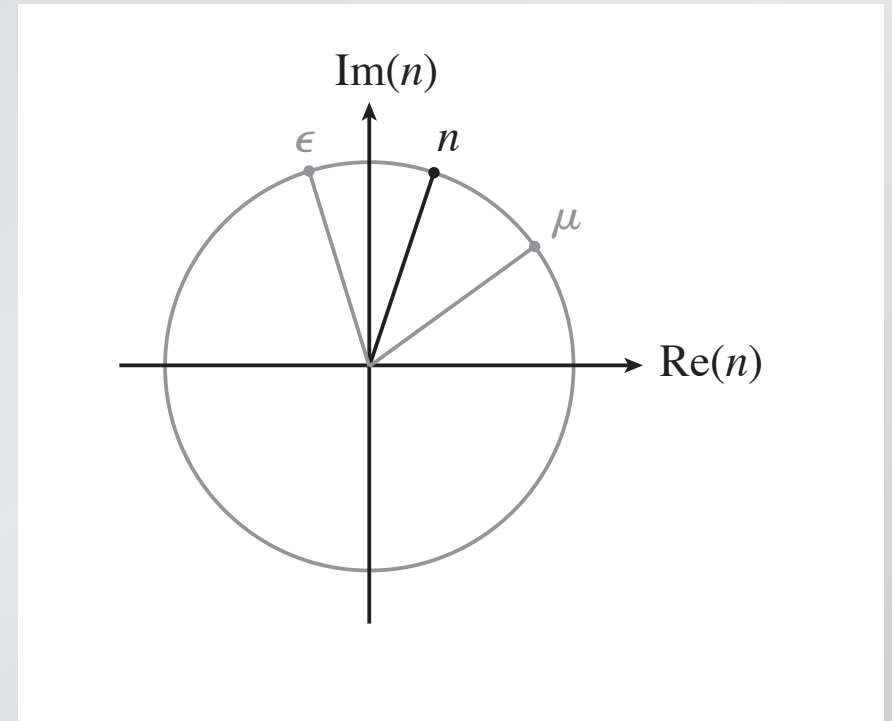


**Q: Is this the only possible solution?**

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



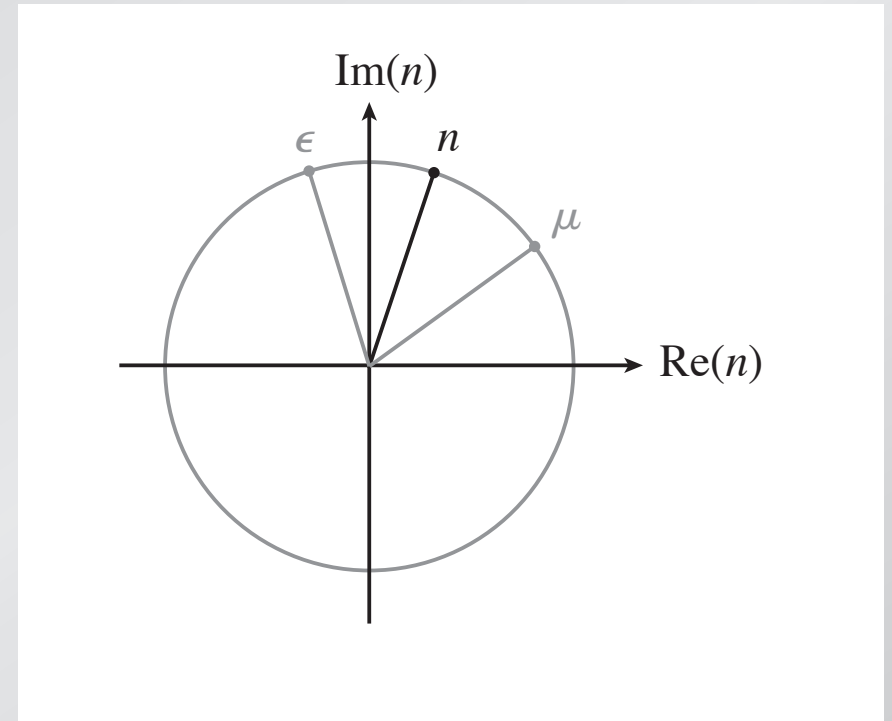
There *is* another root...



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Can add  $2\pi$  to exponent

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





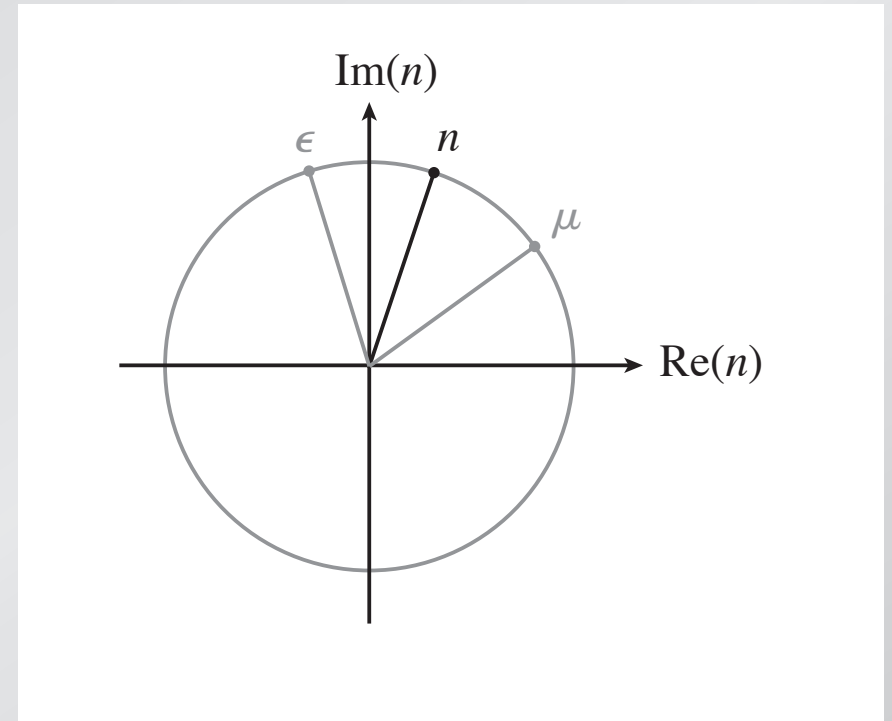
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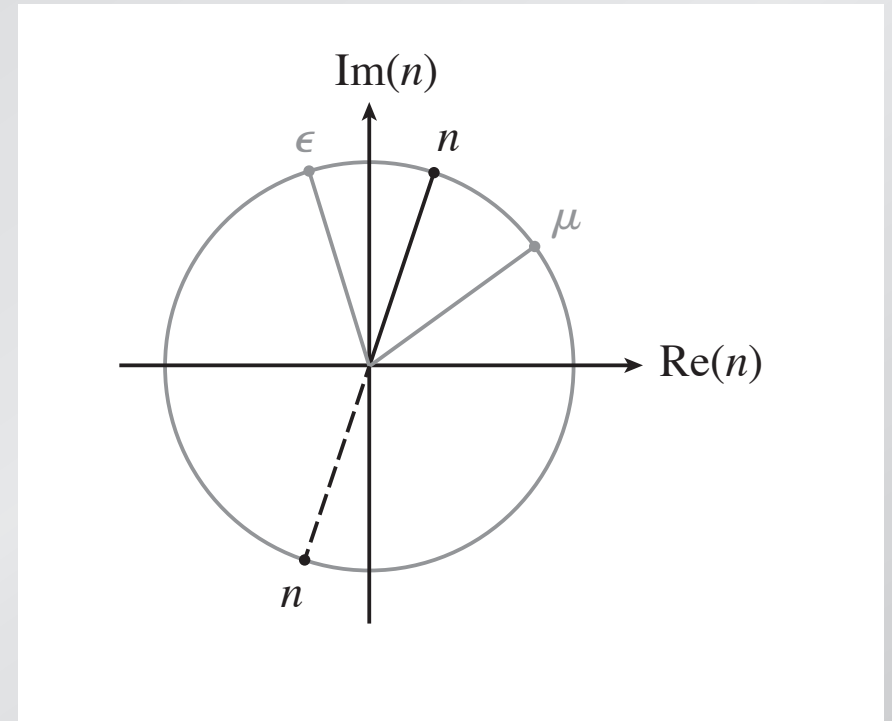
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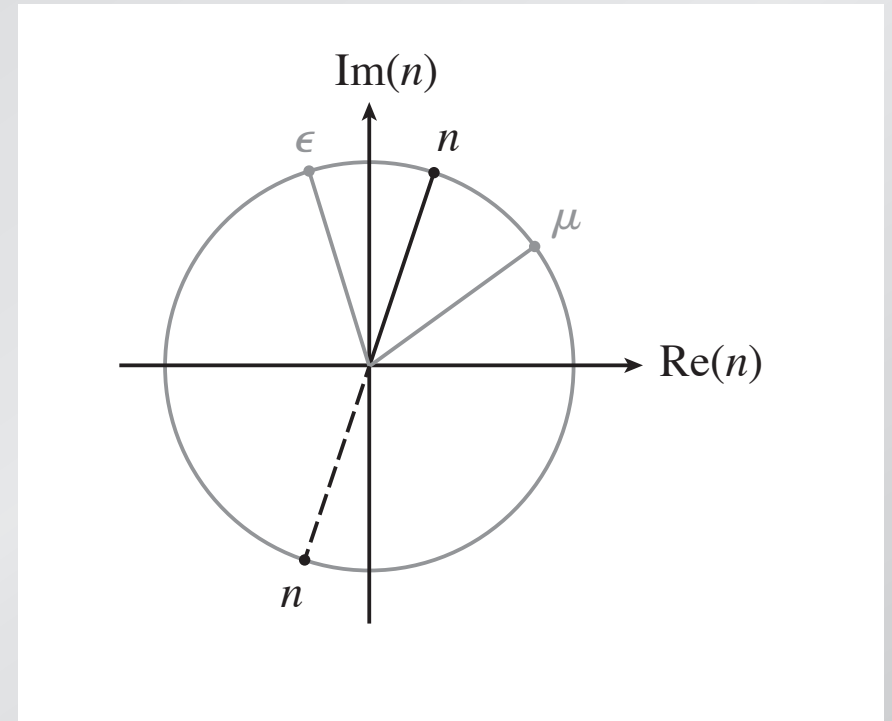
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$$k = \frac{2\pi n}{\lambda_o} = \frac{2\pi(n' + in'')}{\lambda_o} = k' + ik''$$



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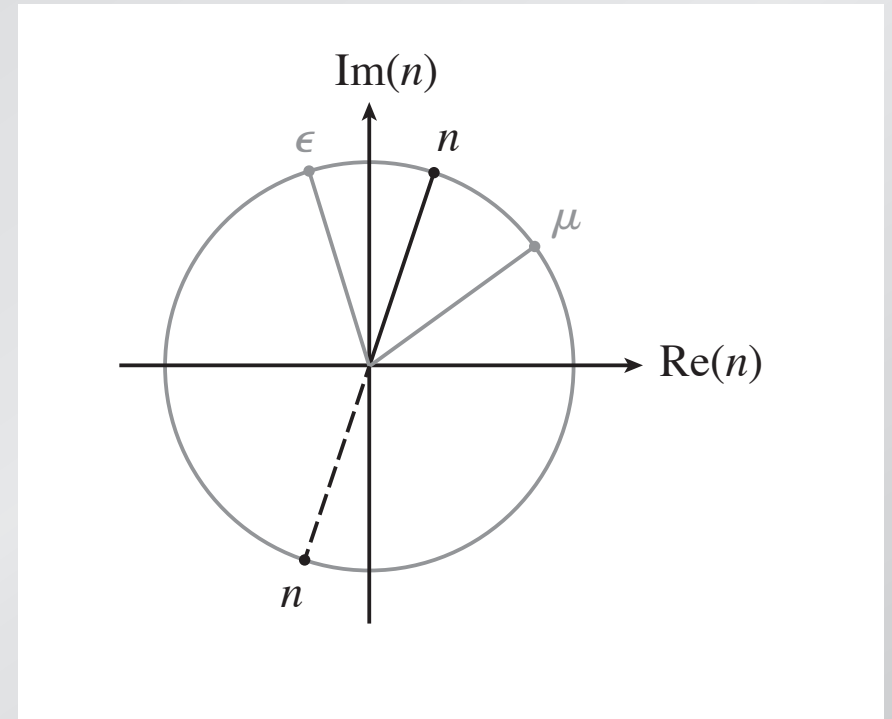
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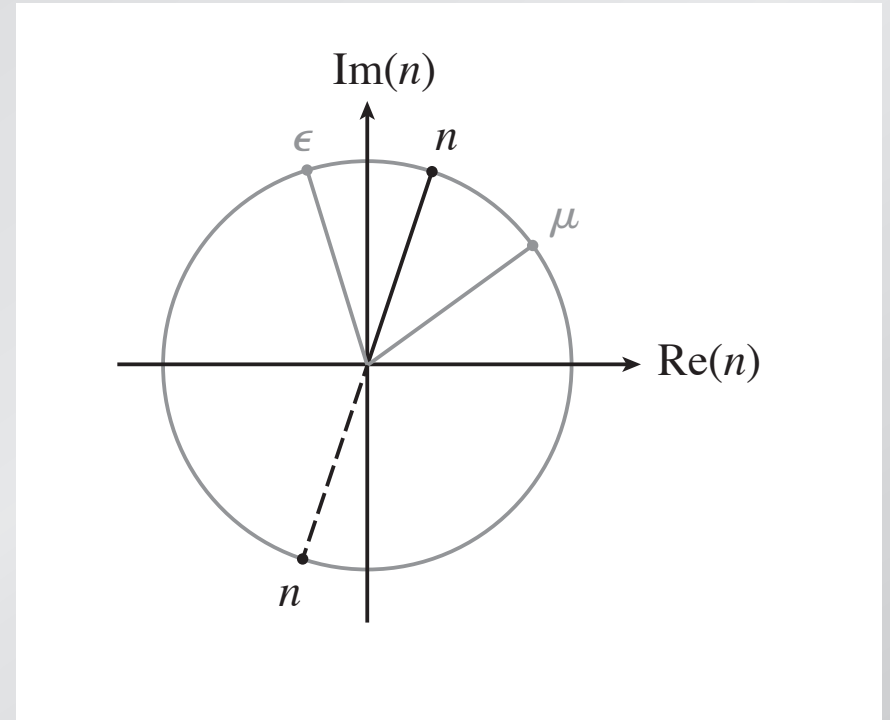
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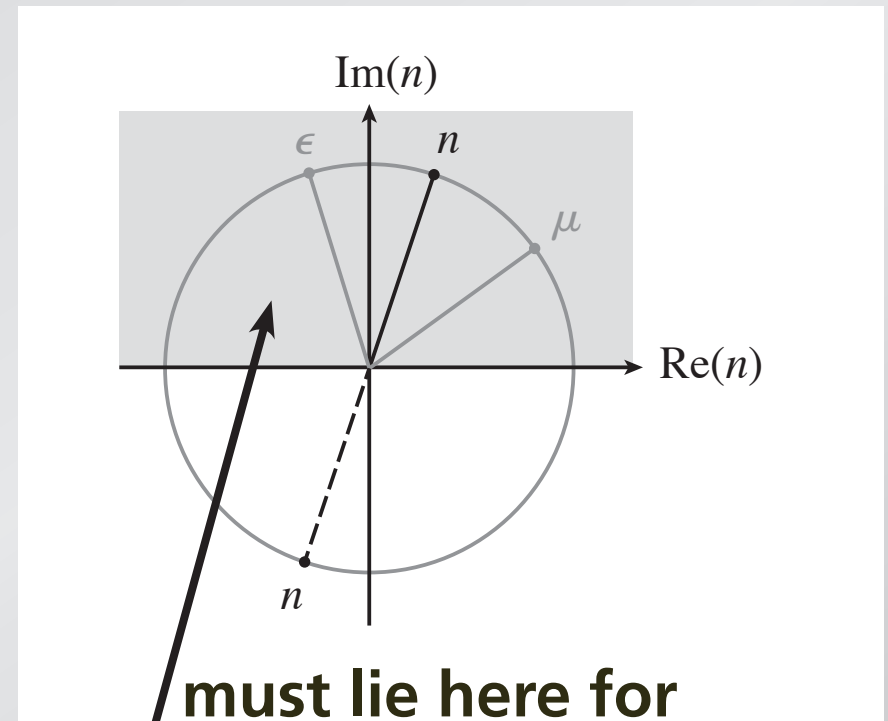
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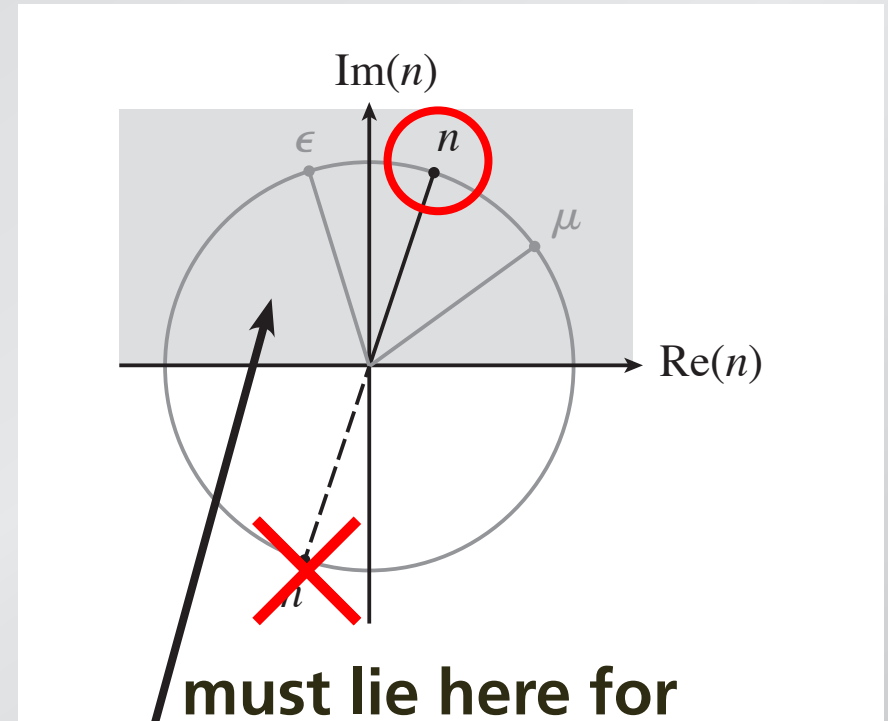
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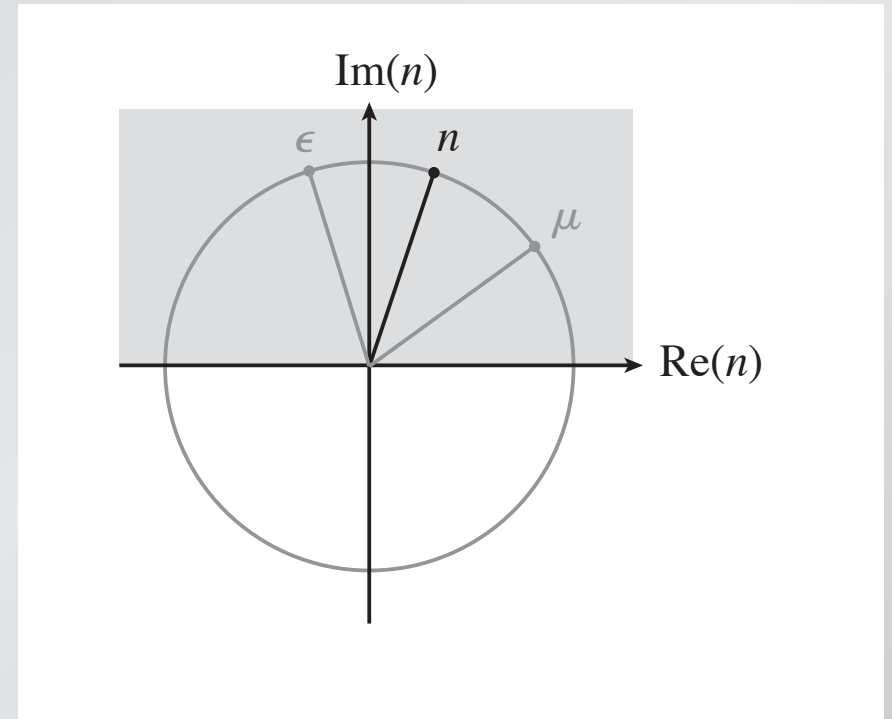
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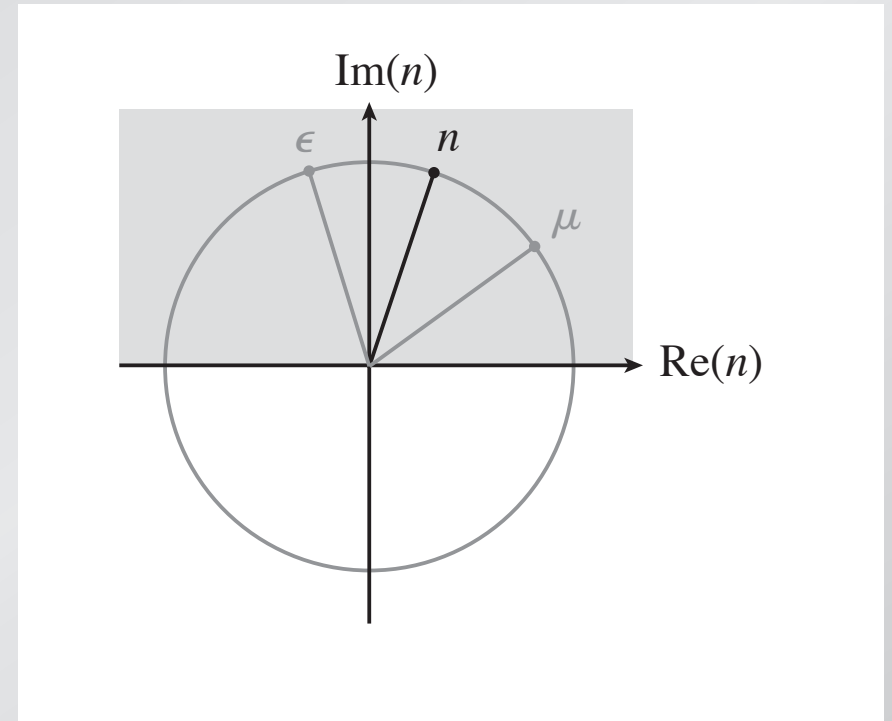
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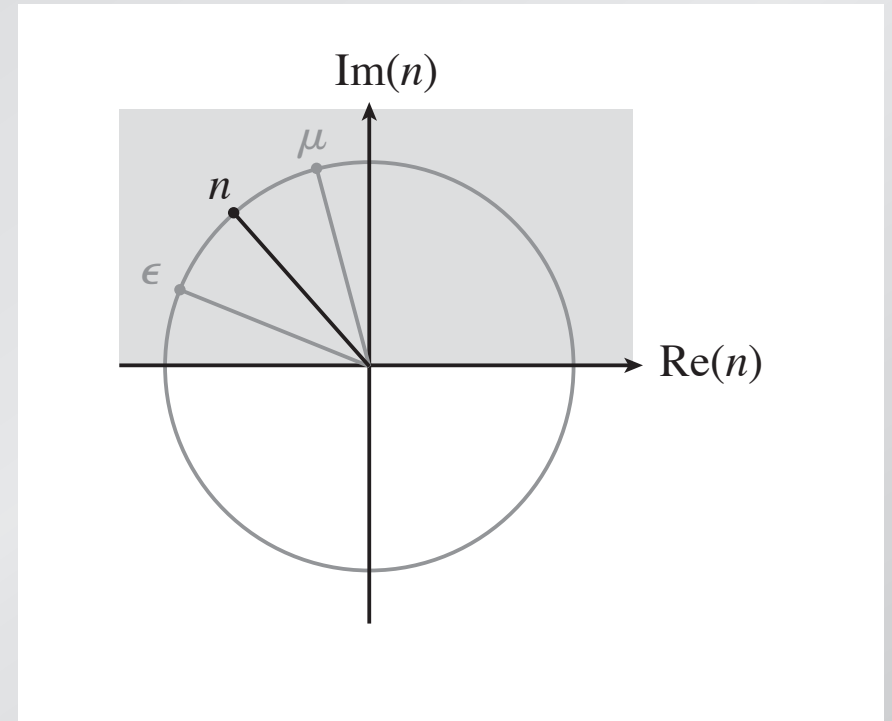


To find  $n$  (passive materials):

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



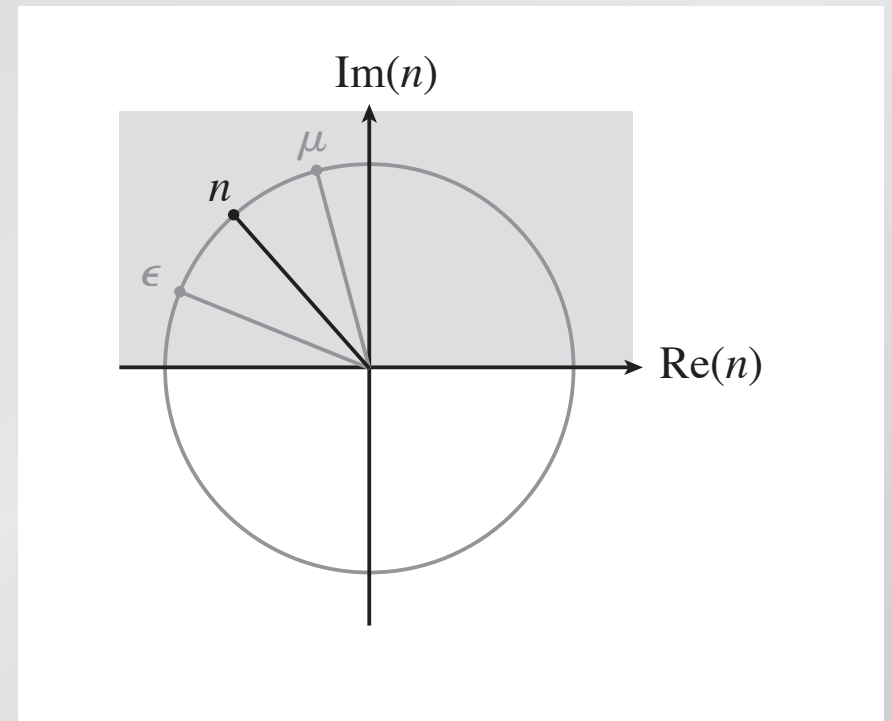
For certain values of  $\epsilon$  and  $\mu$   
we can get a *negative*  $\text{Re}(n)$ !



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

**1. yes**

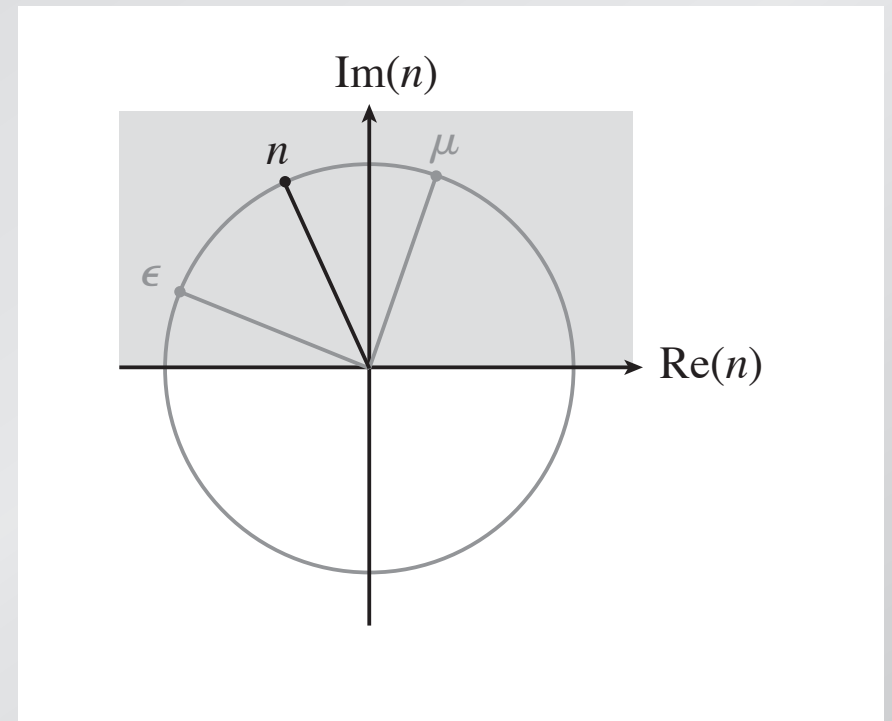
**2. no**



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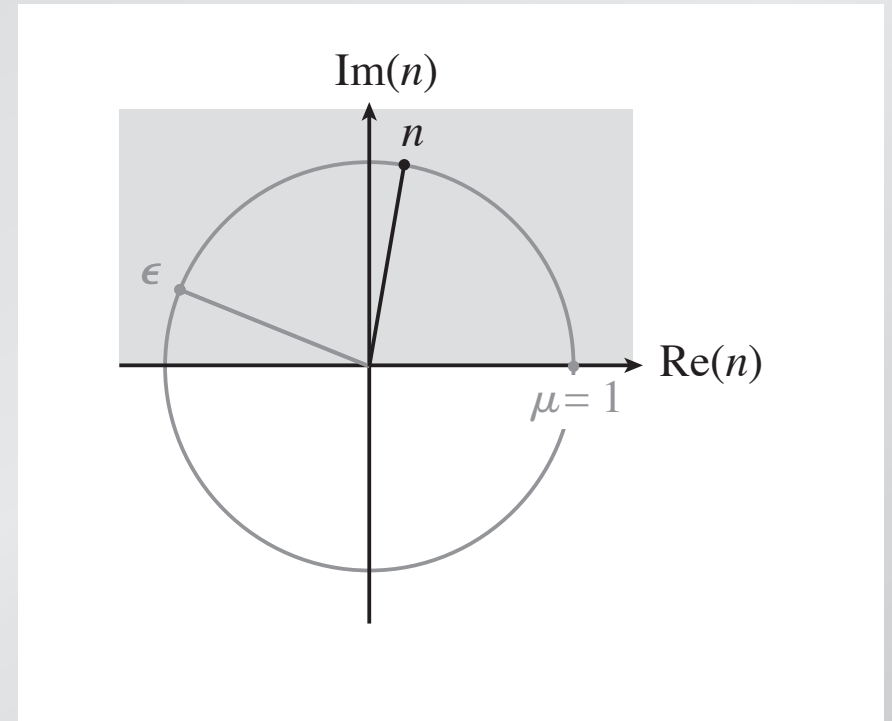
1. yes

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



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Spatial and temporal dependence of wave component

$$E = E_o e^{i(kx - \omega t)} = E_o e^{-k''x} e^{i(k'x - \omega t)}$$

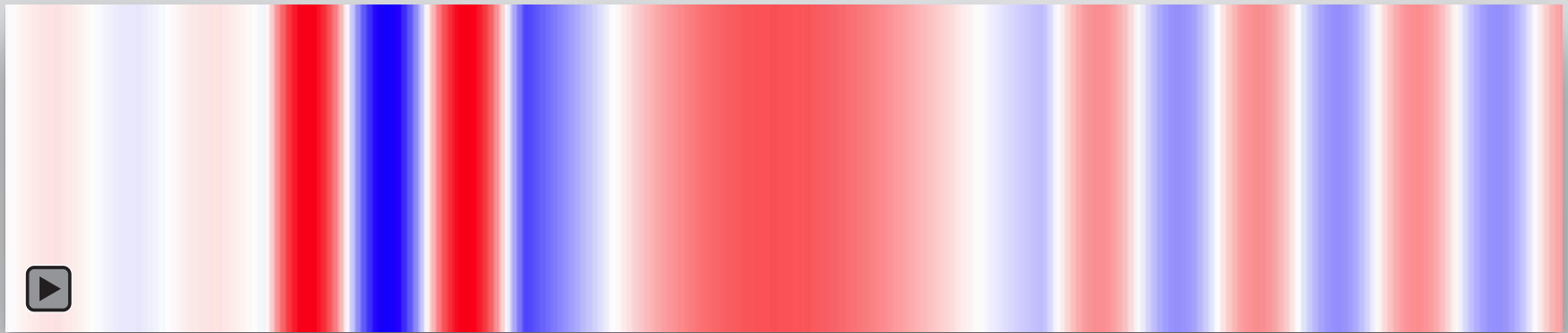
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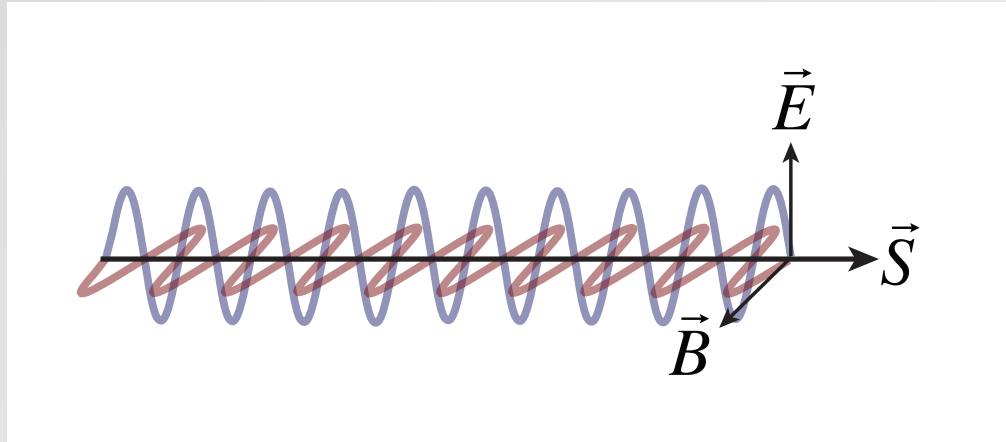
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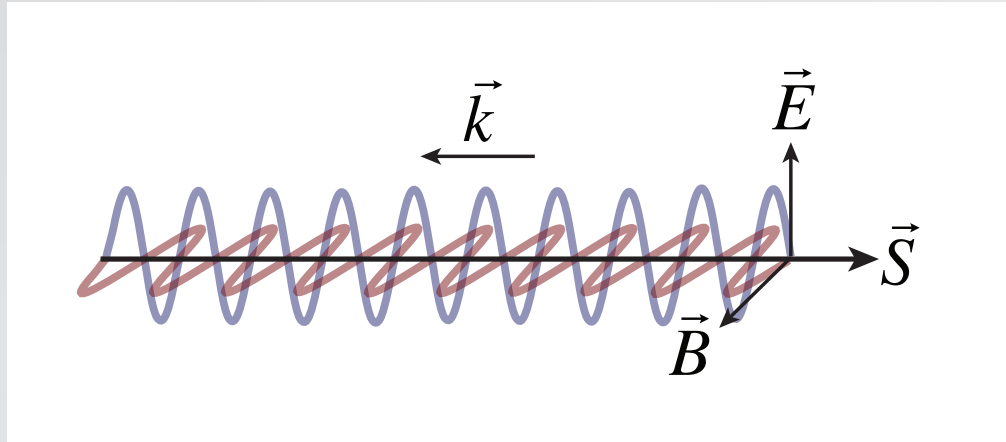


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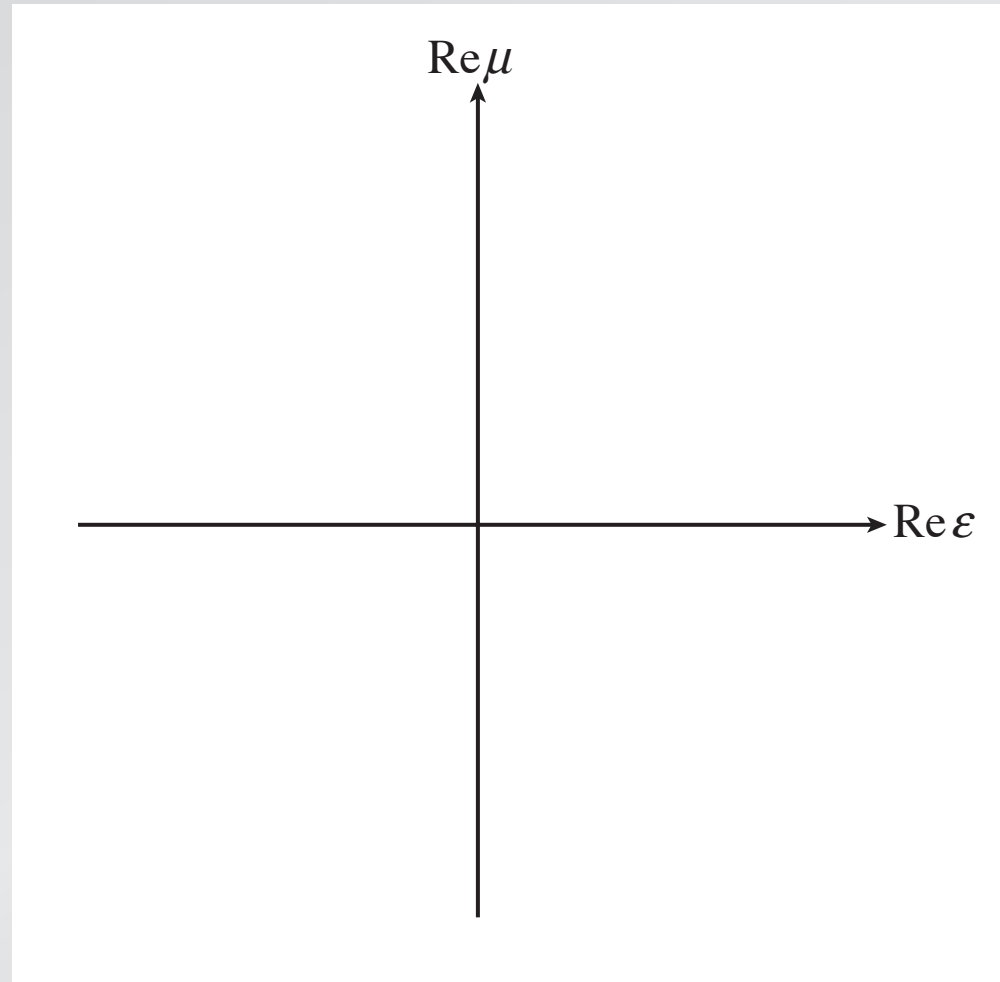
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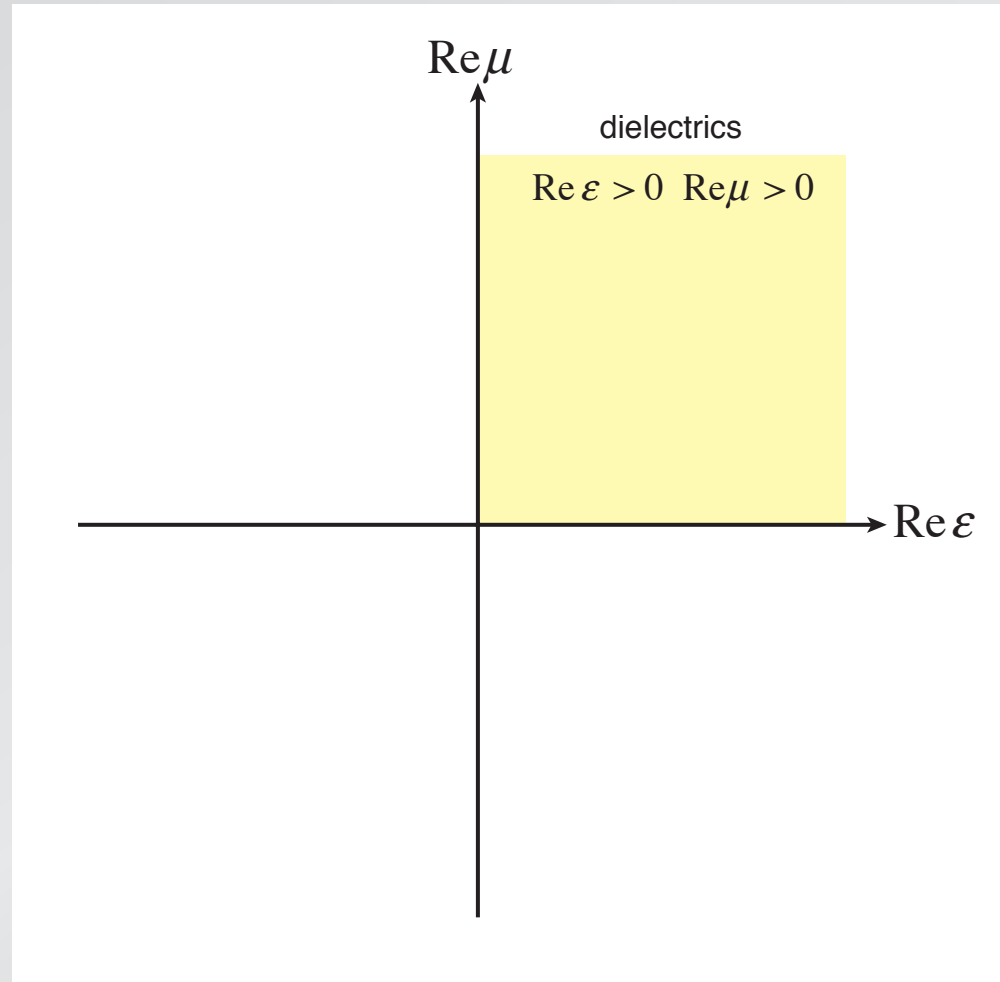


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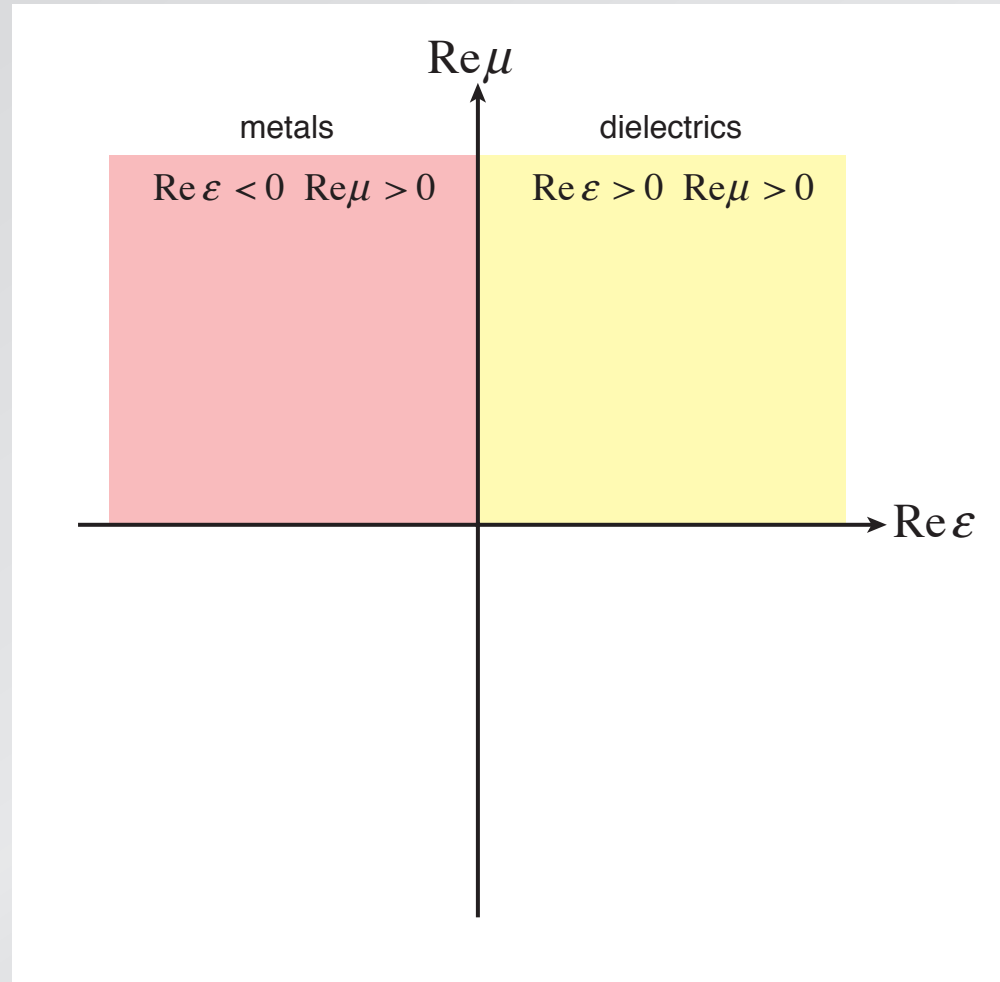
## classification of (non-lossy) materials



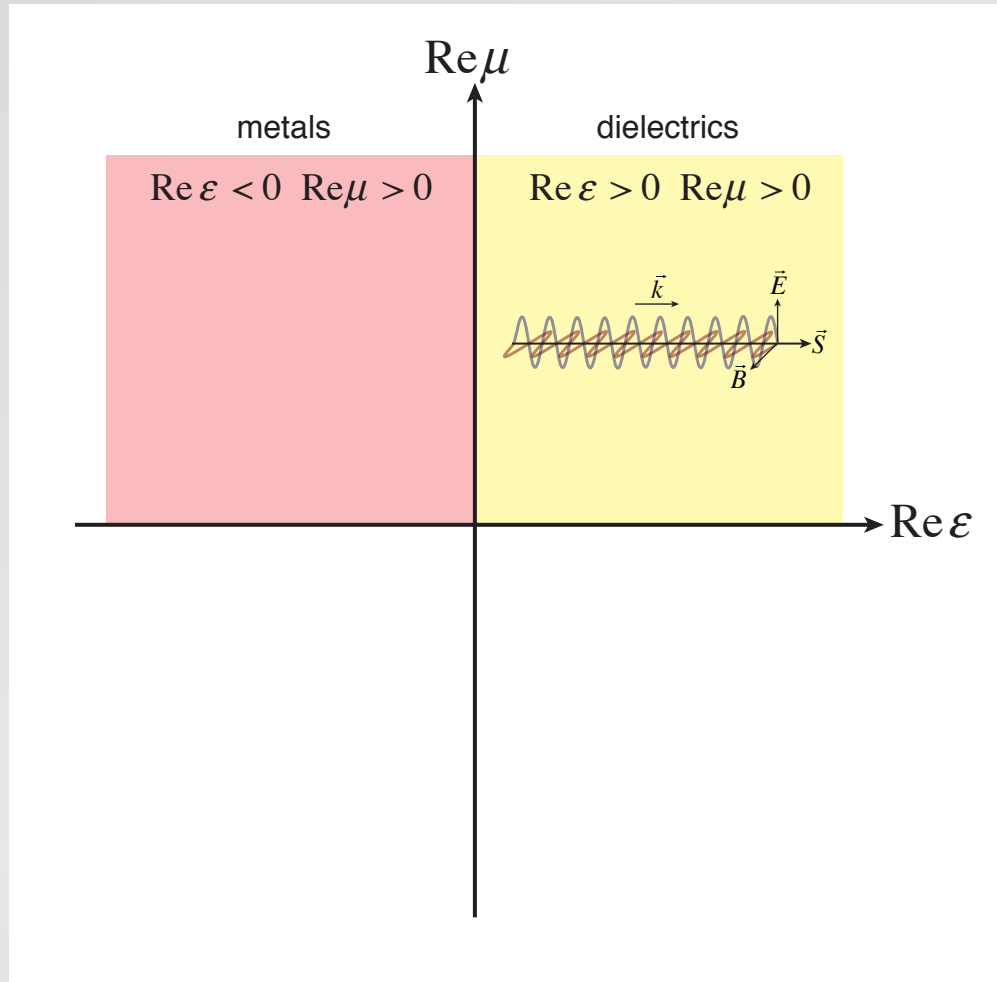
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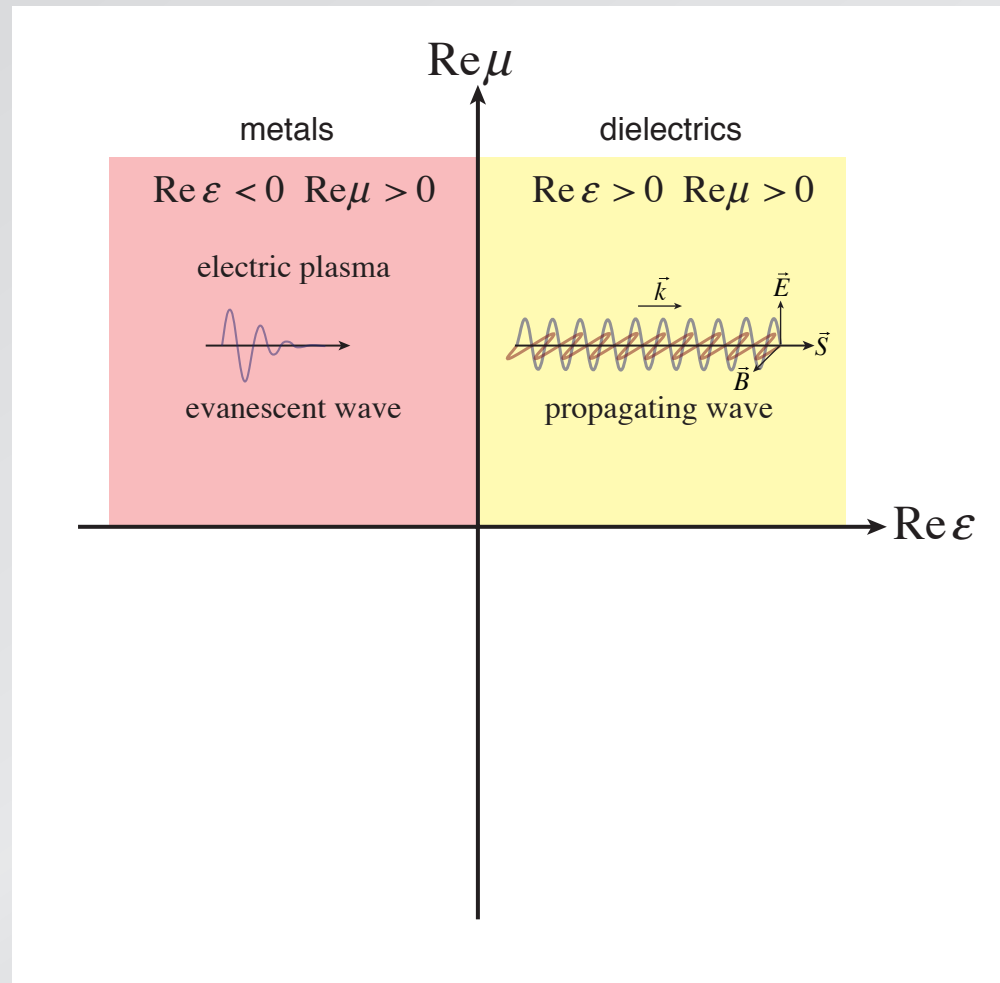
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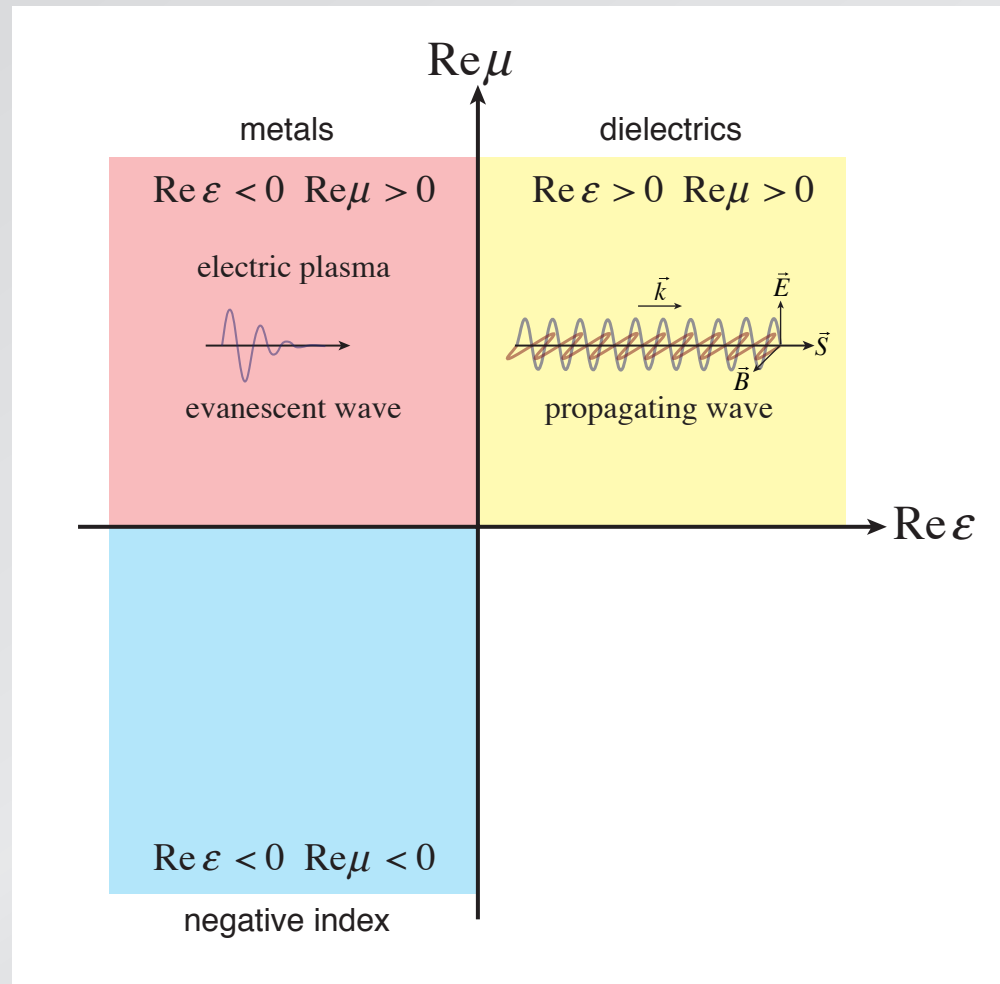
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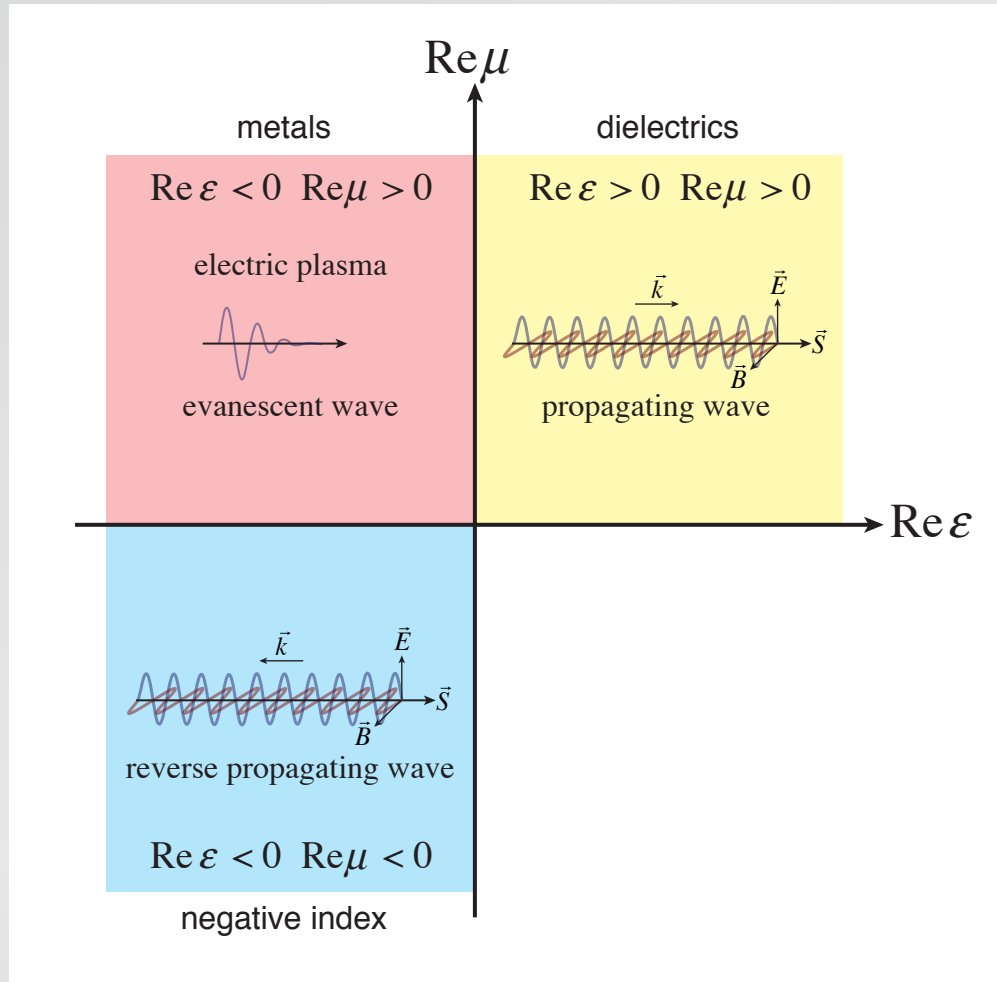
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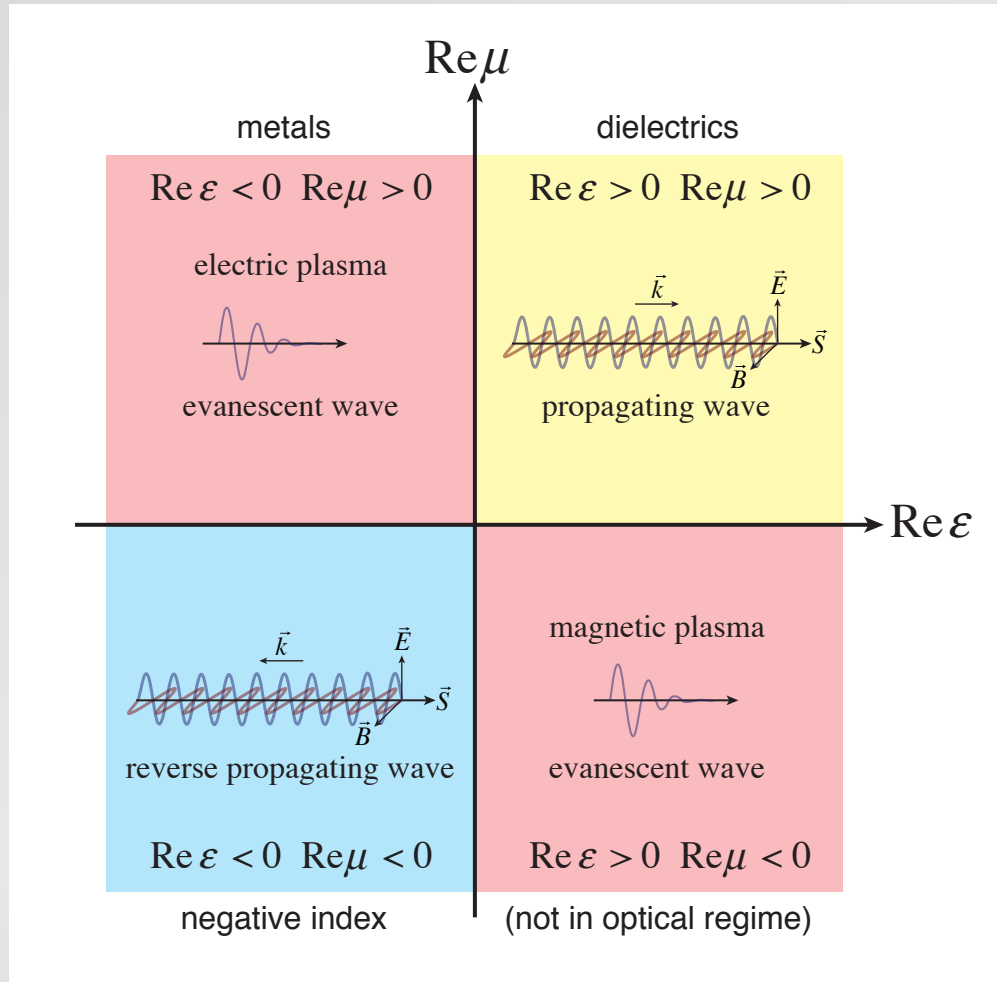


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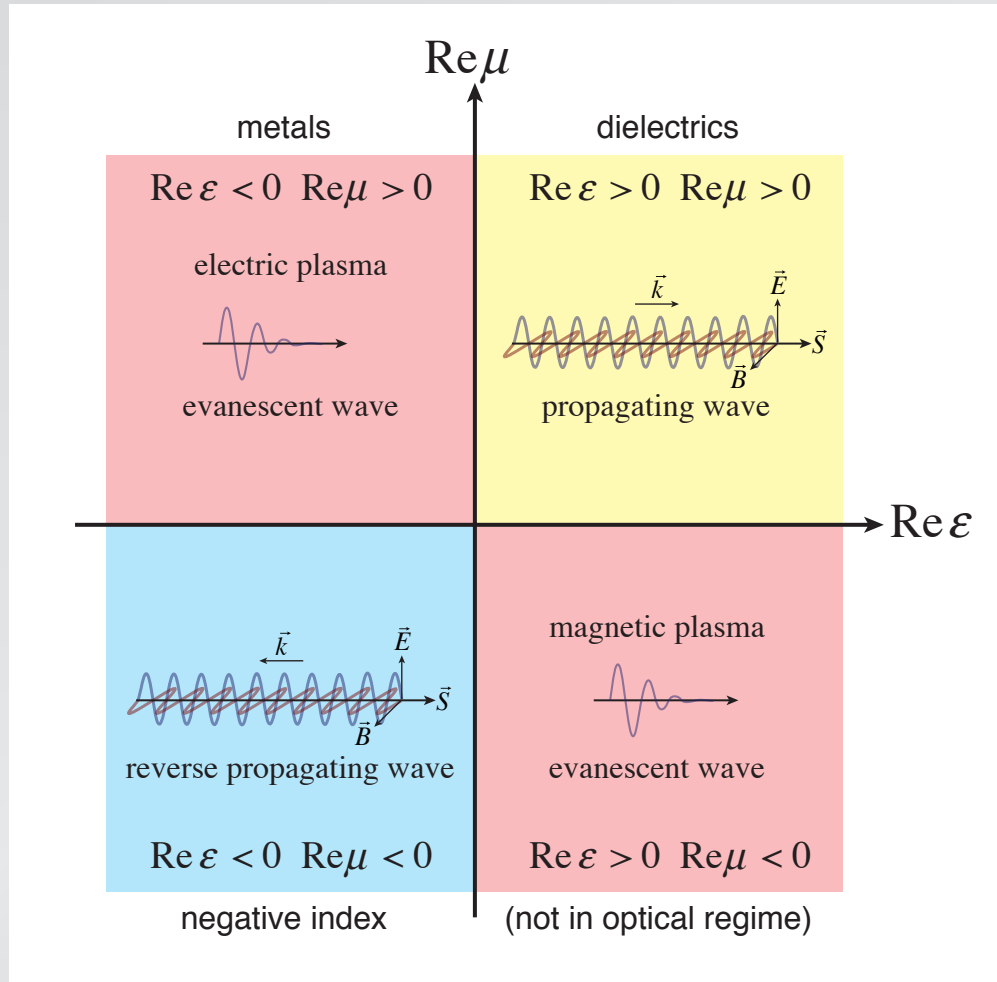




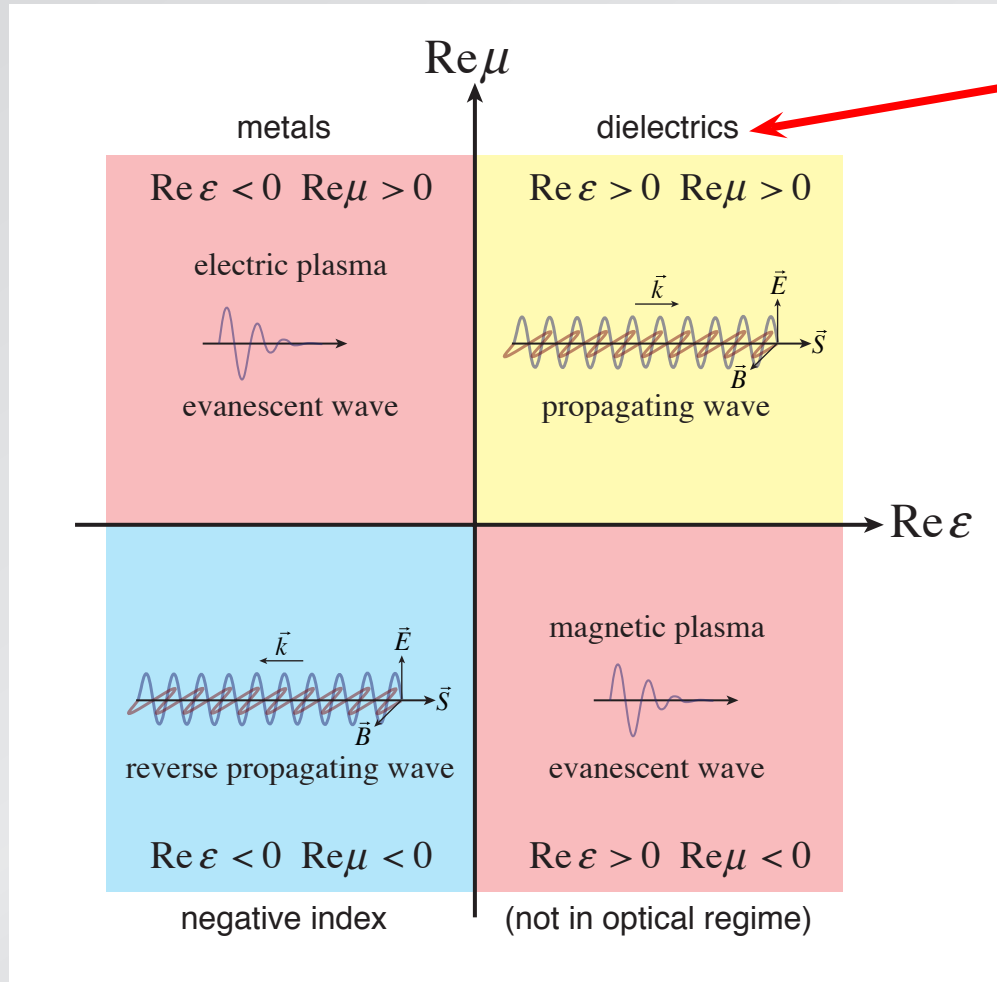
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# common materials very limited



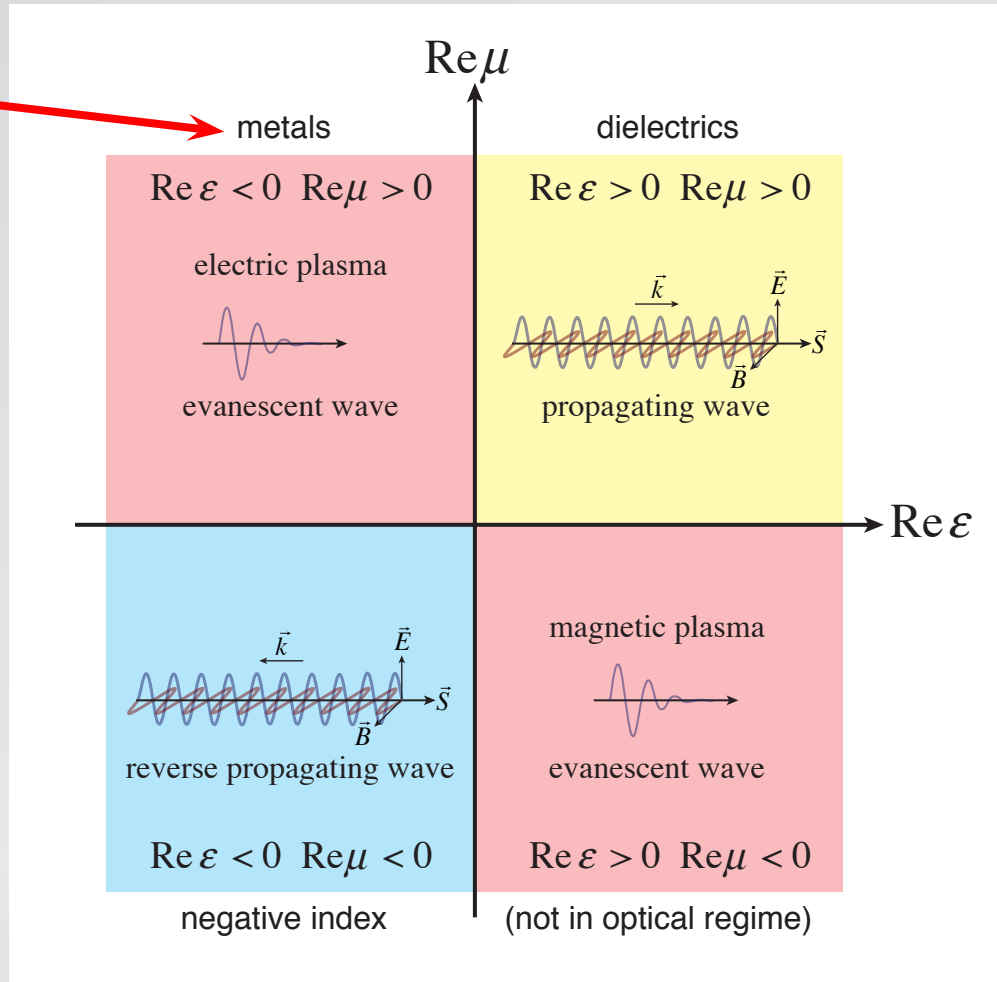
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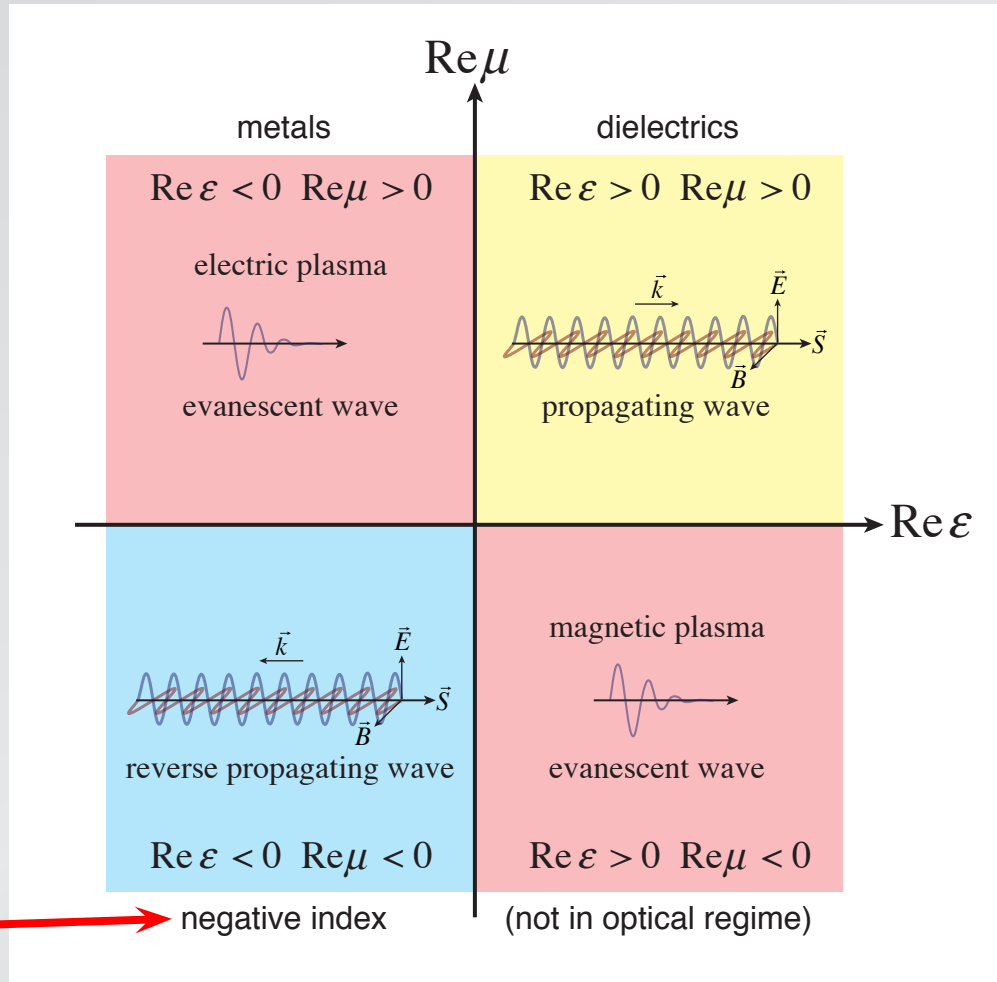
limited by diffraction

# common materials very limited

lossy & no propagation



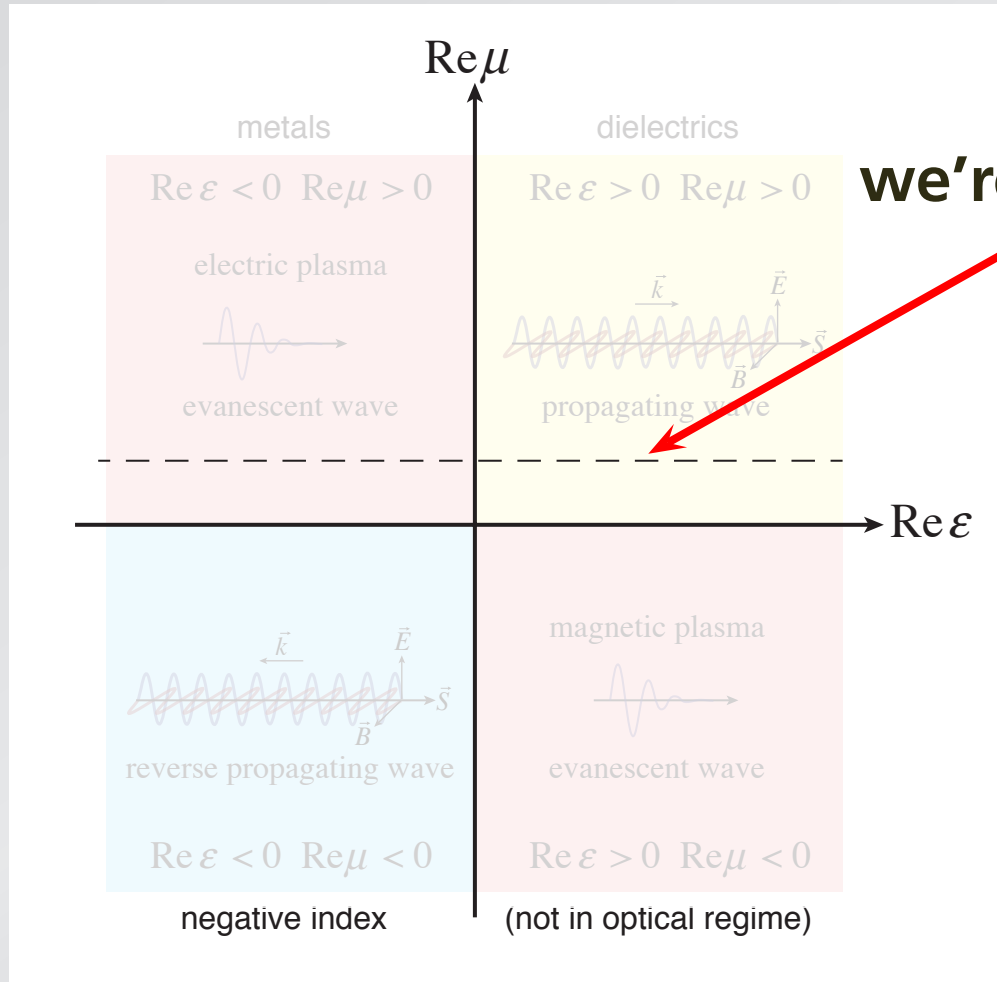
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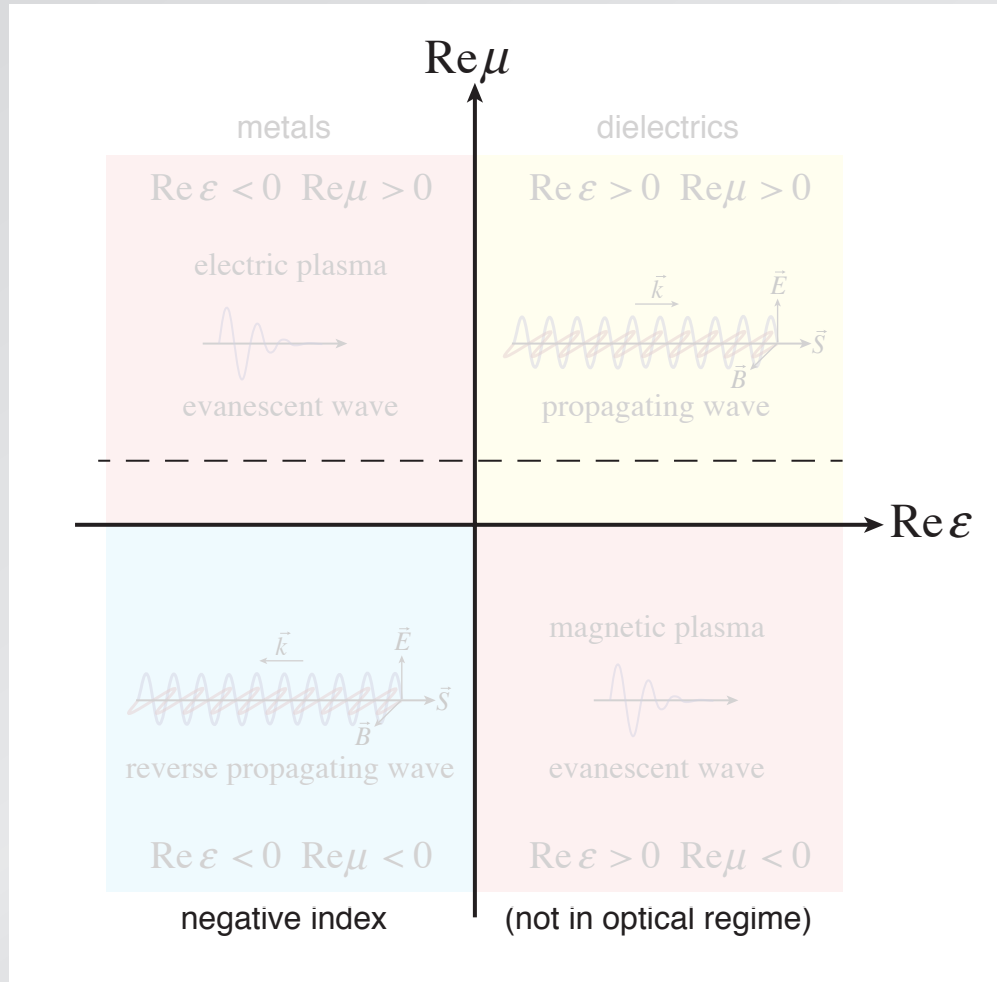
superlensing  
but...



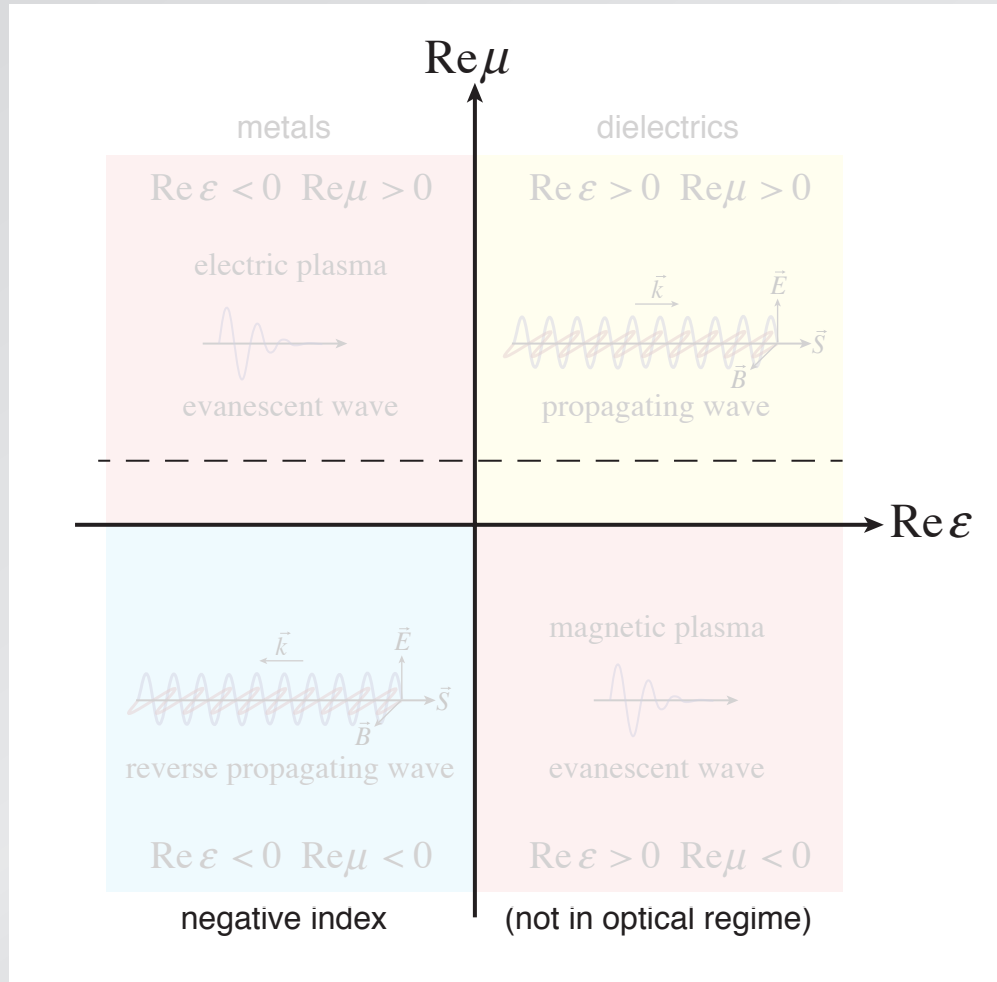
# common materials very limited



# What happens on the axes?

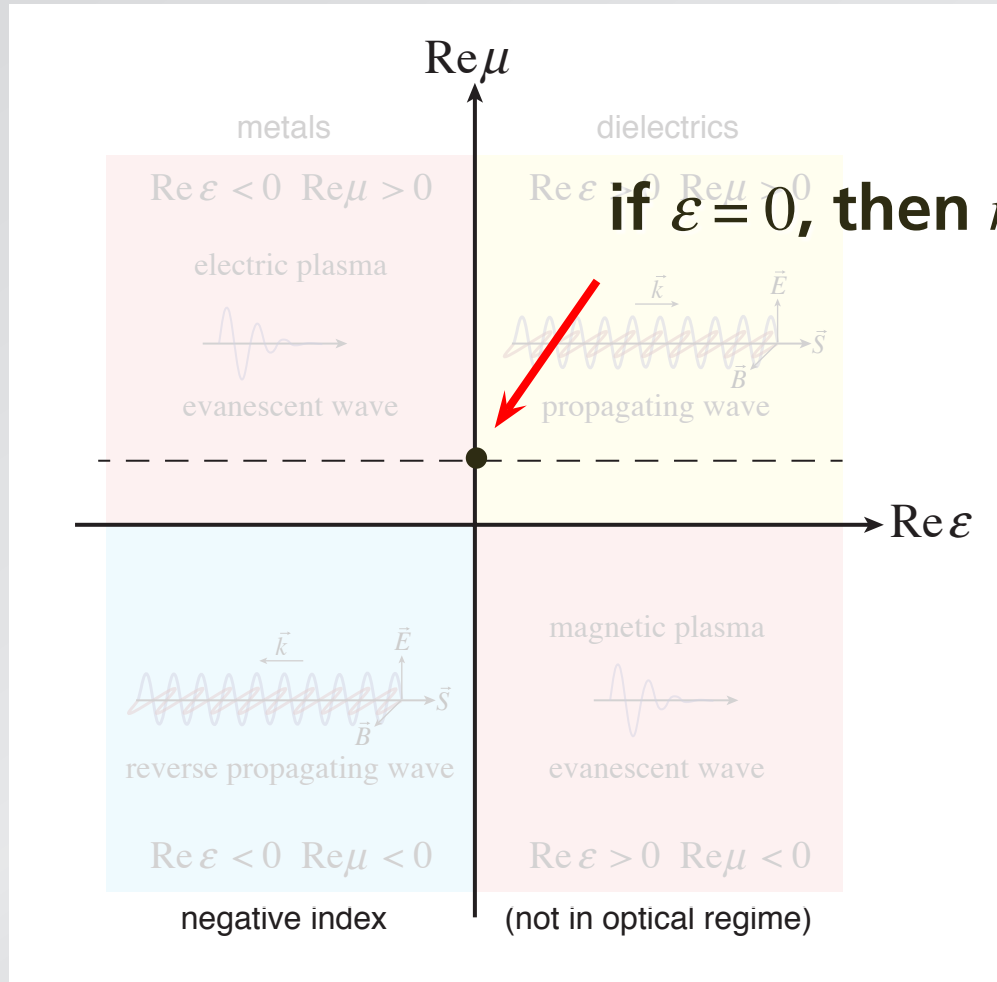


# what if we let $\varepsilon = 0$ ?





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.**

wave equation

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

solution

$$\vec{E} = \vec{E}_0 e^{i(kx - \omega t)}$$

where

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

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

wave equation

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

solution

$$\vec{E} = \vec{E}_0 e^{i(kx - \omega t)} \longrightarrow \vec{E} = \vec{E}_0 e^{-i\omega t}$$

where

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

wave equation

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

solution

$$\vec{E} = \vec{E}_0 e^{i(kx - \omega t)} \longrightarrow \vec{E} = \vec{E}_0 e^{-i\omega t}$$

where

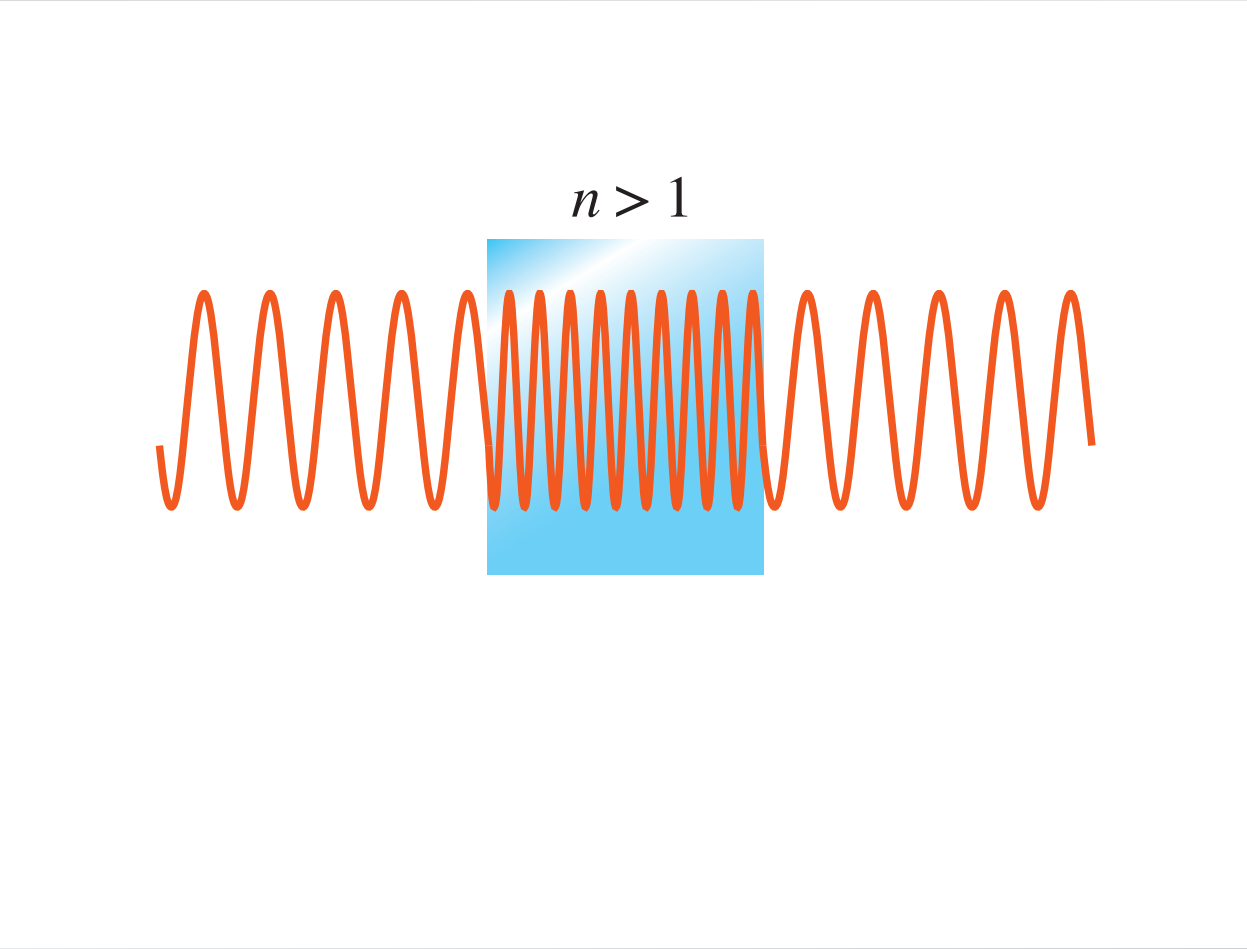
$$\frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c \longrightarrow \infty$$

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.

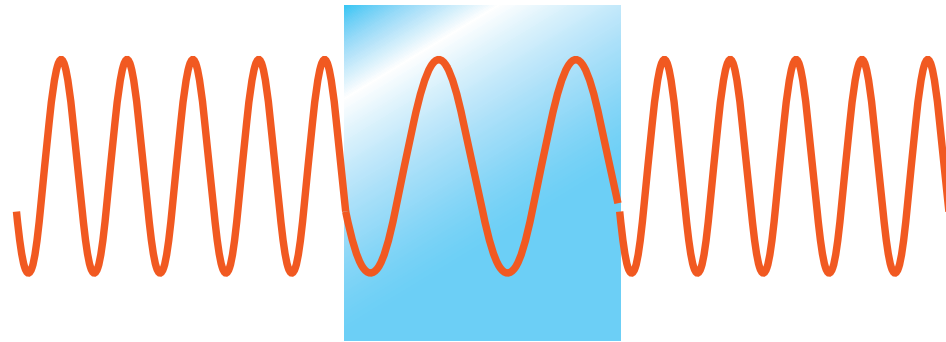


1 index

2 zero index

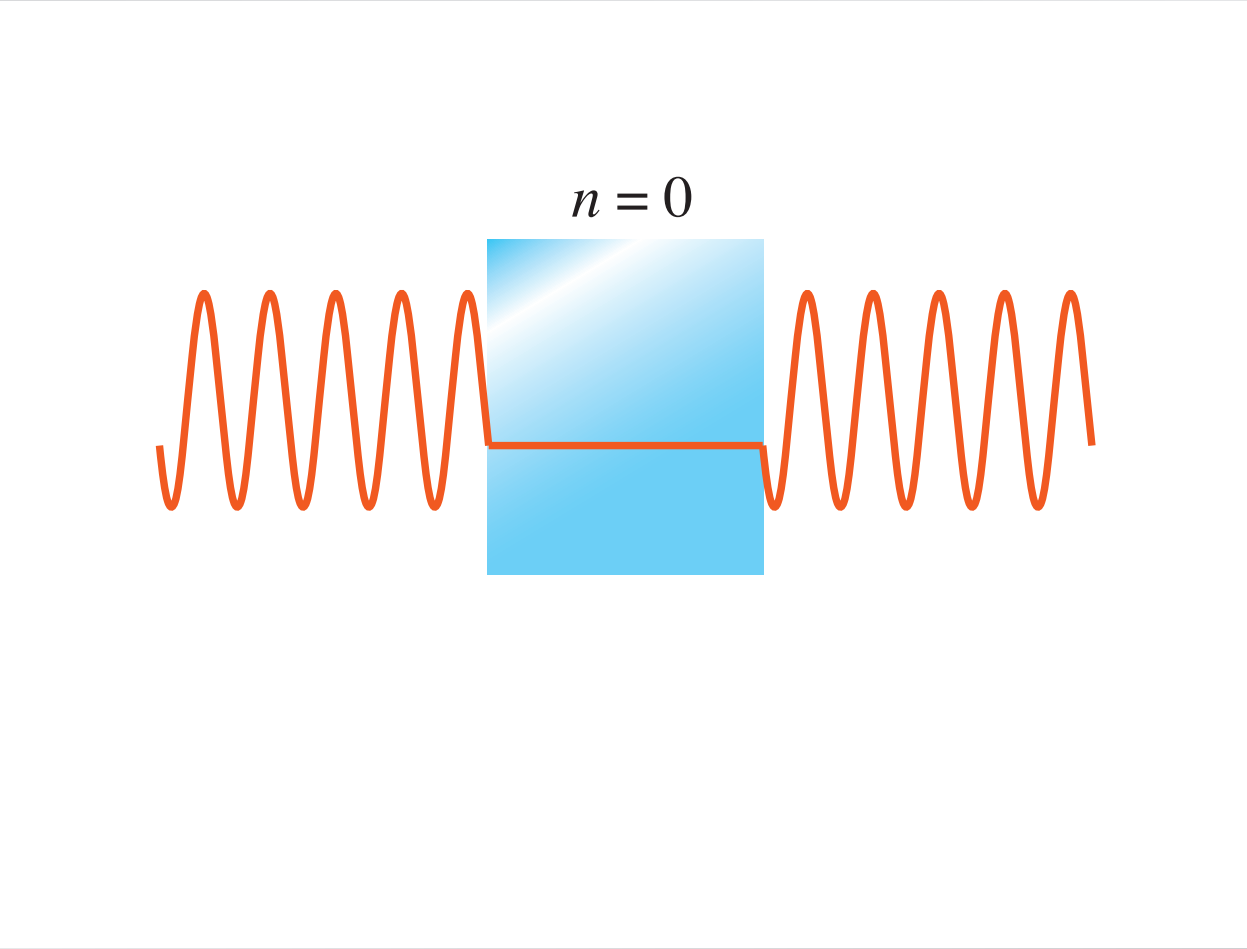


$$0 < n < 1$$



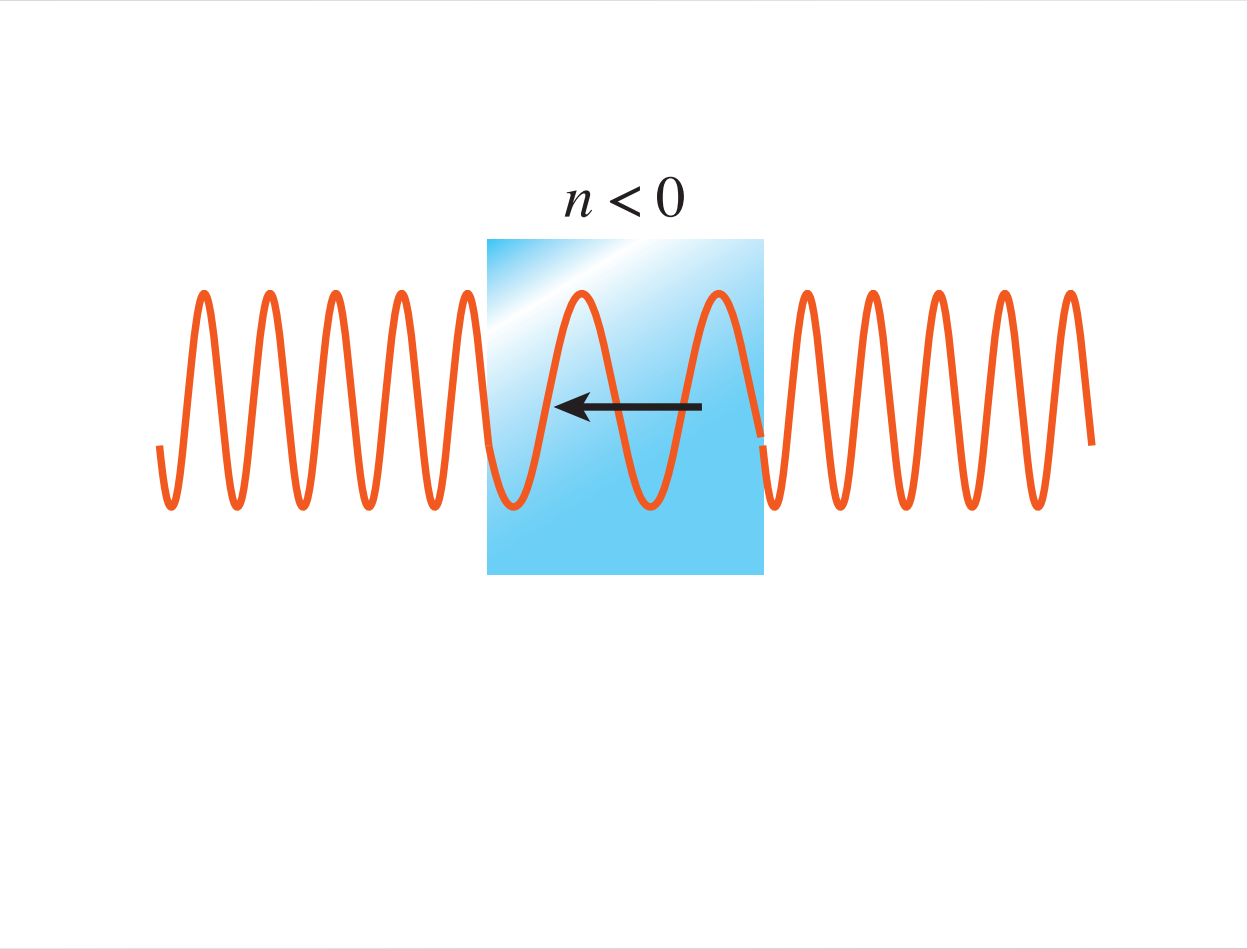
1 index

2 zero index



1 index

2 zero index



1 index

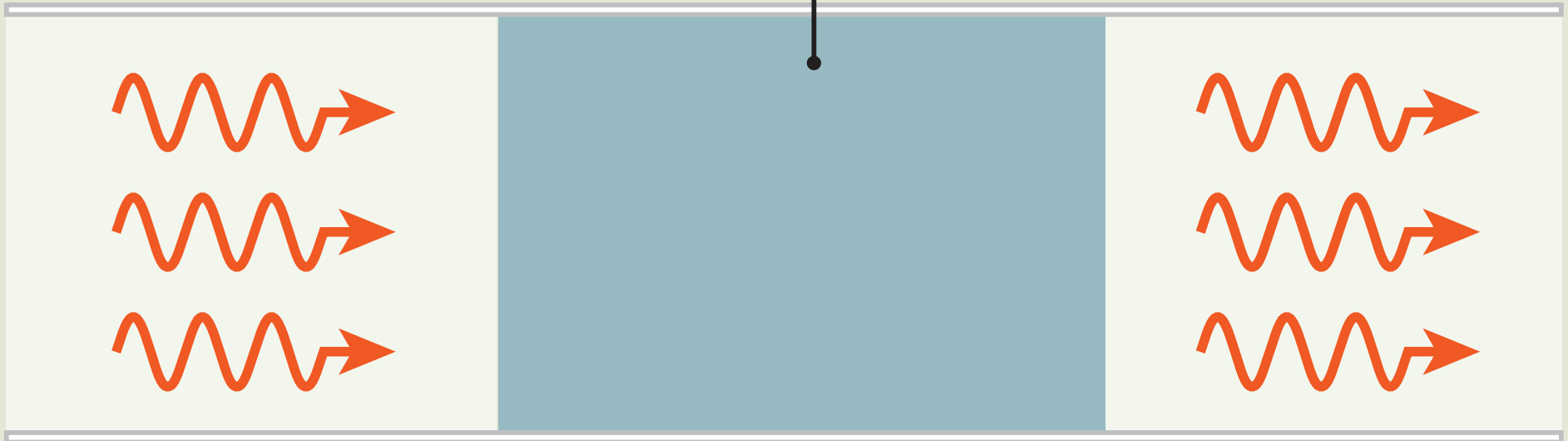
2 zero index



1 index

2 zero index

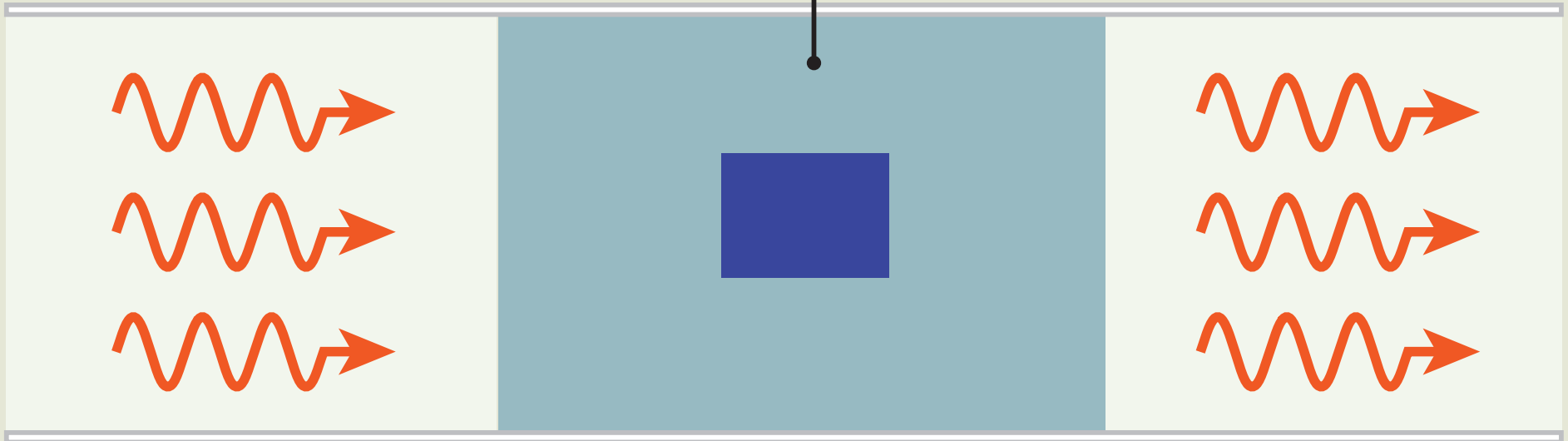
$$n = 0$$



1 index

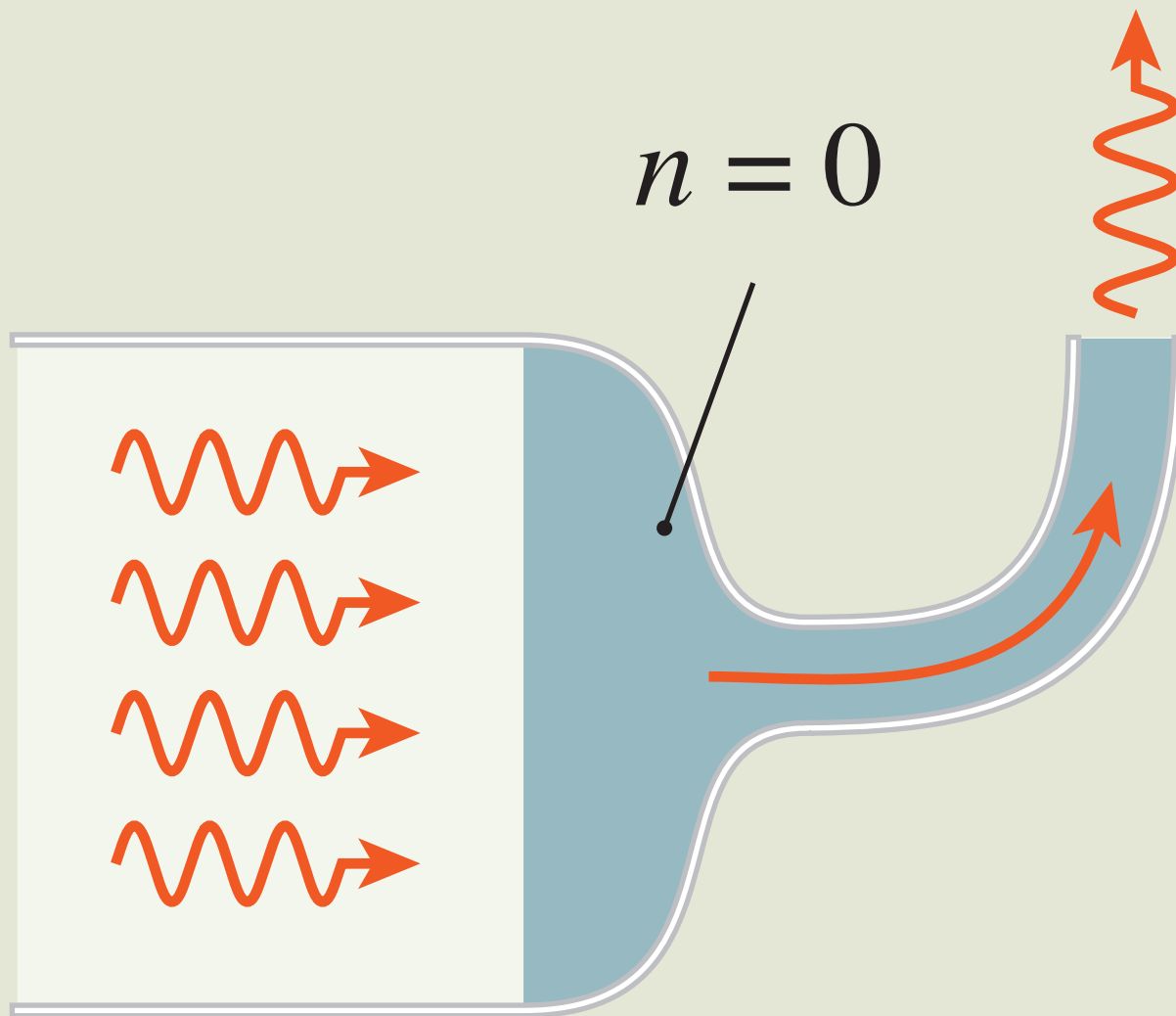
2 zero index

$$n = 0$$



1 index

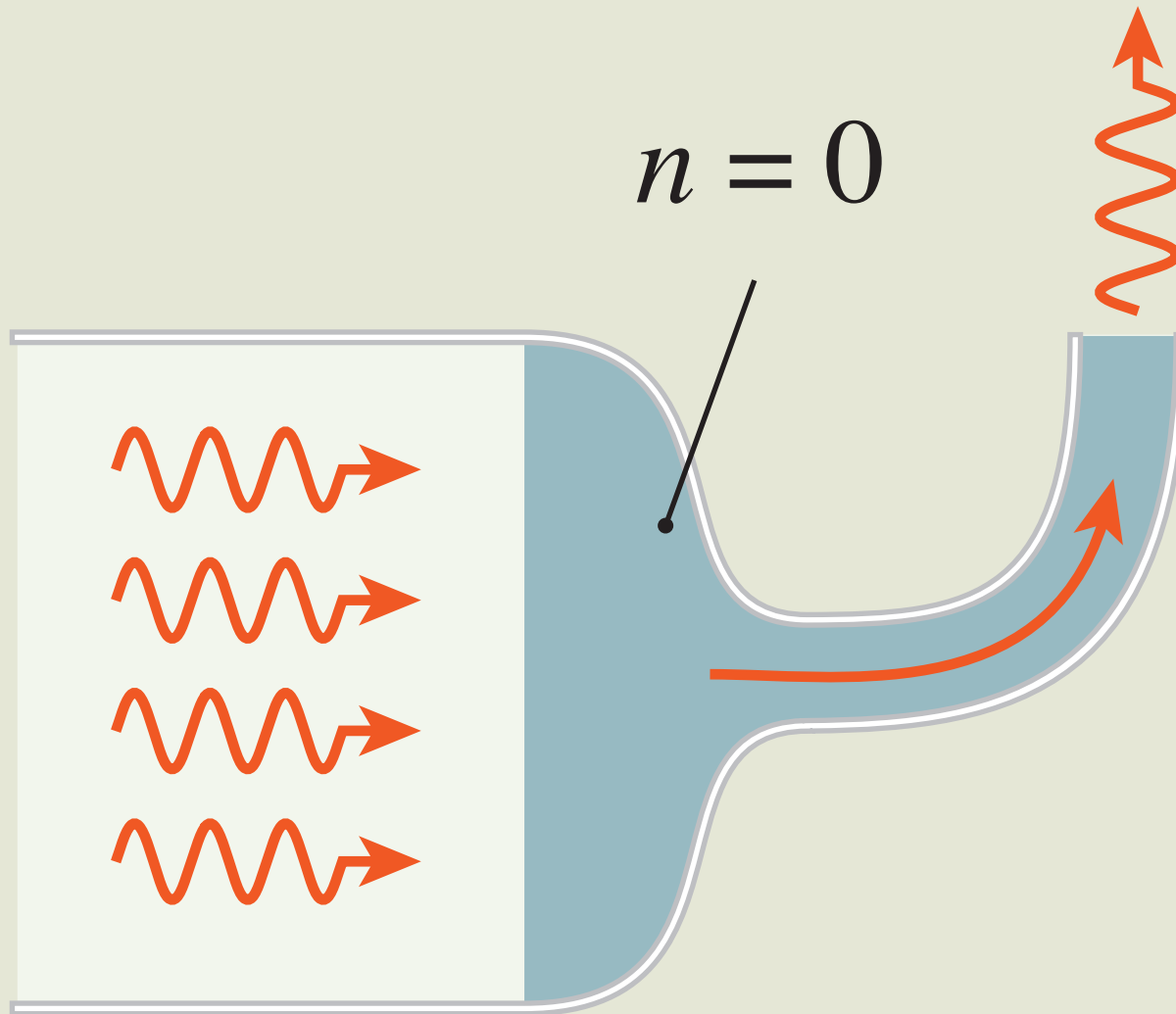
2 zero index



1 index

2 zero index

“tunneling with infinite decay length”



1 index

2 zero index



how?

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

how?

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

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

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

how?

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

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

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

where

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

how?

$$\varepsilon \rightarrow 0$$

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

but  $\varepsilon$  and  $\mu$  also determine reflectivity

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

where

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

how?

$$\varepsilon \rightarrow 0$$

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

but  $\varepsilon$  and  $\mu$  also determine reflectivity

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

where

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

how?

$$\epsilon \rightarrow 0$$

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

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

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

where

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

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

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

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

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



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

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

how?

$$\epsilon, \mu \rightarrow 0$$

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

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

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

where

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

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

1 index

2 zero index

3 experiments

# Engineering a magnetic response

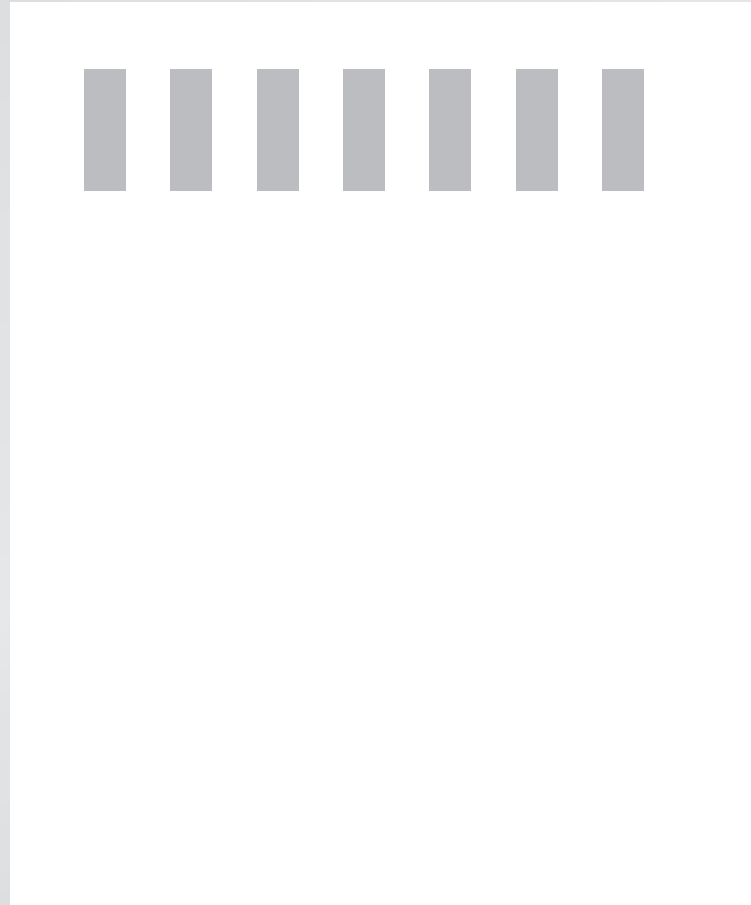
**1** index

**2** zero index

**3** experiments

# Engineering a magnetic response

use array of dielectric rods



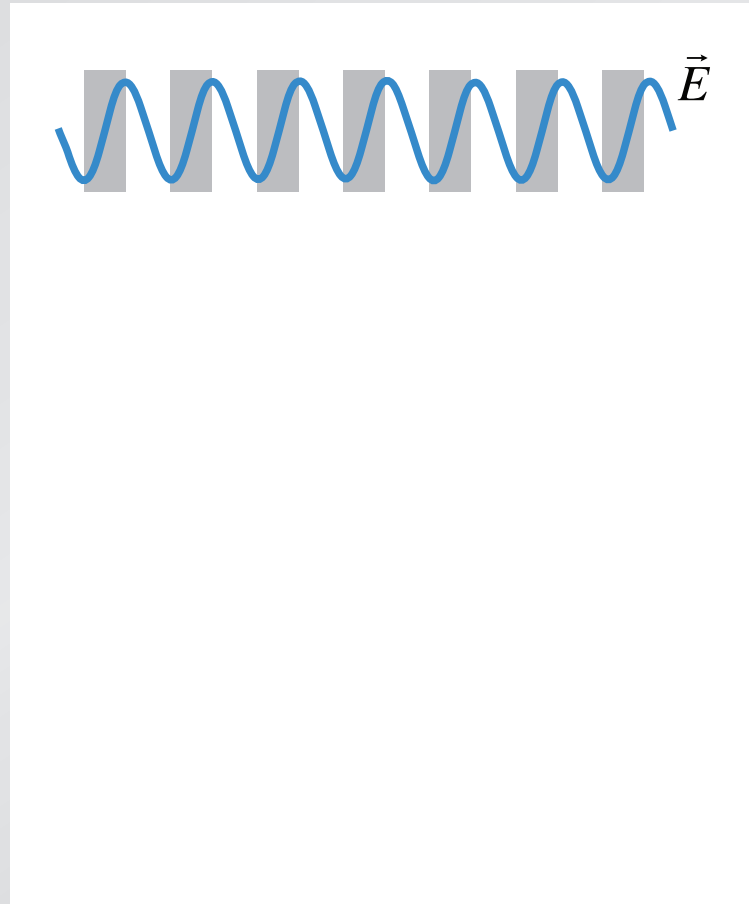
**1** index

**2** zero index

**3** experiments

# Engineering a magnetic response

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

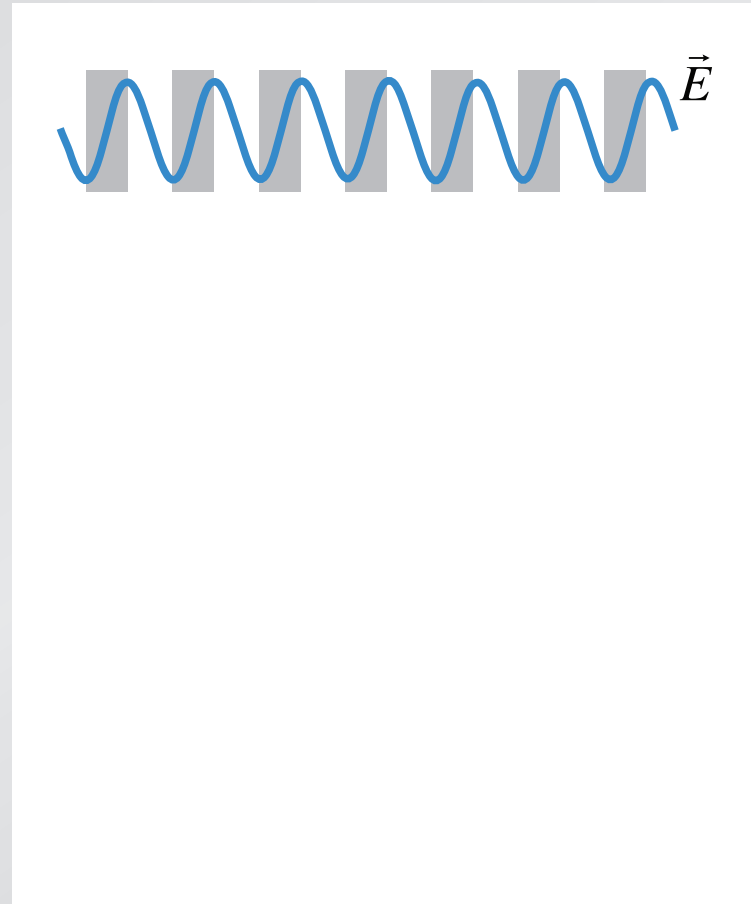


1 index

2 zero index

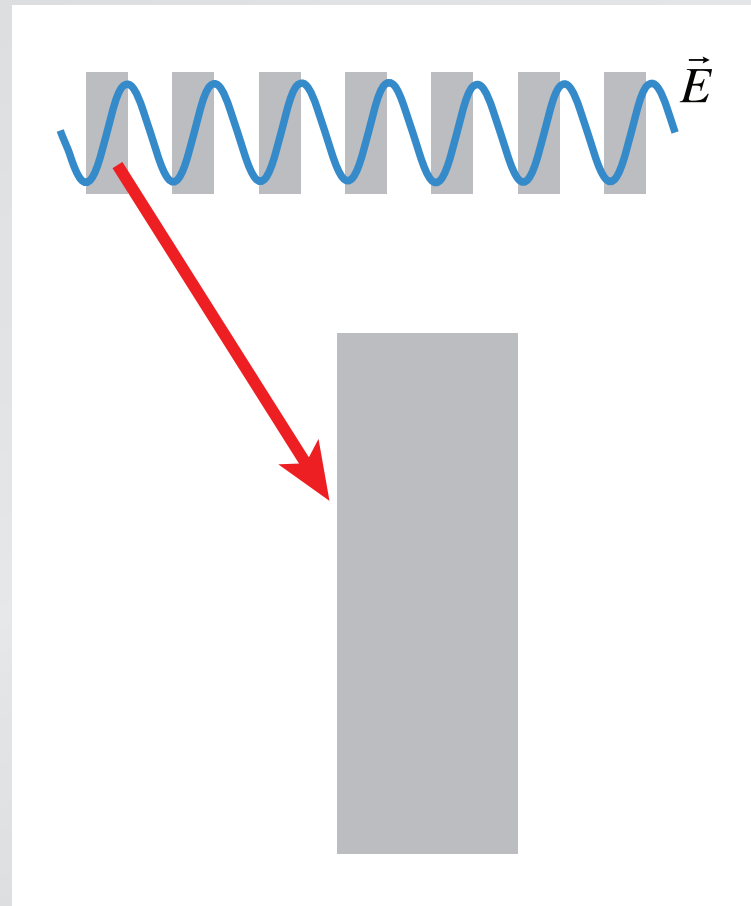
# Engineering a magnetic response

produces an electric response...



# Engineering a magnetic response

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



1 index

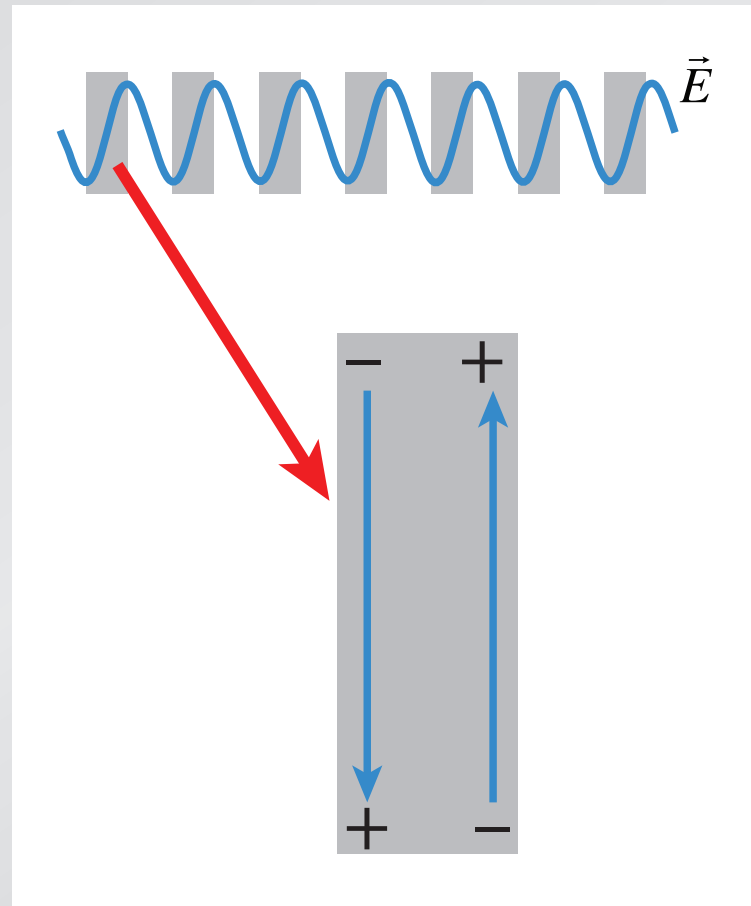
2 zero index

3 experiments



# Engineering a magnetic response

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



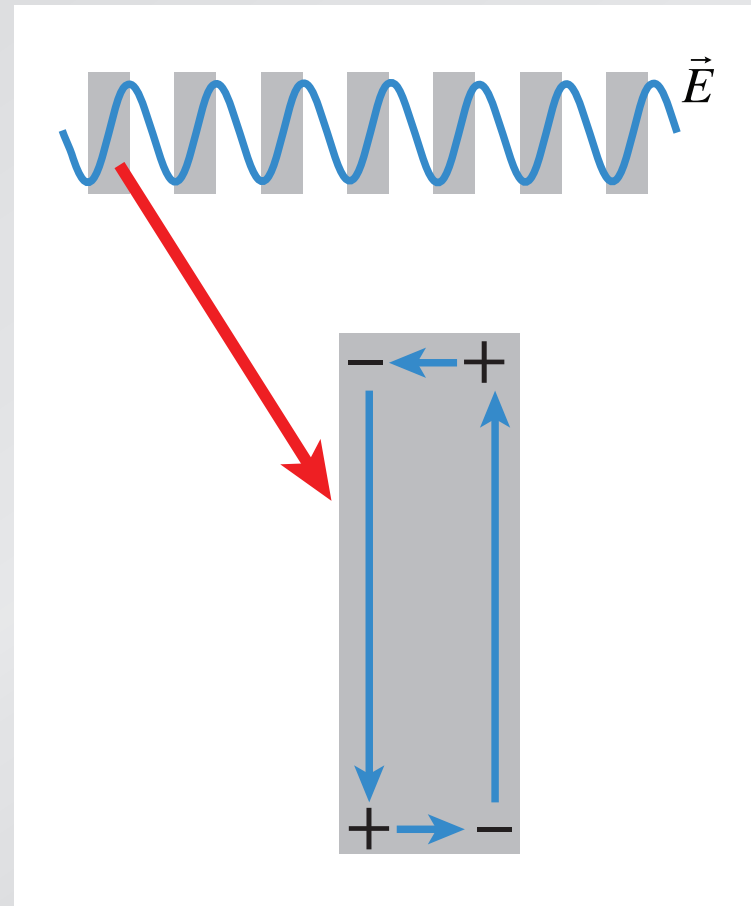
1 index

2 zero index

3 experiments

# Engineering a magnetic response

...causing a current loop...



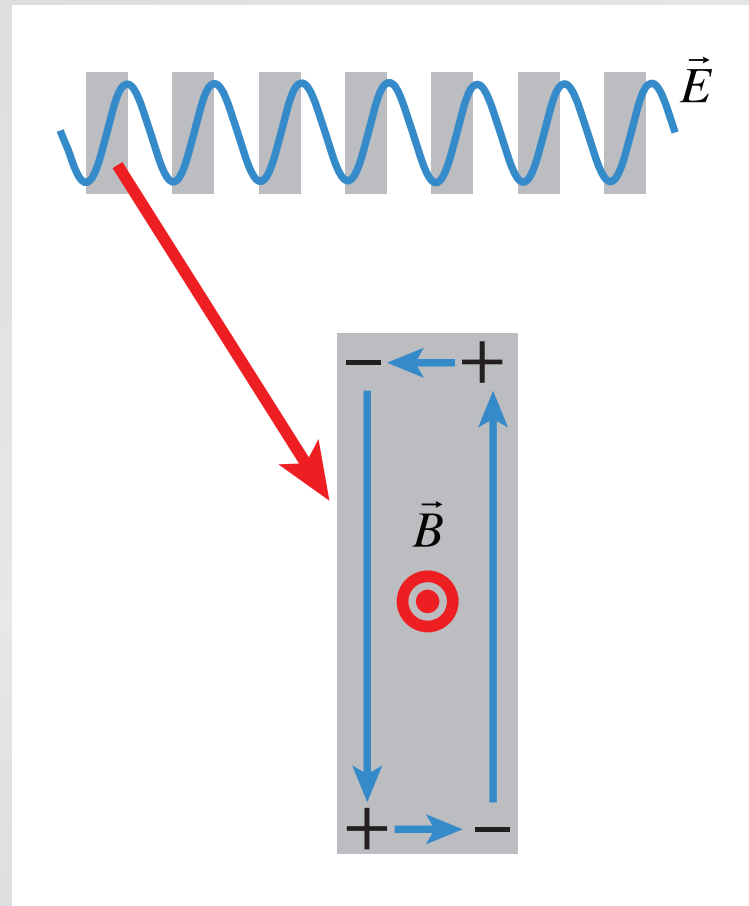
1 index

2 zero index

3 experiments

# Engineering a magnetic response

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



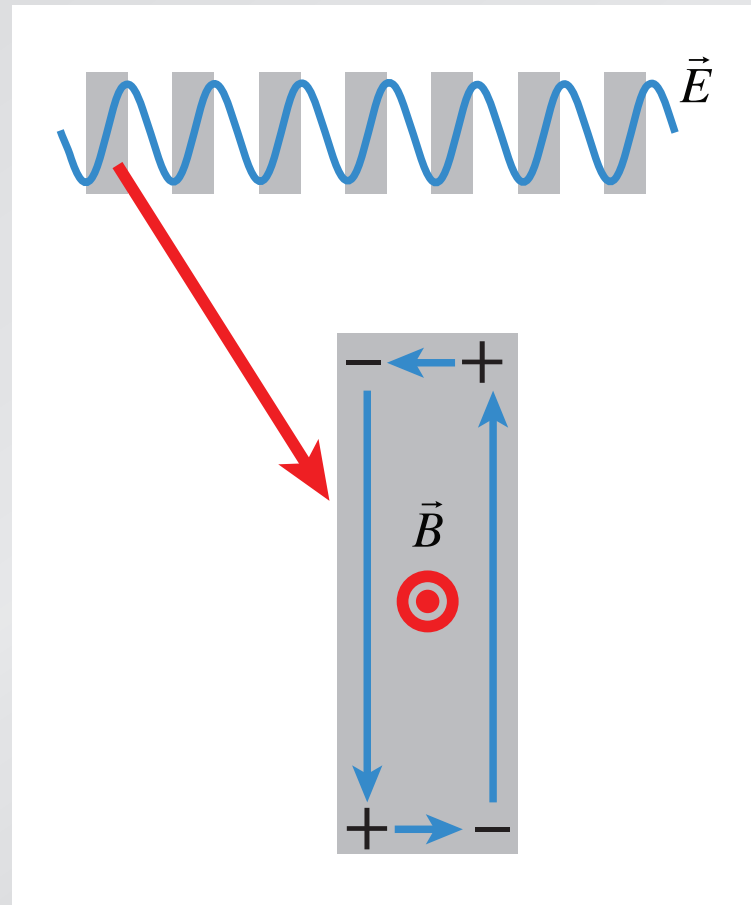
1 index

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



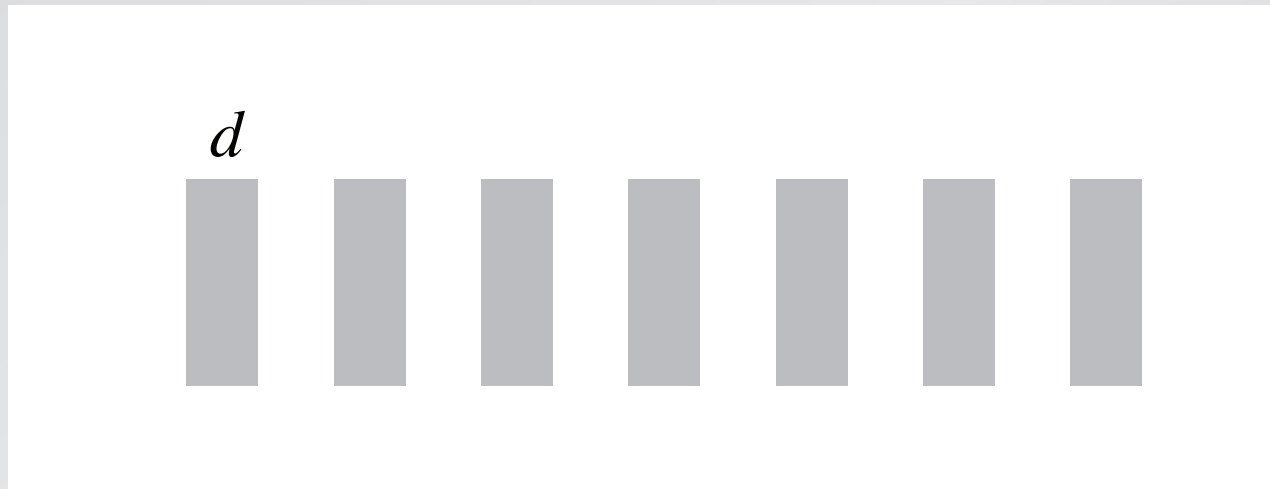
**1** index

**2** zero index

**3** experiments

# Engineering a magnetic response

adjustable parameters



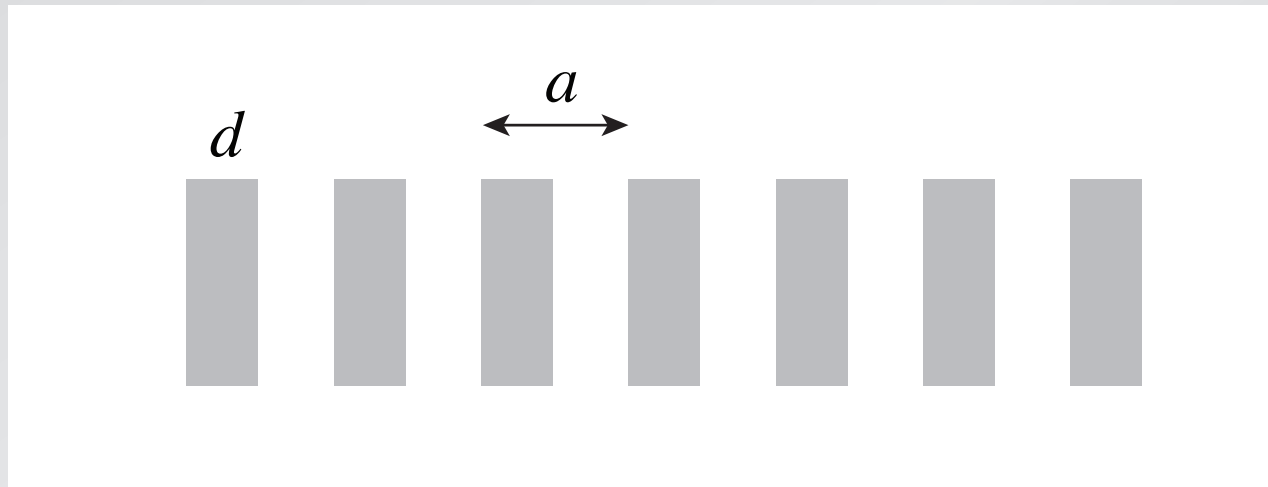
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters



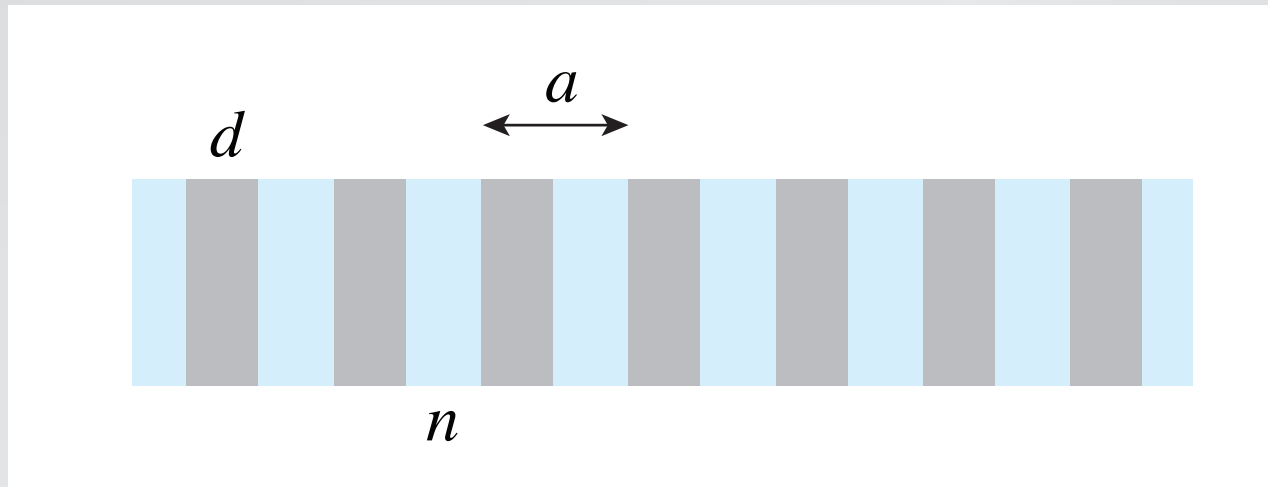
1 index

2 zero index

3 experiments

# Engineering a magnetic response

adjustable parameters

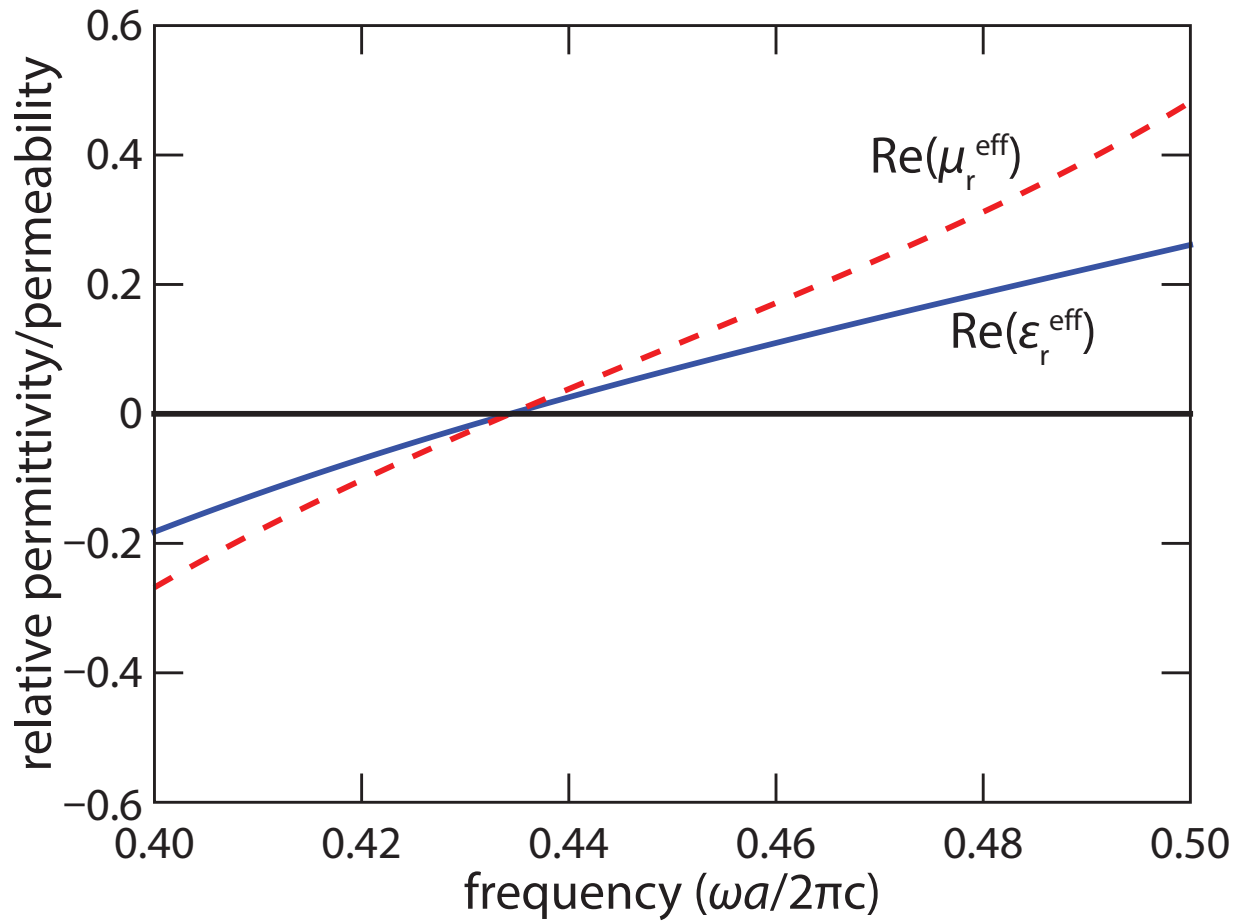


1 index

2 zero index

3 experiments

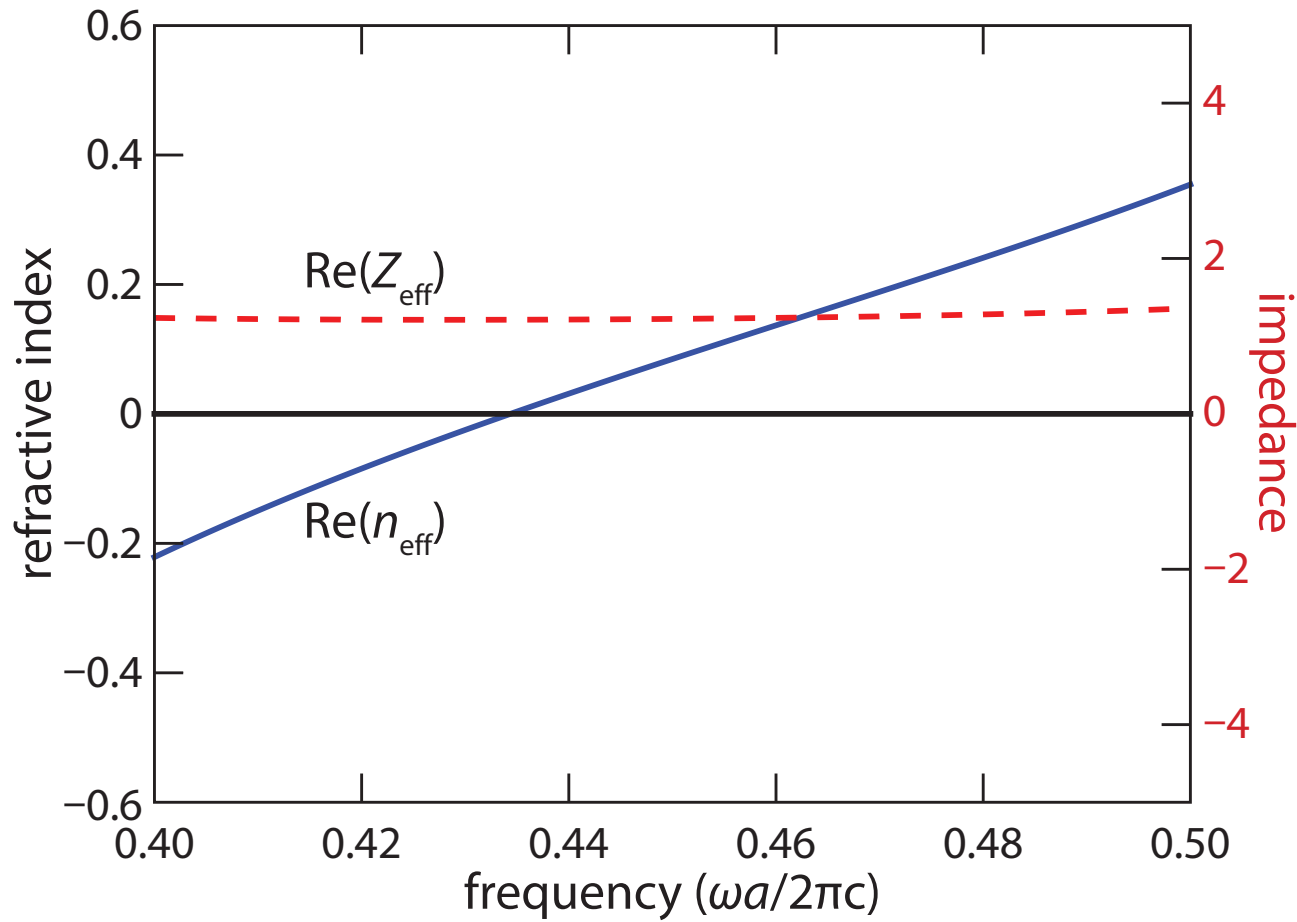




1 index

2 zero index

3 experiments

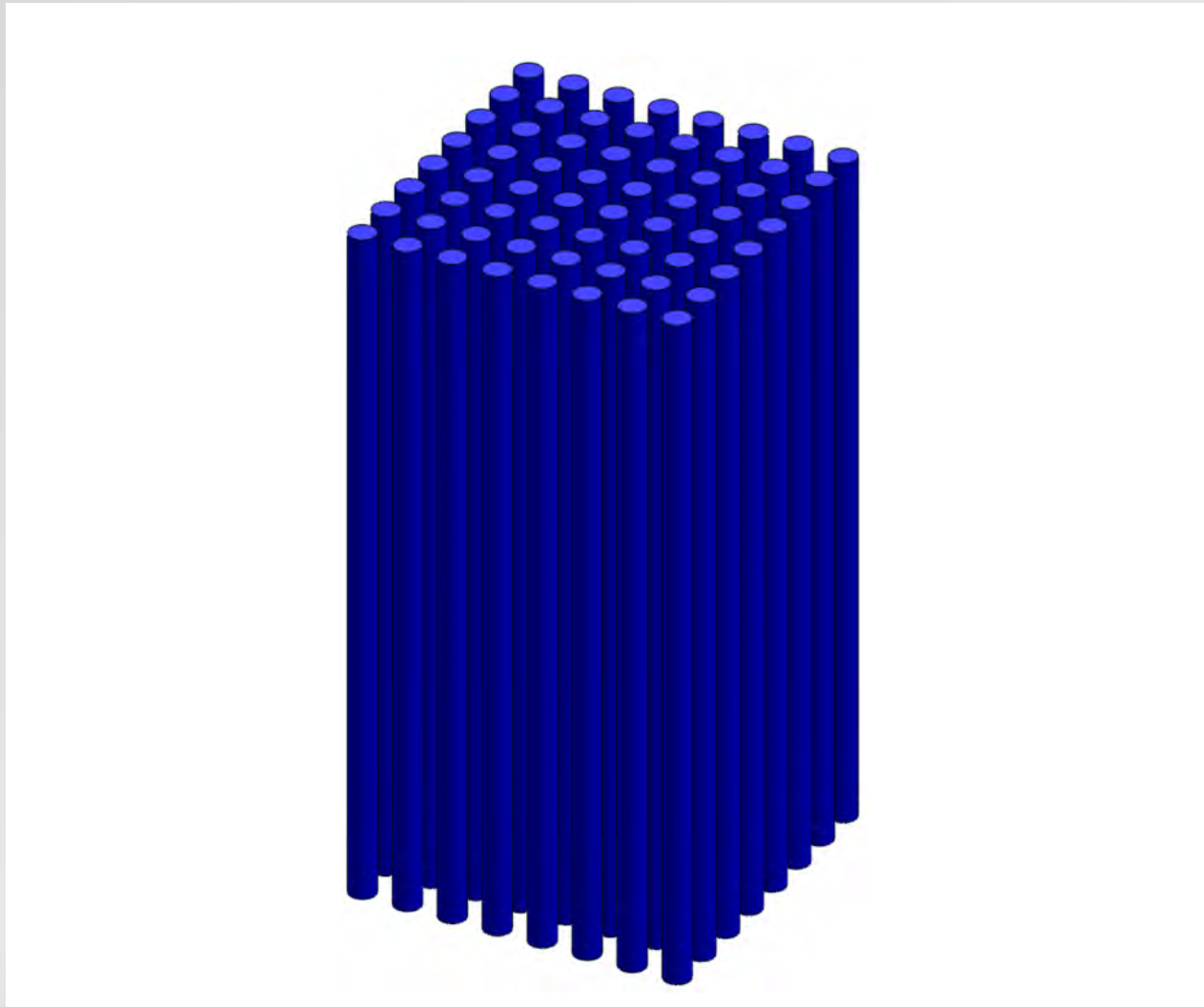


1 index

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

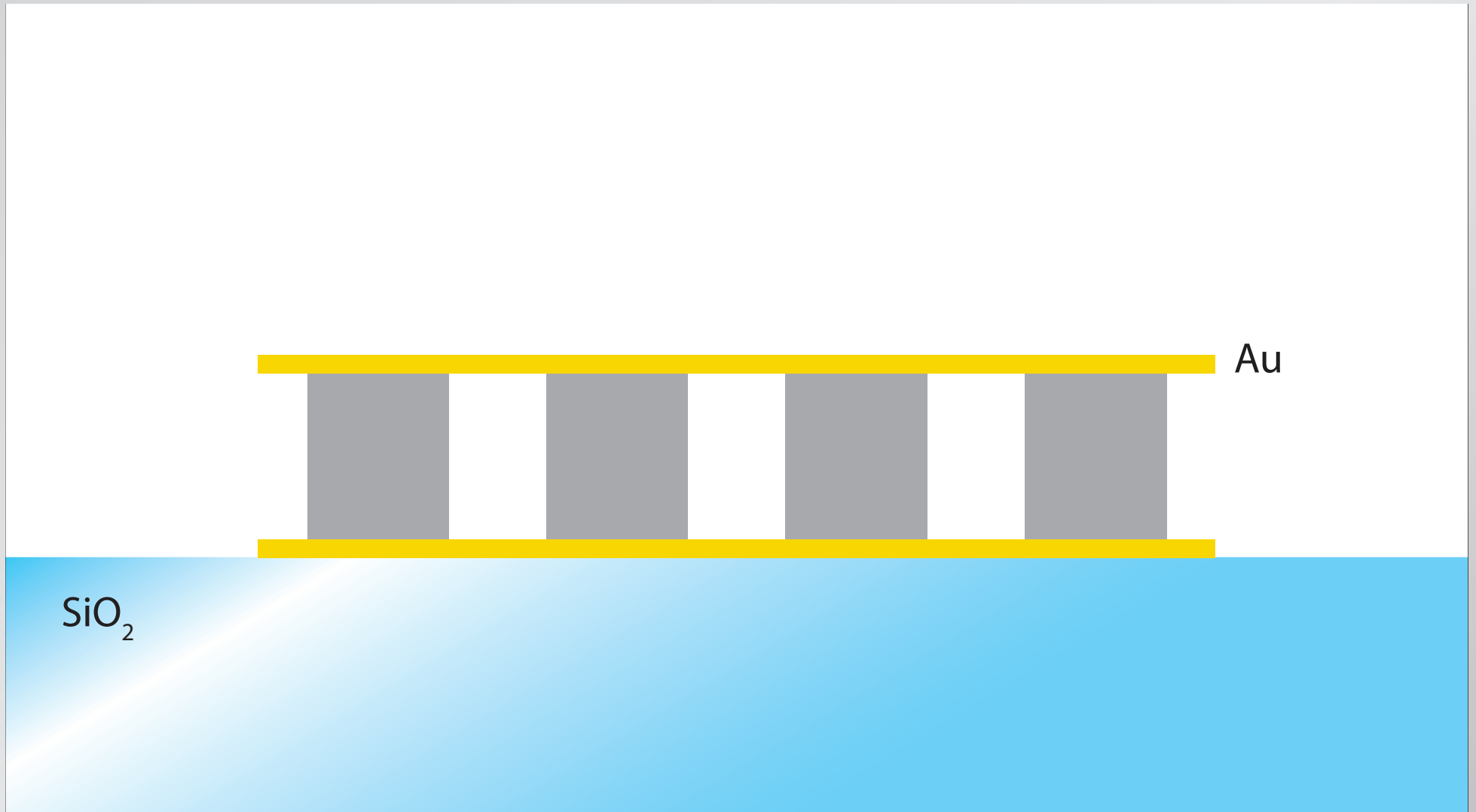


① index

② zero index

③ experiments

# On-chip zero-index fabrication



1 index

2 zero index

3 experiments

# On-chip zero-index fabrication



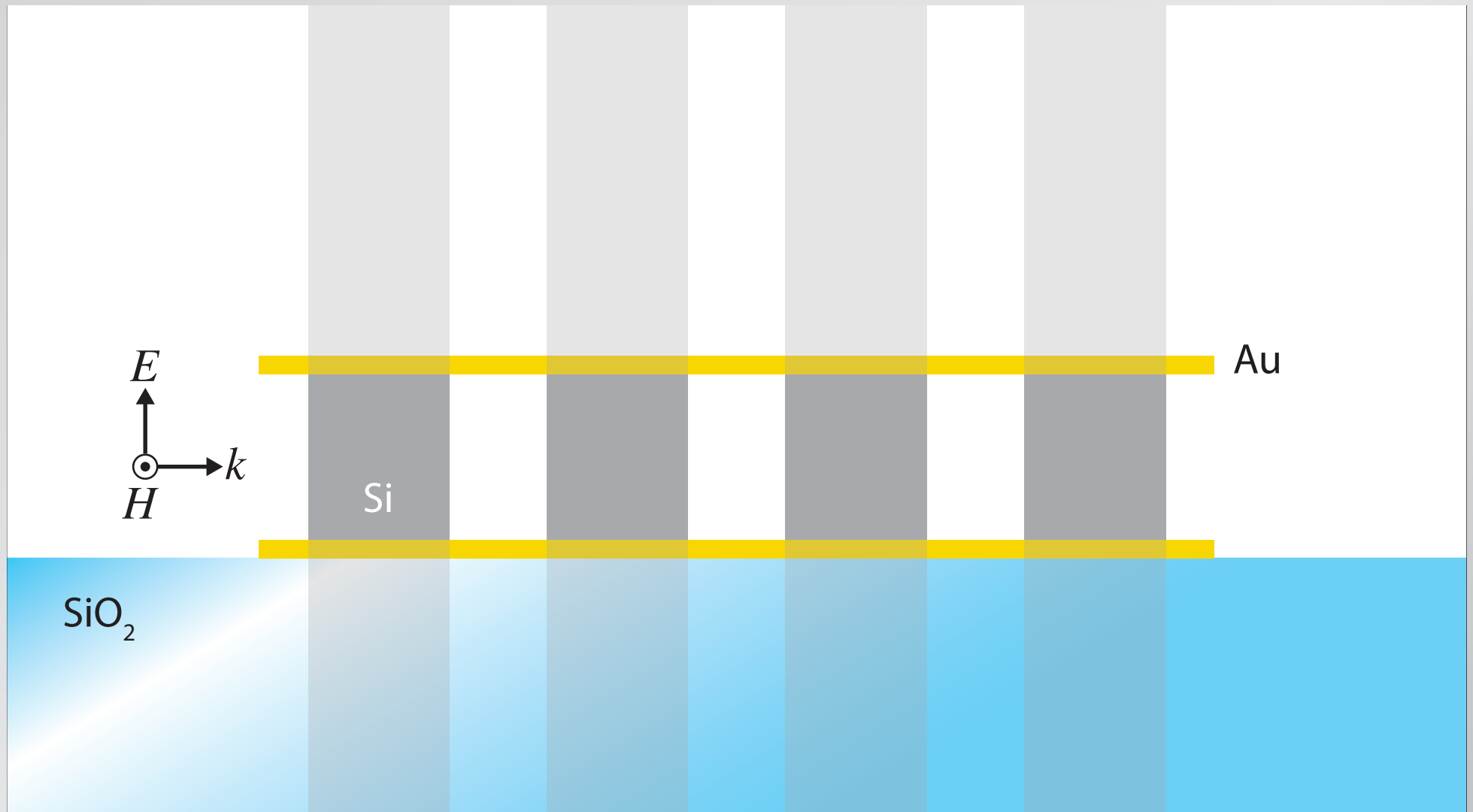
1 index

2 zero index

3 experiments



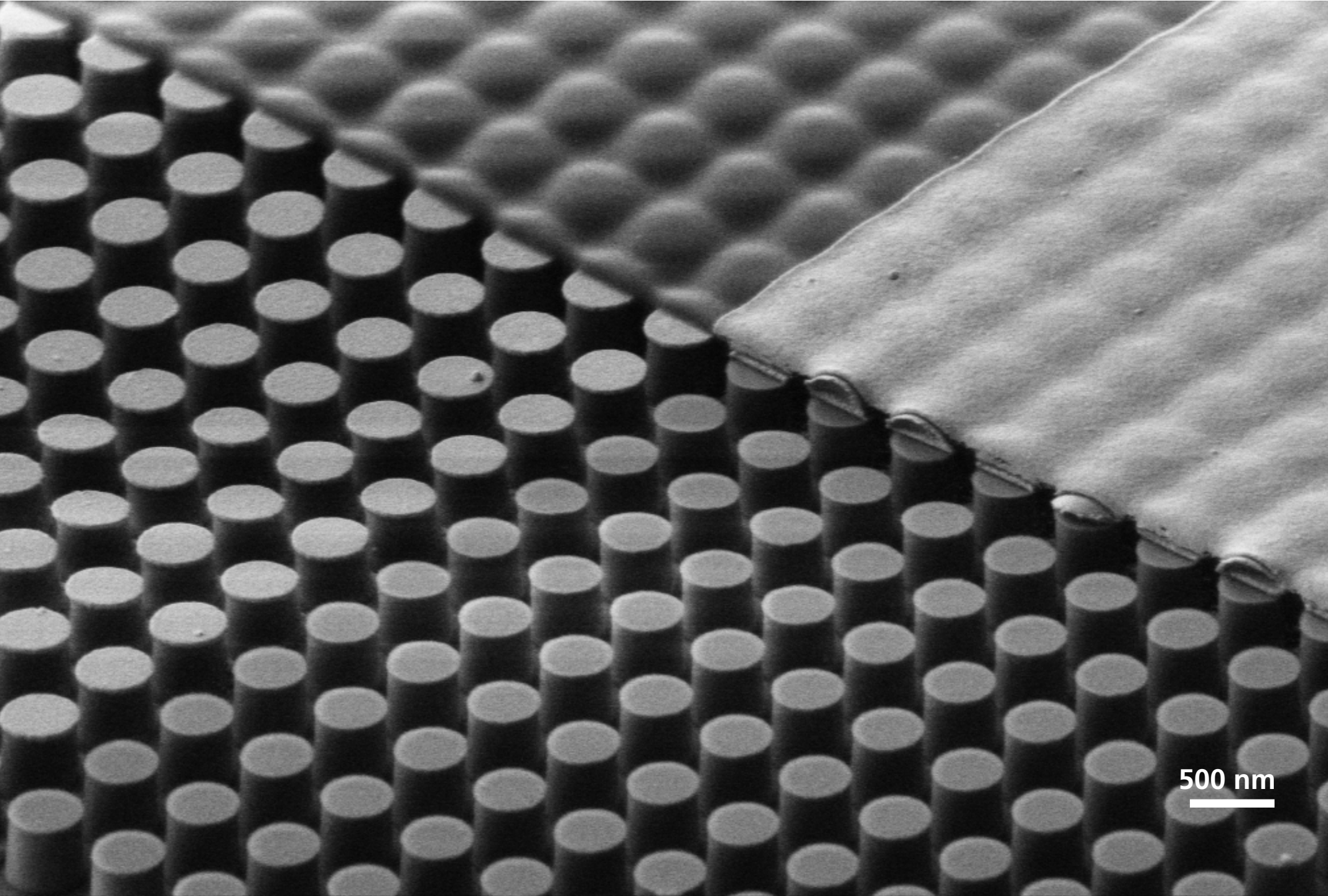
# On-chip zero-index fabrication



1 index

2 zero index

3 experiments

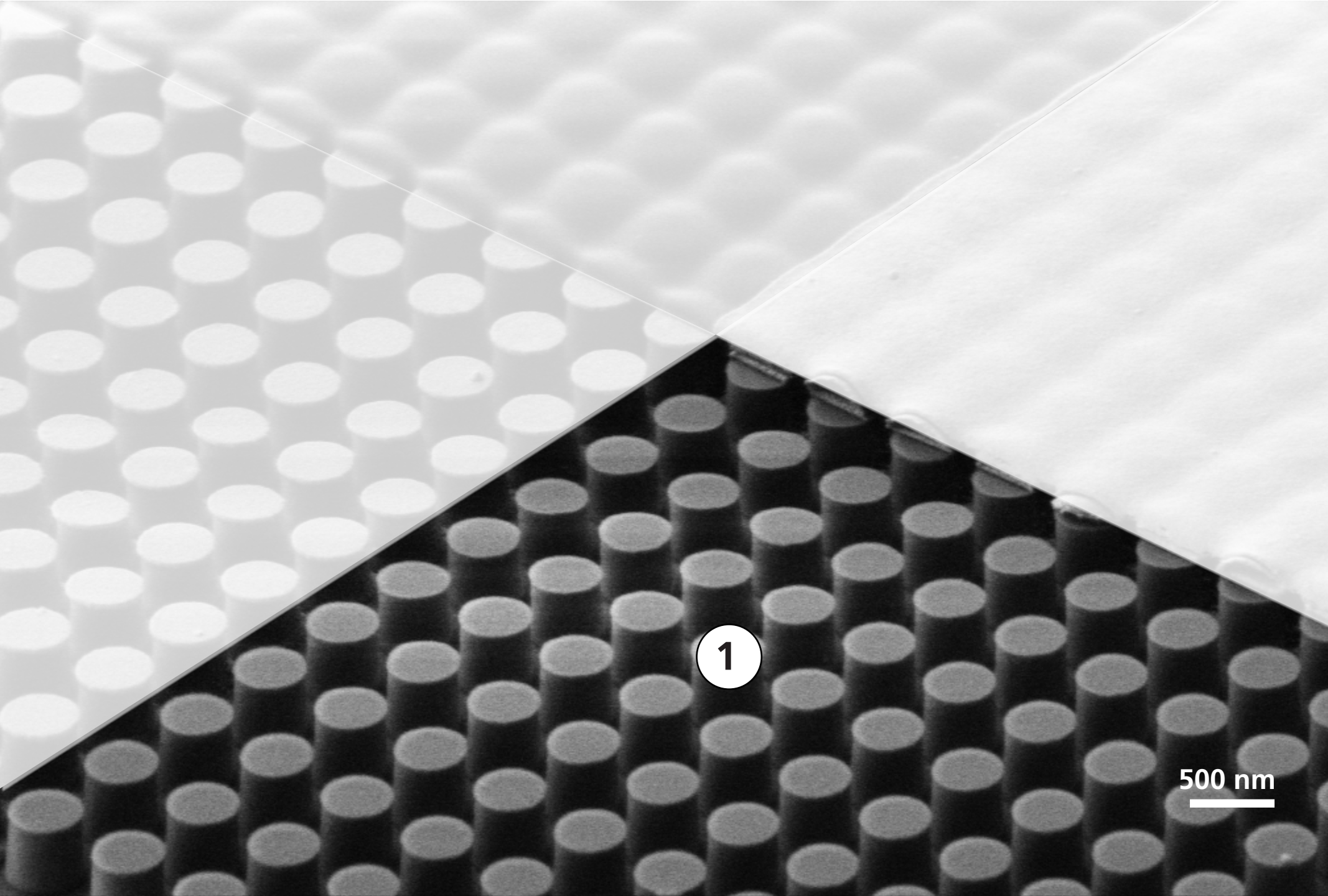


500 nm

**1** index

**2** zero index

**3** experiments



1

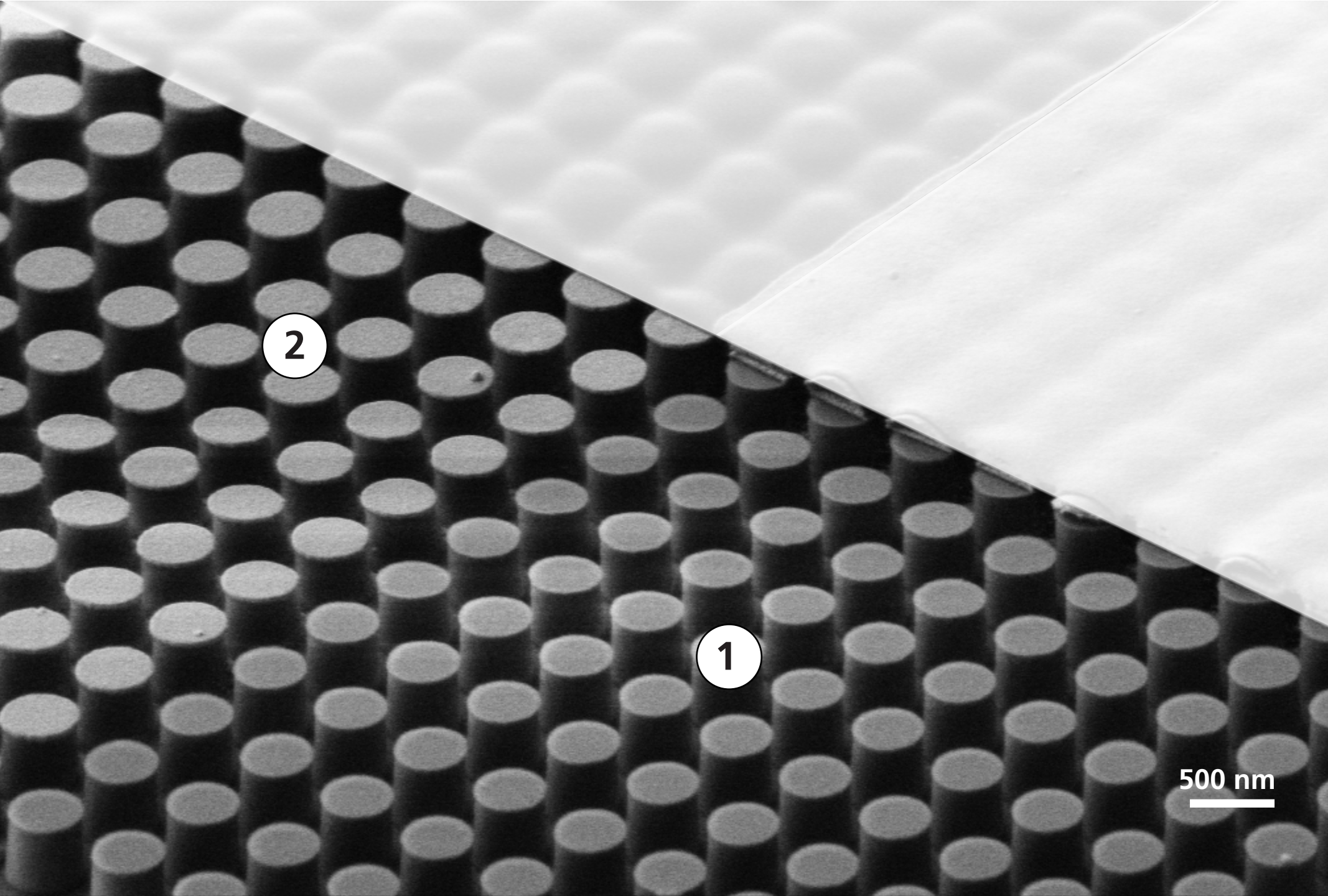
500 nm

1 index

2 zero index

3 experiments

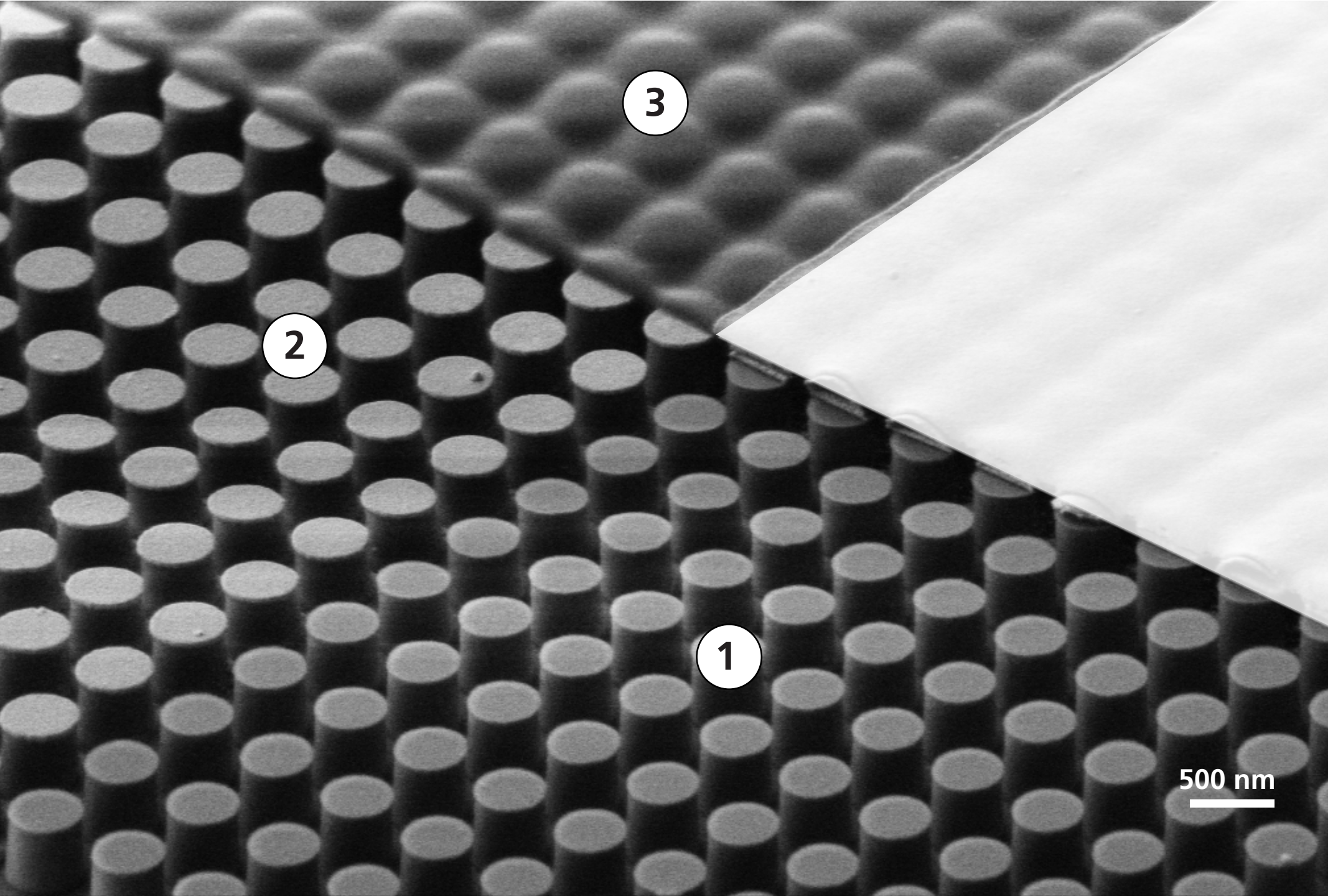




**1** index

**2** zero index

**3** experiments

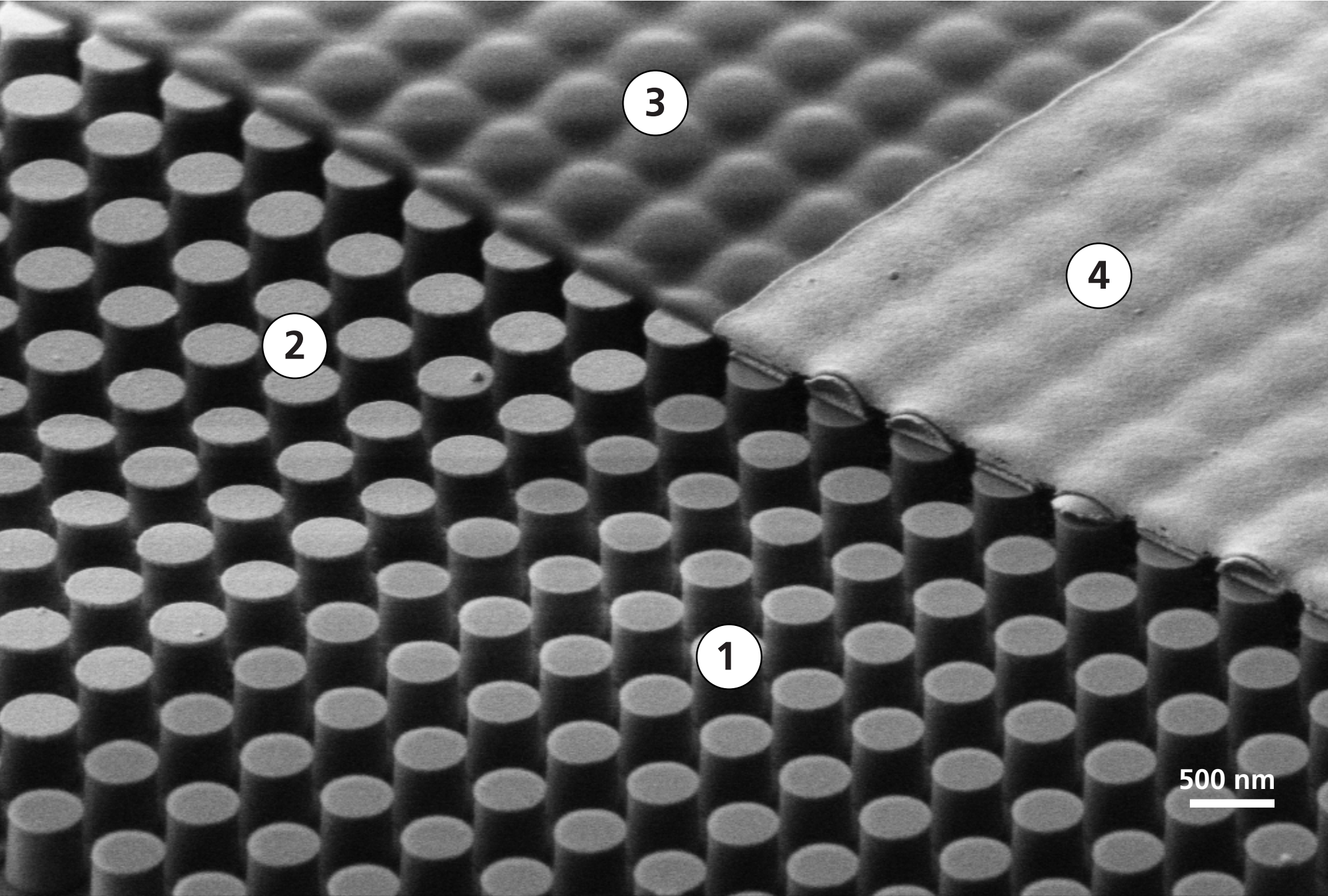


**1** index

**2** zero index

**3** experiments

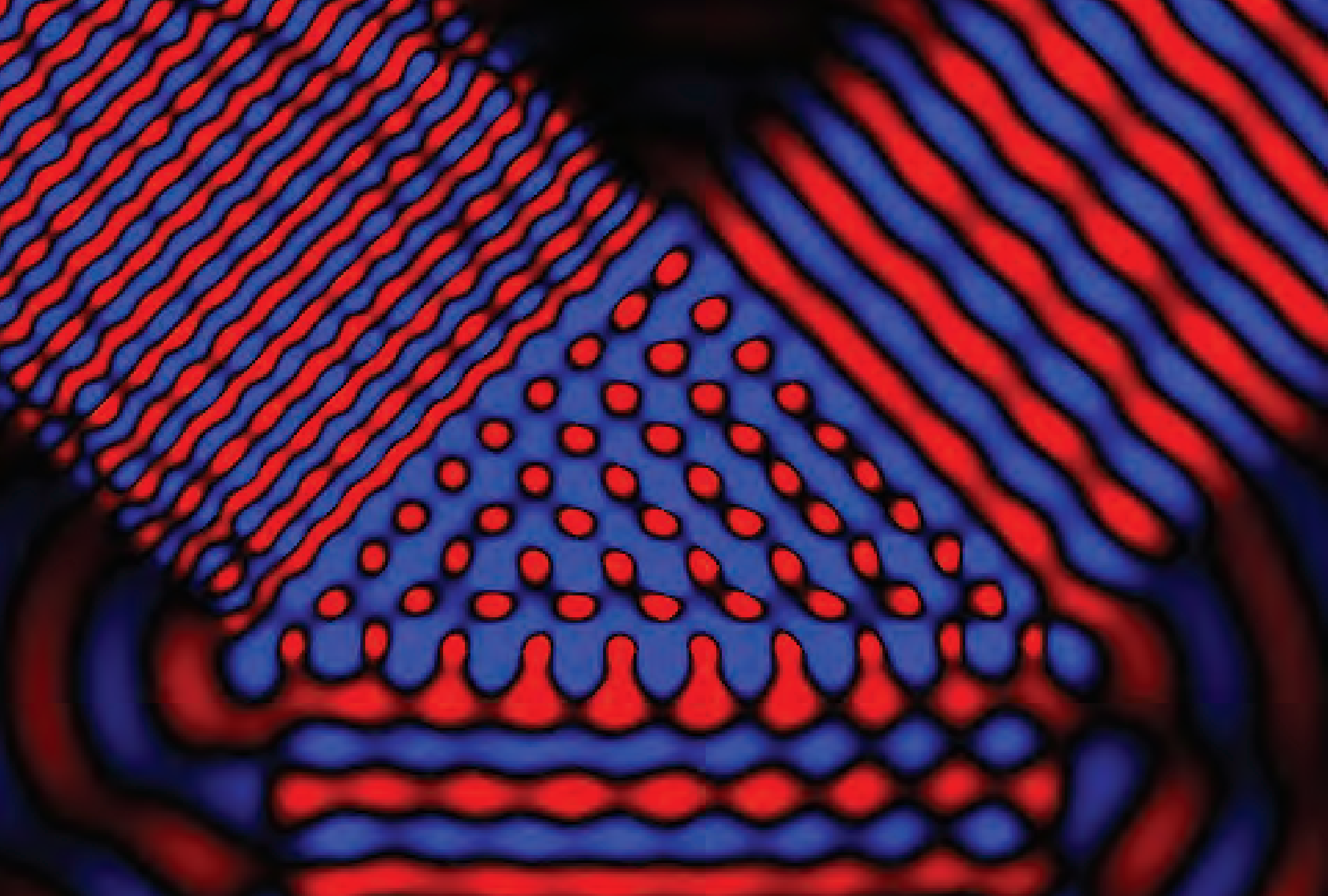




**1** index

**2** zero index

**3** experiments



1 index

2 zero index

3 experiments

# On-chip zero-index prism



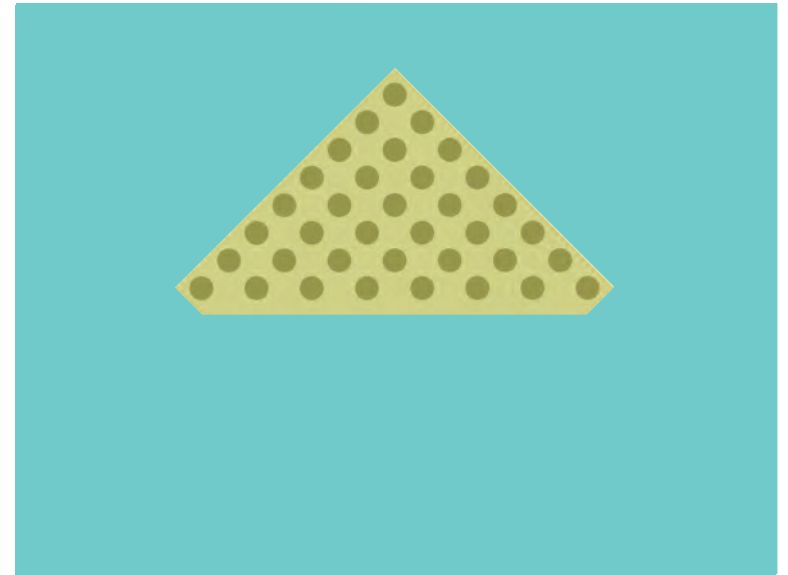
1 index

2 zero index

3 experiments



# On-chip zero-index prism

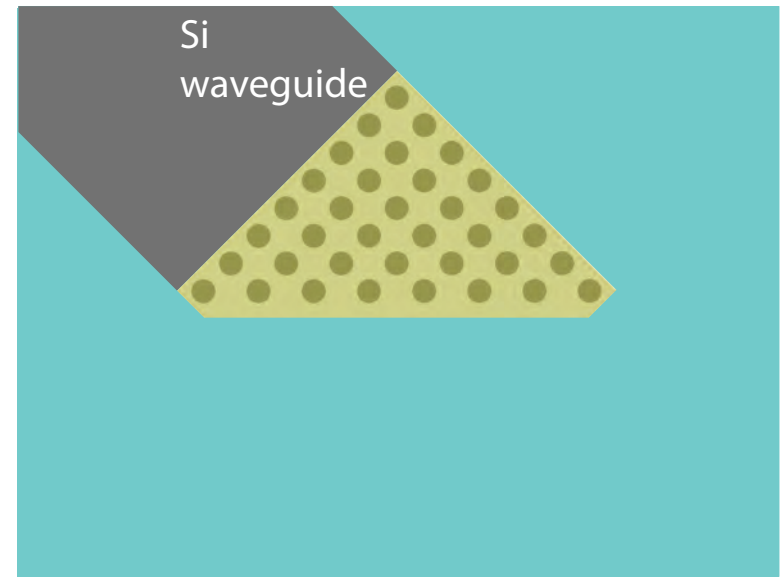


1 index

2 zero index

3 experiments

# On-chip zero-index prism

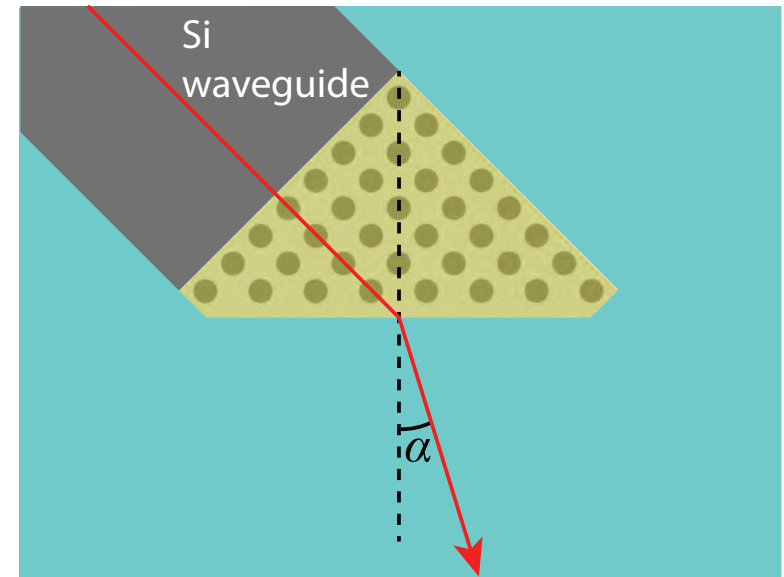


1 index

2 zero index

3 experiments

# On-chip zero-index prism

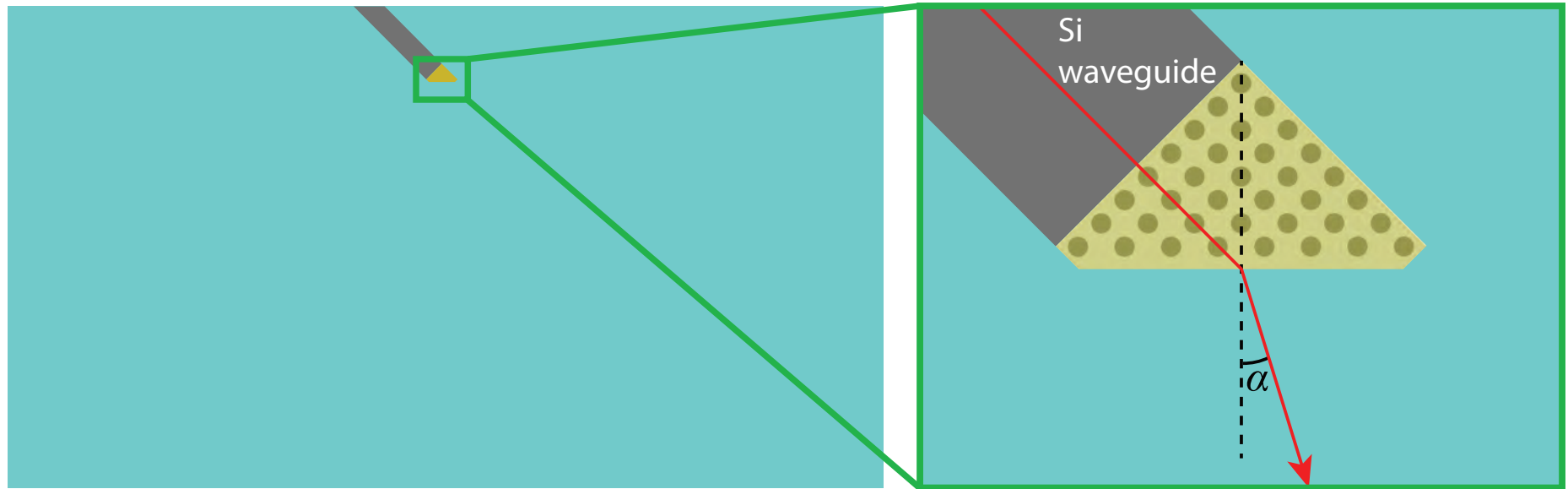


1 index

2 zero index

3 experiments

# On-chip zero-index prism

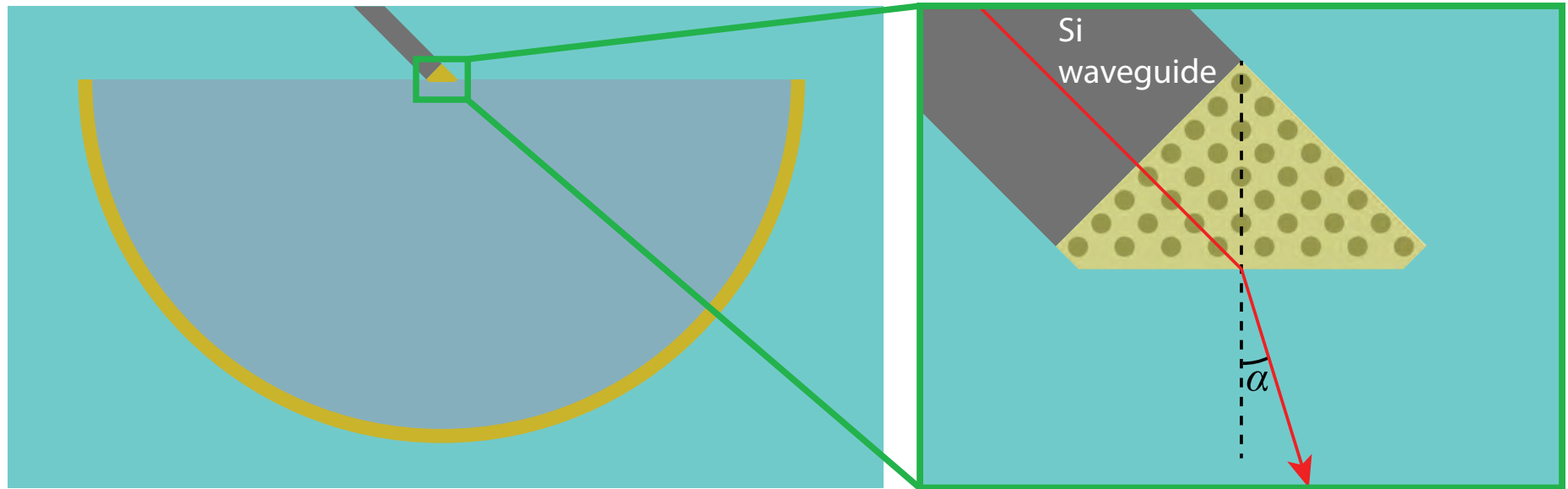


1 index

2 zero index

3 experiments

# On-chip zero-index prism

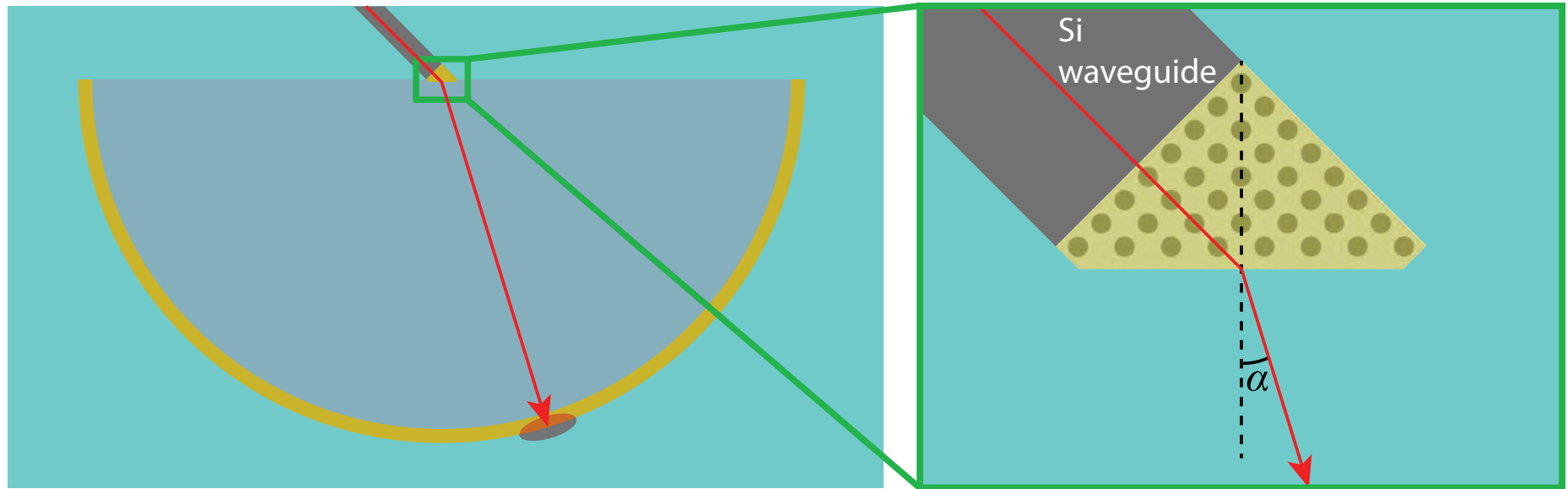


1 index

2 zero index

3 experiments

# On-chip zero-index prism

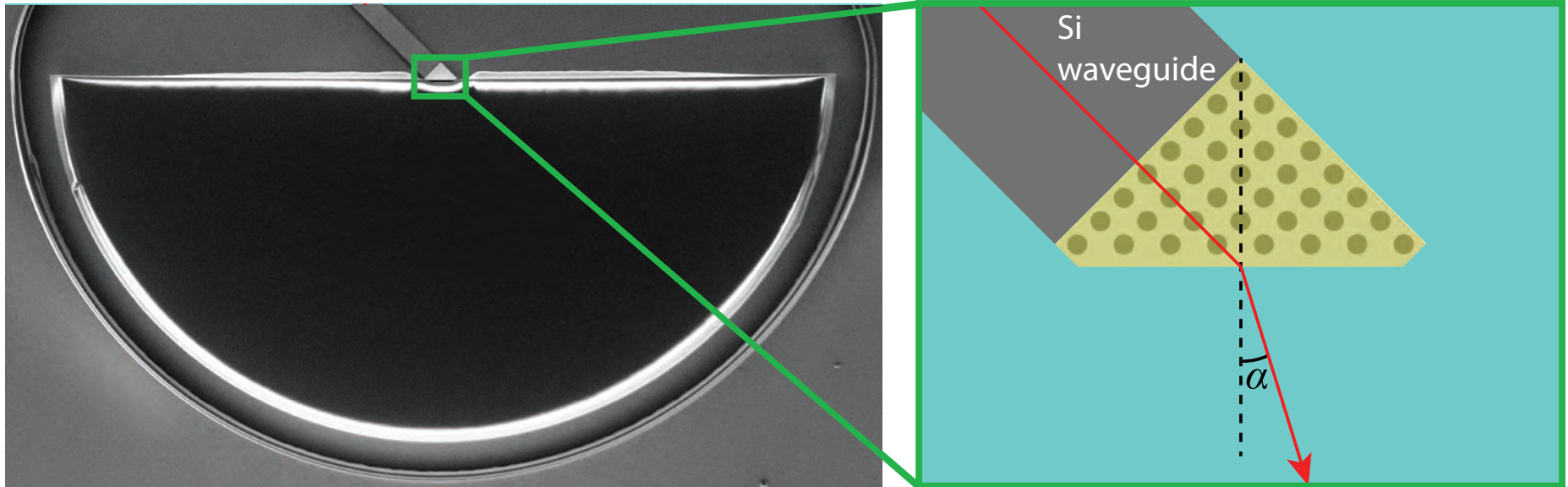


1 index

2 zero index

3 experiments

# On-chip zero-index prism

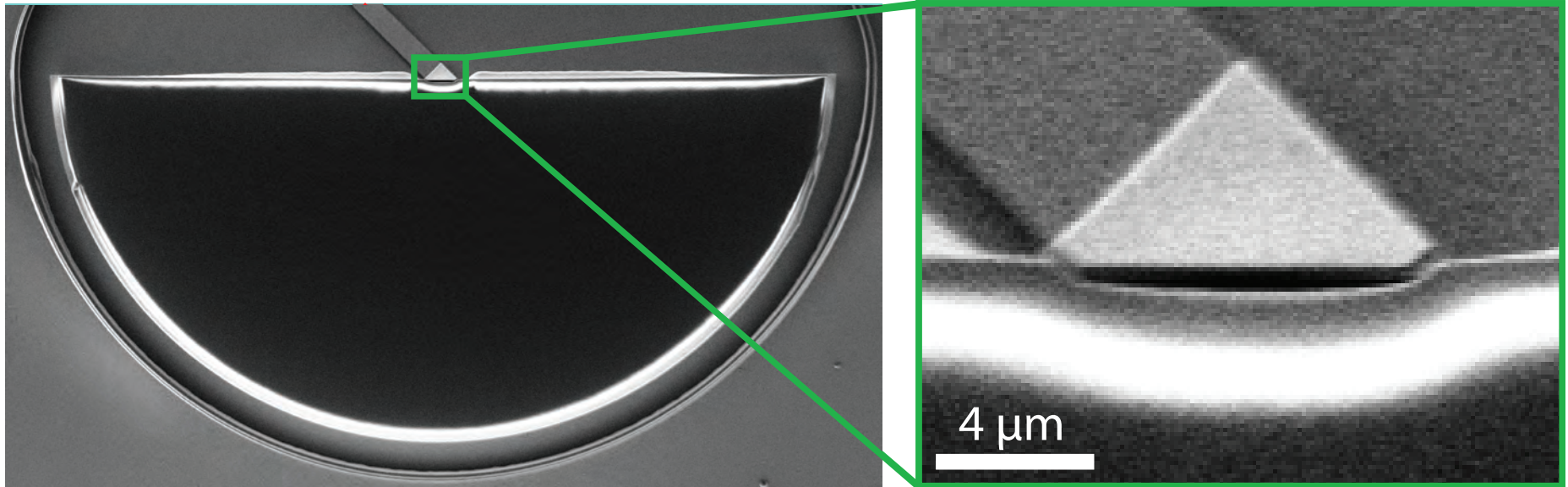


1 index

2 zero index

3 experiments

# On-chip zero-index prism

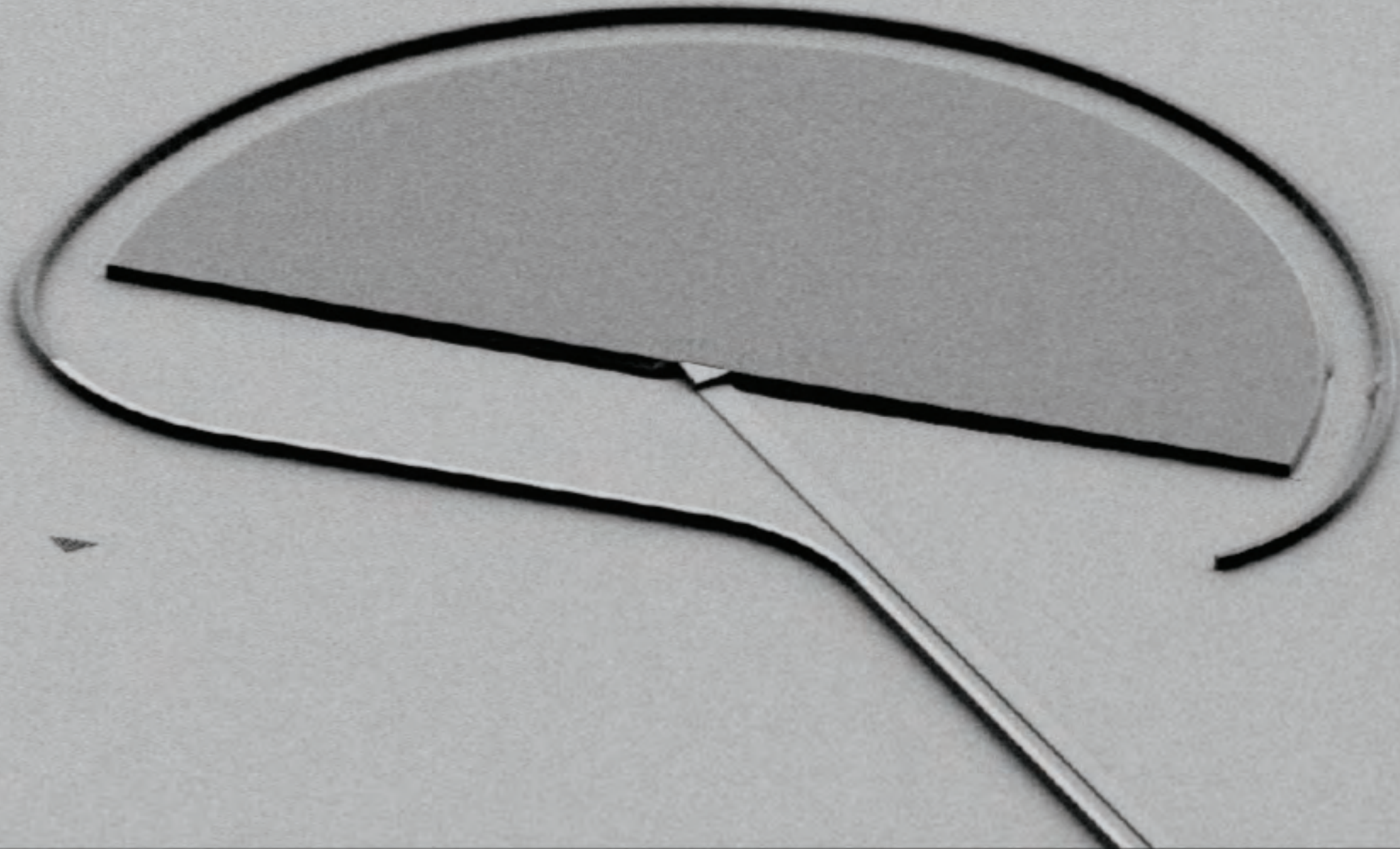


1 index

2 zero index

3 experiments



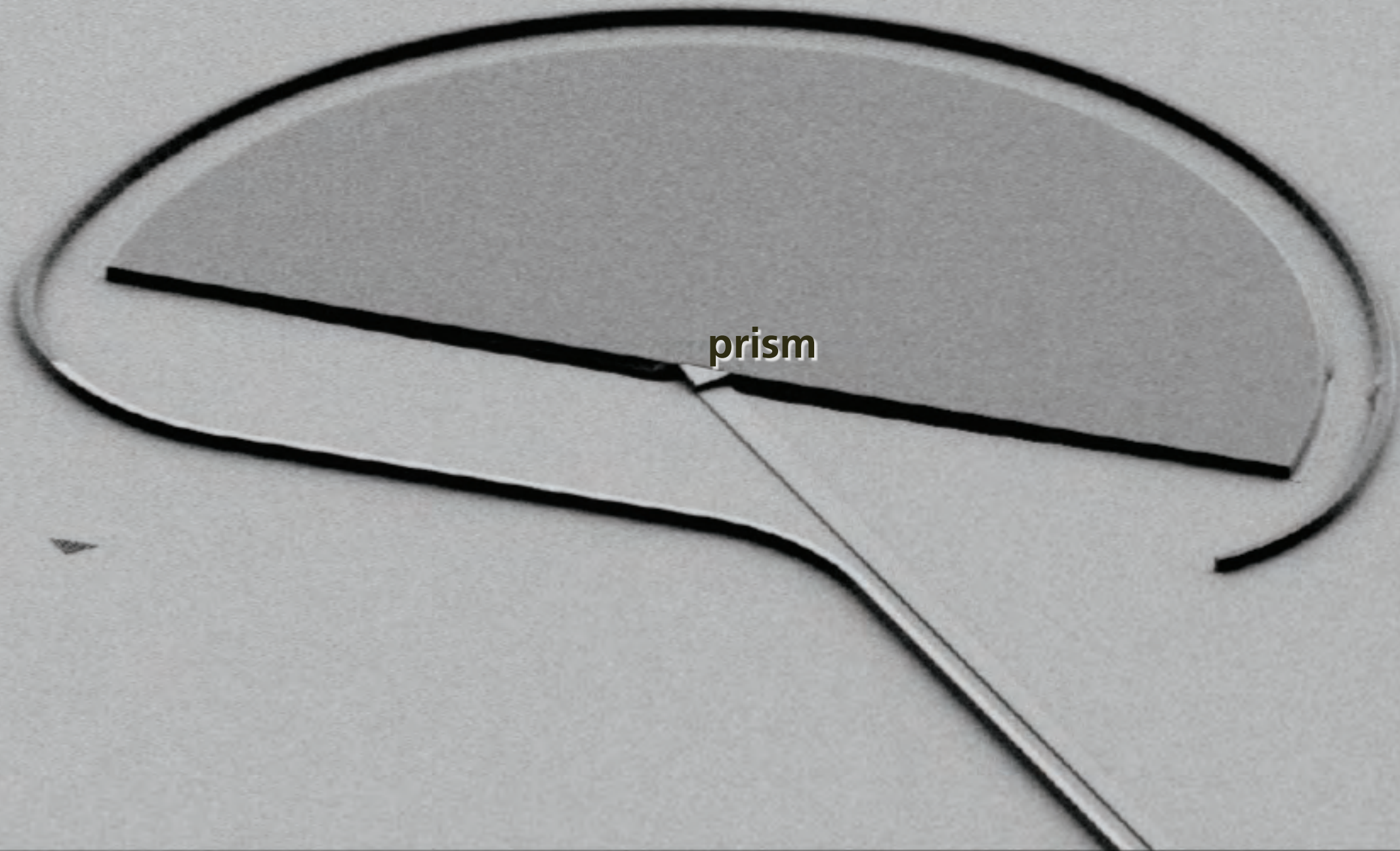


**1** index

**2** zero index

**3** experiments



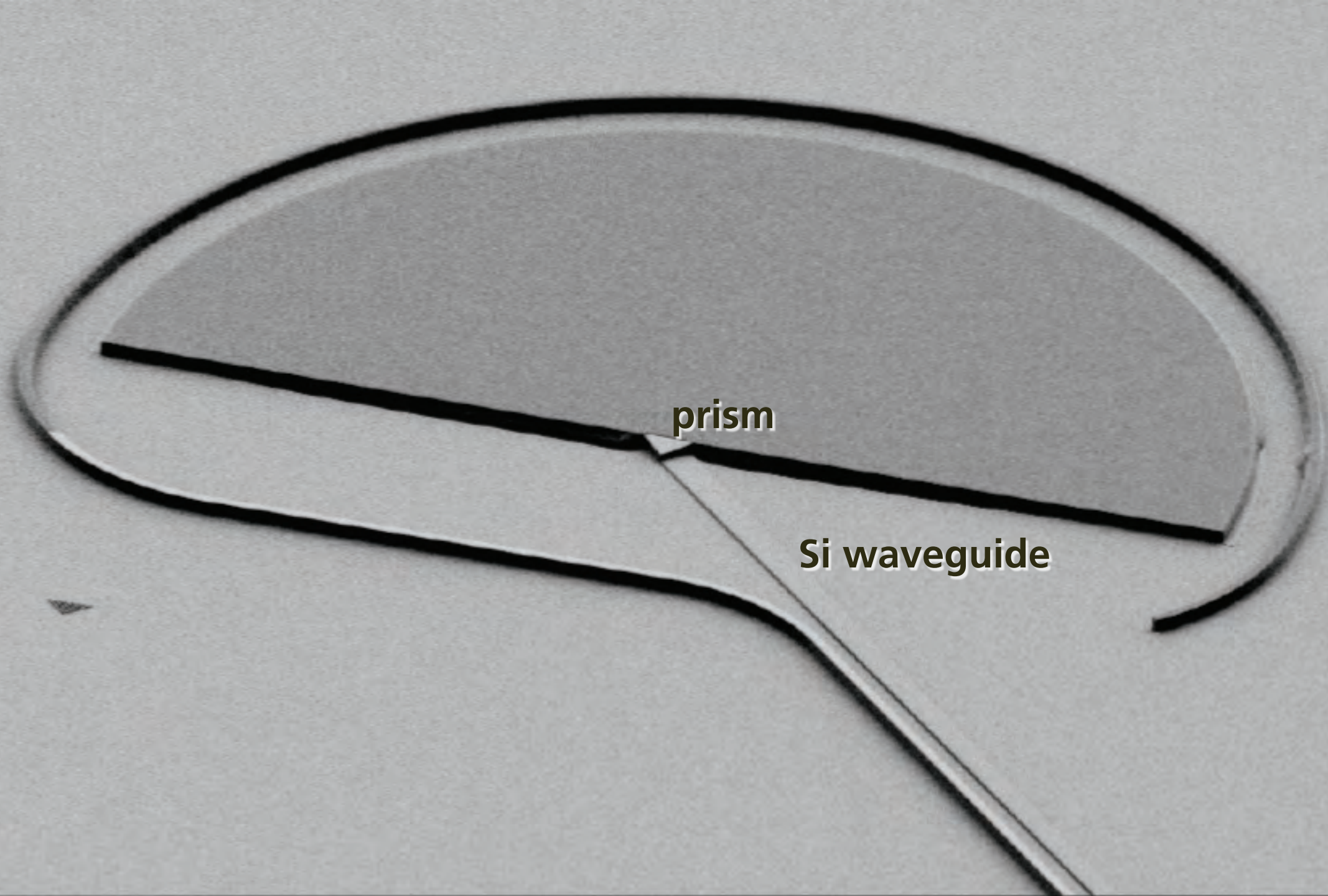


**1** index

**2** zero index

**3** experiments





prism

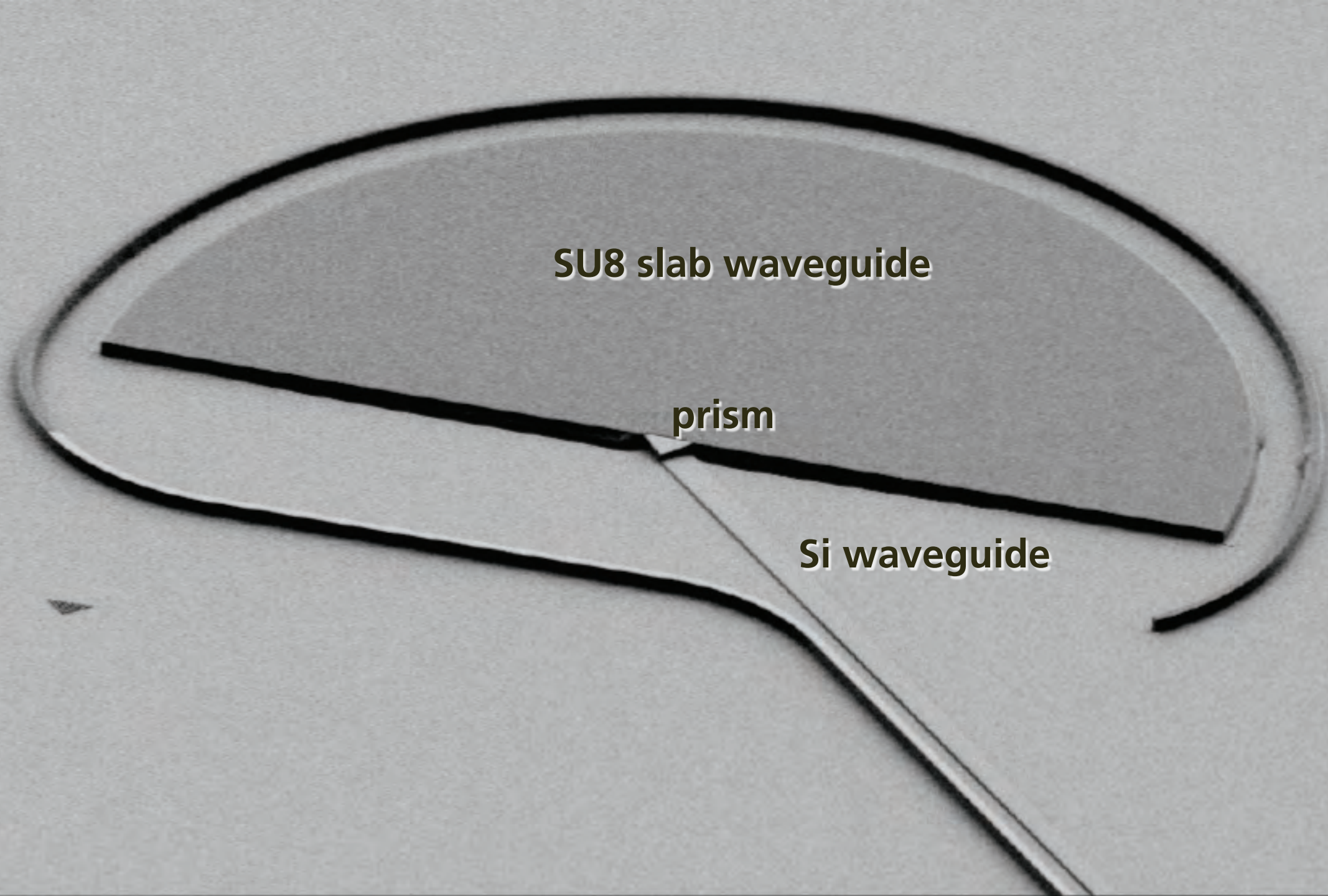
Si waveguide

1 index

2 zero index

3 experiments





SU8 slab waveguide

prism

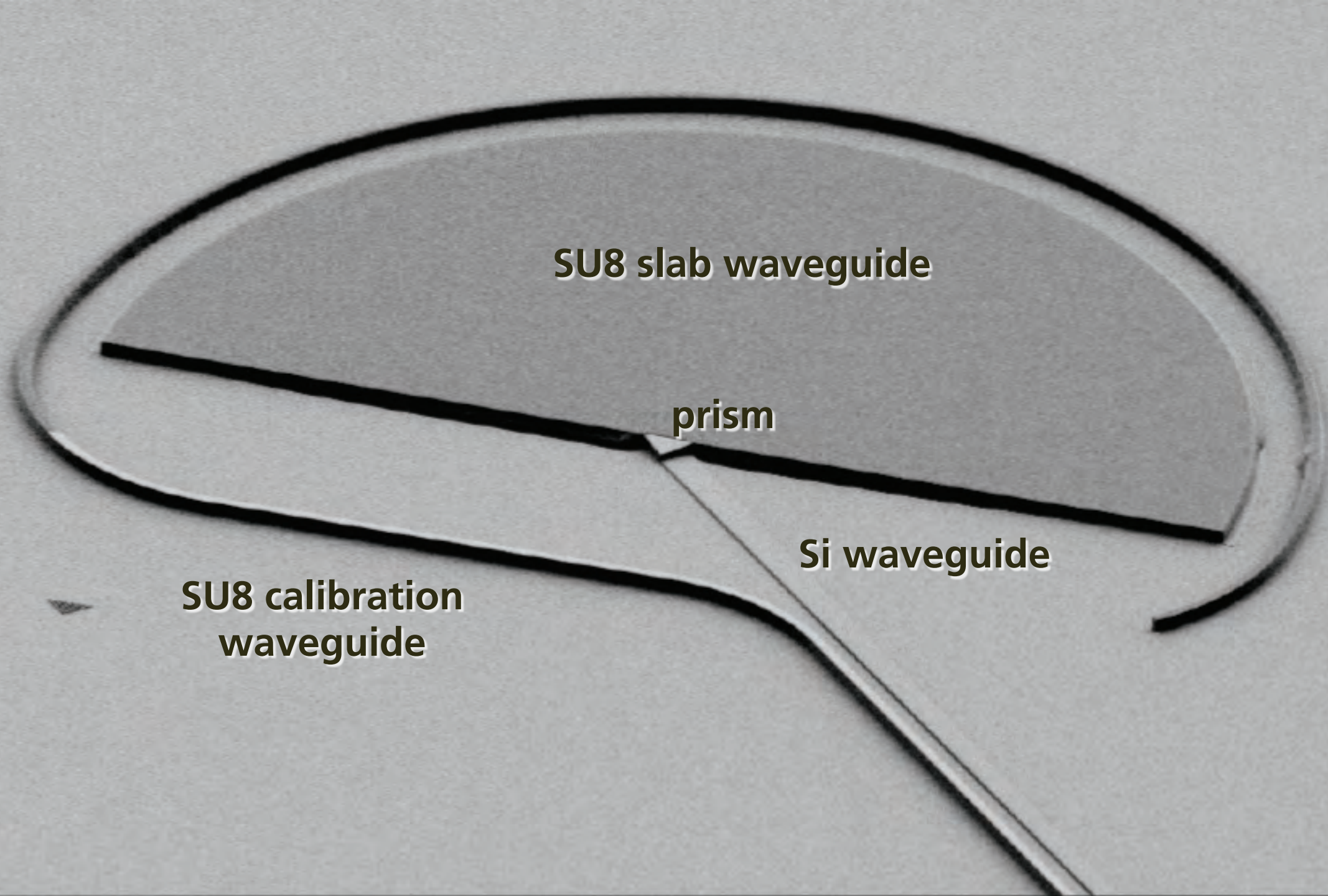
Si waveguide

1 index

2 zero index

3 experiments





SU8 slab waveguide

prism

Si waveguide

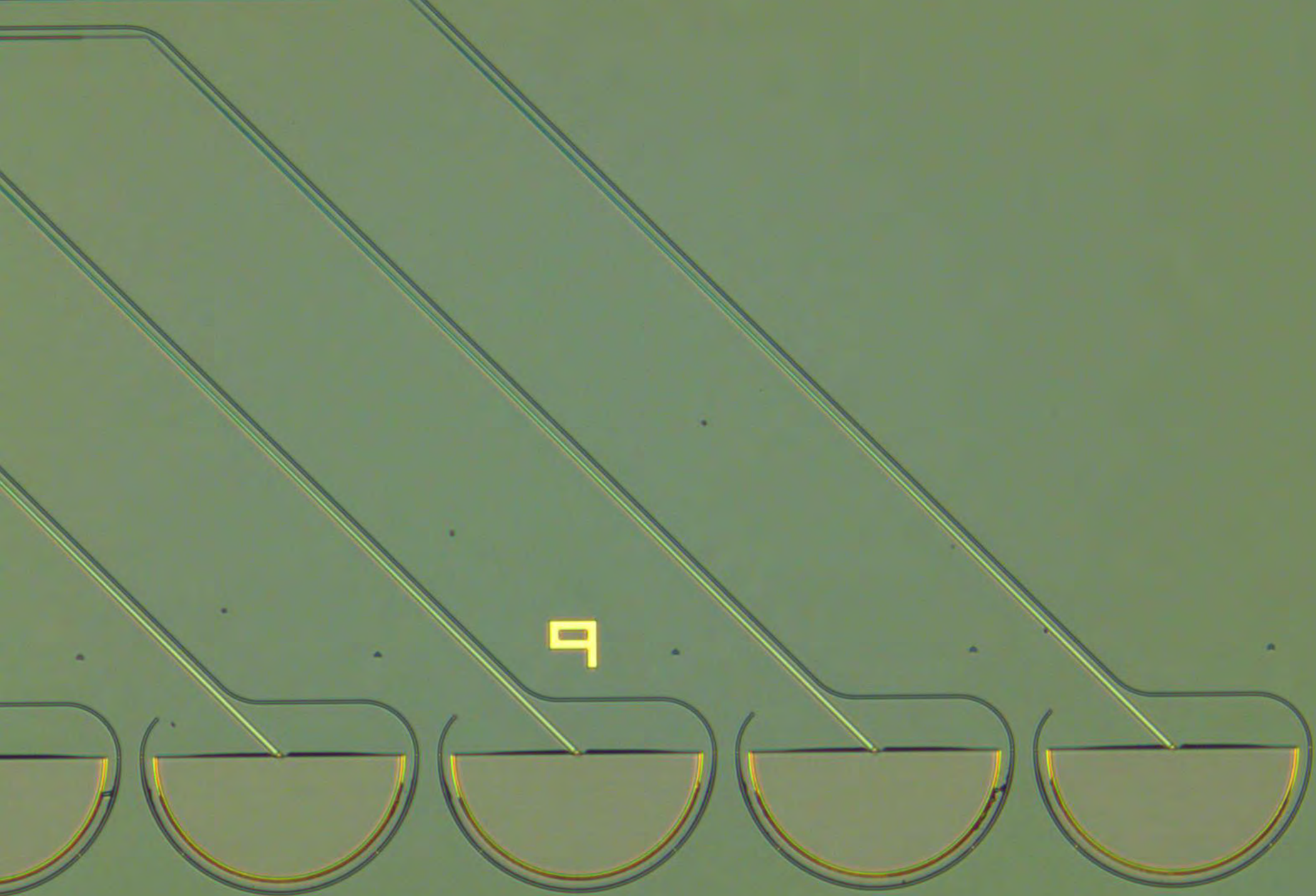
SU8 calibration  
waveguide

1 index

2 zero index

3 experiments



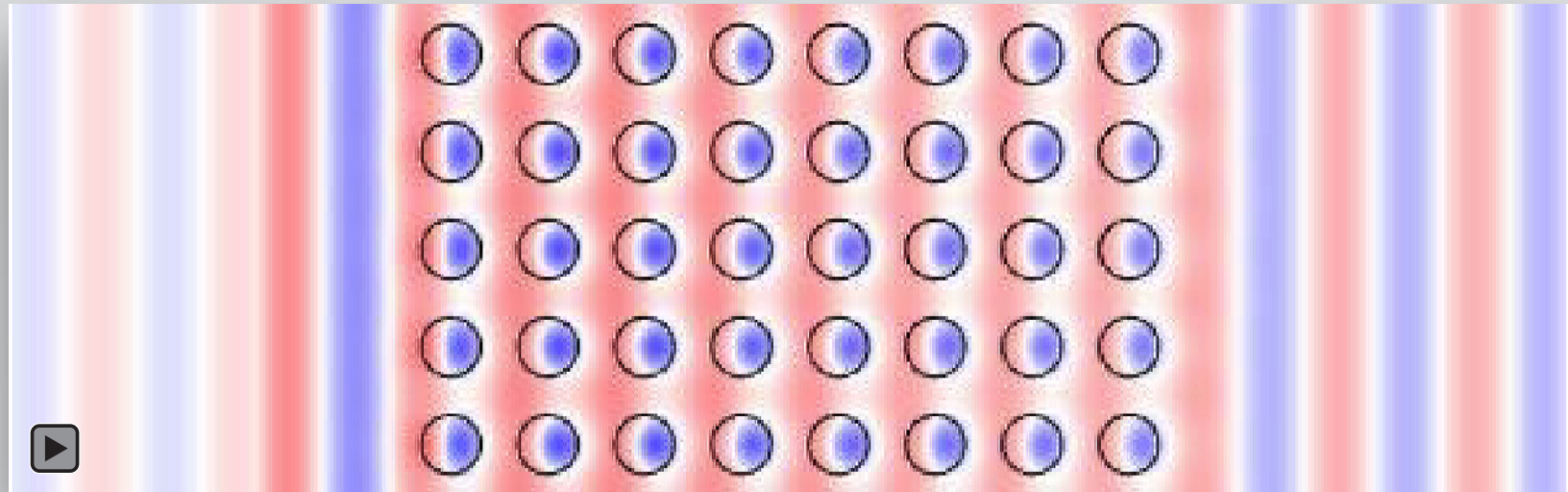


**1** index

**2** zero index

**3** experiments

at design wavelength (1590 nm)

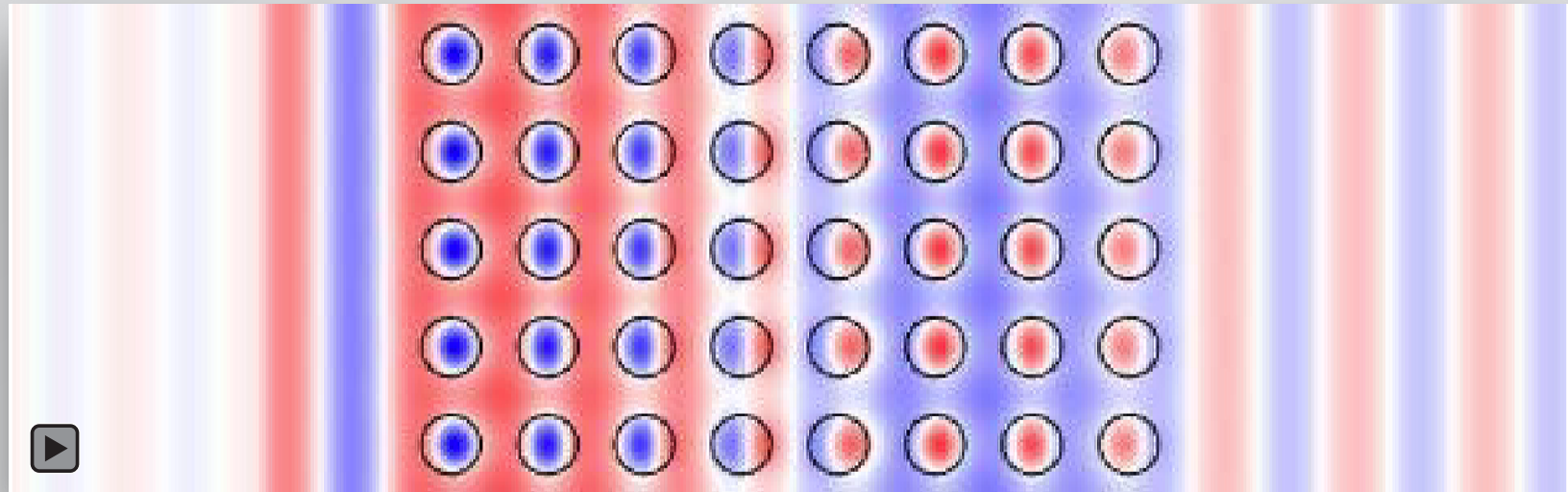


**1** index

**2** zero index

**3** experiments

below design wavelength (1530 nm)



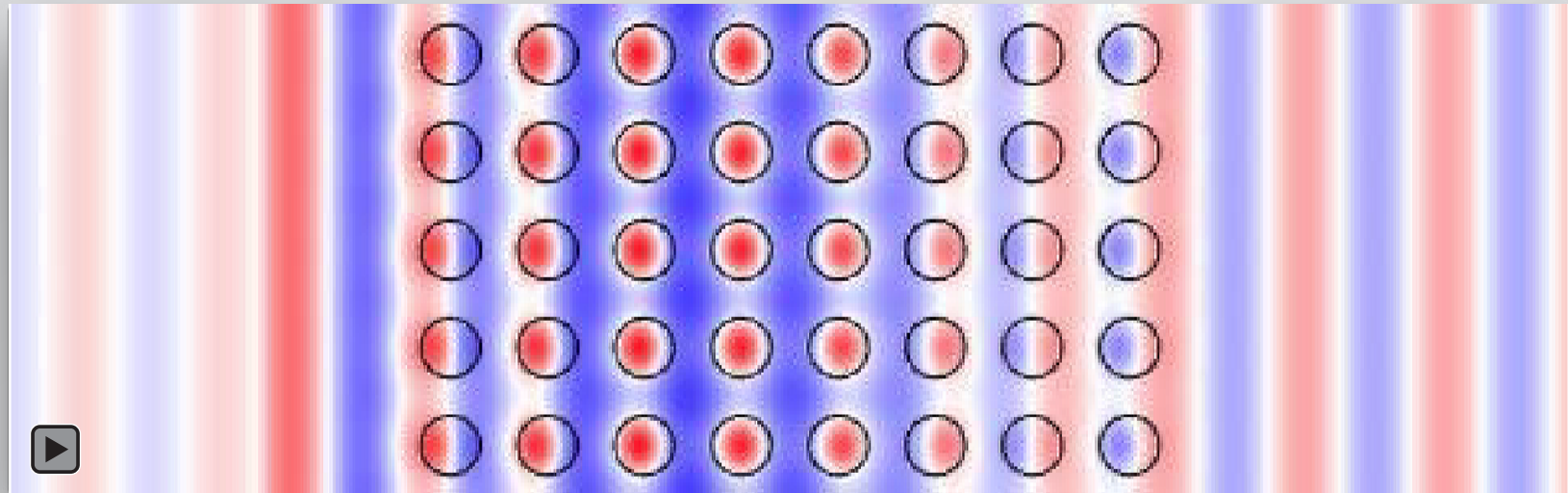
1 index

2 zero index

3 experiments



above design wavelength (1650 nm)

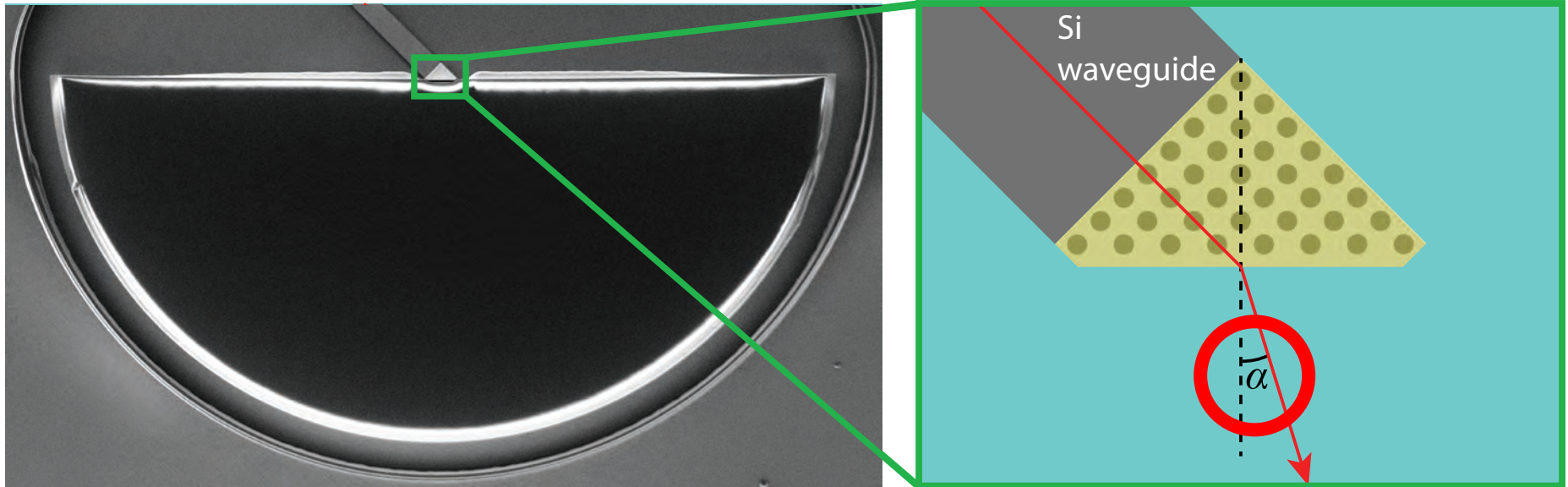


1 index

2 zero index

3 experiments

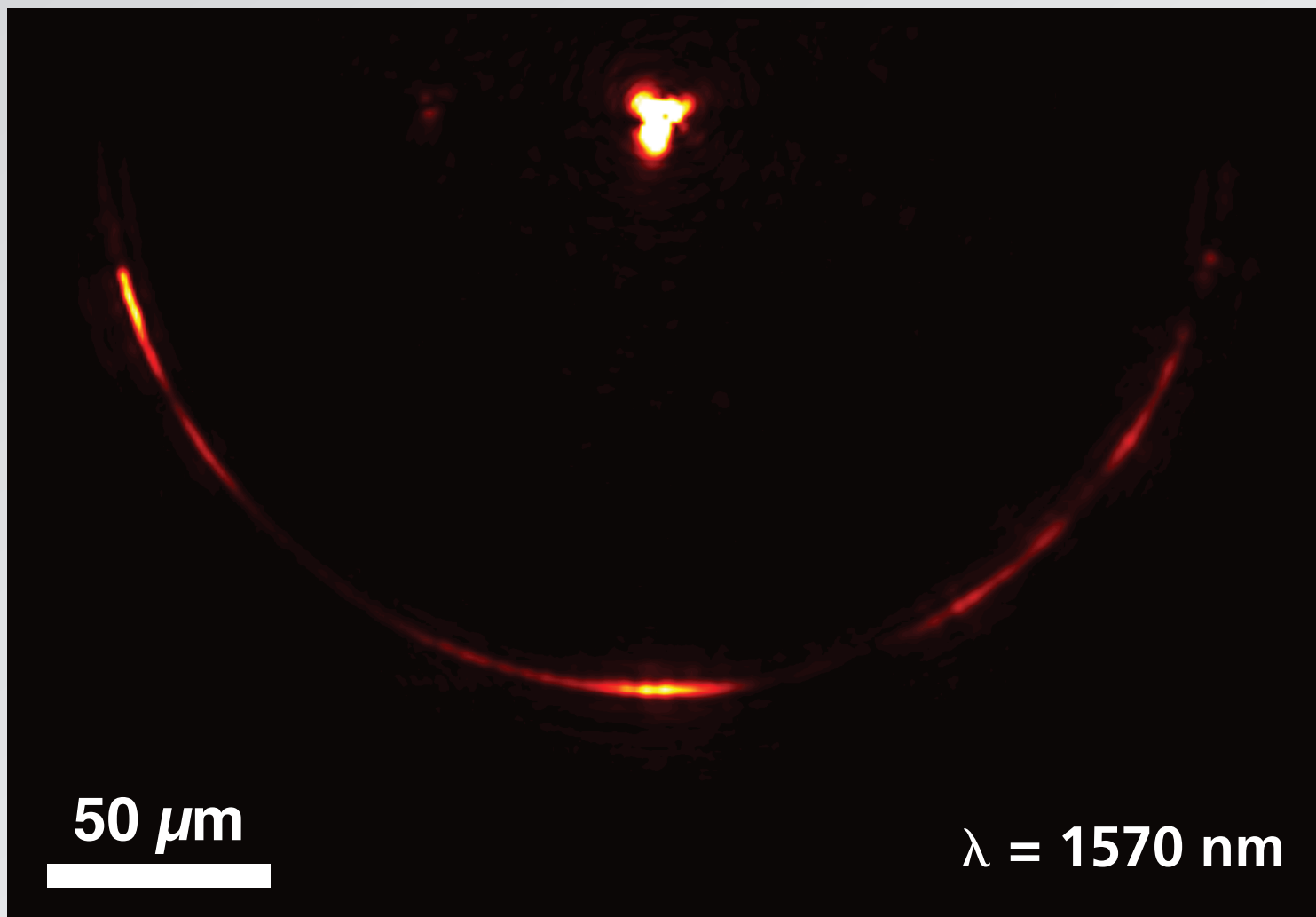
# On-chip zero-index prism



1 index

2 zero index

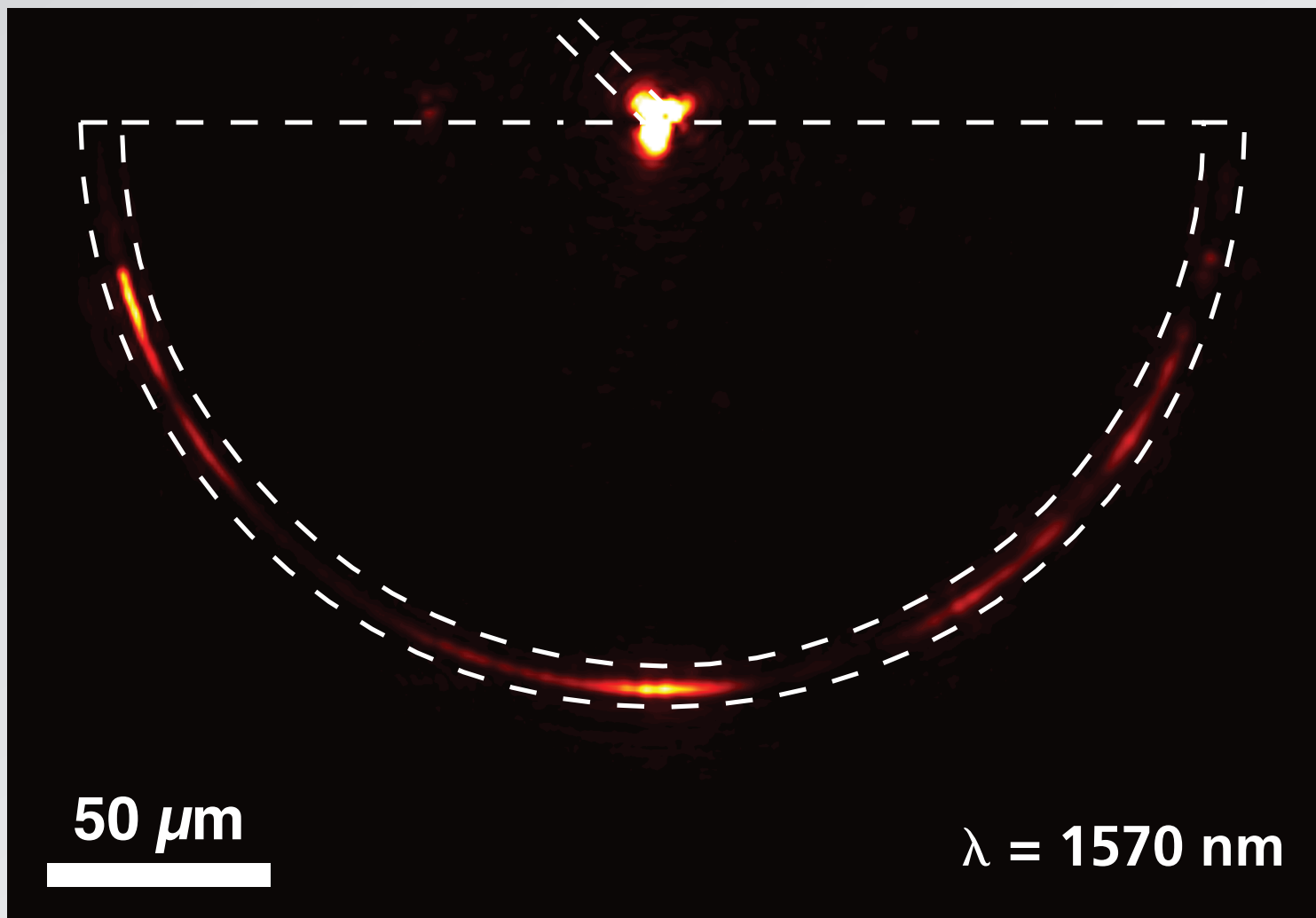
3 experiments



1 index

2 zero index

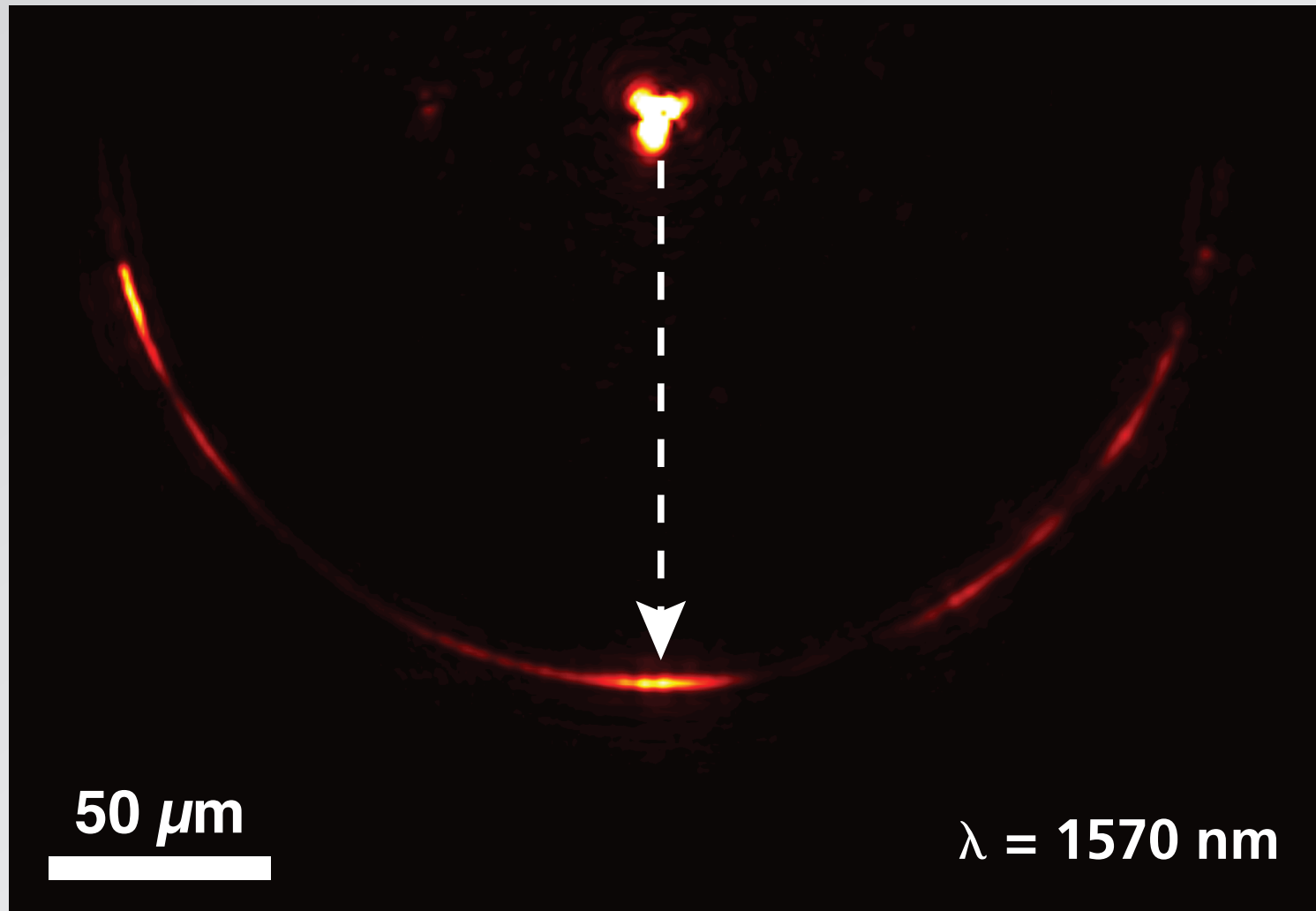
3 experiments



1 index

2 zero index

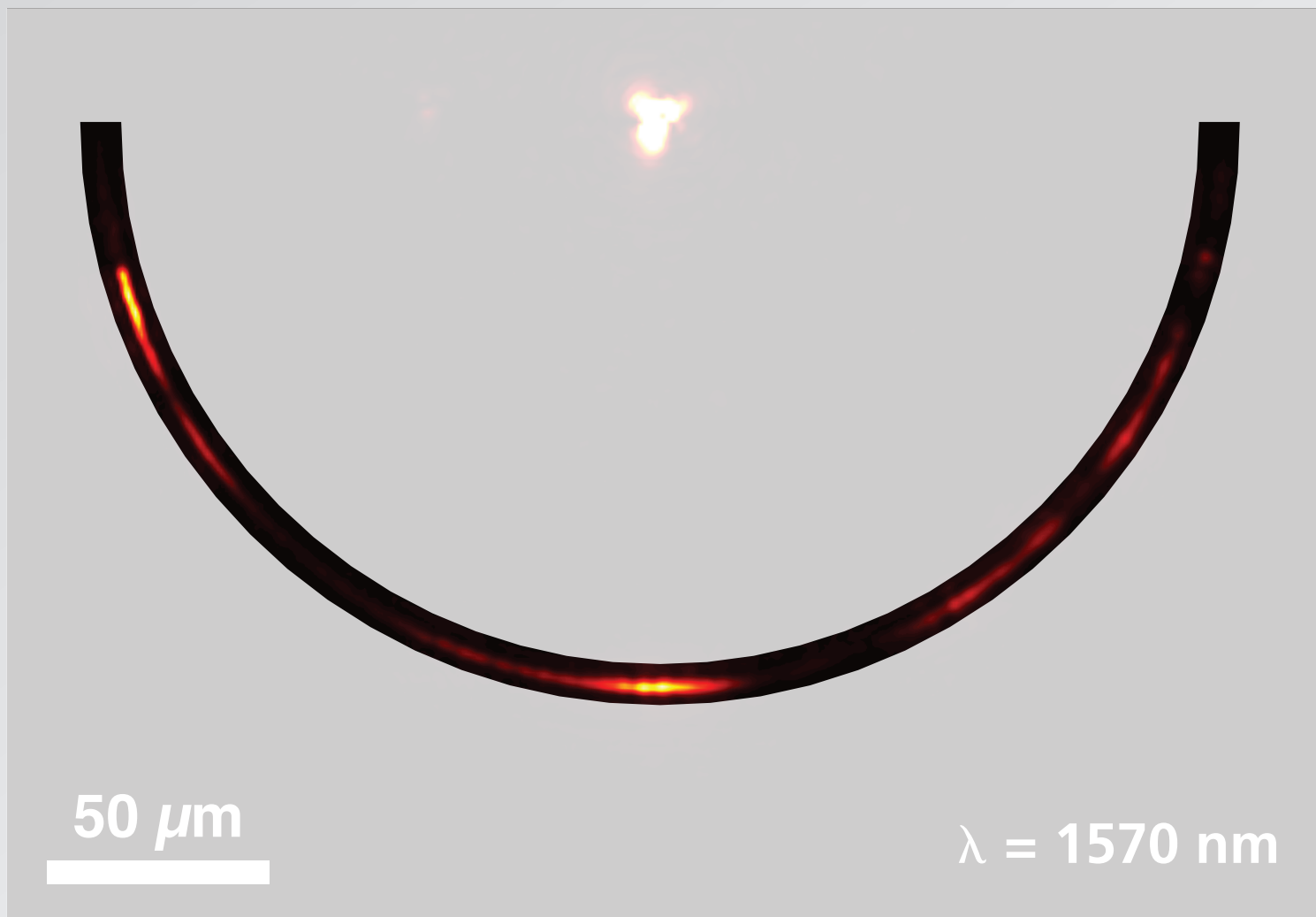
3 experiments



1 index

2 zero index

3 experiments

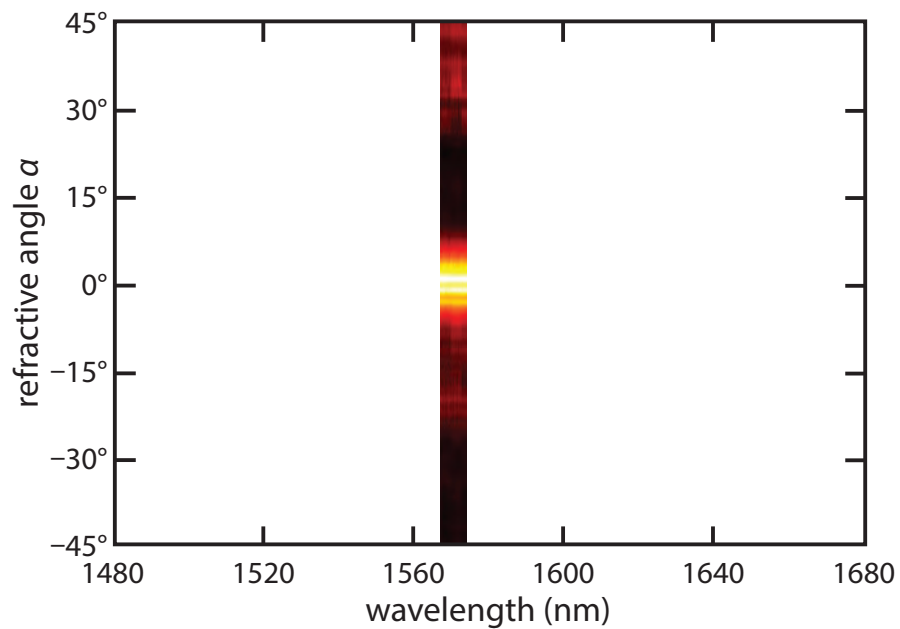


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

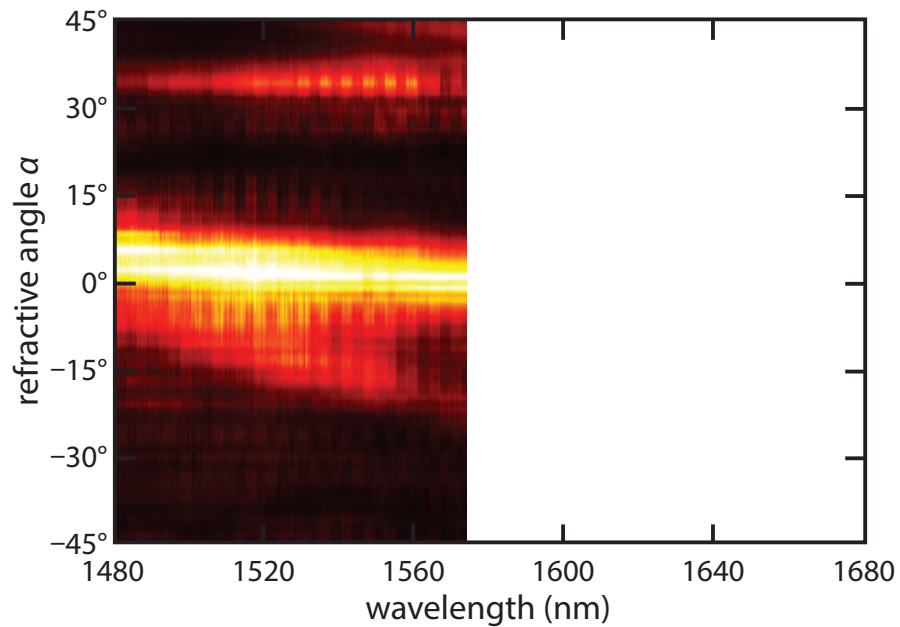


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle



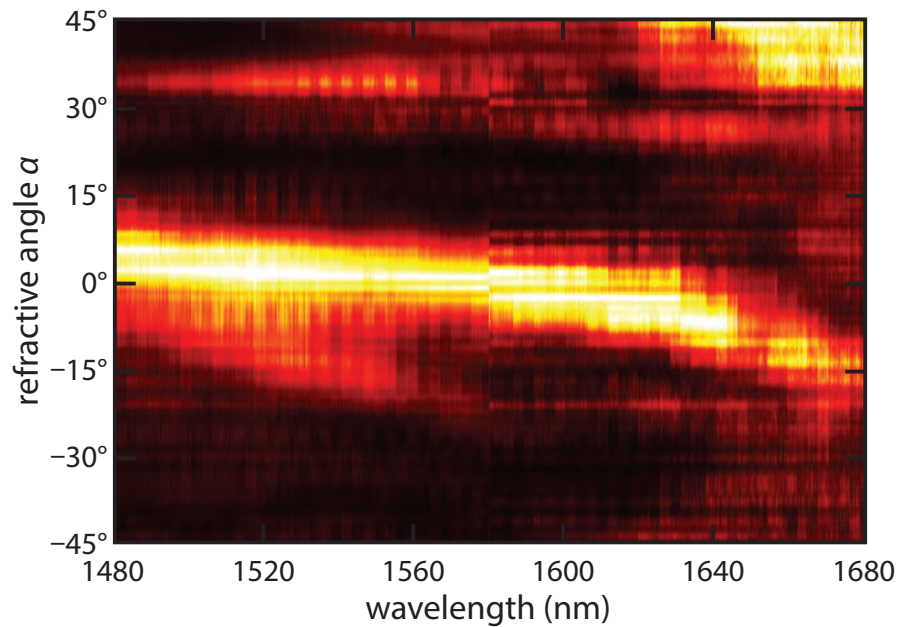
1 index

2 zero index

3 experiments



# Wavelength dependence of refraction angle

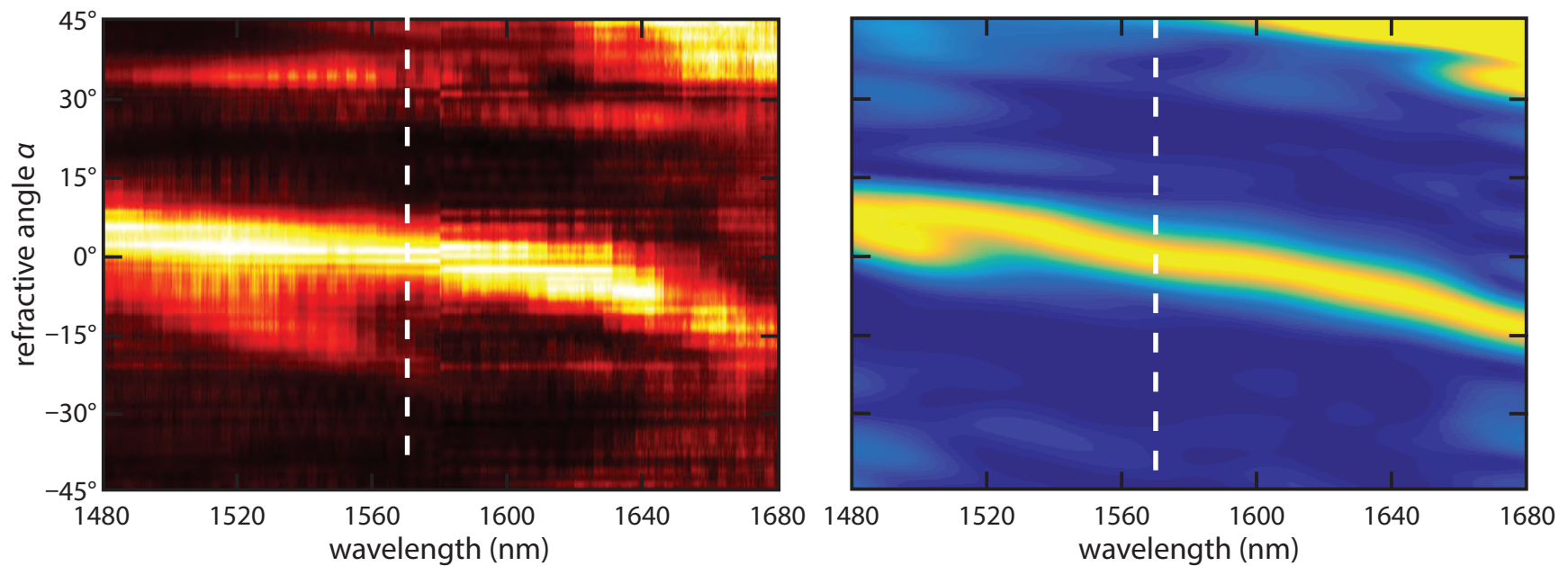


1 index

2 zero index

3 experiments

# Wavelength dependence of refraction angle

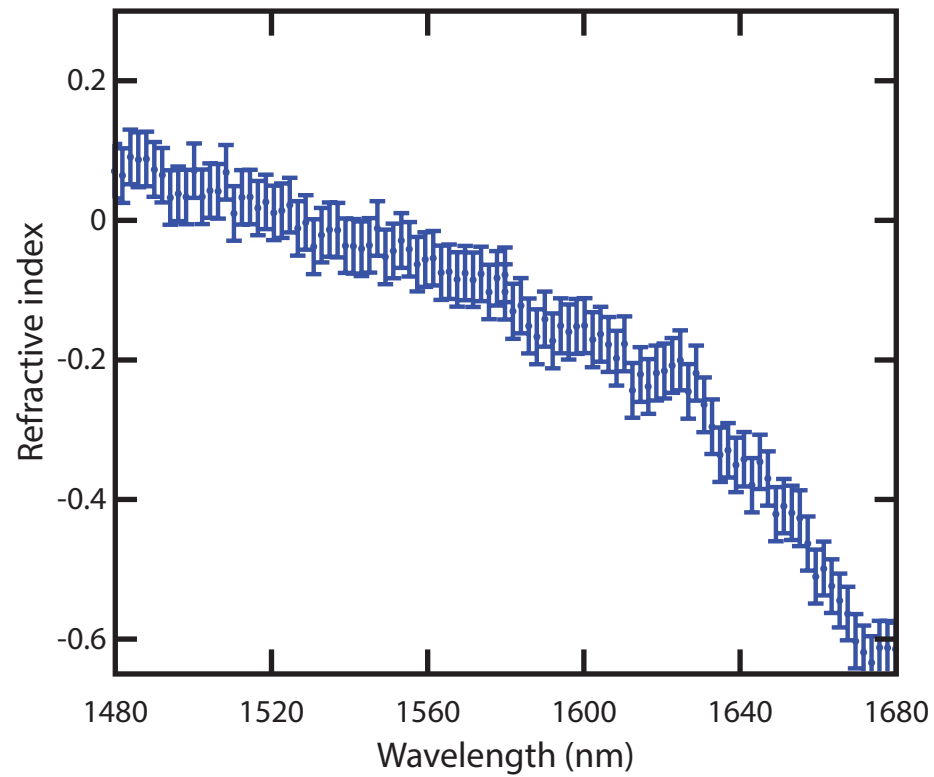


1 index

2 zero index

3 experiments

# Wavelength dependence of index

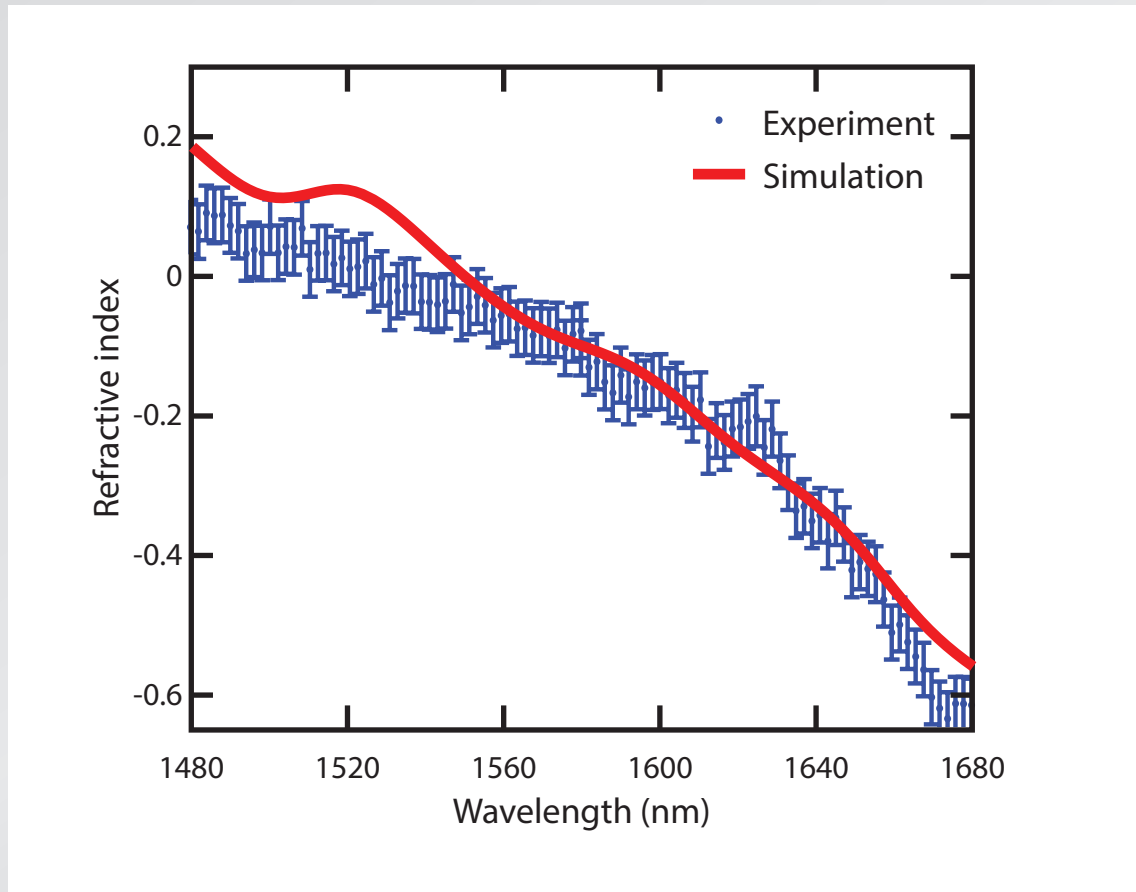


1 index

2 zero index

3 experiments

# Wavelength dependence of index



1 index

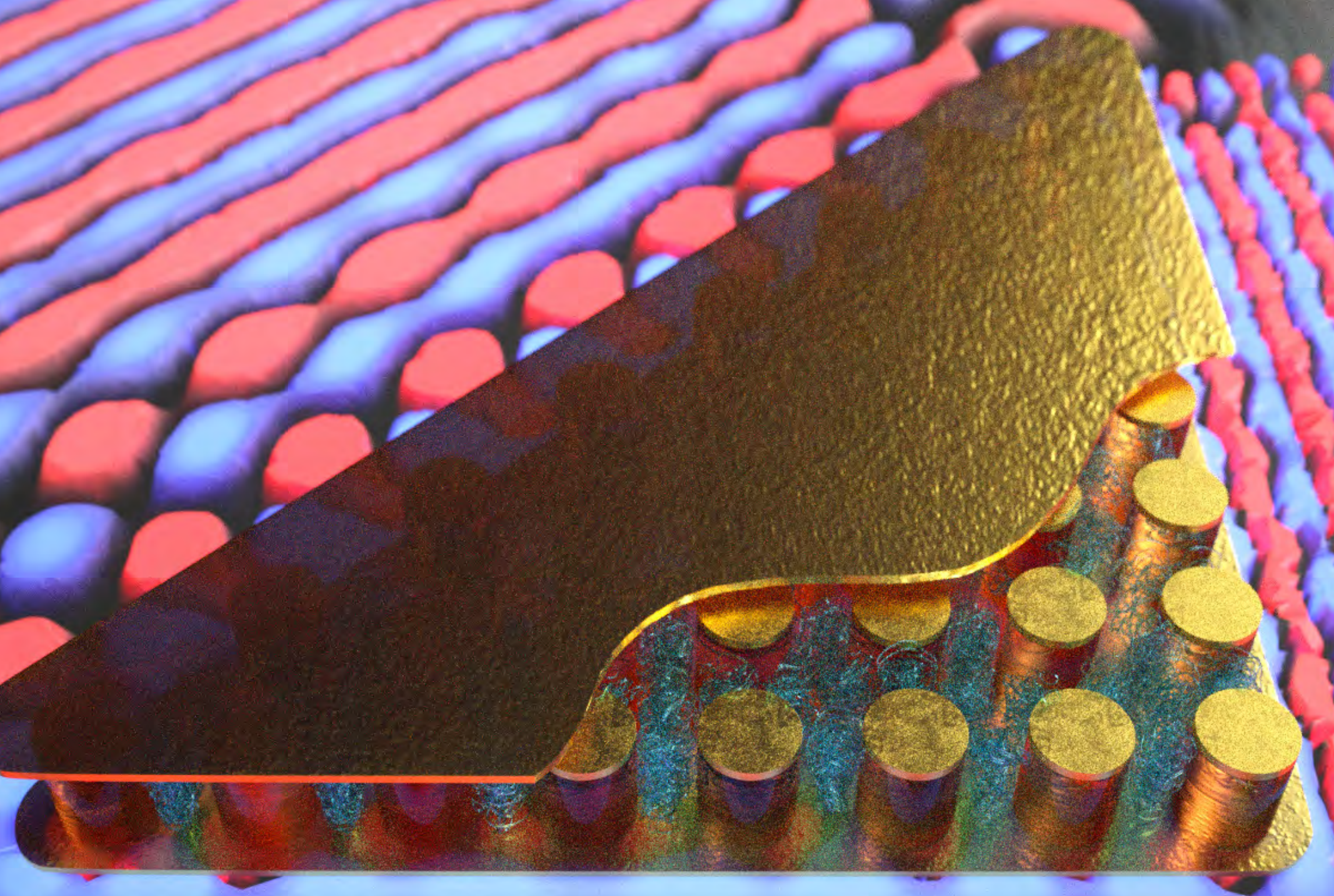
2 zero index

3 experiments

## More extreme optics

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



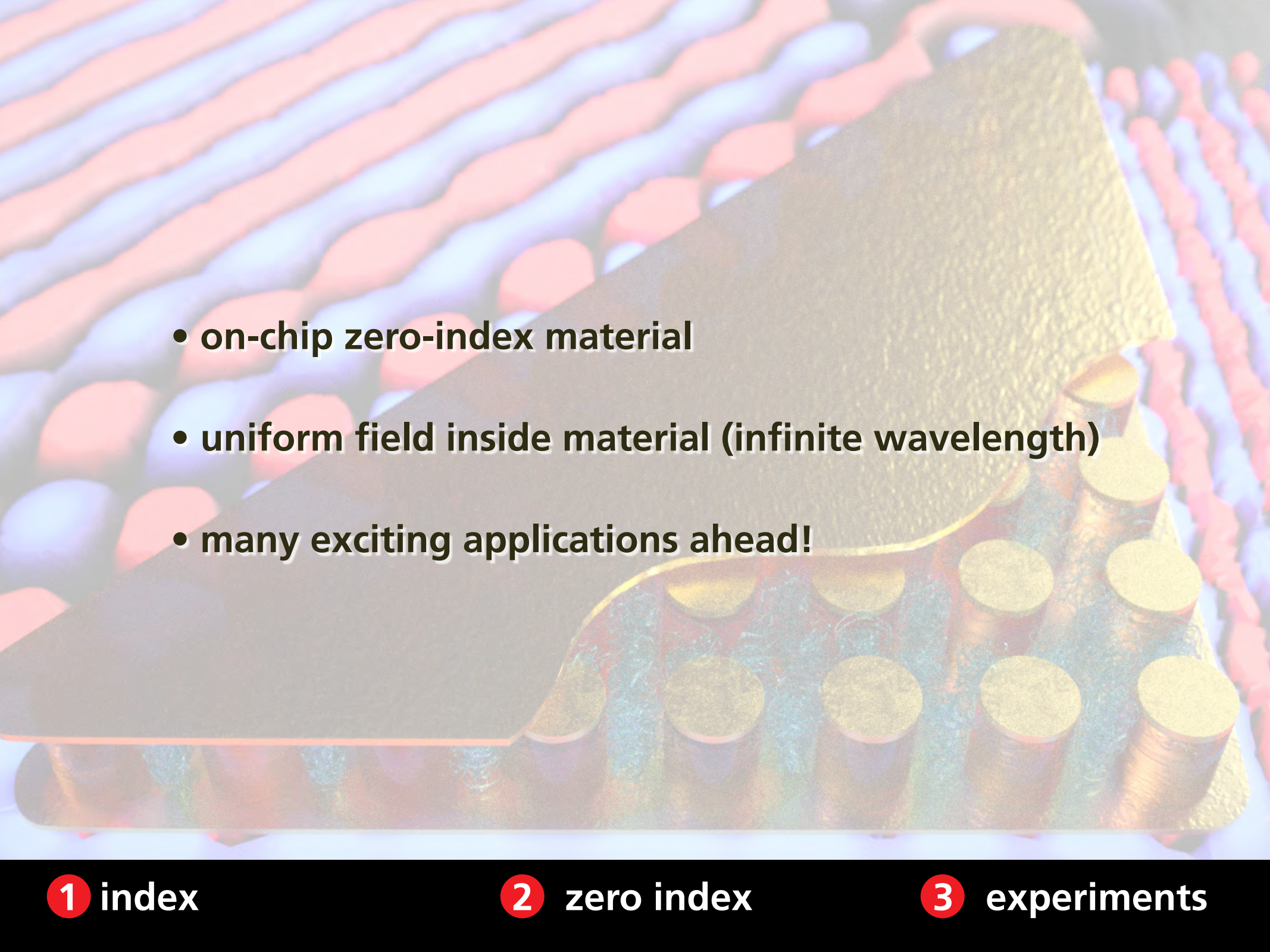


**1** index

**2** zero index

**3** experiments



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

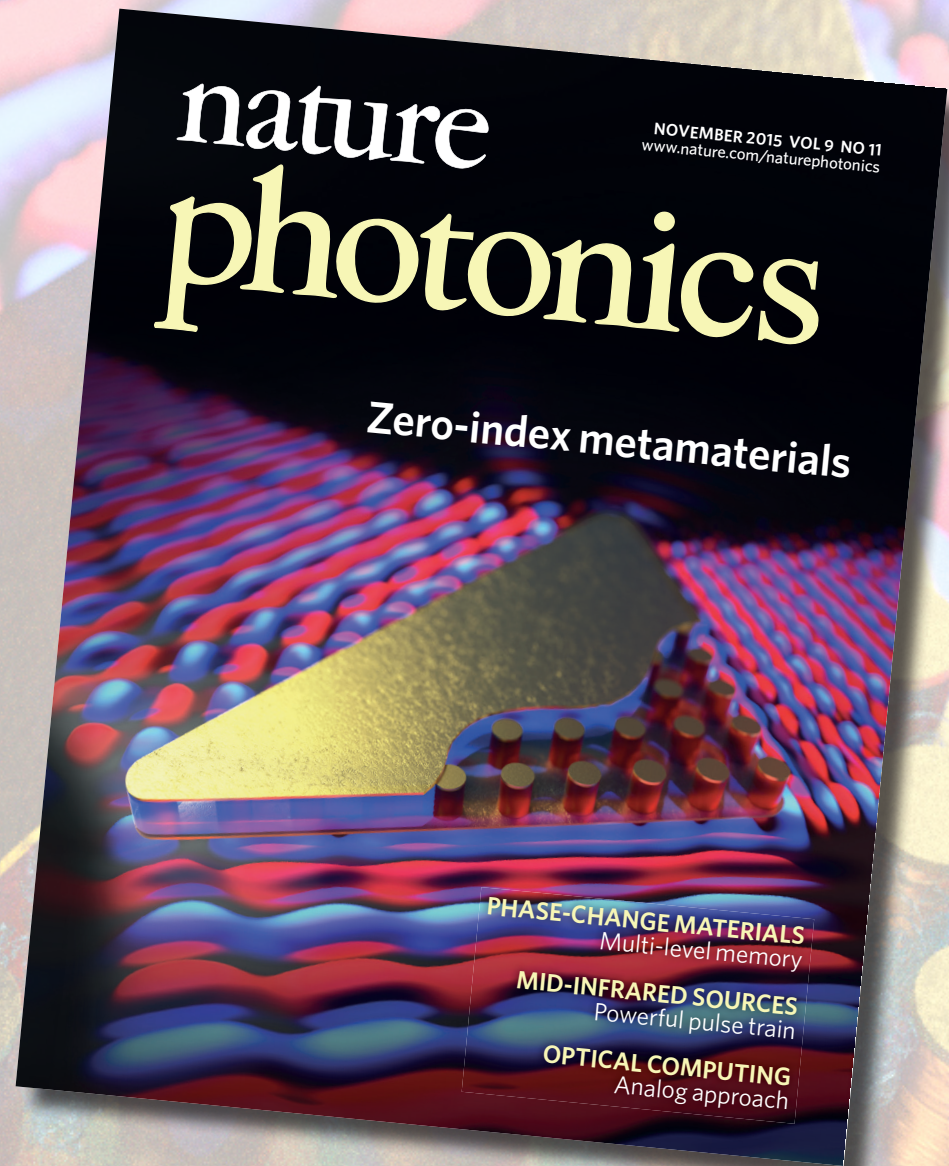
**1** index

**2** zero index

**3** experiments



More info: download paper!



1 index

2 zero index

3 experiments



**The Team: Yang Li, Shota Kita,  
Orad Reshef, Philip Muñoz, Daryl Vulis, Marko Lončar**

**Funding: National Science Foundation**

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