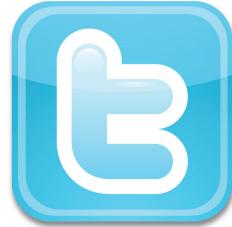


# On-chip zero-index metamaterials



**Advanced laser applications workshop**  
**KIMM**  
**Daejeon, South Korea, 28 August 2015**

# On-chip zero-index metamaterials



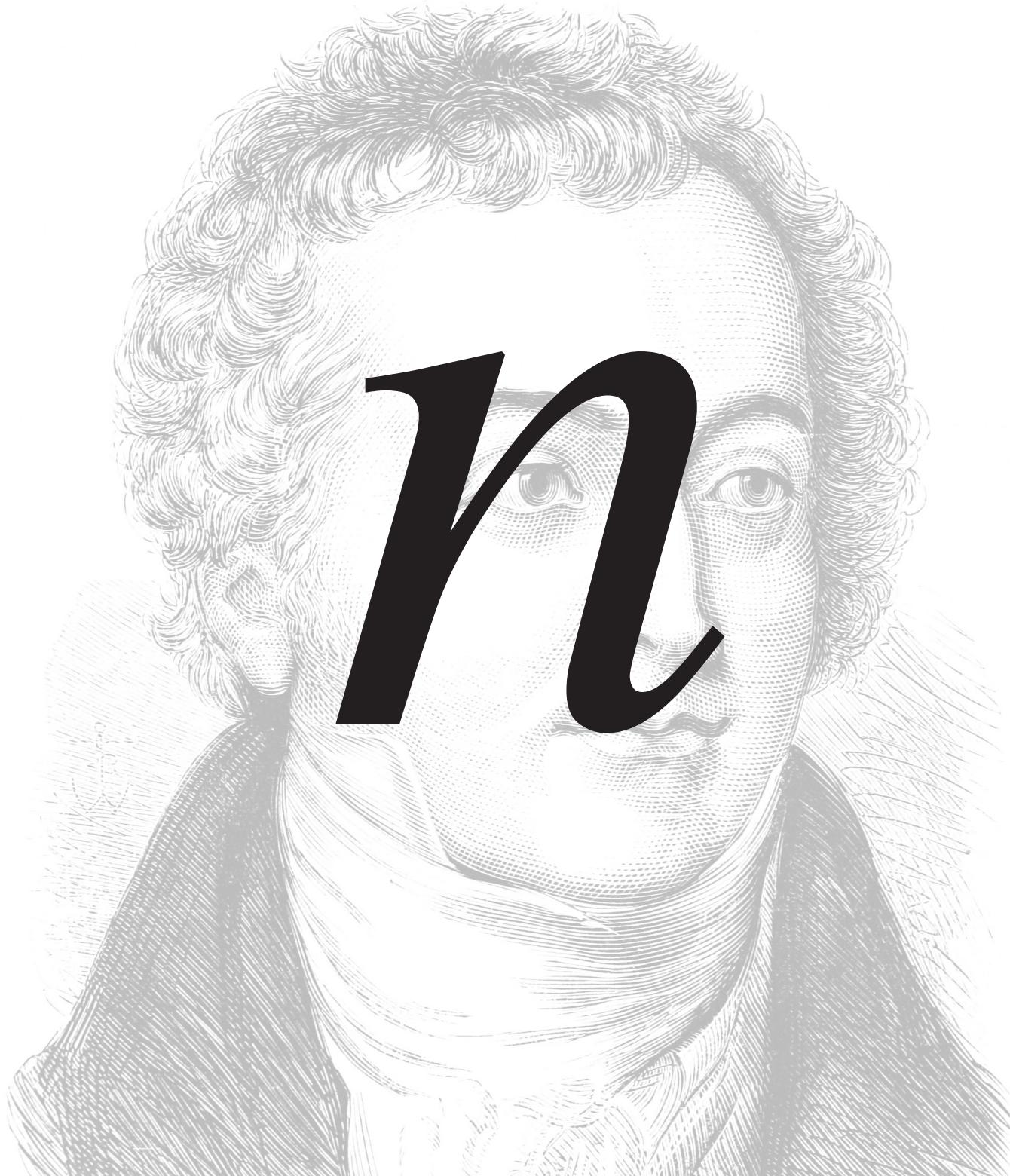
@eric\_mazur

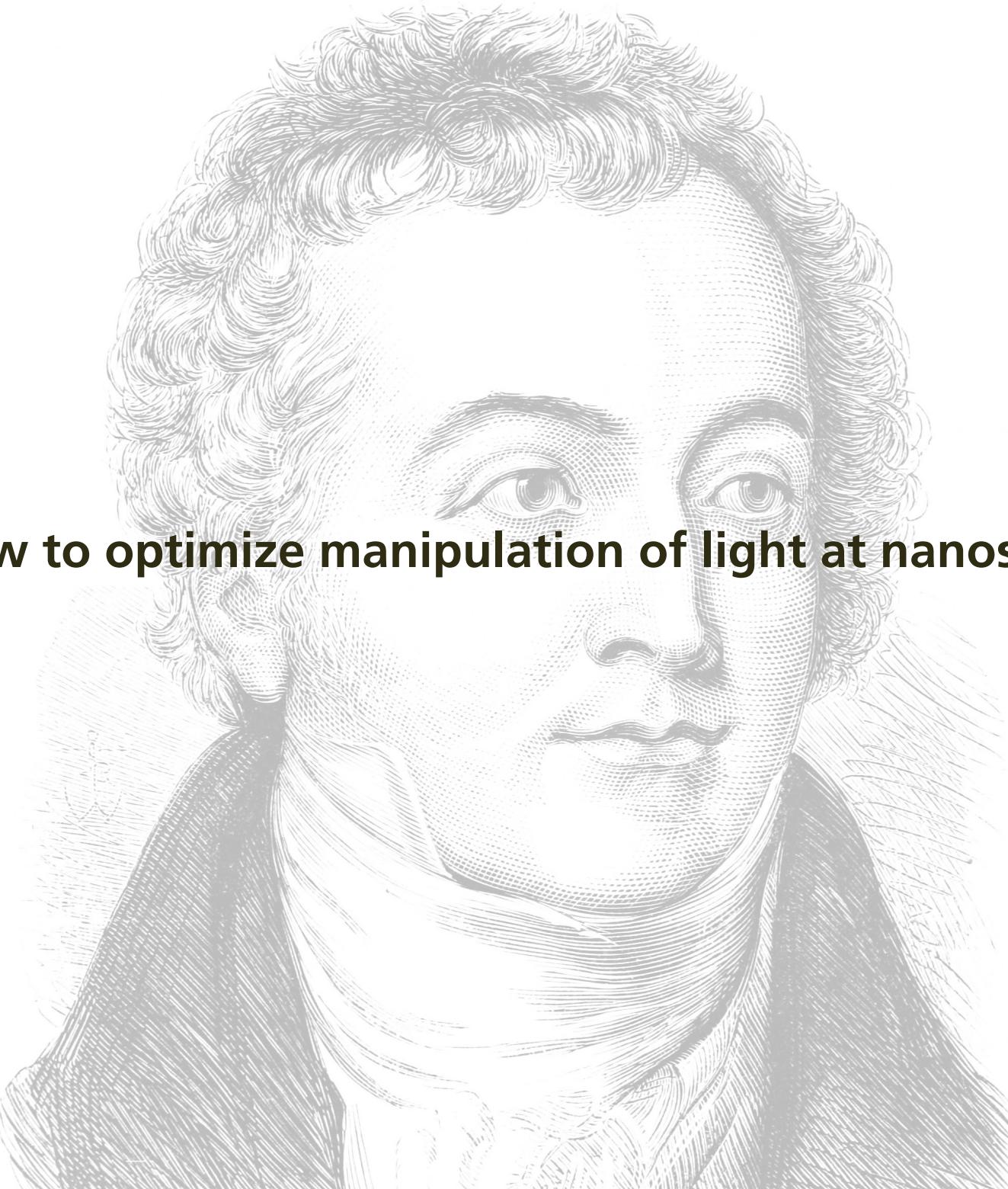
Advanced laser applications w p  
KIMM  
Daejeon, South Korea, 28 August 5



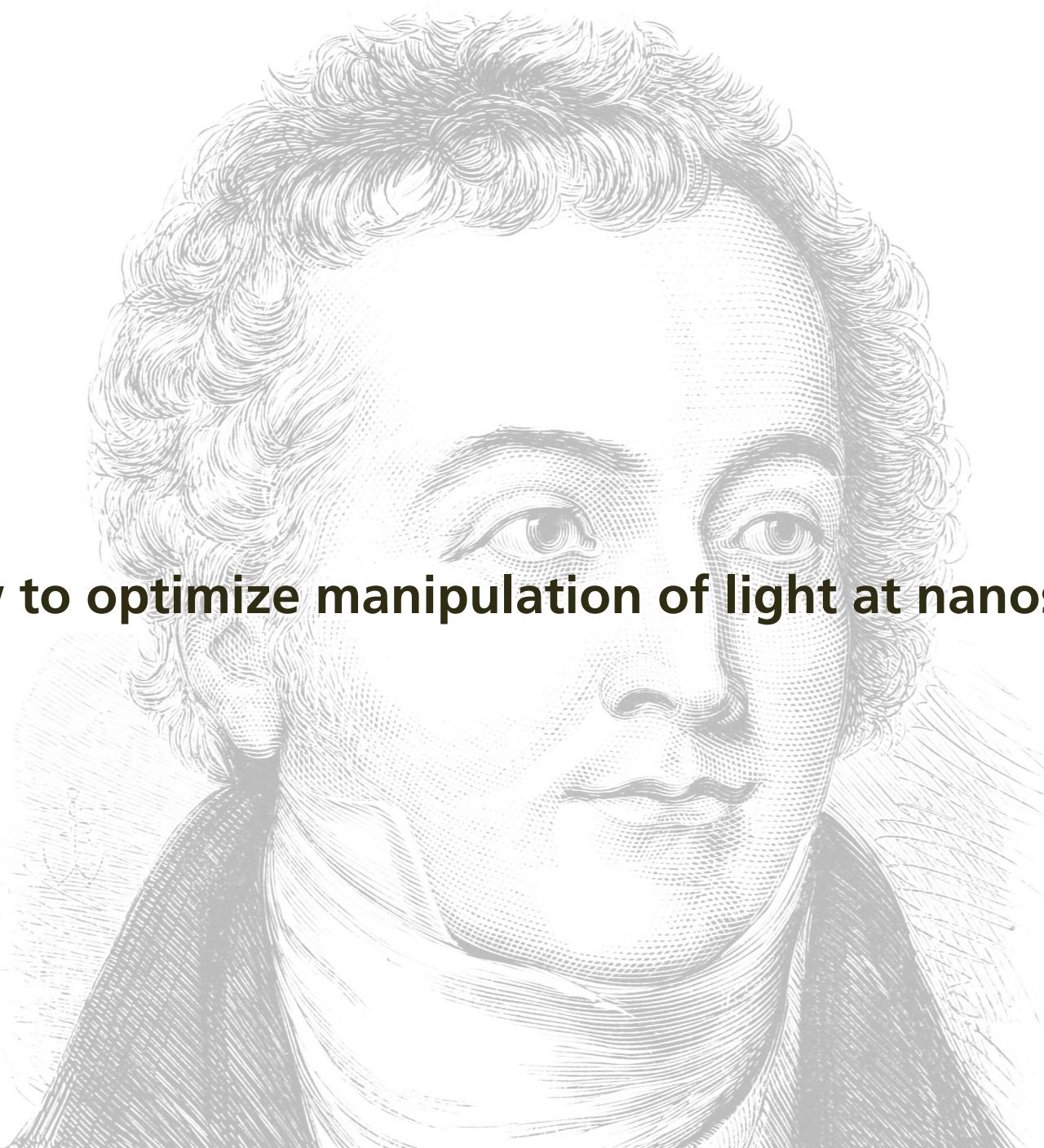


**η**



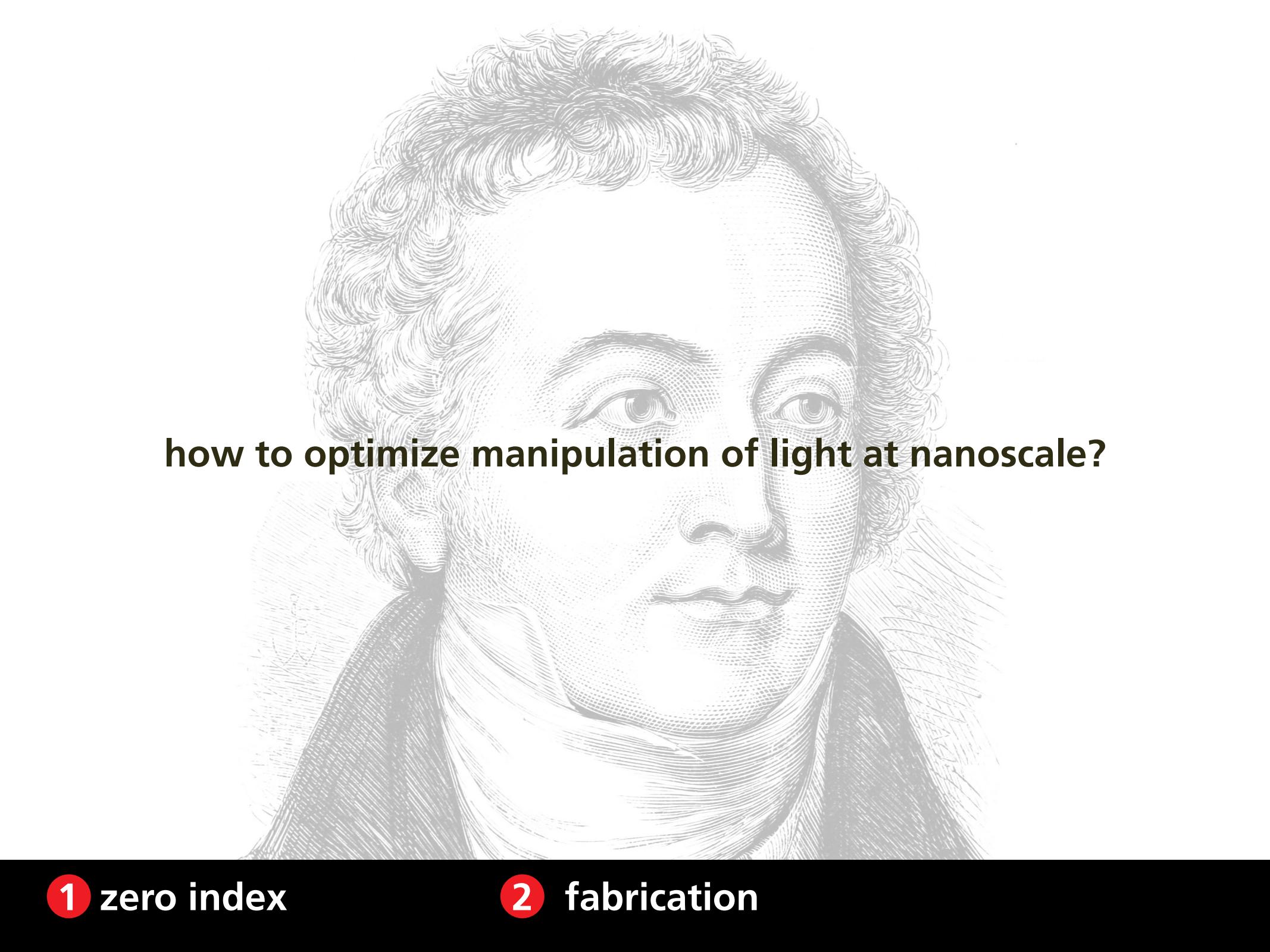


**how to optimize manipulation of light at nanoscale?**



**how to optimize manipulation of light at nanoscale?**

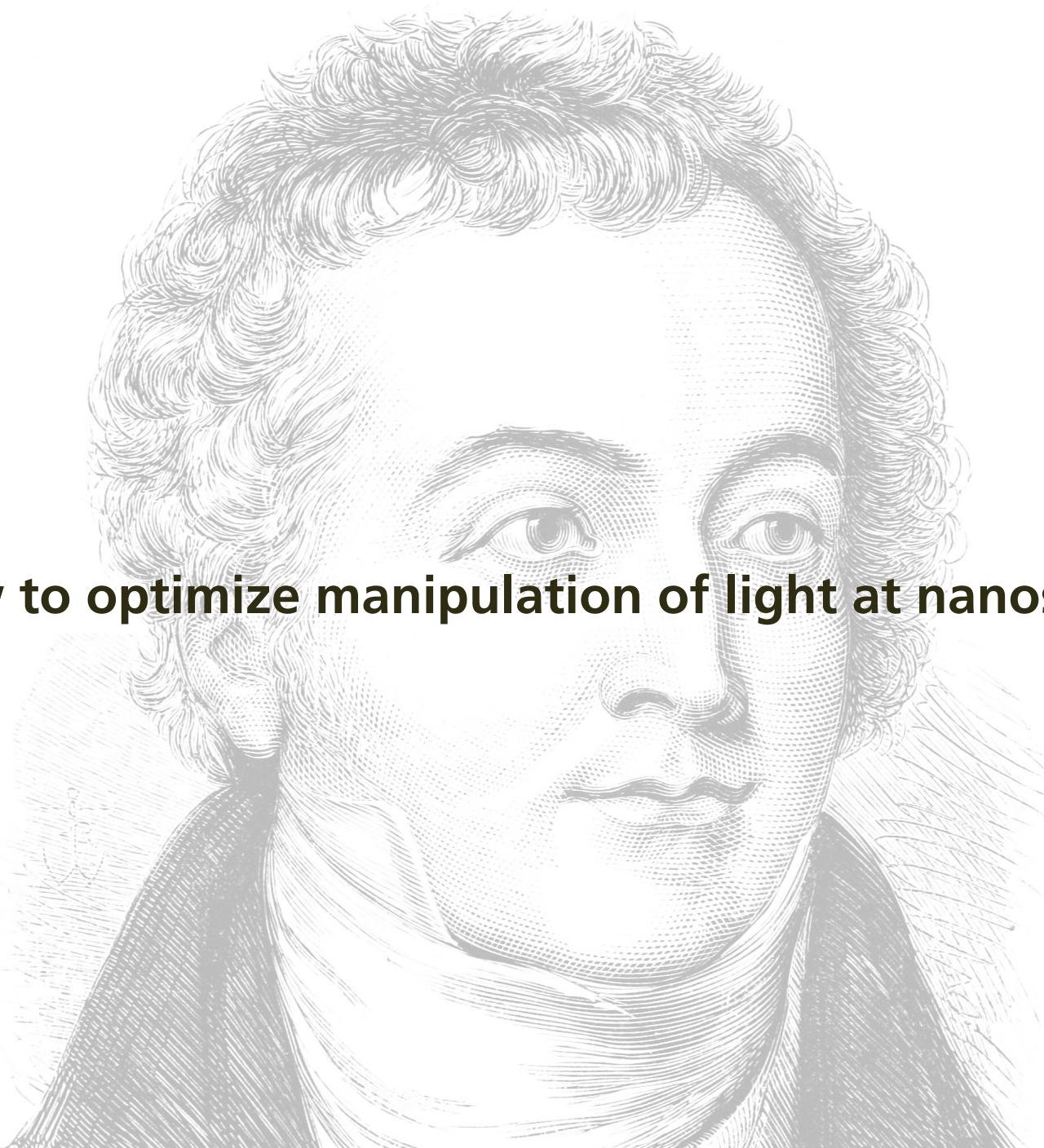
**1** zero index



**how to optimize manipulation of light at nanoscale?**

**1** zero index

**2** fabrication



**how to optimize manipulation of light at nanoscale?**

**1** zero index

**2** fabrication

**3** results

# Propagation of EM wave

1 zero index

# Propagation of EM wave

governed by wave equation

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

# Propagation of EM wave

governed by wave equation

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

Solution:

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

# Propagation of EM wave

governed by wave equation

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

Solution:

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

where

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

# Propagation of EM wave

governed by wave equation

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

Solution:

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

where

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

and

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

# Propagation of EM wave

governed by wave equation

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

Solution:

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

where

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

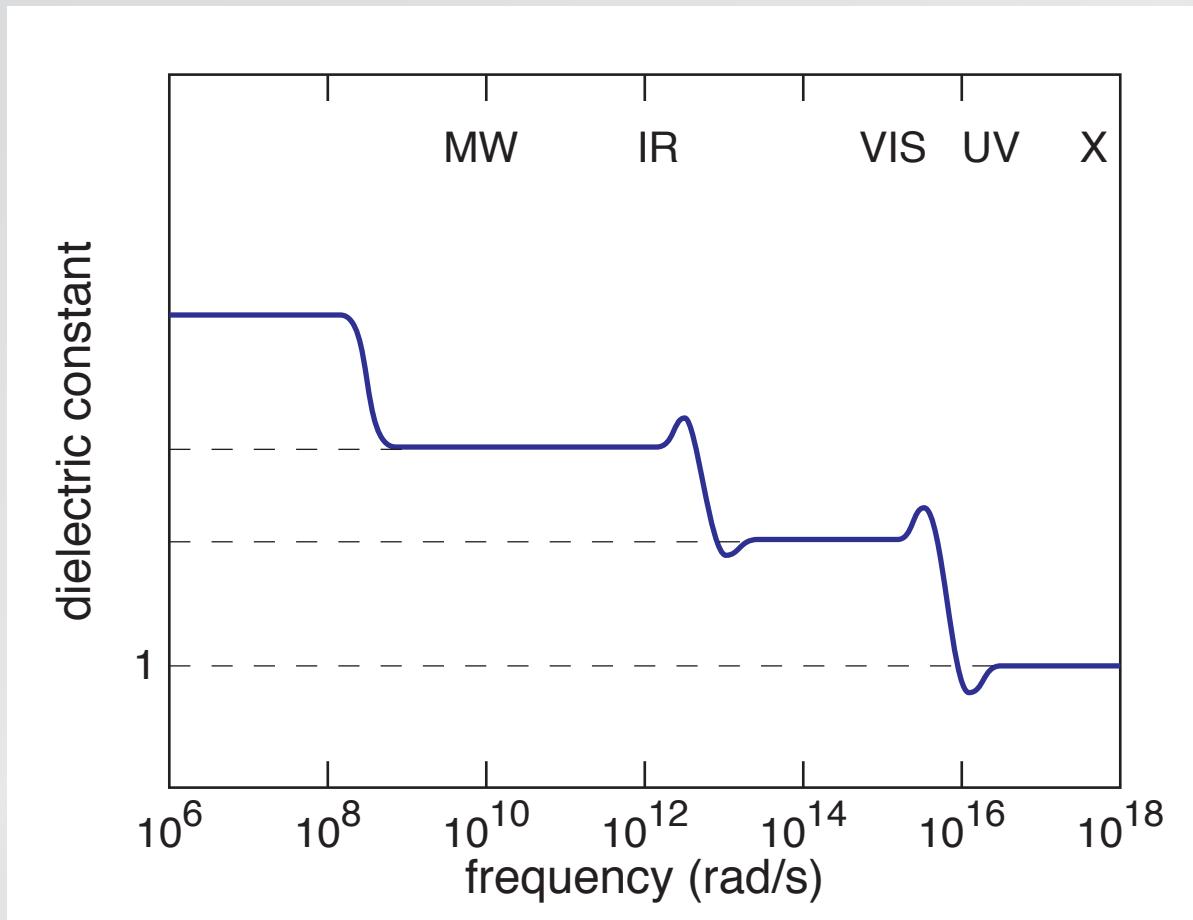
and

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

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

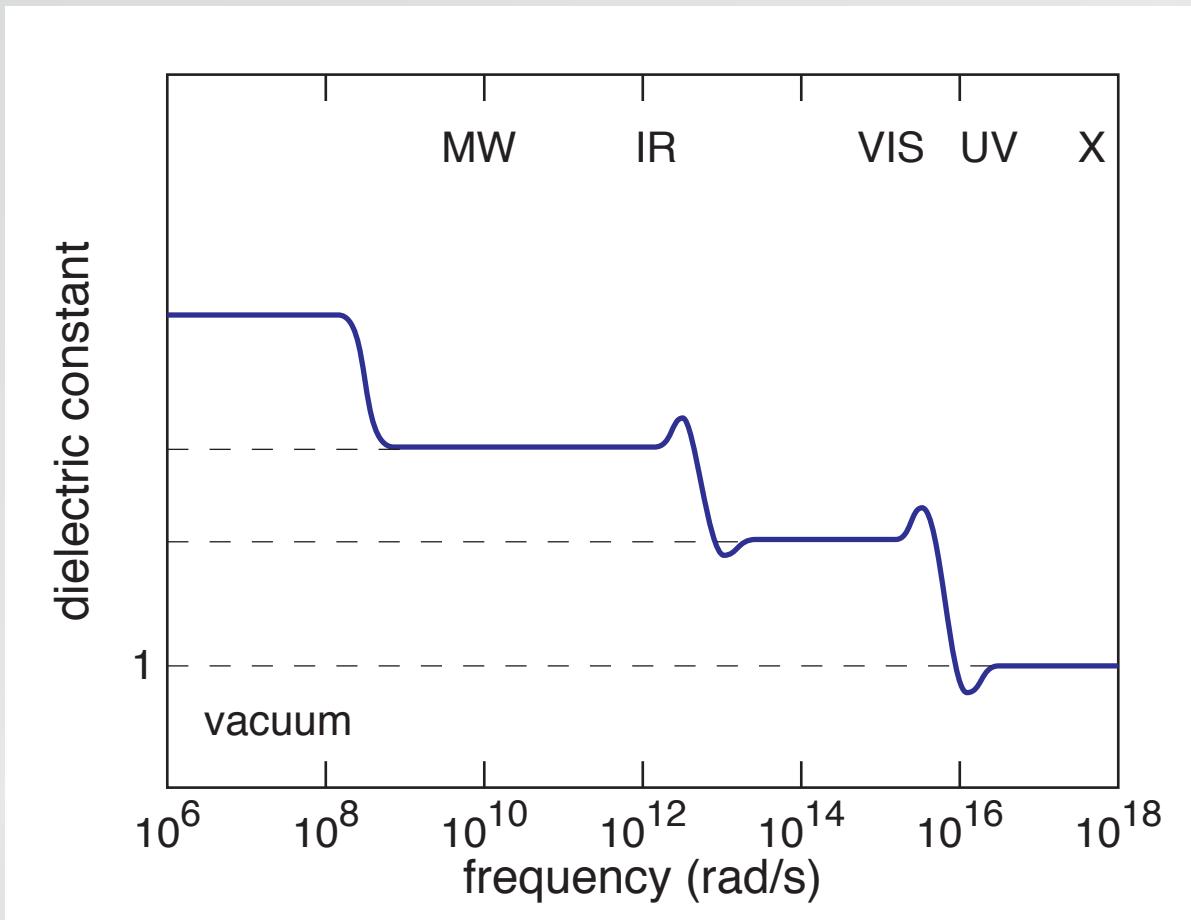
1 zero index

# Propagation of EM wave



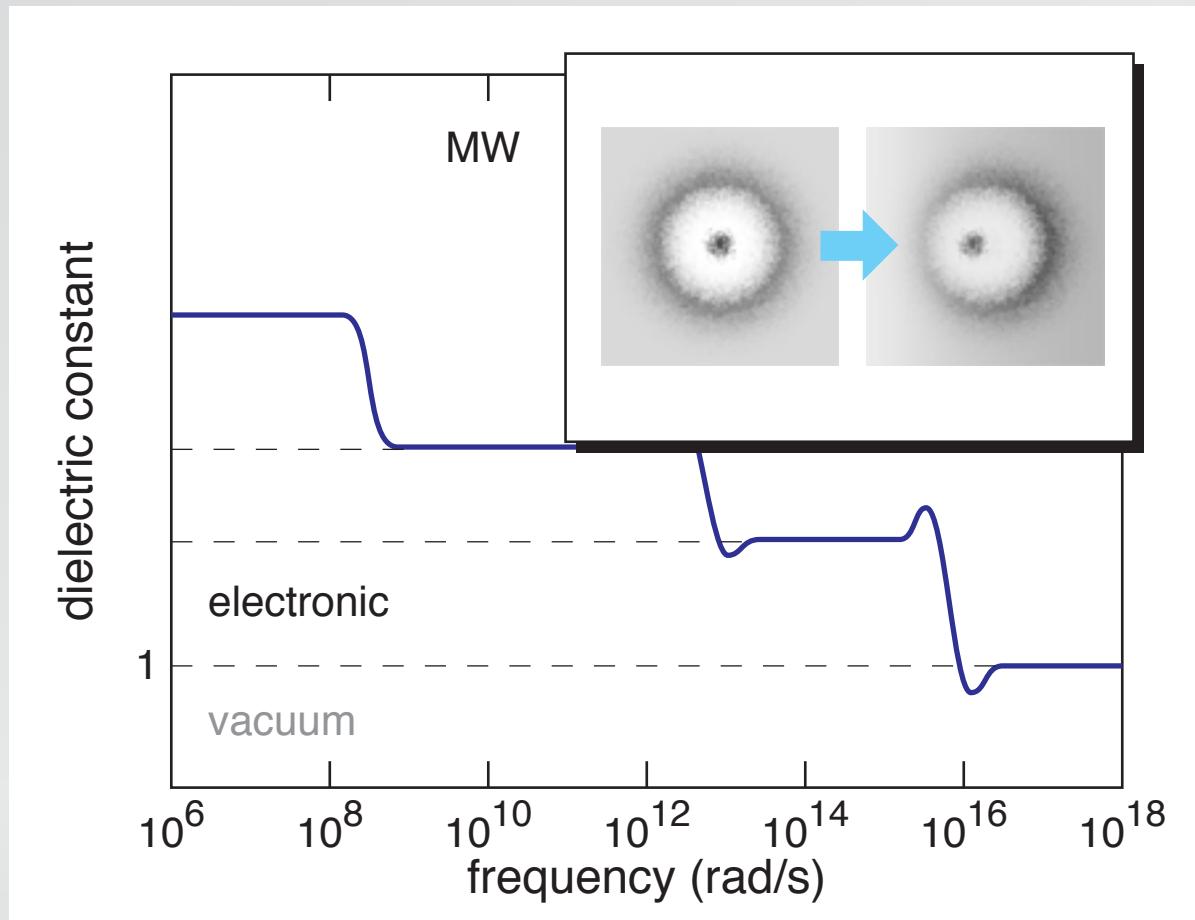
1 zero index

# Propagation of EM wave



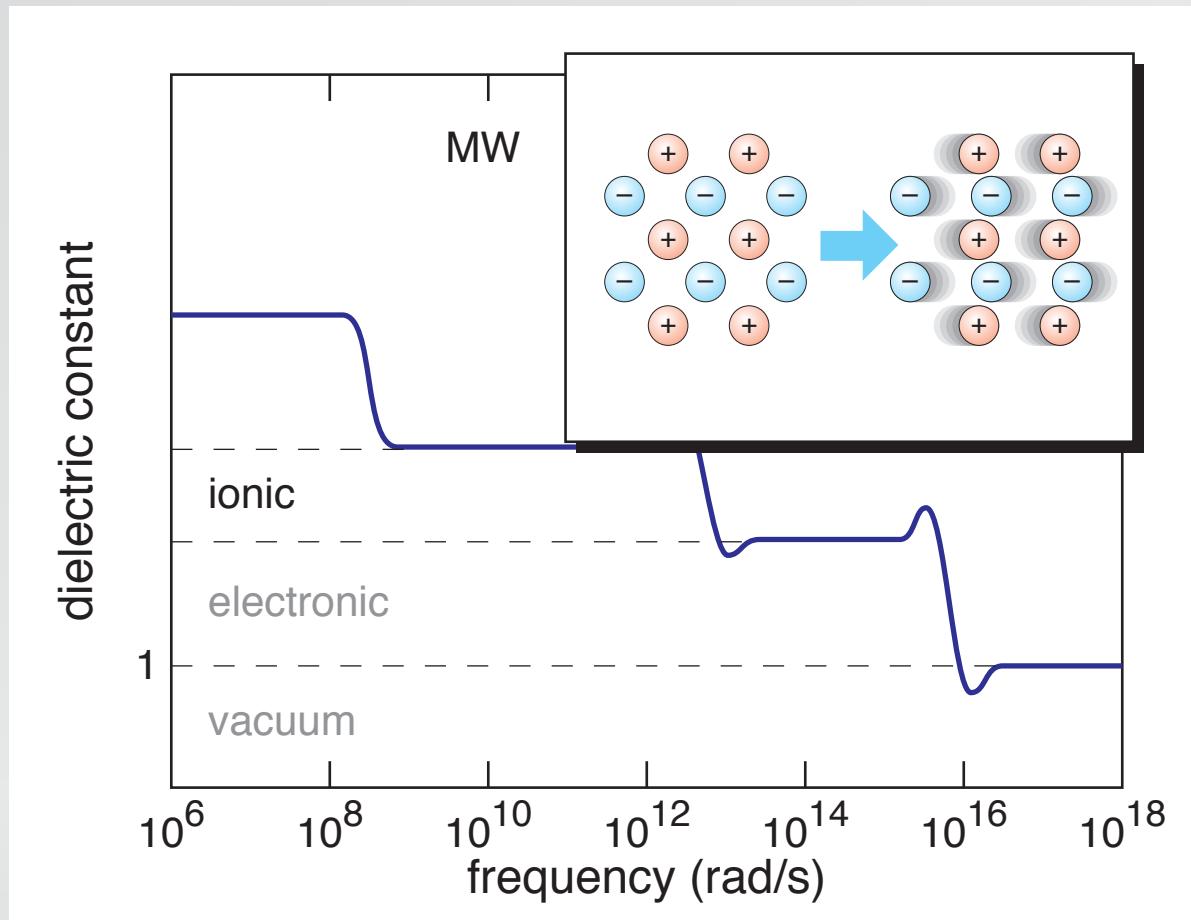
1 zero index

# Propagation of EM wave



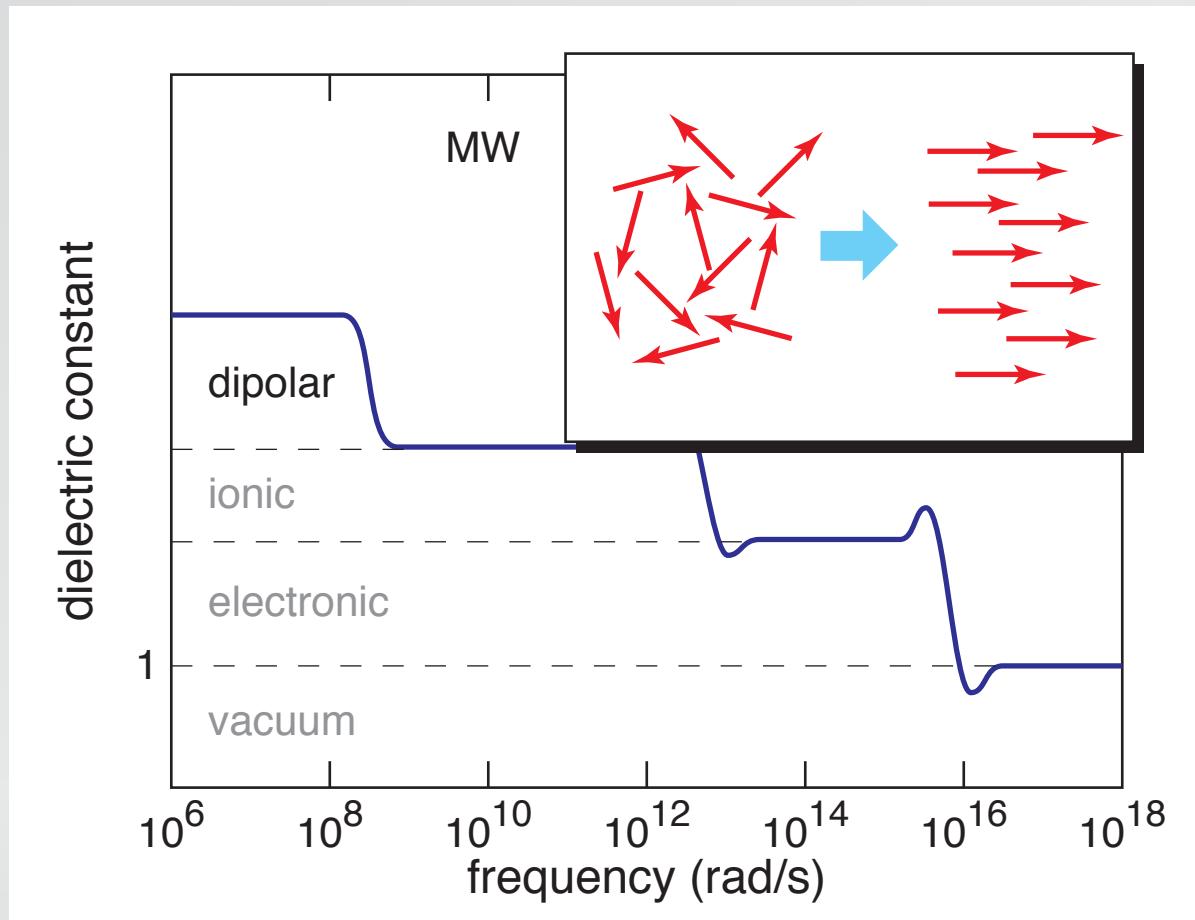
1 zero index

# Propagation of EM wave



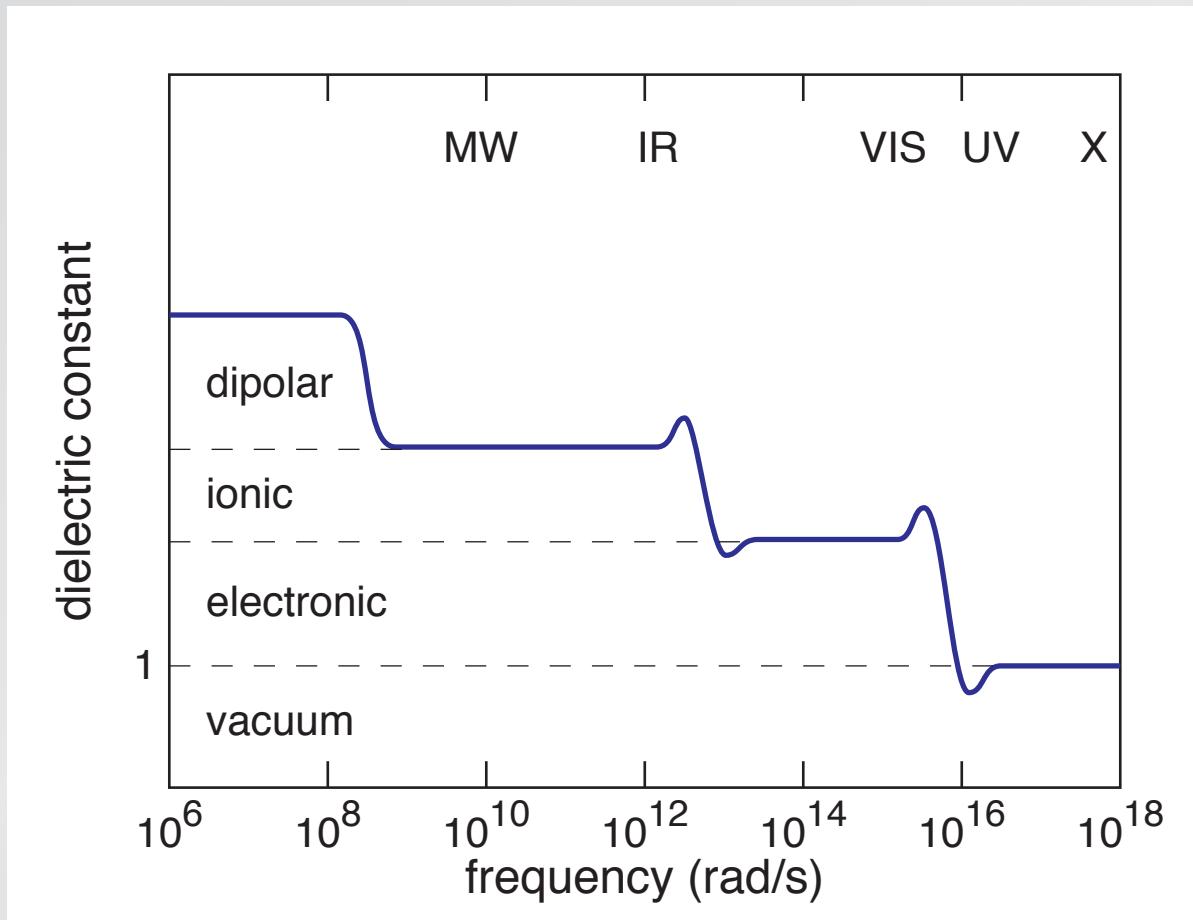
1 zero index

# Propagation of EM wave



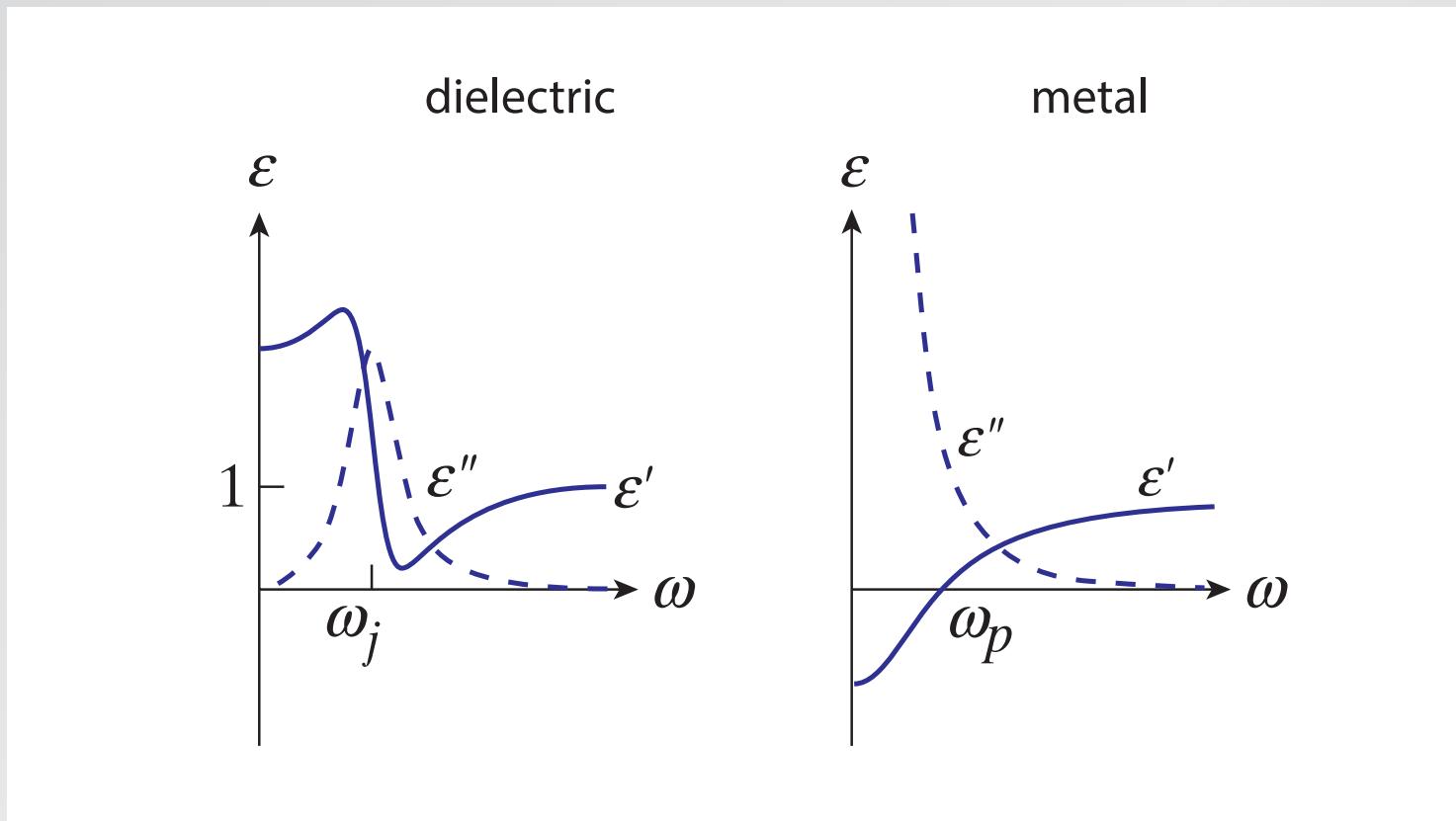
1 zero index

# Propagation of EM wave



1 zero index

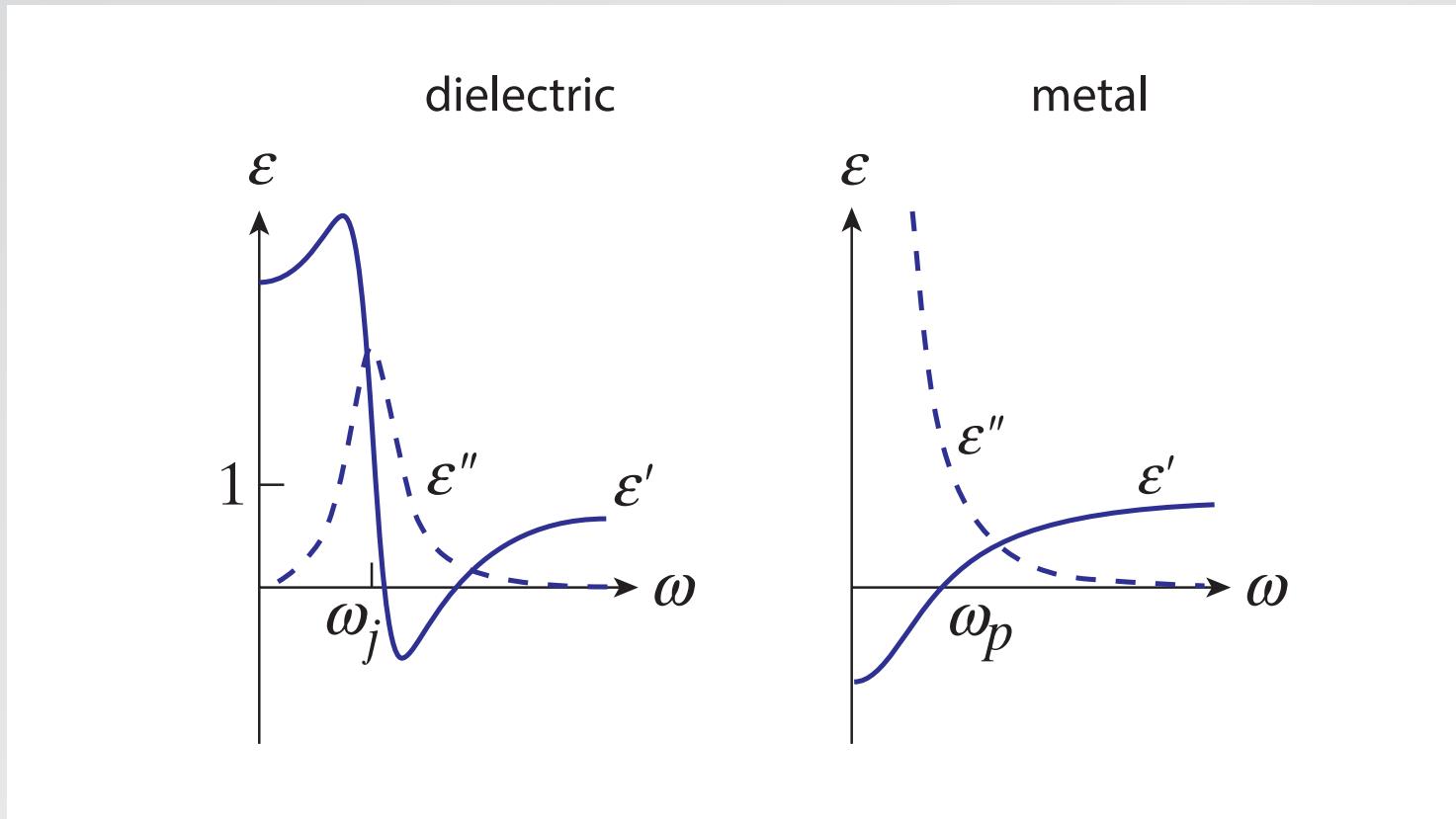
# Lorentz and Drude models



1 zero index

# Lorentz and Drude models

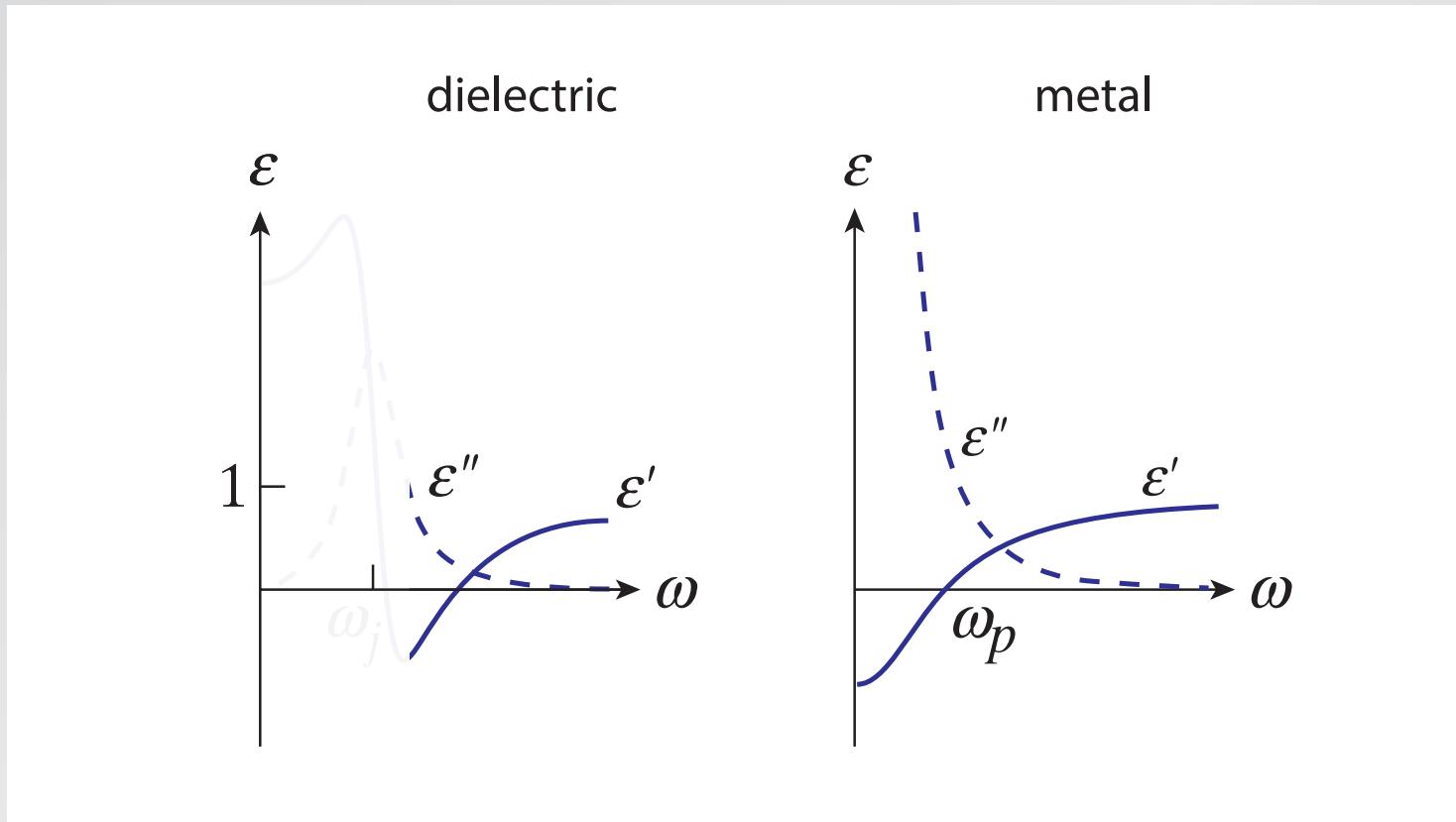
for a strong (dielectric) resonance  $\epsilon$  can become negative



1 zero index

# Lorentz and Drude models

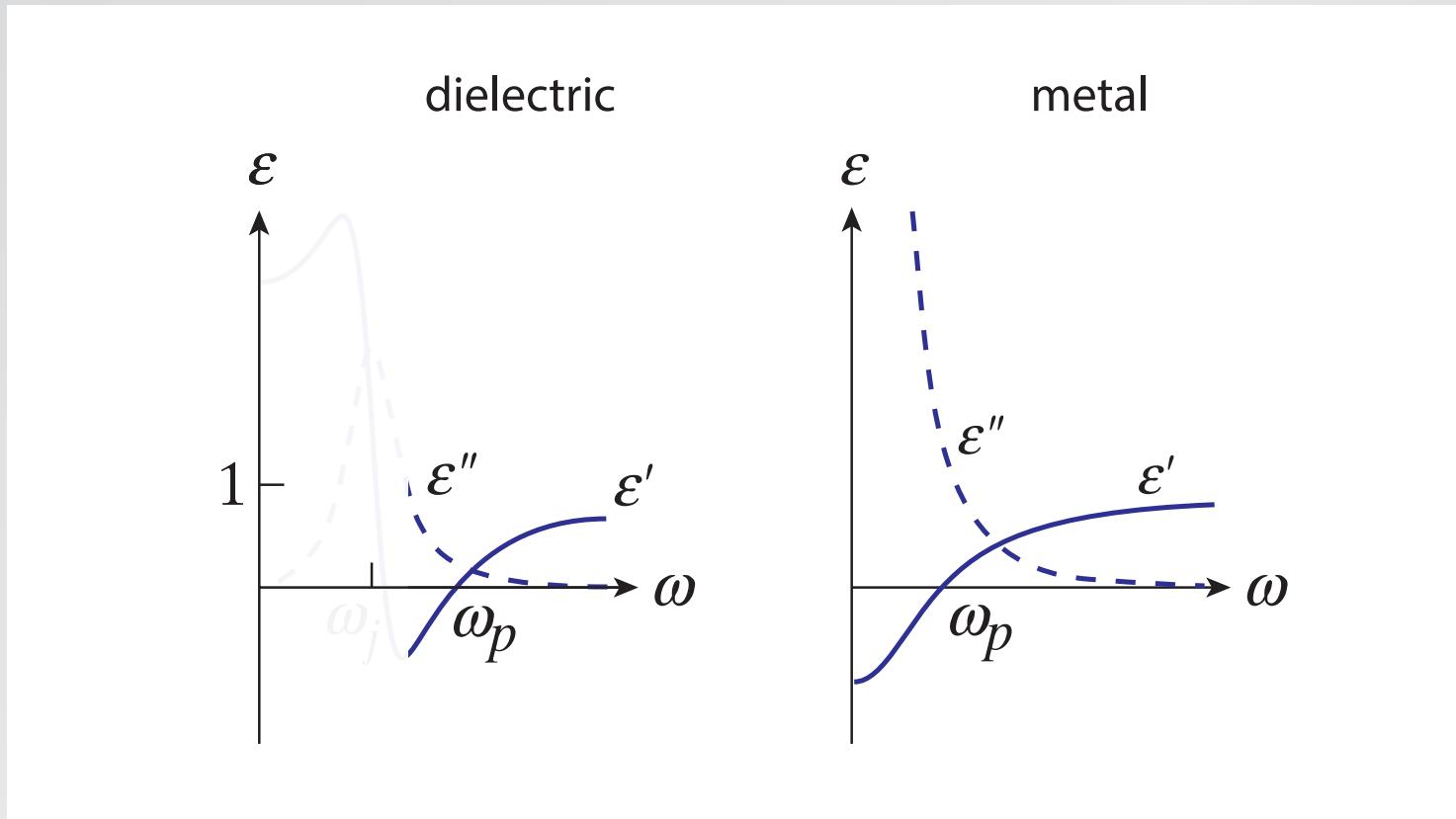
valence electrons in dielectric then behave like a plasma



1 zero index

# Lorentz and Drude models

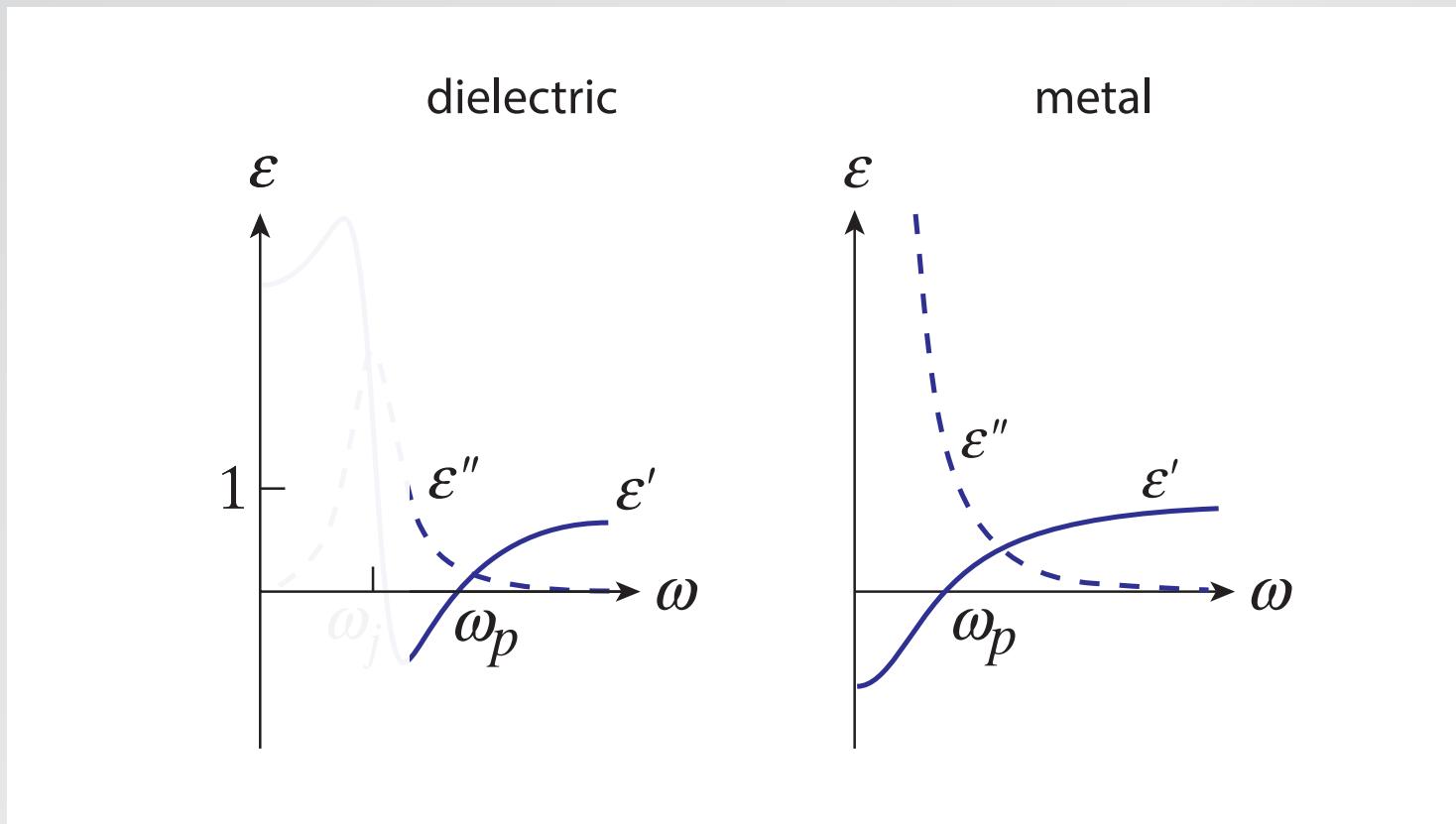
with plasma frequency above the resonance



1 zero index

# Lorentz and Drude models

(and far below the UV region)



1 zero index

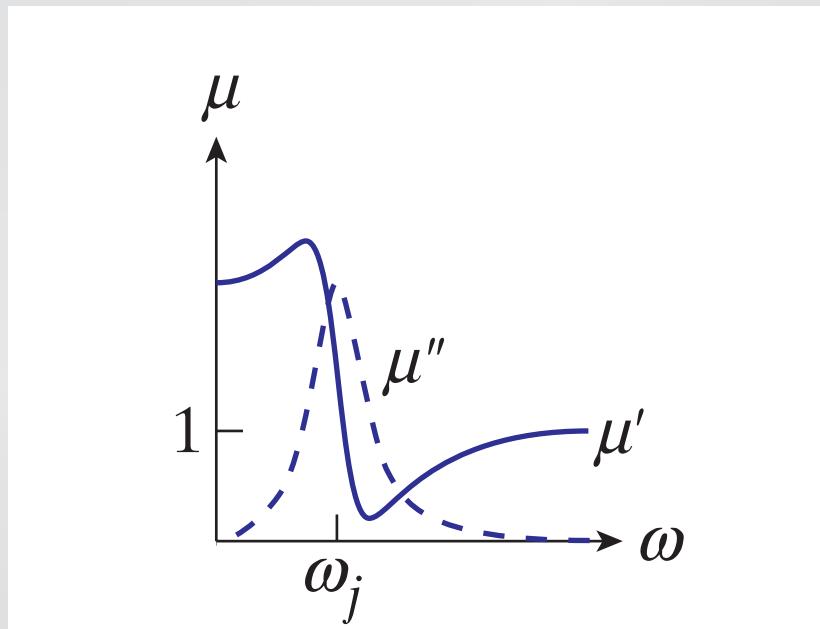
**Index also determined by magnetic response**

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

**Index also determined by magnetic response**

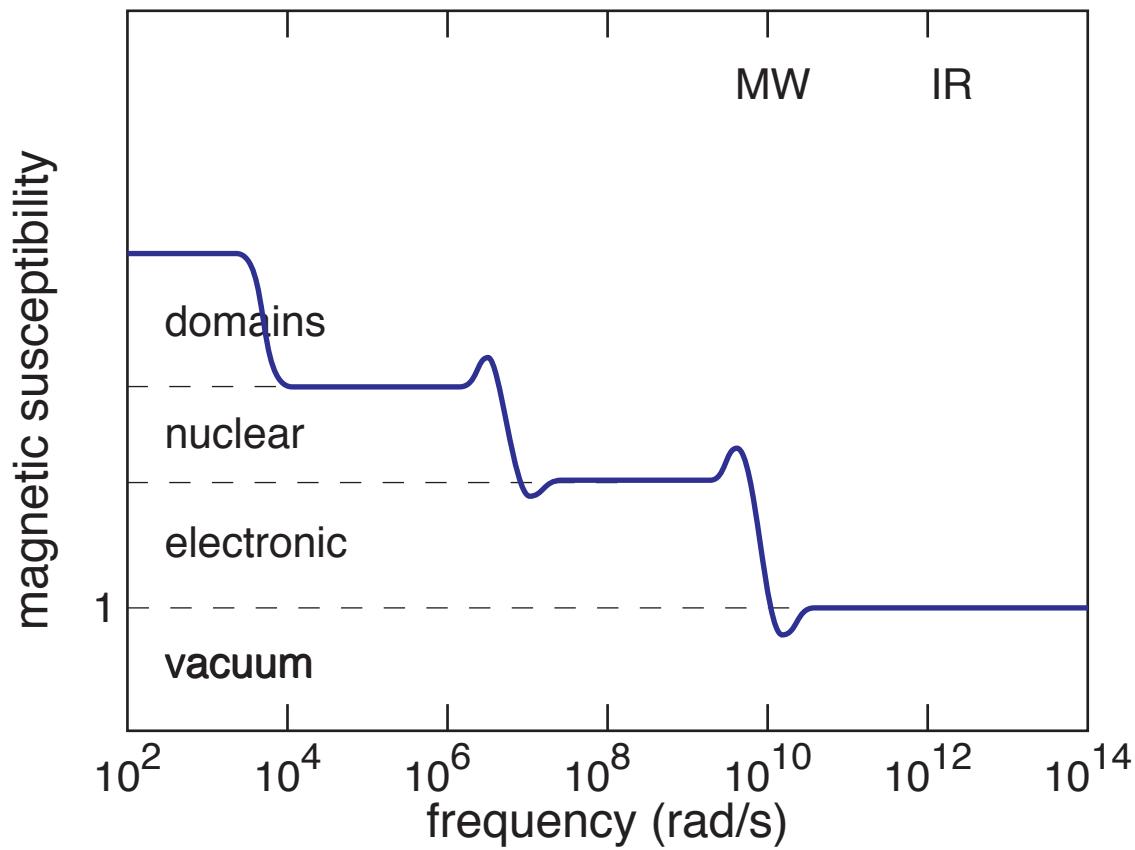
$$n = \sqrt{\epsilon \mu}$$

**and magnetic response shows similar resonances**



**1 zero index**

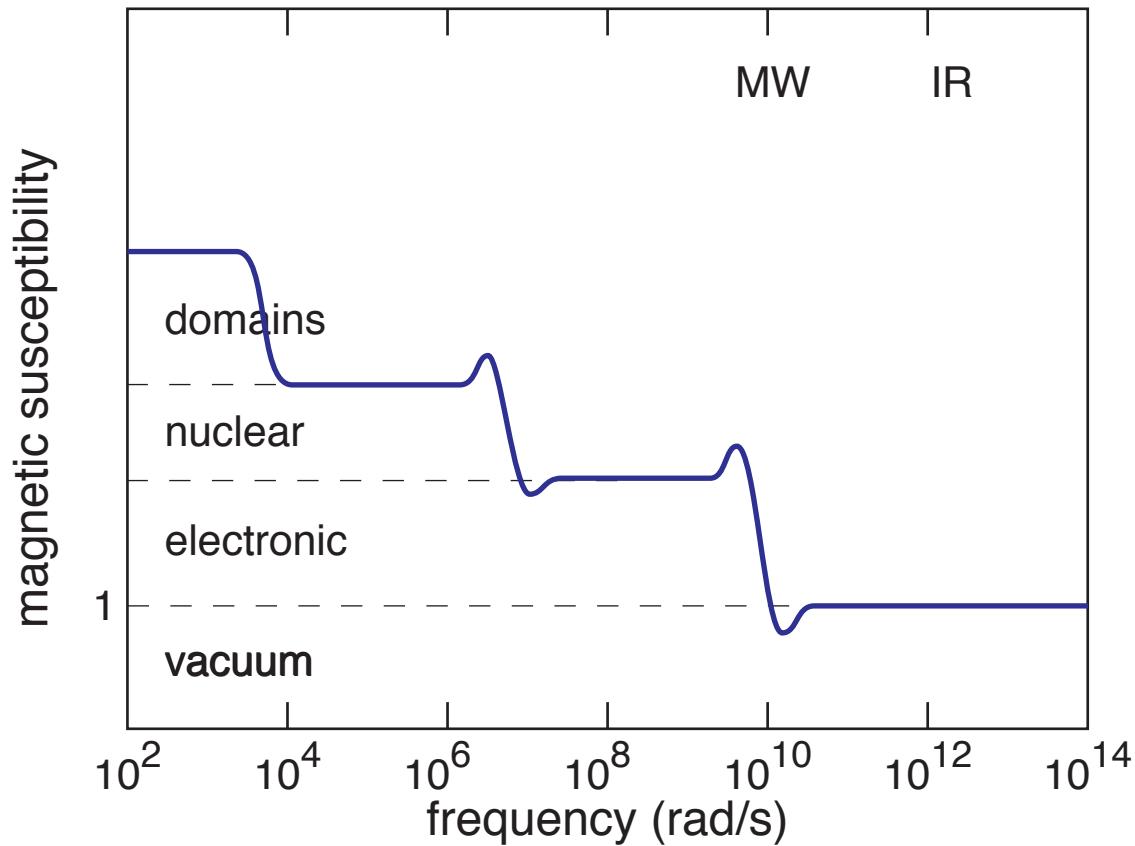
# Magnetic response



1 zero index

# Magnetic response

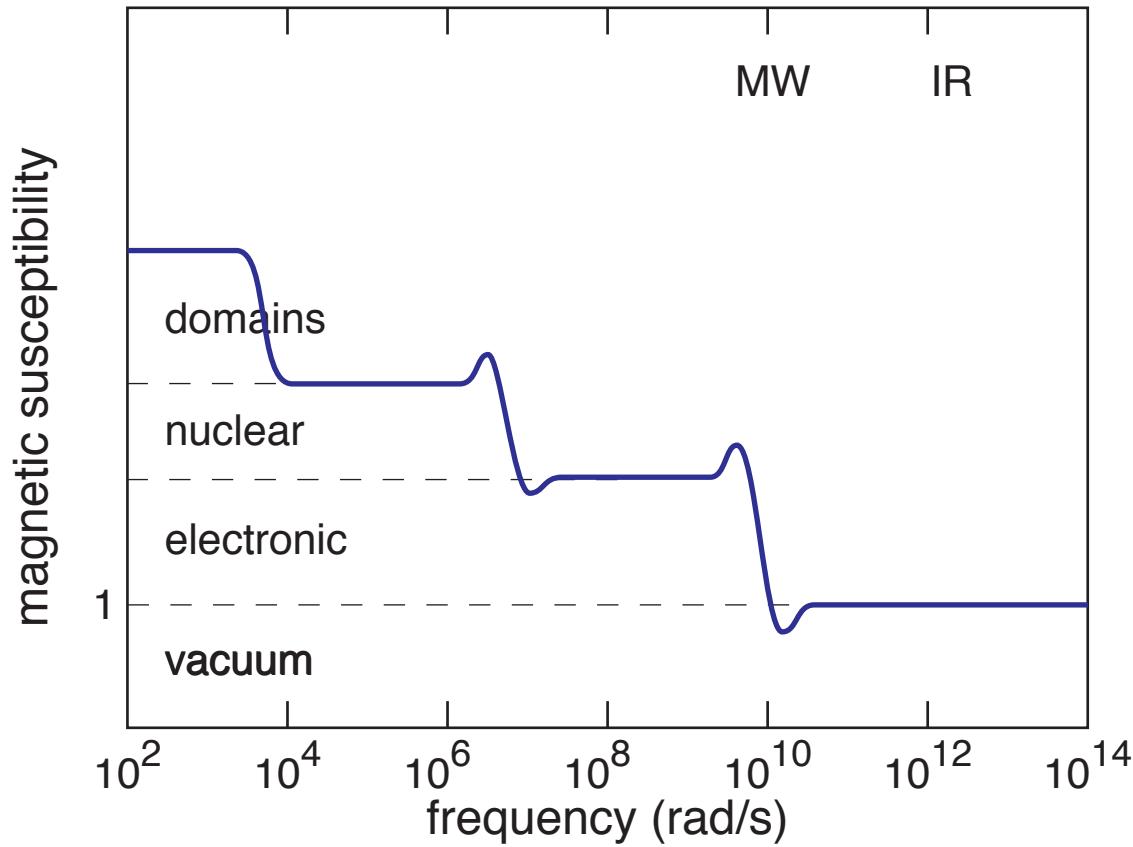
but magnetic resonances occur below optical frequencies



1 zero index

# 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.

## Index of refraction

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

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

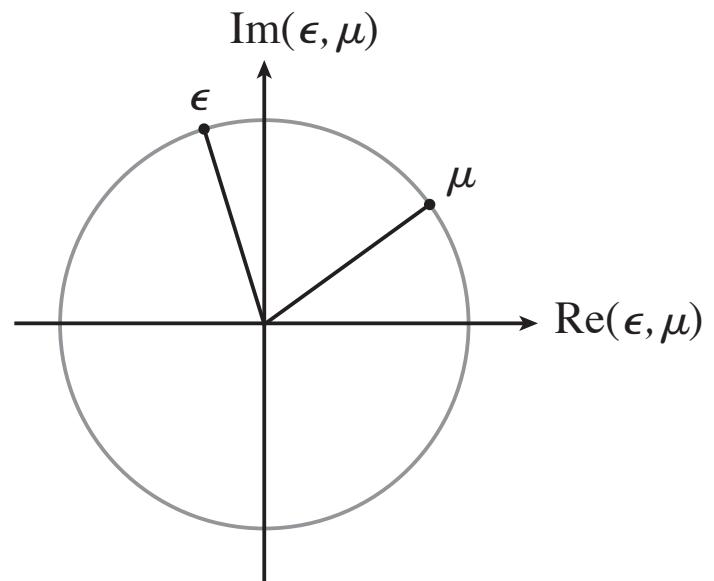
What happens when  $\text{Re}\epsilon$  and/or  $\text{Re}\mu$  is negative?

**Write complex quantities as**

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

**Write complex quantities as**

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

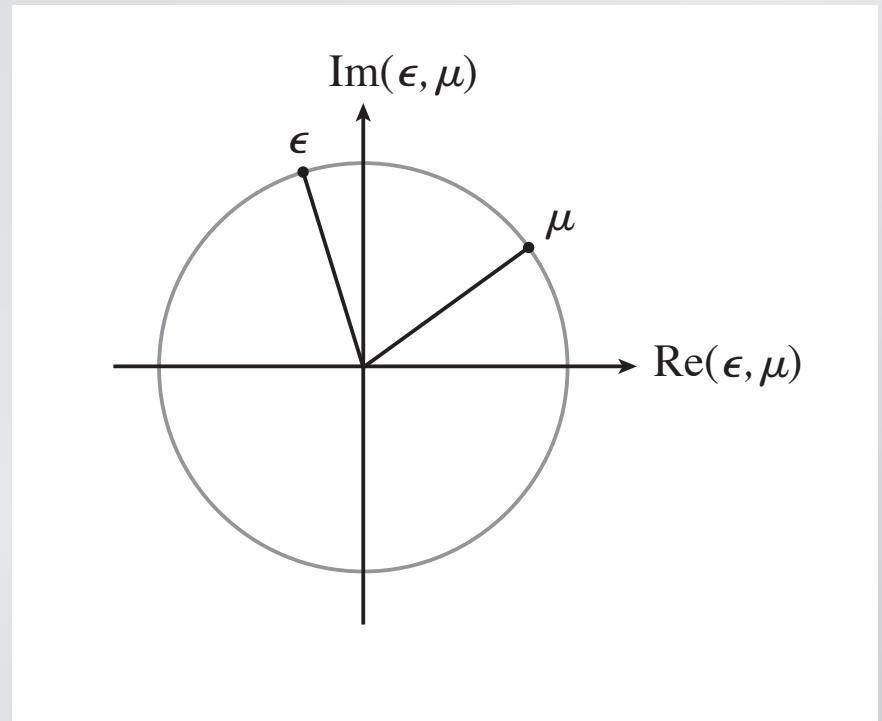


**Write complex quantities as**

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

**Index**

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



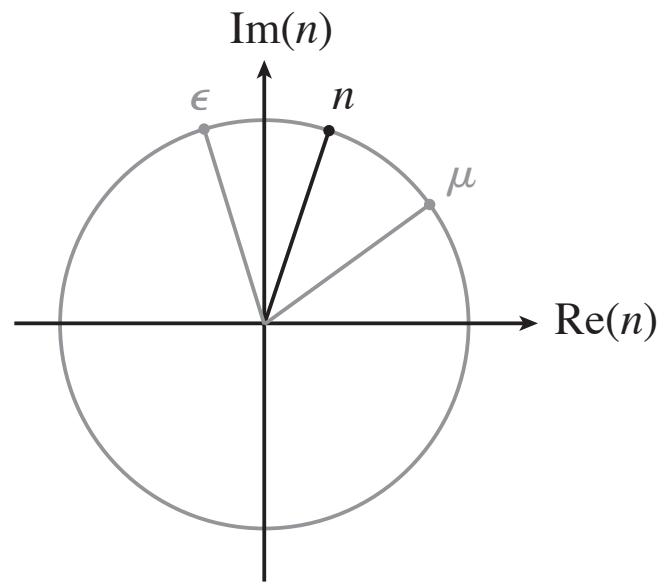
**1 zero index**

**Write complex quantities as**

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

**Index**

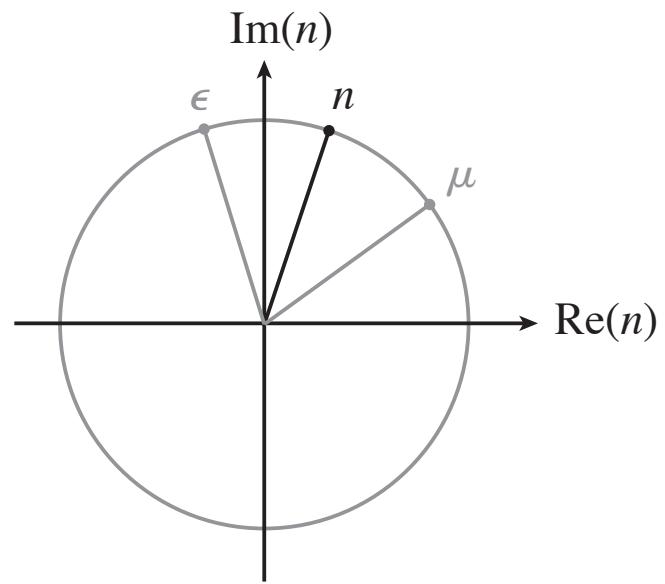
$$n = \sqrt{|\epsilon||\mu|} e^{i\frac{\theta+\phi}{2}}$$



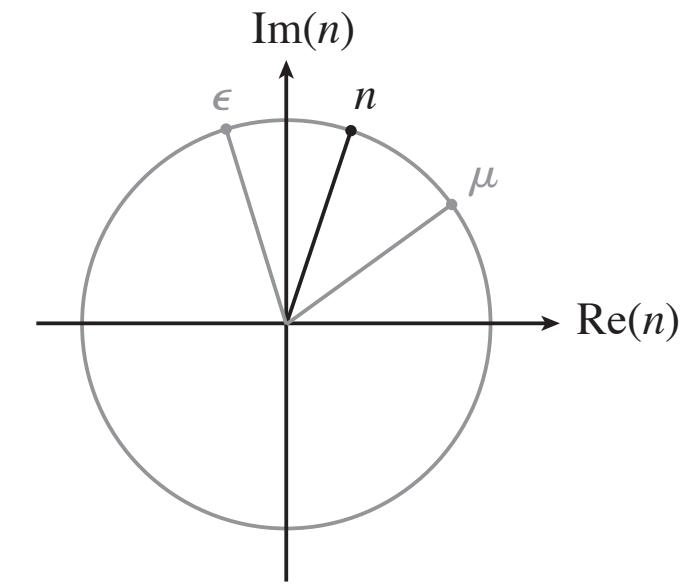
**1 zero index**

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

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



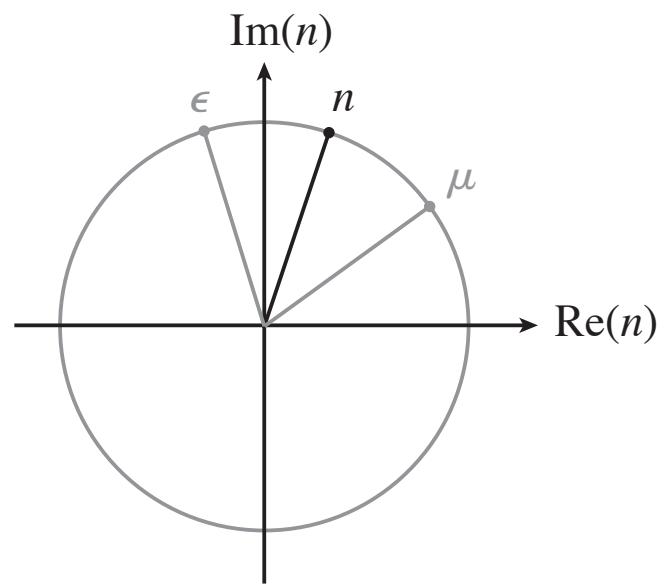
**There *is* another root...**



**There *is* another root...**

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

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



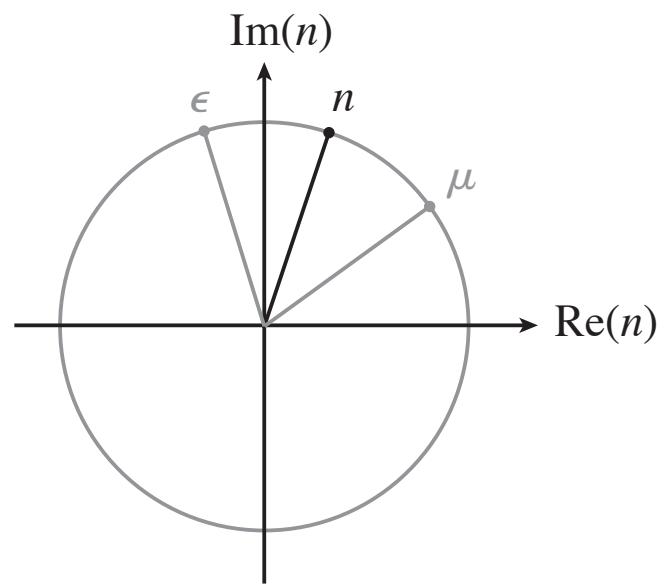
**There *is* another root...**

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

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

**and so**

$$n = \sqrt{|\epsilon||\mu|} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$



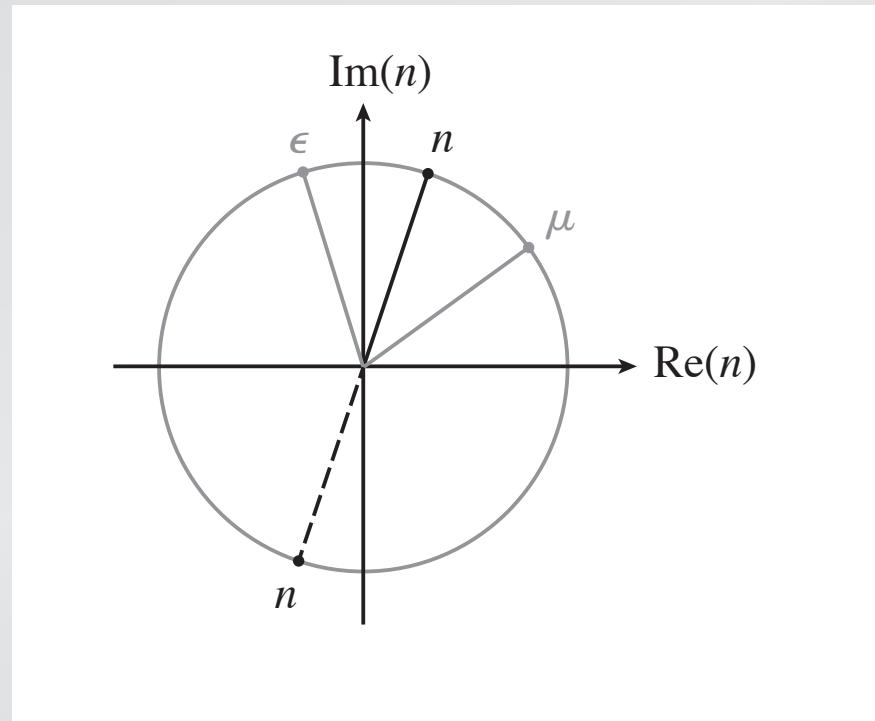
**There *is* another root...**

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

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

**and so**

$$n = \sqrt{|\epsilon||\mu|} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$



**There *is* another root...**

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

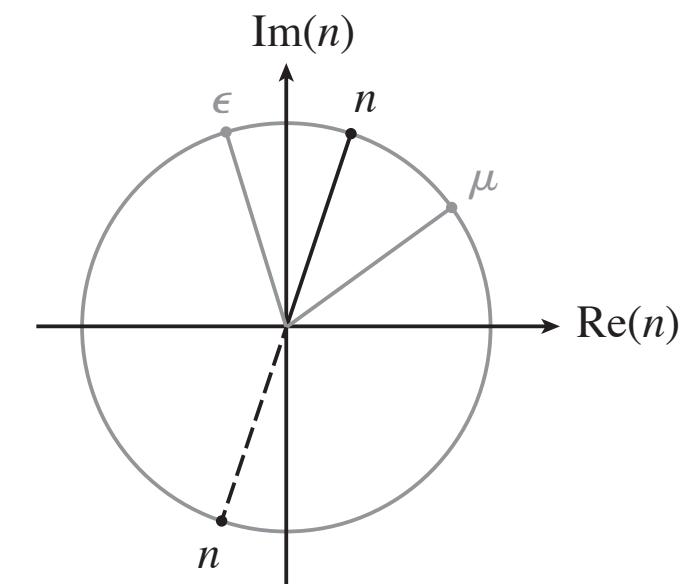
$$e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]}$$

**and so**

$$n = \sqrt{|\epsilon||\mu|} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$

**but...**

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



**There *is* another root...**

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

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

**and so**

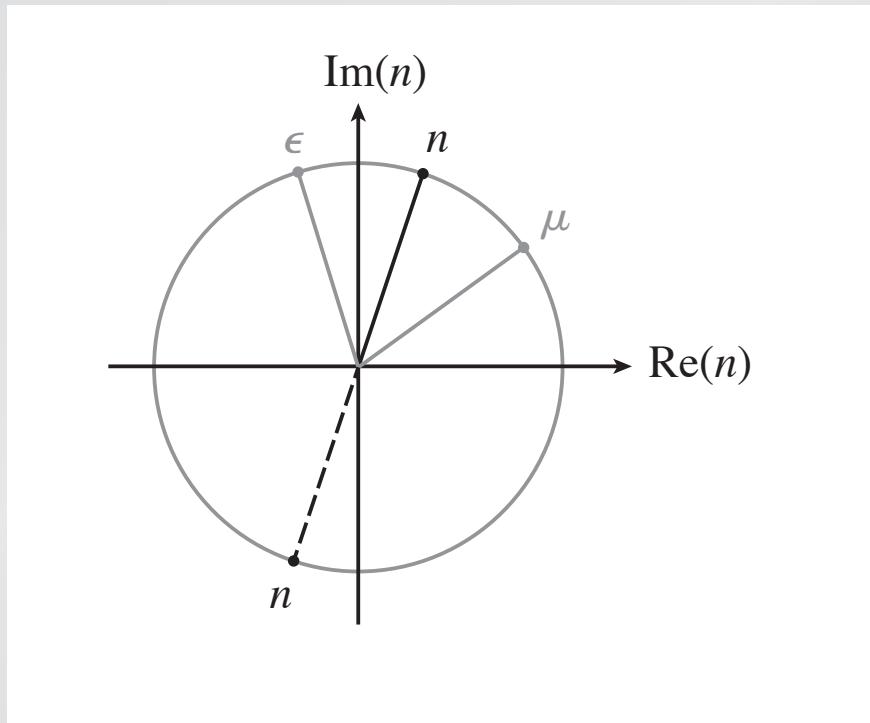
$$n = \sqrt{|\epsilon||\mu|} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$

**but...**

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

**and**

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



**1 zero index**

**There *is* another root...**

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

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

**and so**

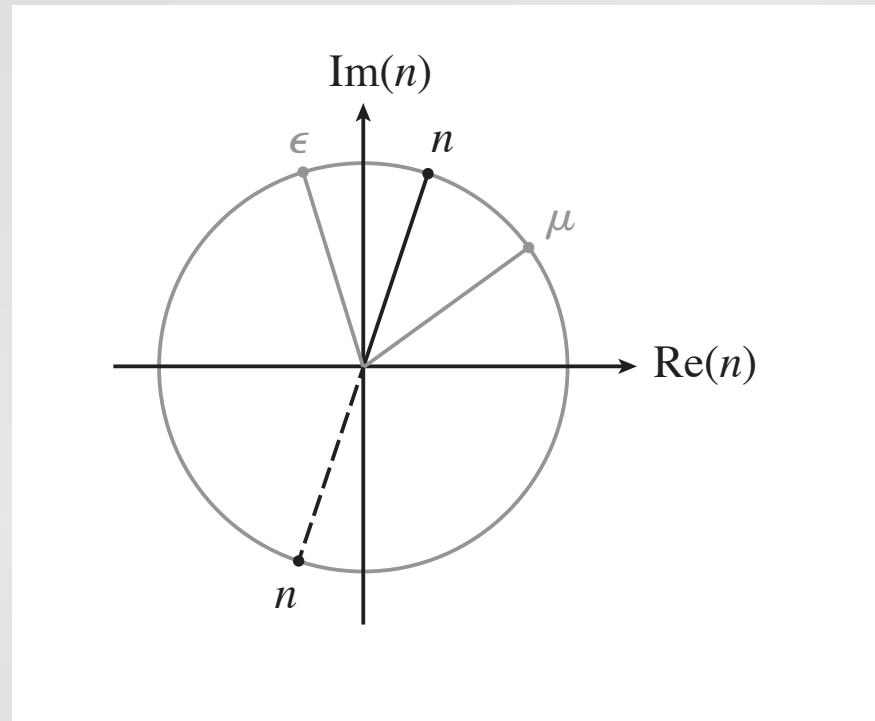
$$n = \sqrt{|\epsilon||\mu|} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$

**but...**

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

**and**

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



**1 zero index**

**There *is* another root...**

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

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

**and so**

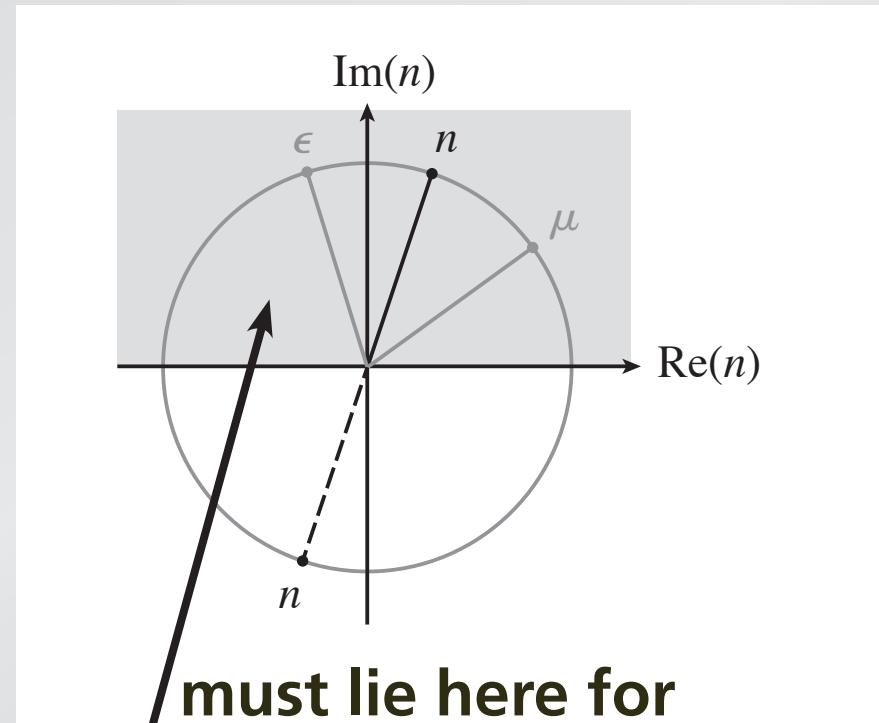
$$n = \sqrt{|\epsilon||\mu|} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$

**but...**

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

**and**

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



**must lie here for  
passive material**

**1 zero index**

**There *is* another root...**

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

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

**and so**

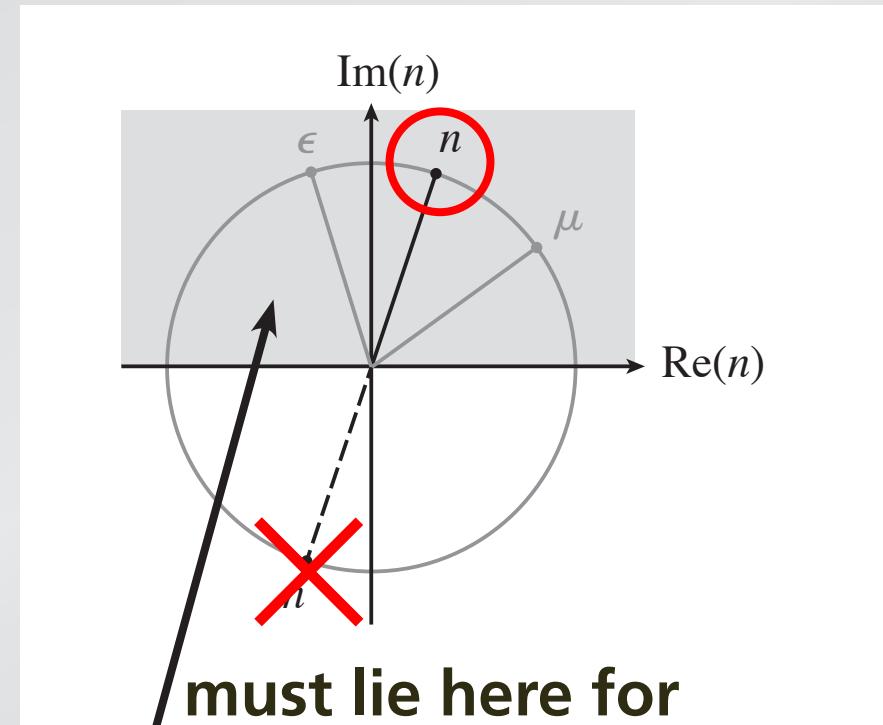
$$n = \sqrt{\epsilon \mu} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$

**but...**

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

**and**

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



**must lie here for  
passive material**

**1 zero index**

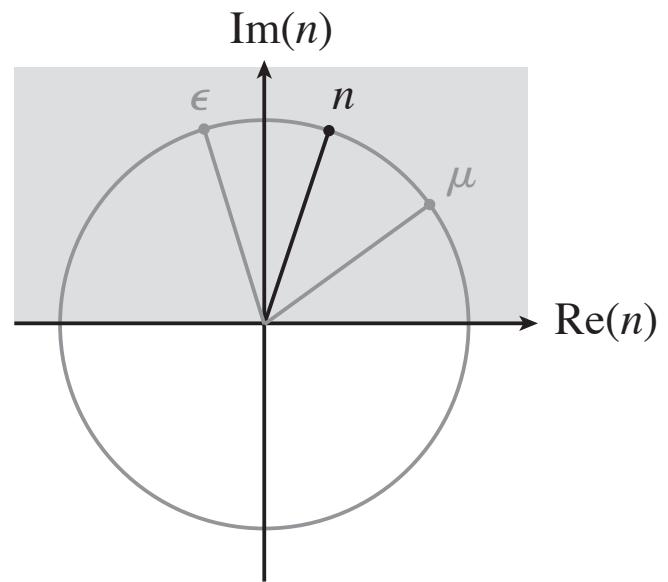
## Q: Is this the only possible solution?

1. yes ✓

2. no, there's one more

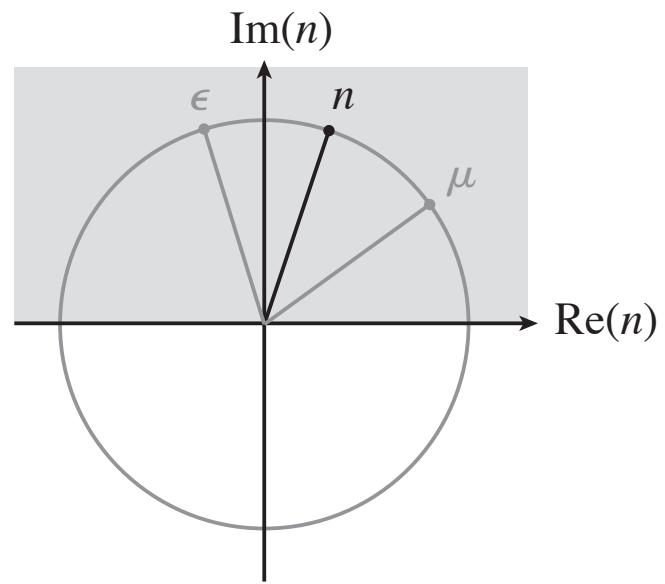
3. there are many more

4. it depends

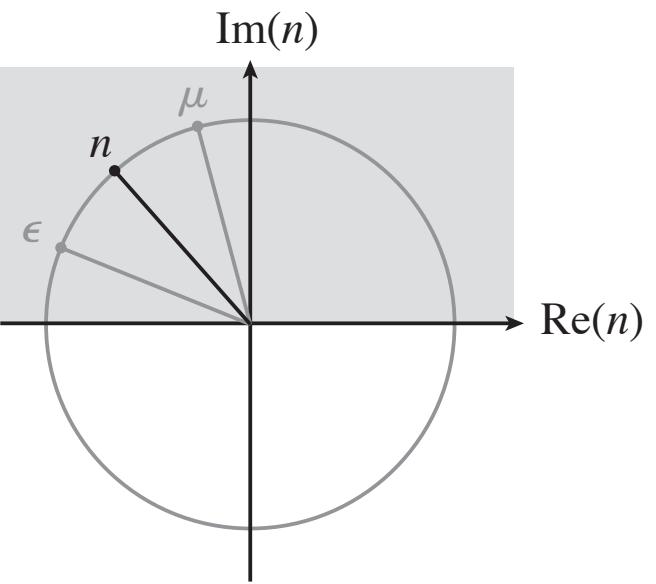


To find  $n$  (passive materials):

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



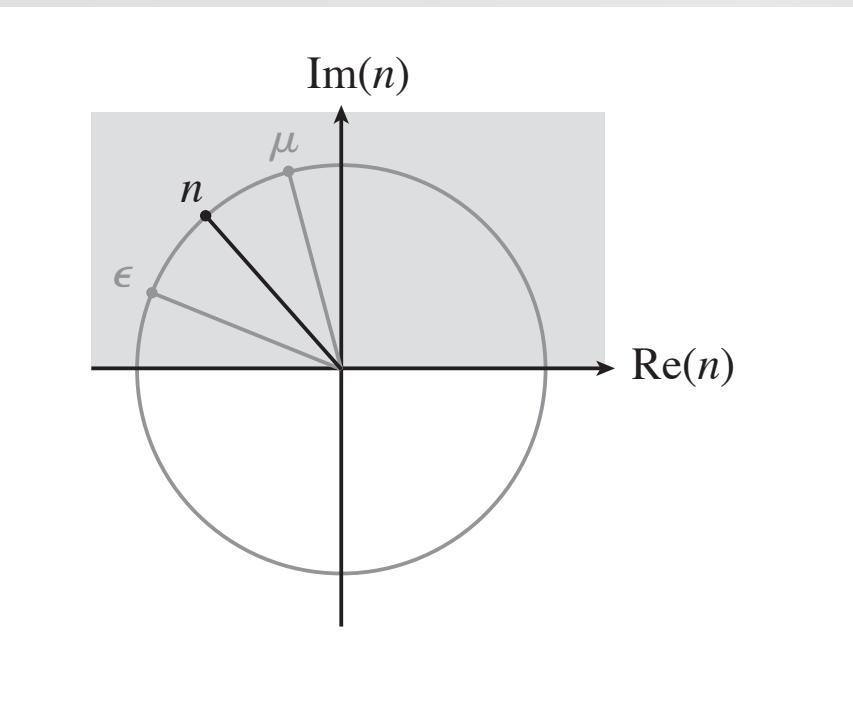
**For certain values of  $\epsilon$  and  $\mu$   
we can get a *negative*  $\text{Re}(n)$ !**



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

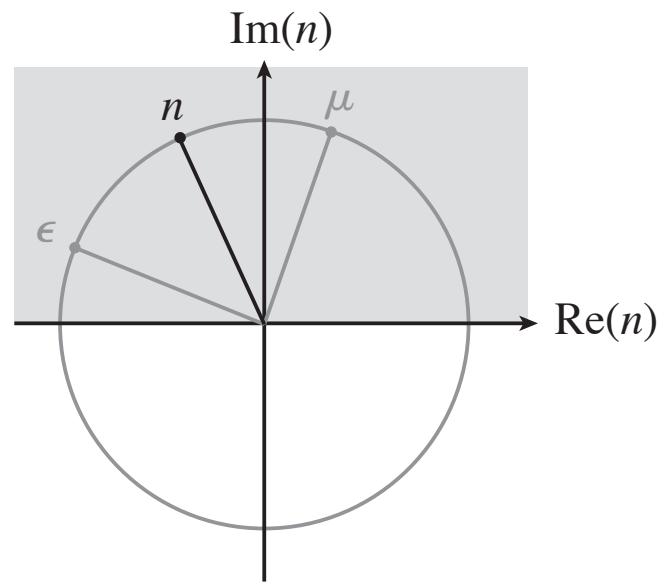
1. yes
2. no

1 zero index

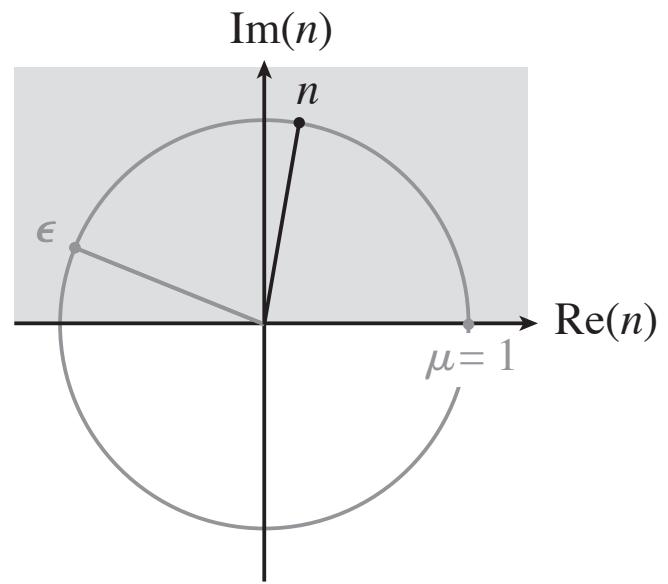


**Q: Must both  $\operatorname{Re}\epsilon < 0$  and  $\operatorname{Re}\mu < 0$  to get a negative index?**

1. yes
2. no ✓



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



**Now remember**

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

**1 zero index**

**Now remember**

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

**Spatial and temporal dependence of wave component**

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

**Now remember**

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

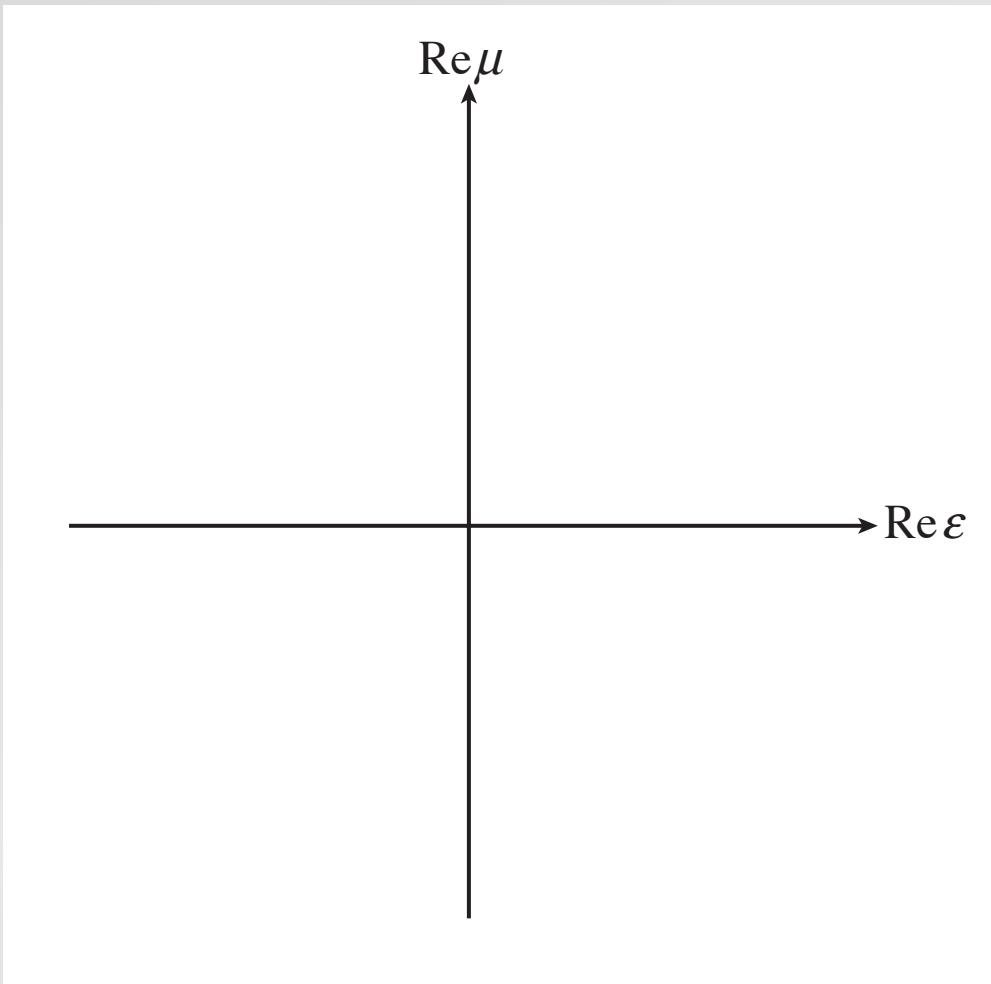
**Spatial and temporal dependence of wave component**

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

**When  $\text{Re}(n) < 0$ ,  $k' < 0$ , and so phase velocity reversed!**

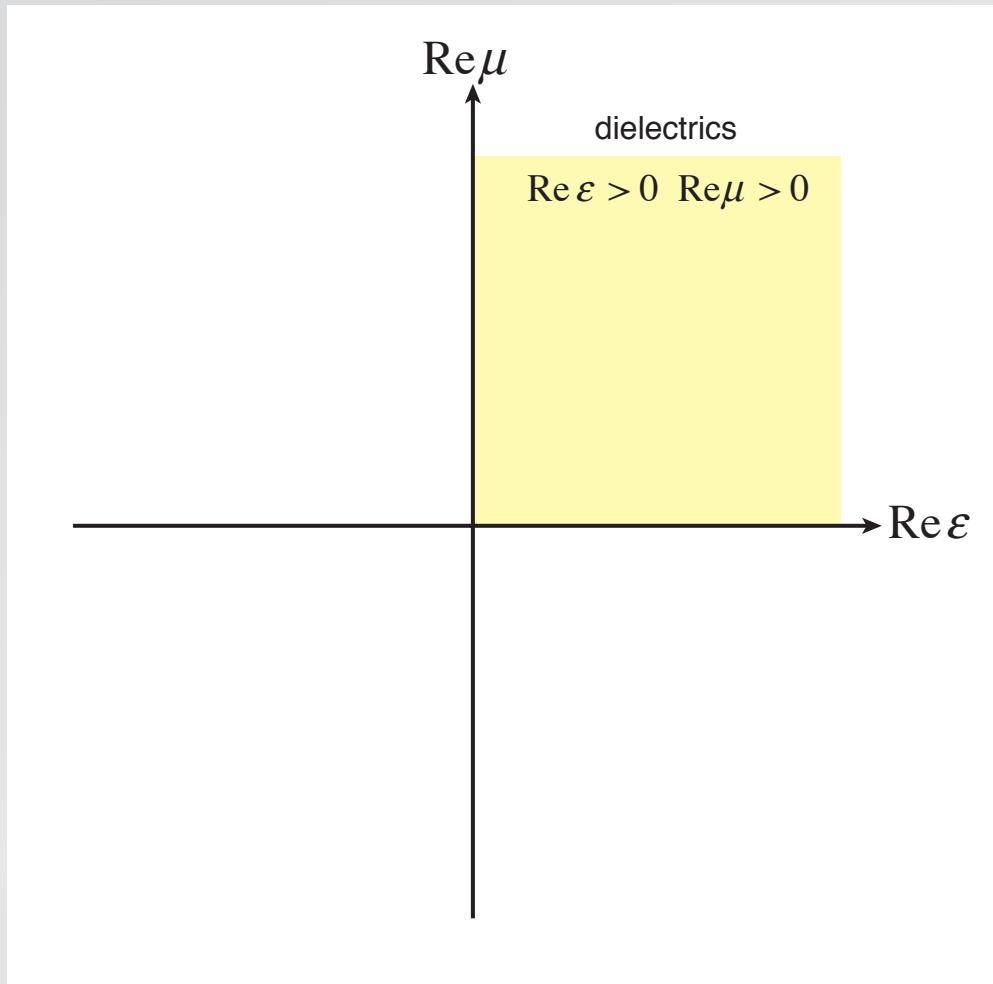
**1 zero index**

## classification of (non-lossy) materials



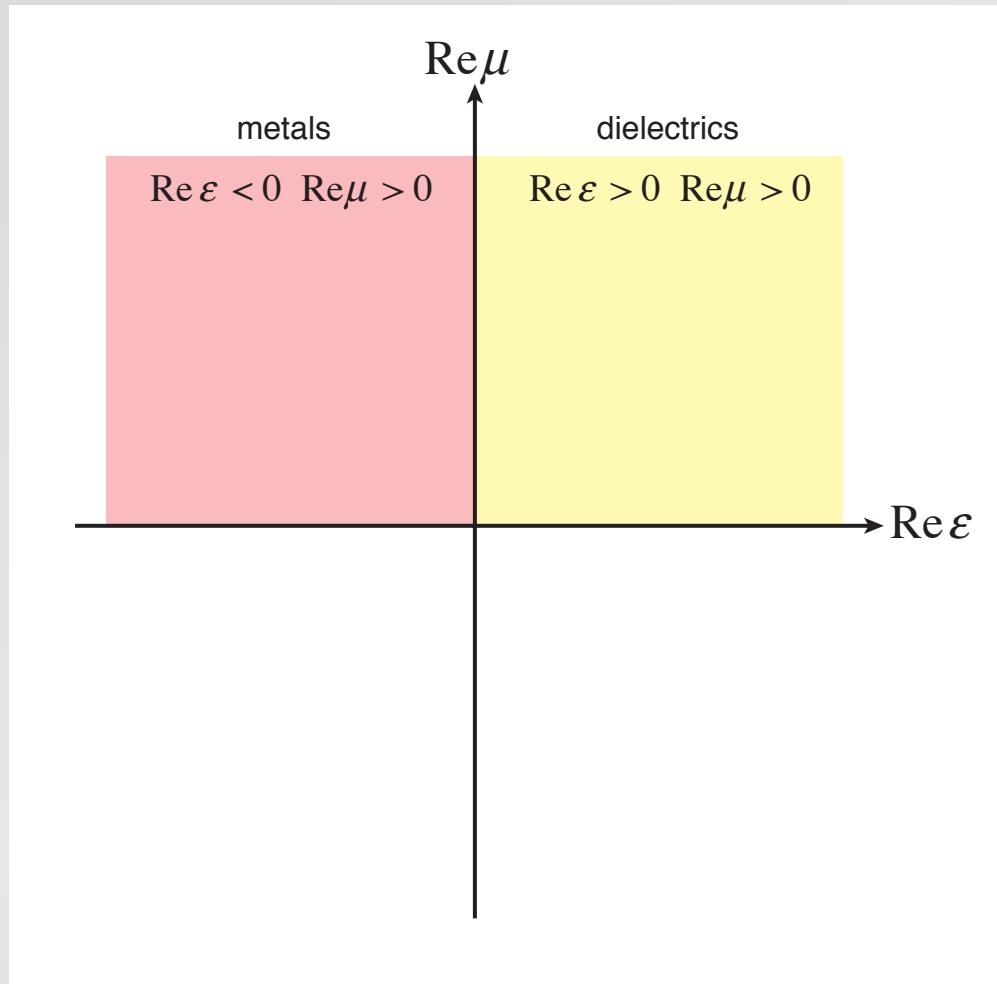
1 zero index

# classification of (non-lossy) materials



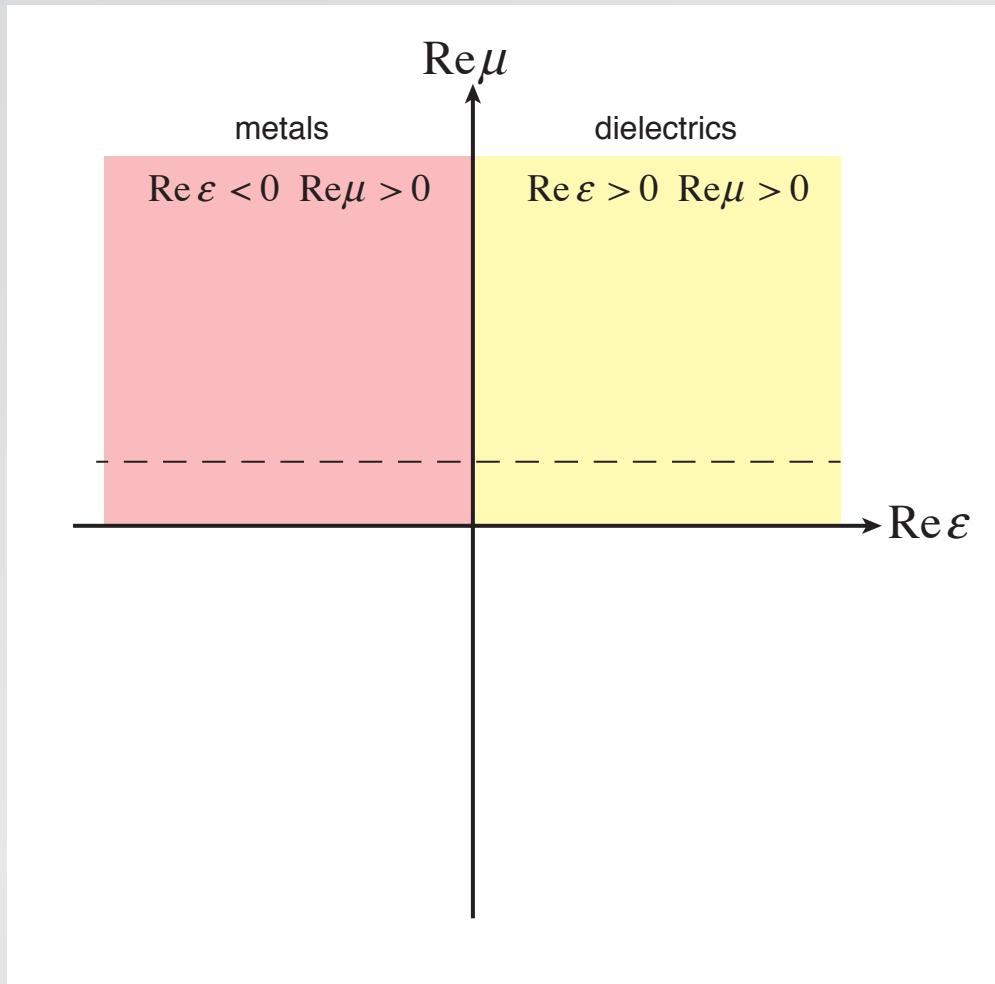
1 zero index

# classification of (non-lossy) materials



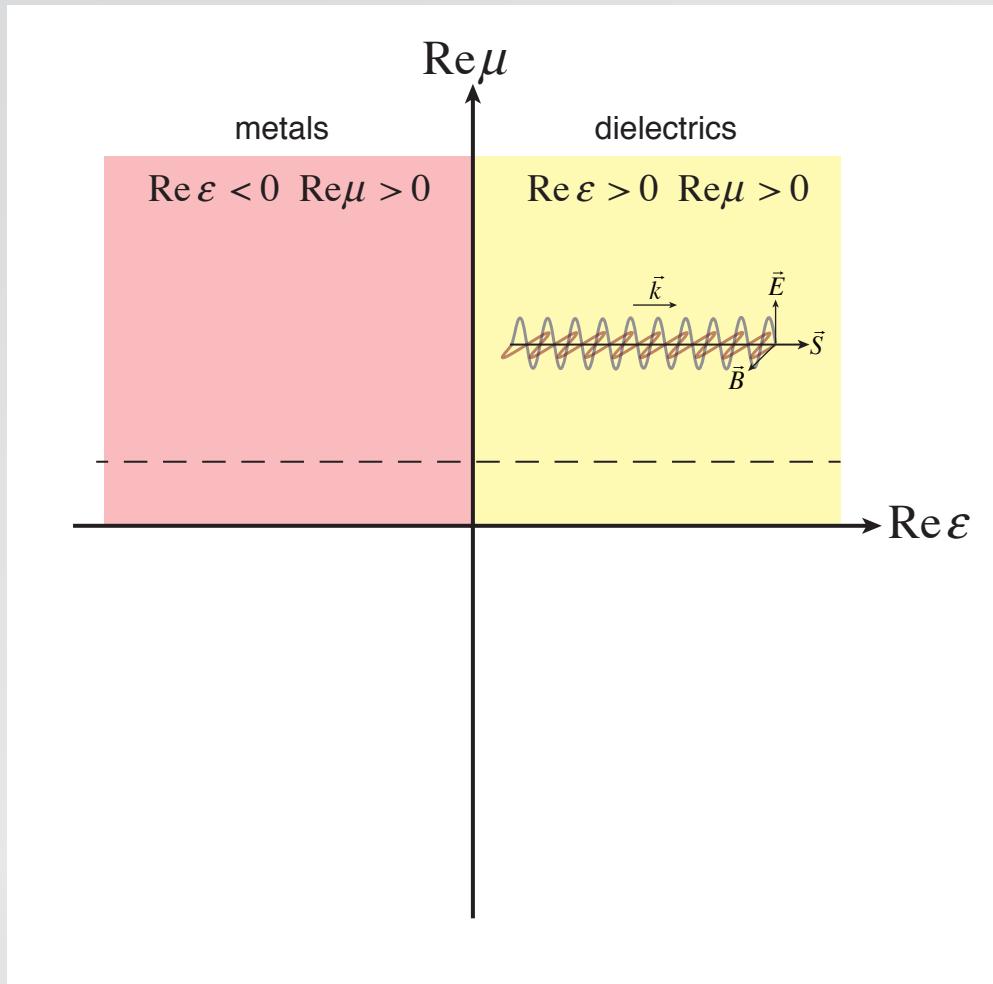
1 zero index

# classification of (non-lossy) materials



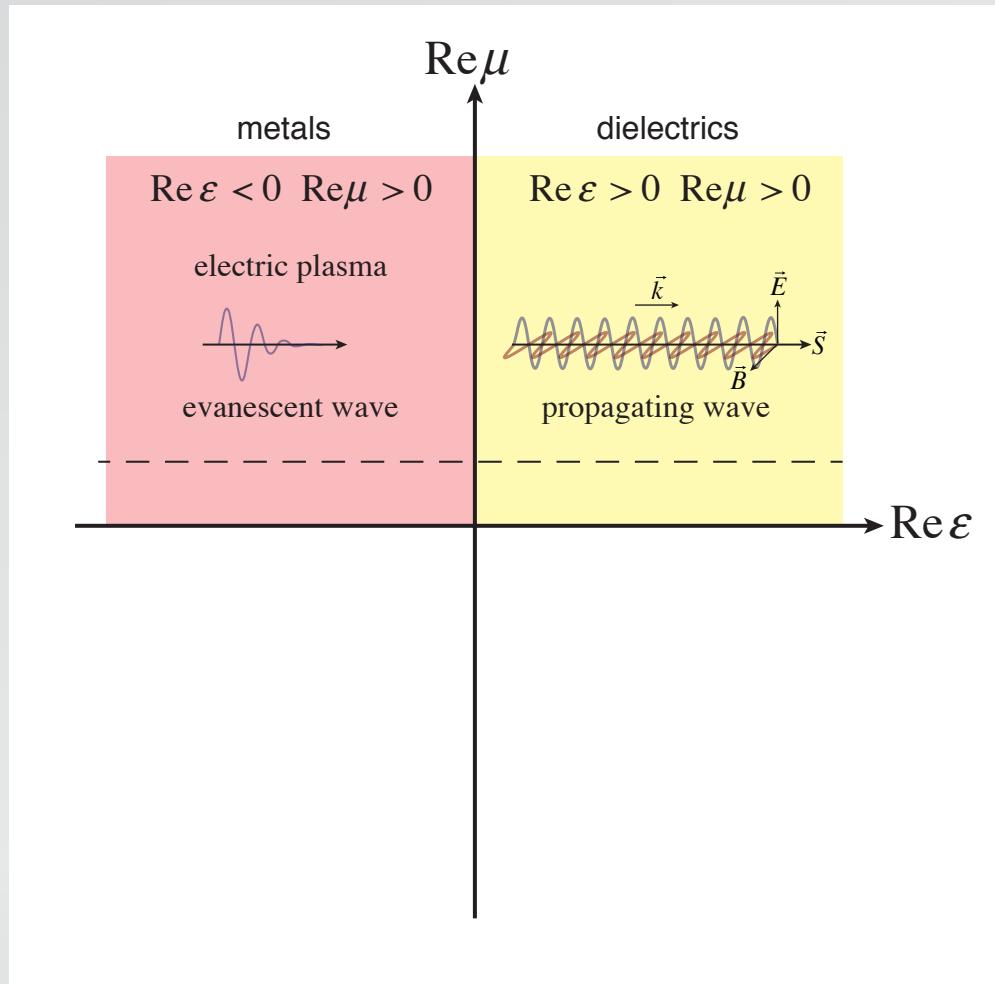
1 zero index

# classification of (non-lossy) materials



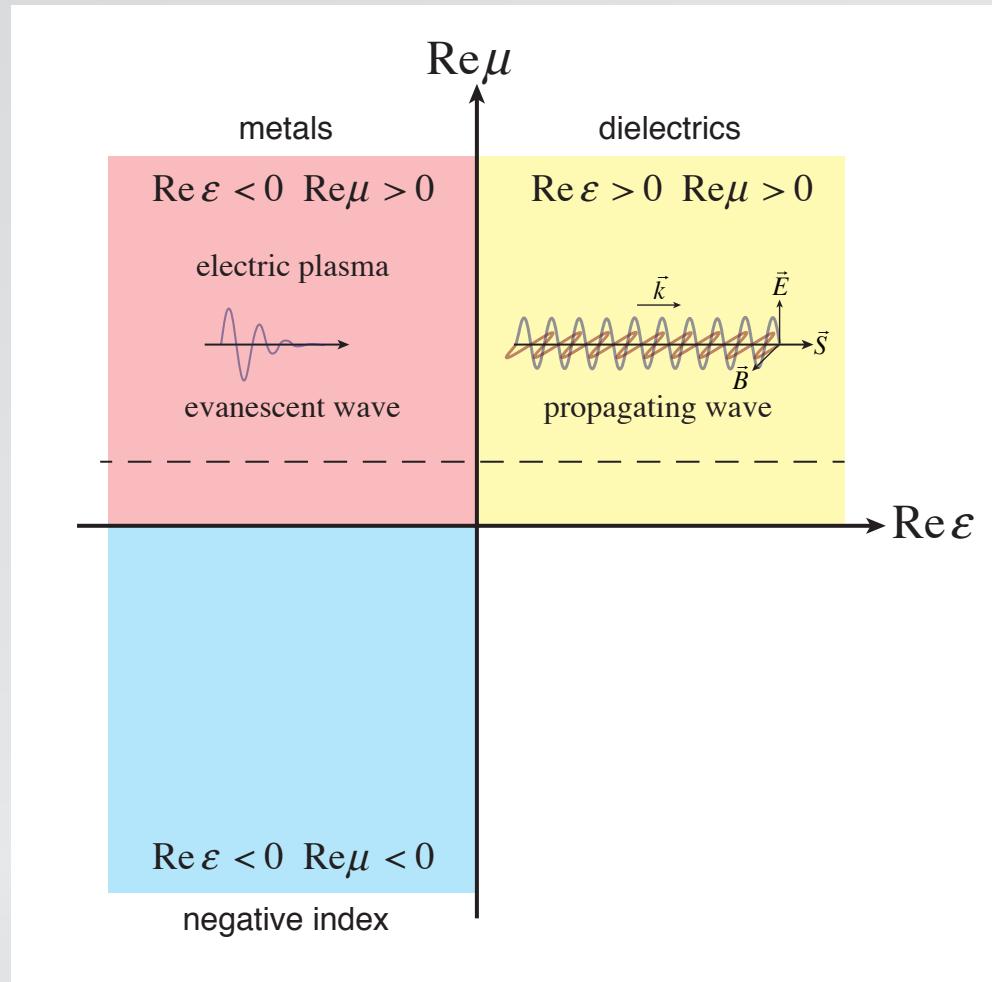
1 zero index

# classification of (non-lossy) materials



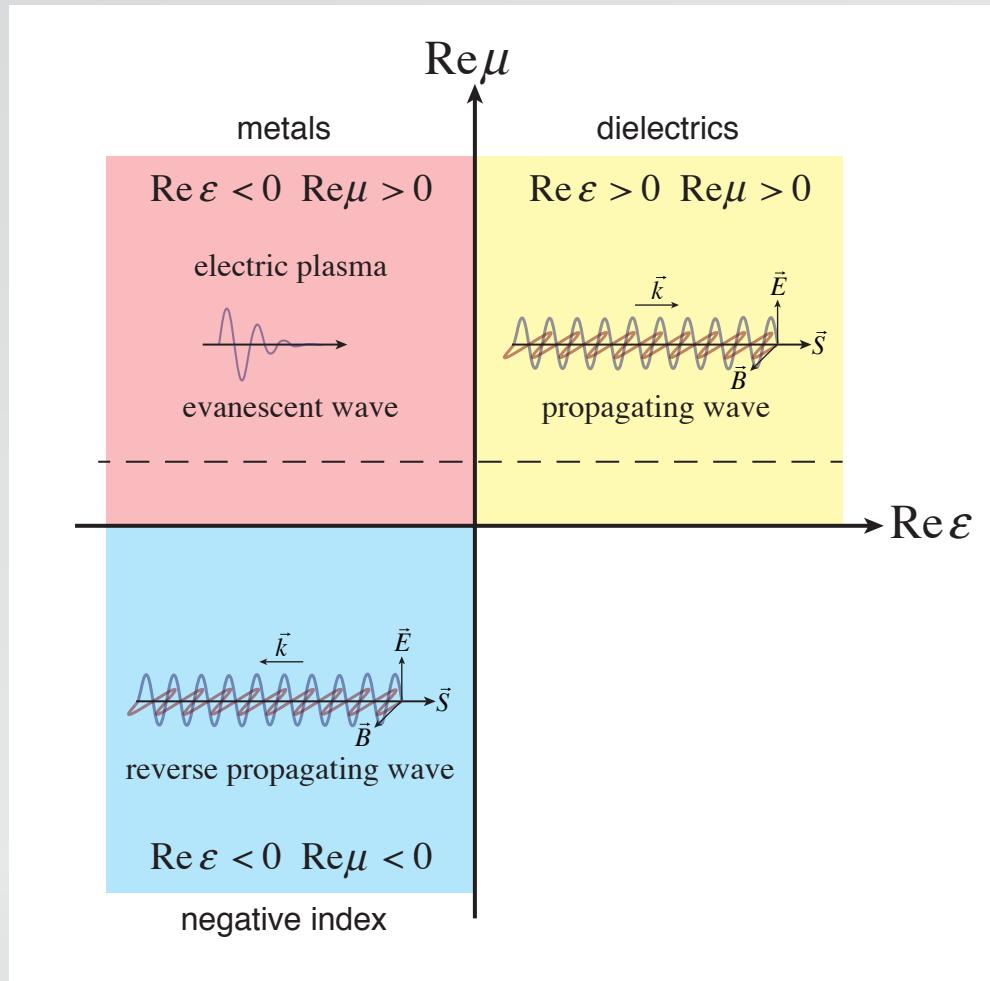
1 zero index

# classification of (non-lossy) materials



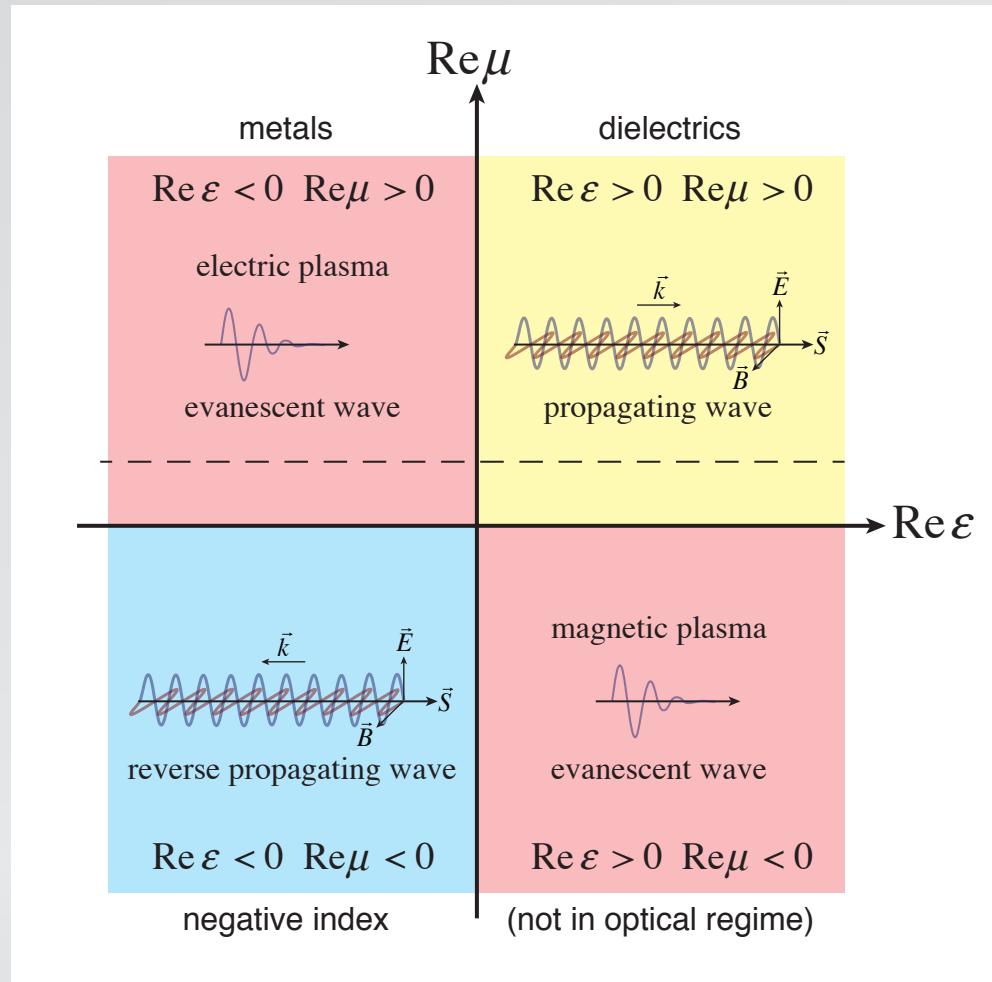
1 zero index

# classification of (non-lossy) materials



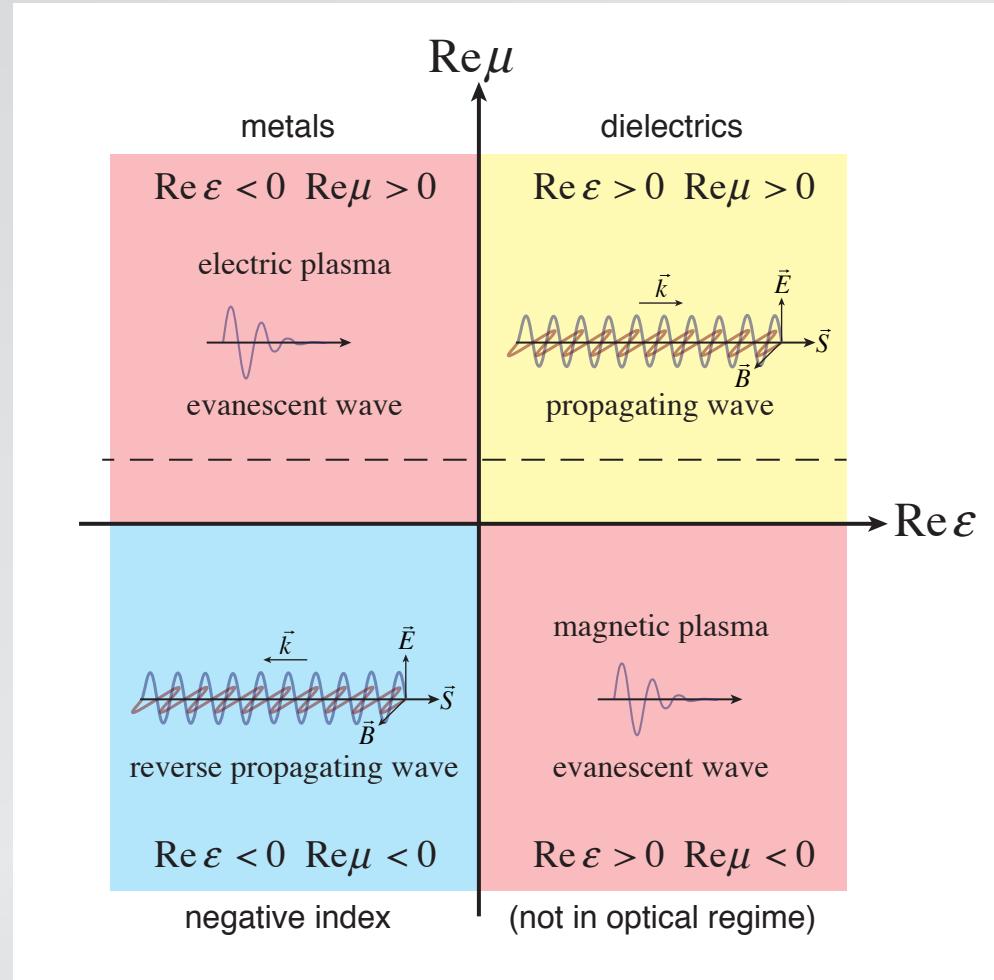
1 zero index

# classification of (non-lossy) materials



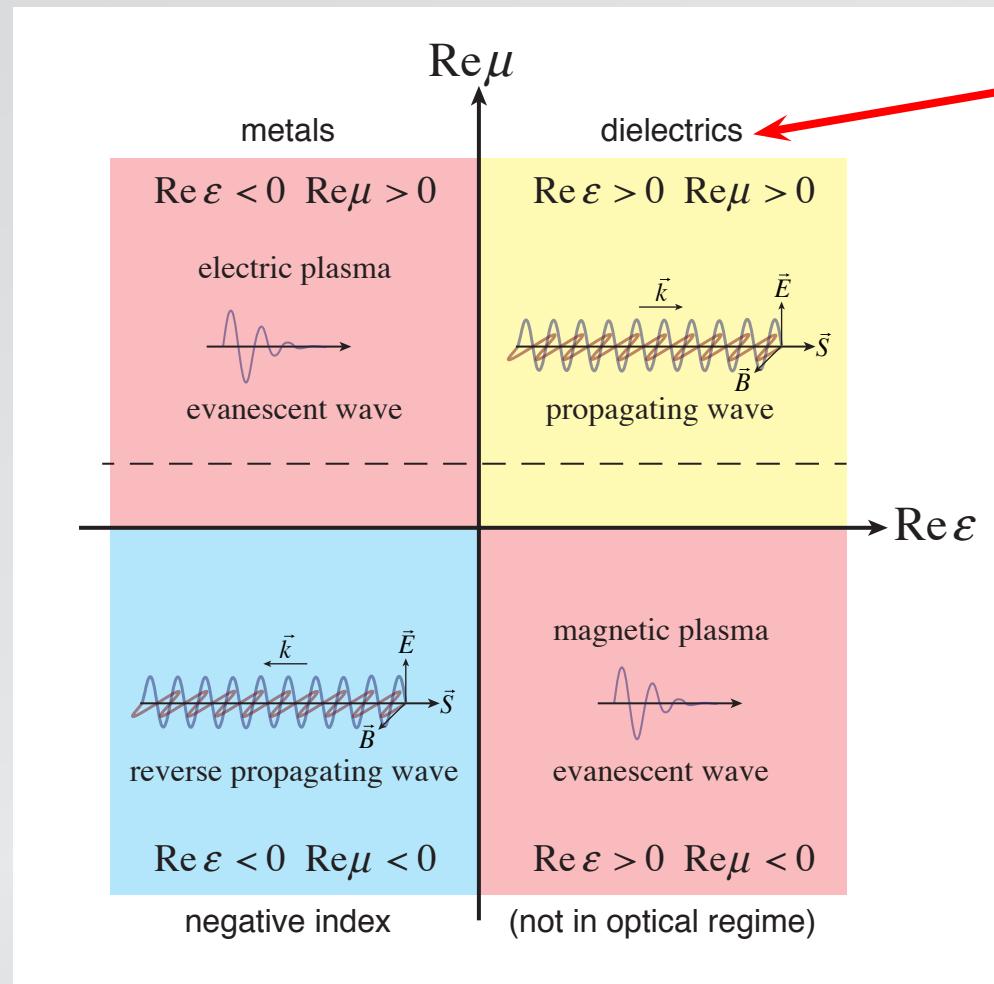
1 zero index

# common materials very limited



1 zero index

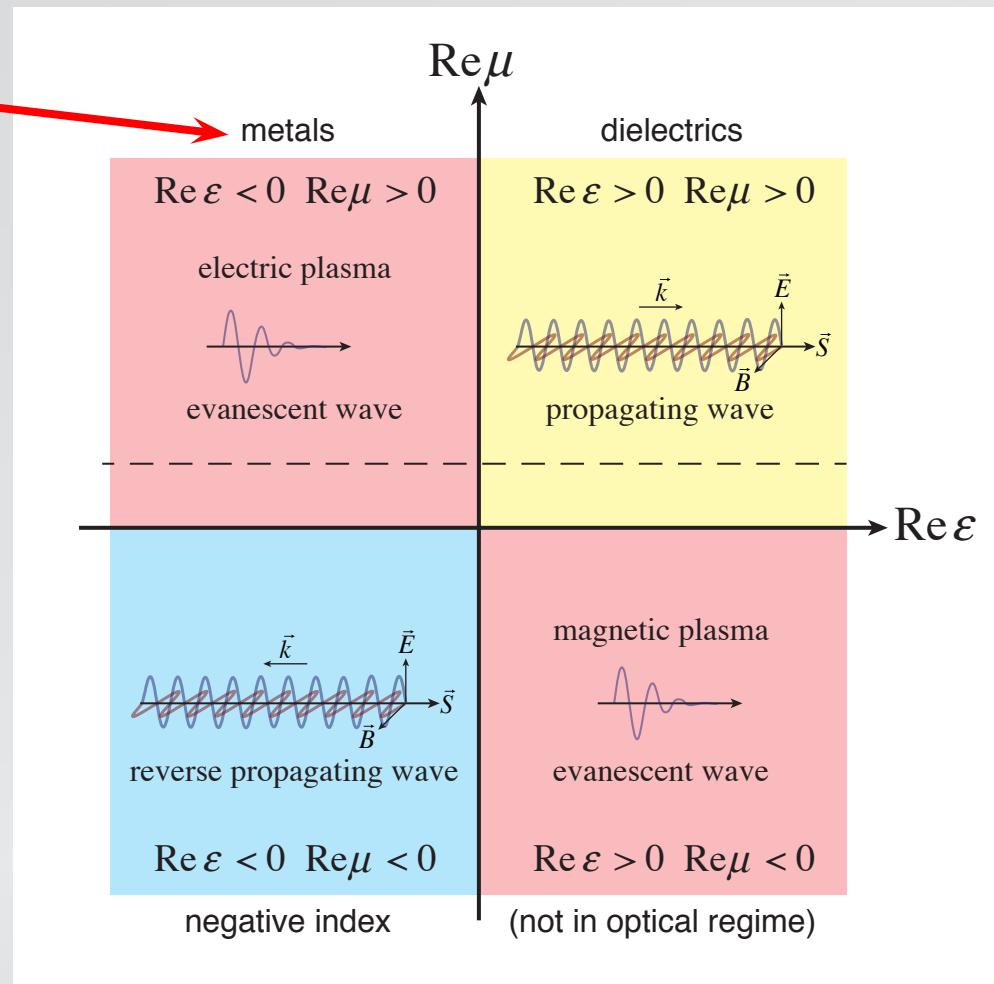
# common materials very limited



limited by diffraction

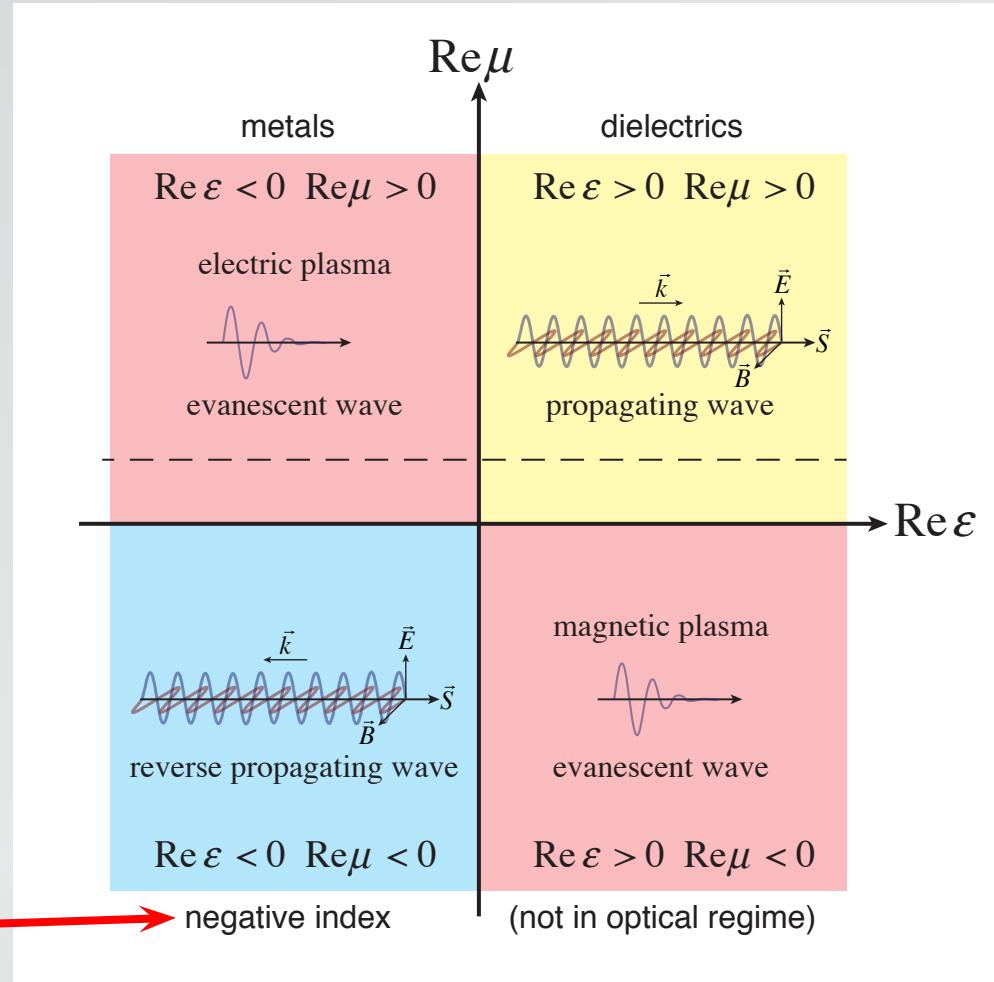
common materials very limited

lossy & no propagation



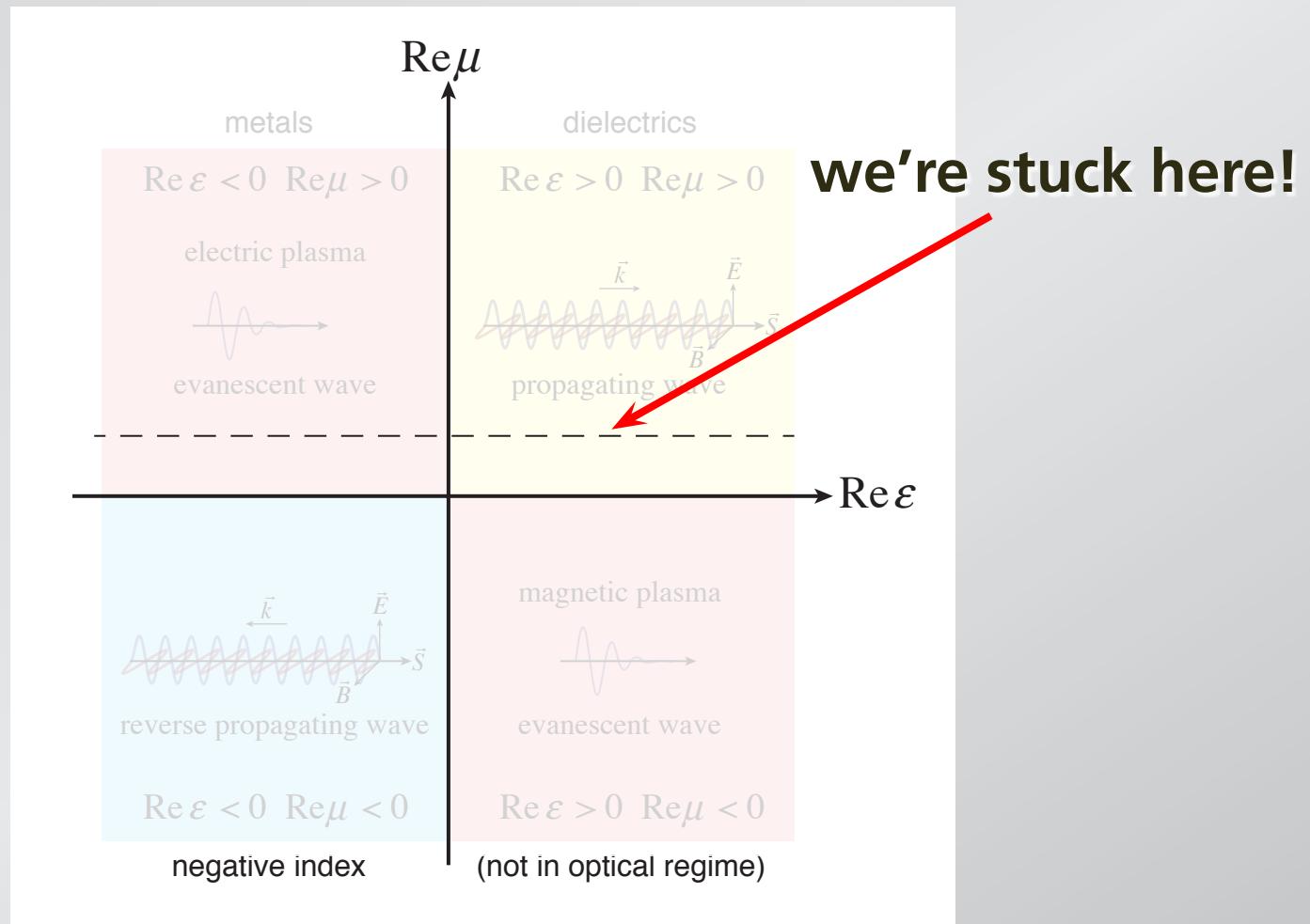
1 zero index

# common materials very limited



1 zero index

# common materials very limited



1 zero index

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

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

**if  $\varepsilon = 0$ , then  $n = 0$ !**

**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.**

## wave equation

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

## solution

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

where

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

1 zero index

## wave equation

$$\nabla^2 \vec{E} - \frac{\mu \epsilon_0 c^2 \vec{E}}{c^2 \epsilon_0 \mu_0} = 0$$

## 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 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 zero index

## wave equation

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

## solution

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

where

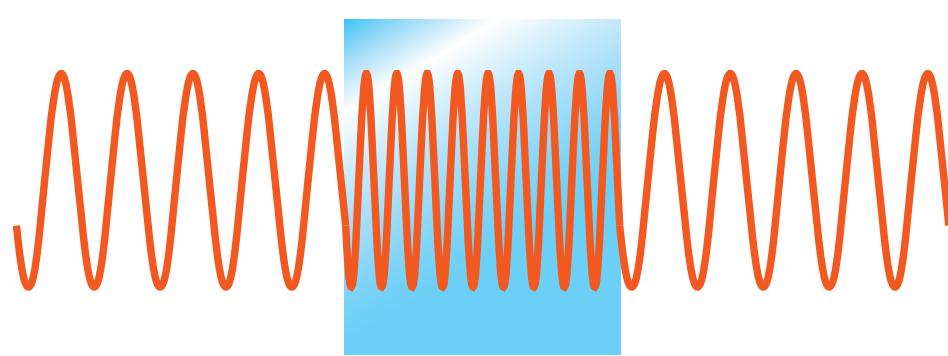
$$\frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c \longrightarrow \infty$$

1 zero index

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

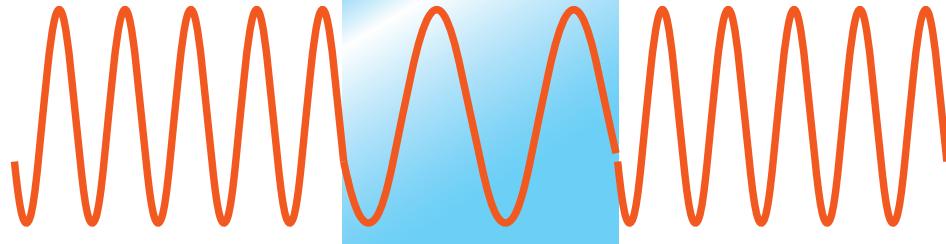
1. the frequency goes to zero.
2. the phase velocity becomes infinite. ✓
3. both of the above.
4. neither of the above.

$n > 1$



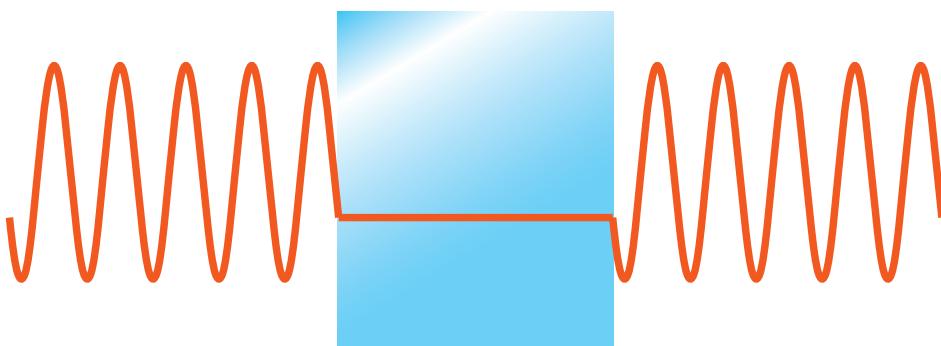
1 zero index

$$0 < n < 1$$



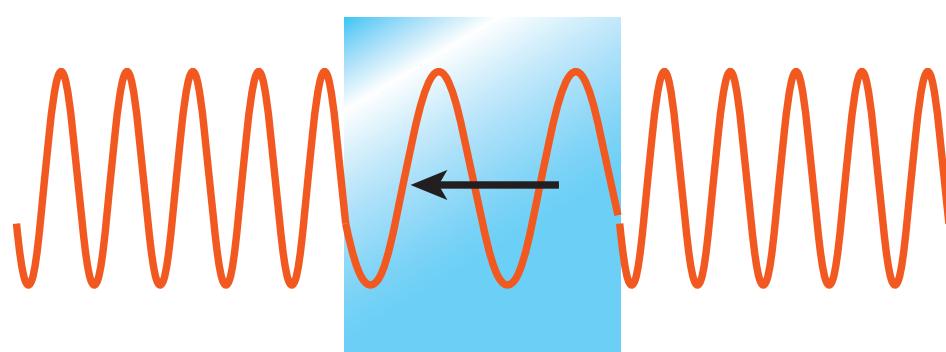
1 zero index

$n = 0$

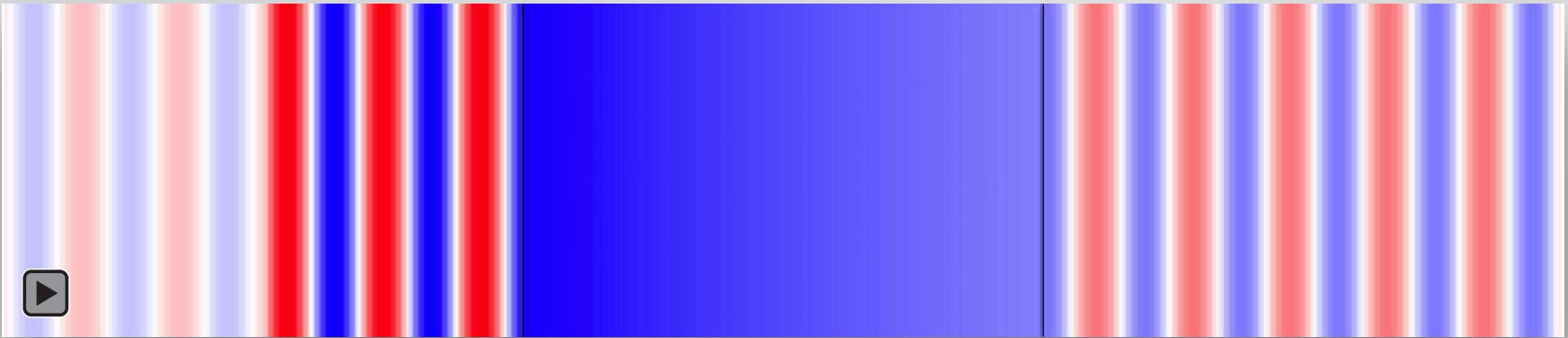


1 zero index

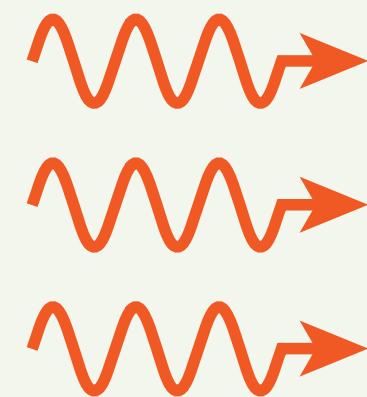
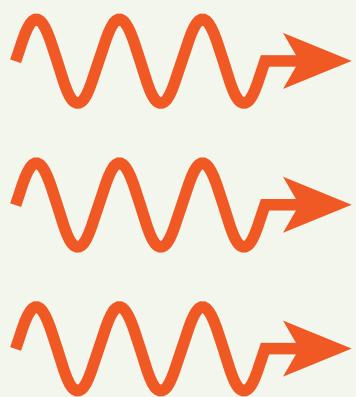
$$n < 0$$



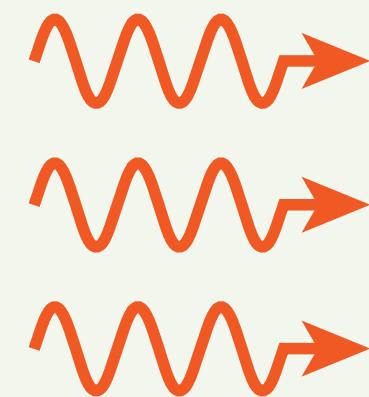
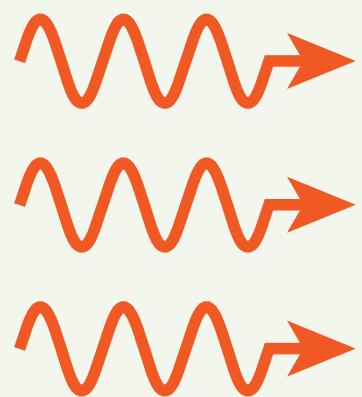
1 zero index



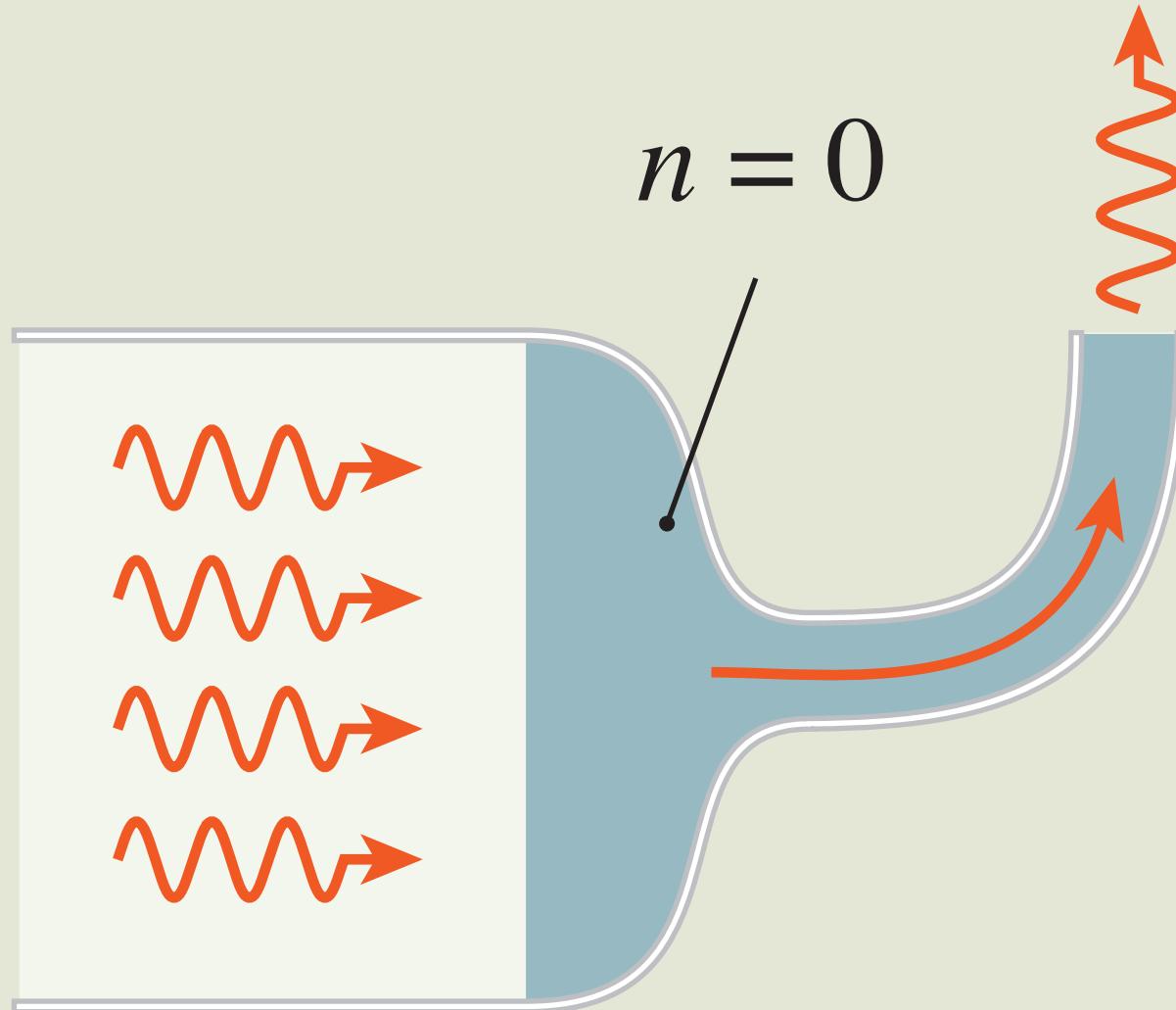
1 zero index

$n = 0$ 

1 zero index

$n = 0$ 

1 zero index



1 zero index

**how?**

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

**1** zero index

**2** fabrication

how?

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

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

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

1 zero index

2 fabrication

**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 zero index**

**2 fabrication**

**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 zero index**

**2 fabrication**

**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 zero index**

**2 fabrication**

**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**

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

**1 zero index**

**2 fabrication**

**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 zero index**

**2 fabrication**

**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 zero index**

**2 fabrication**

**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 zero index**

**2 fabrication**

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

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

1 zero index

2 fabrication

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

**1** zero index

**2** fabrication

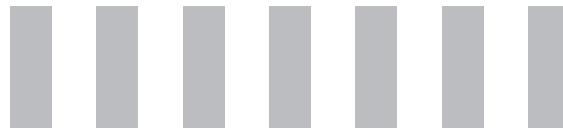
# Engineering a magnetic response

1 zero index

2 fabrication

# Engineering a magnetic response

use array of dielectric rods

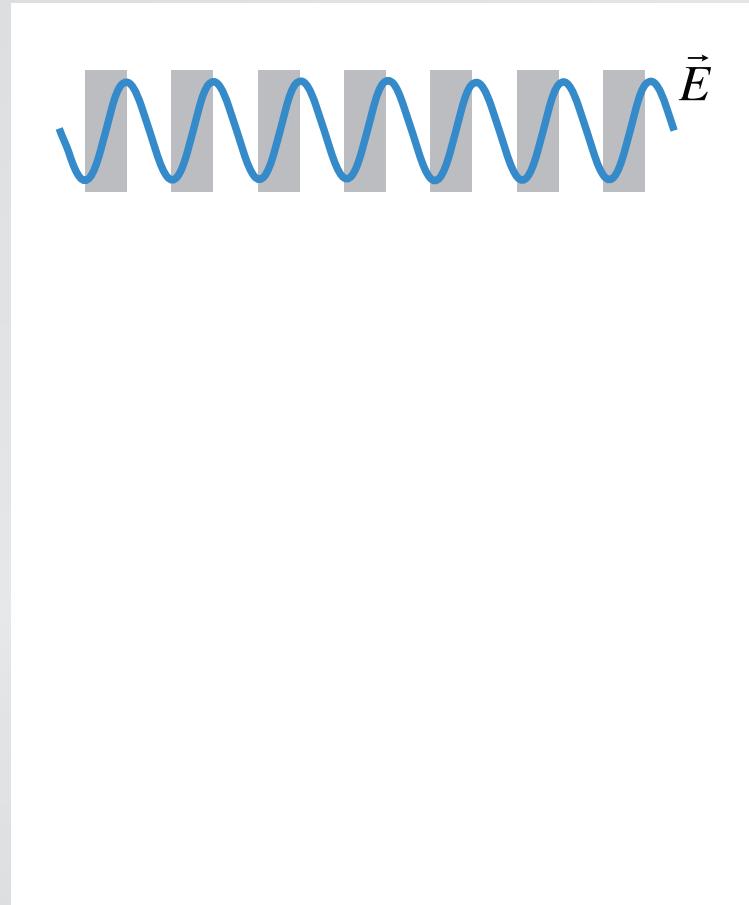


1 zero index

2 fabrication

# Engineering a magnetic response

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

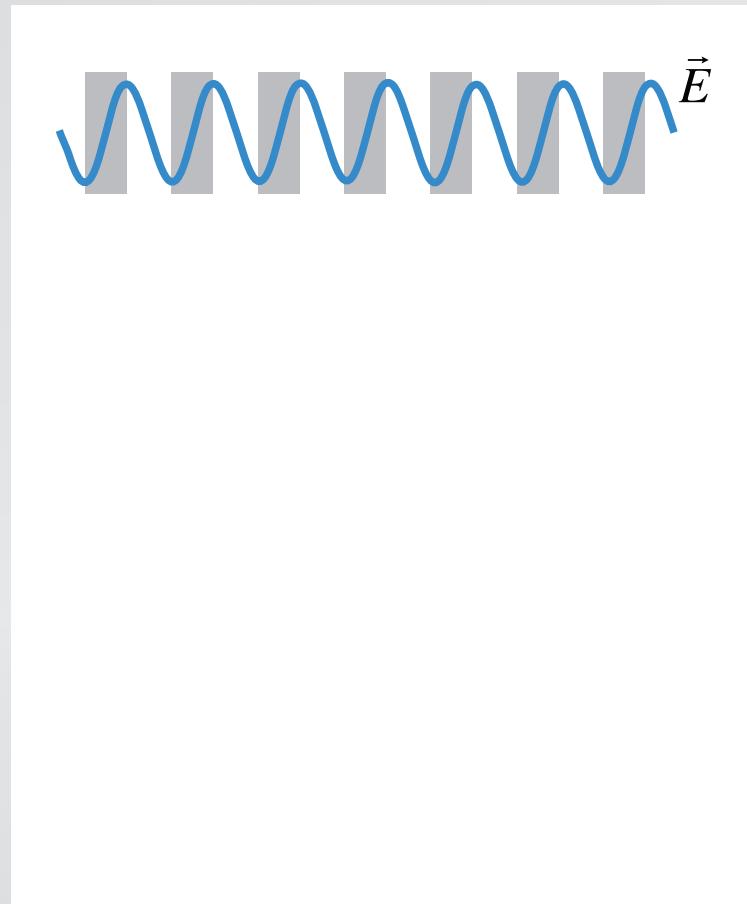


1 zero index

2 fabrication

# Engineering a magnetic response

produces an electric response...

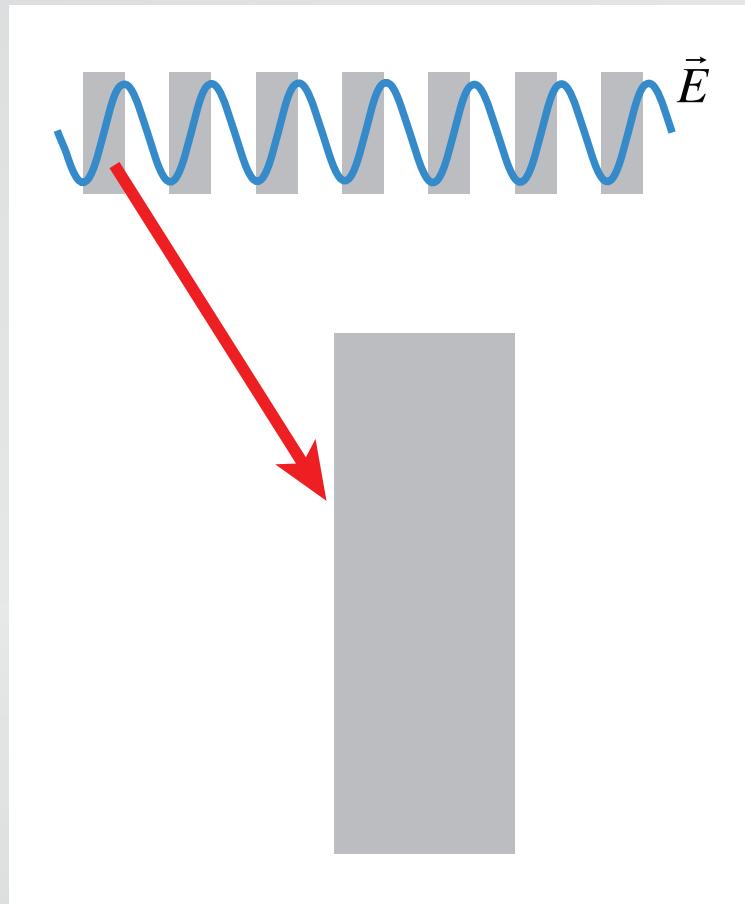


1 zero index

2 fabrication

# Engineering a magnetic response

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

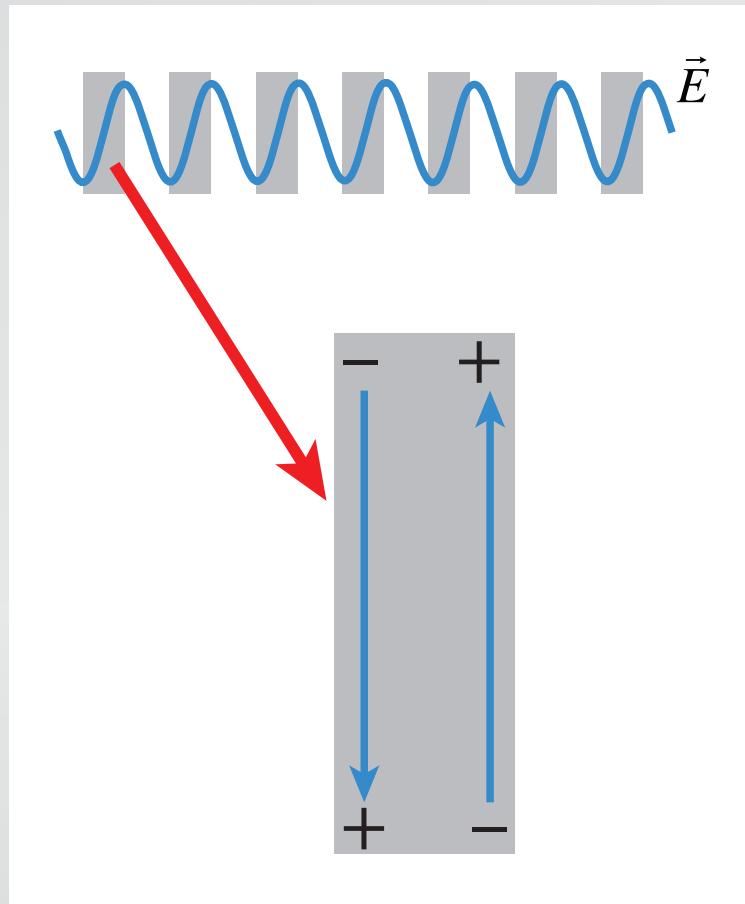


1 zero index

2 fabrication

# Engineering a magnetic response

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

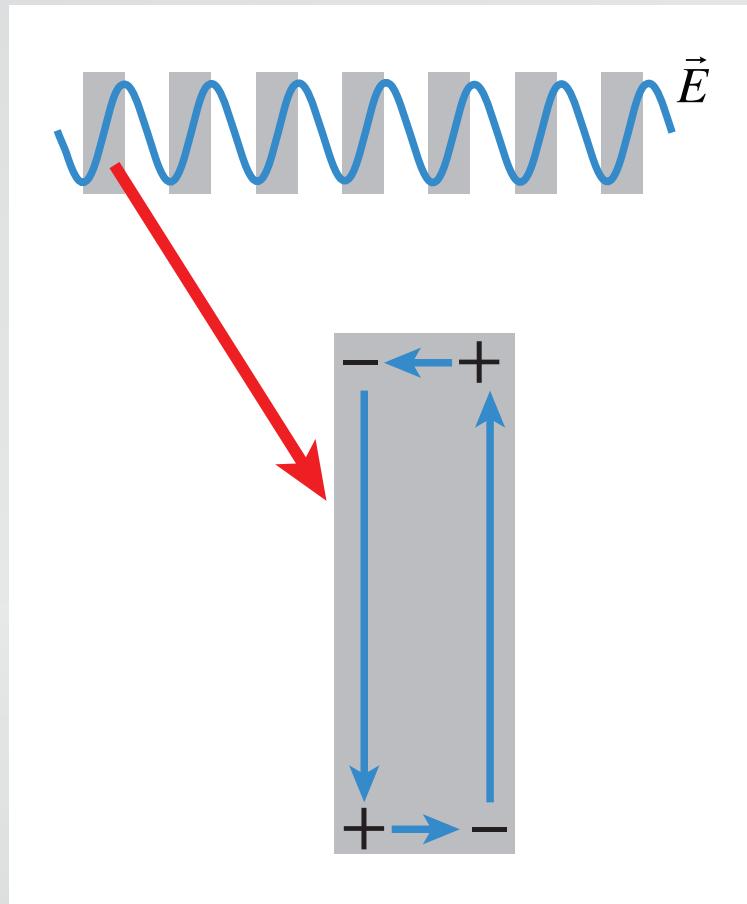


1 zero index

2 fabrication

# Engineering a magnetic response

...causing a current loop...

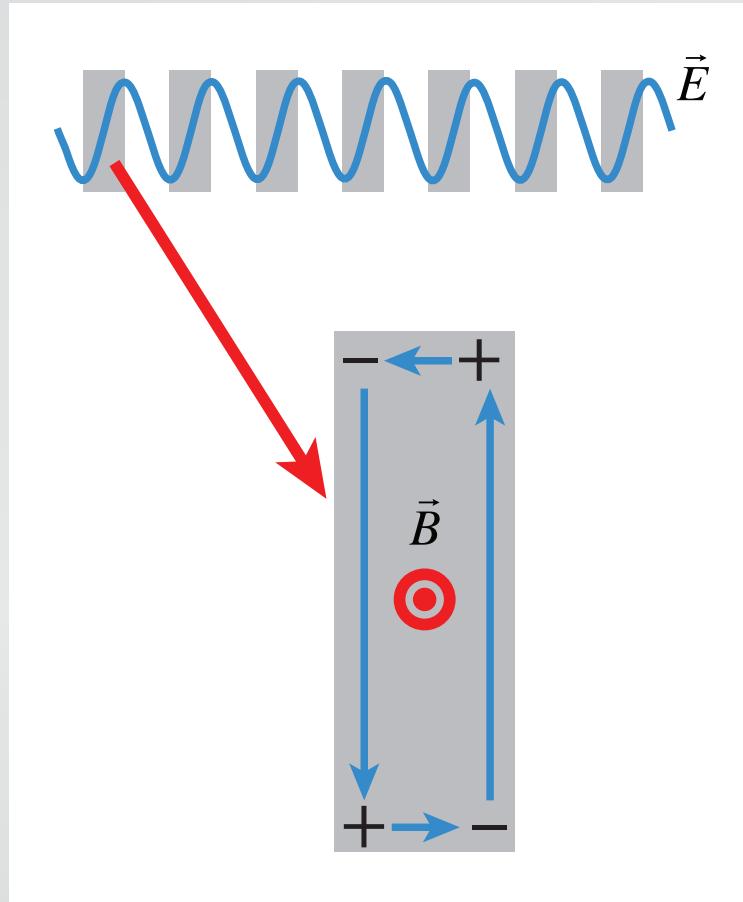


1 zero index

2 fabrication

# Engineering a magnetic response

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

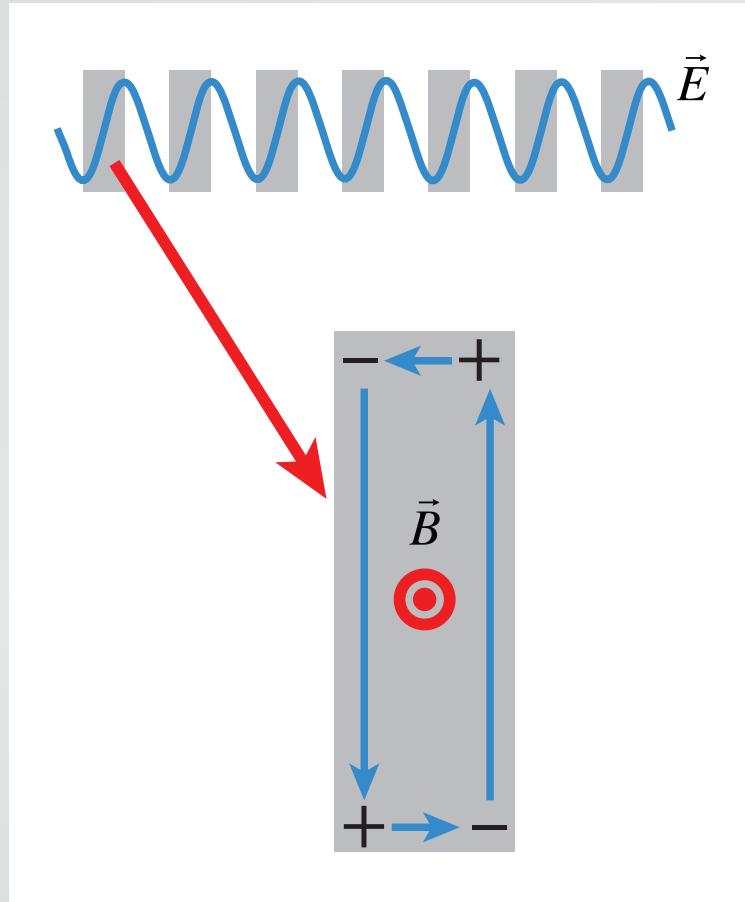


1 zero index

2 fabrication

# Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide

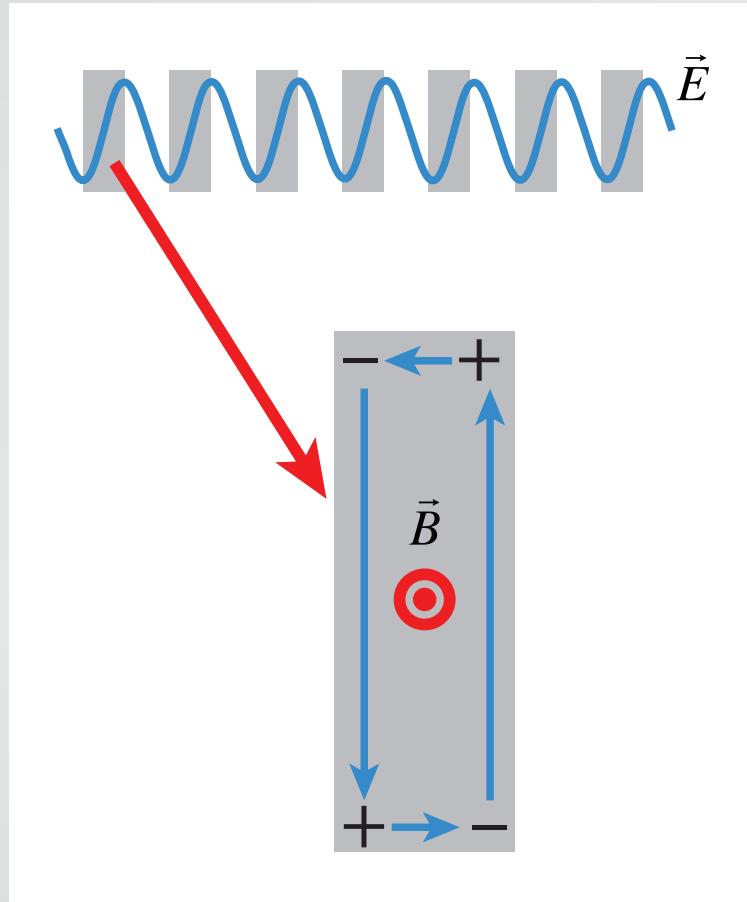


1 zero index

2 fabrication

# Engineering a magnetic response

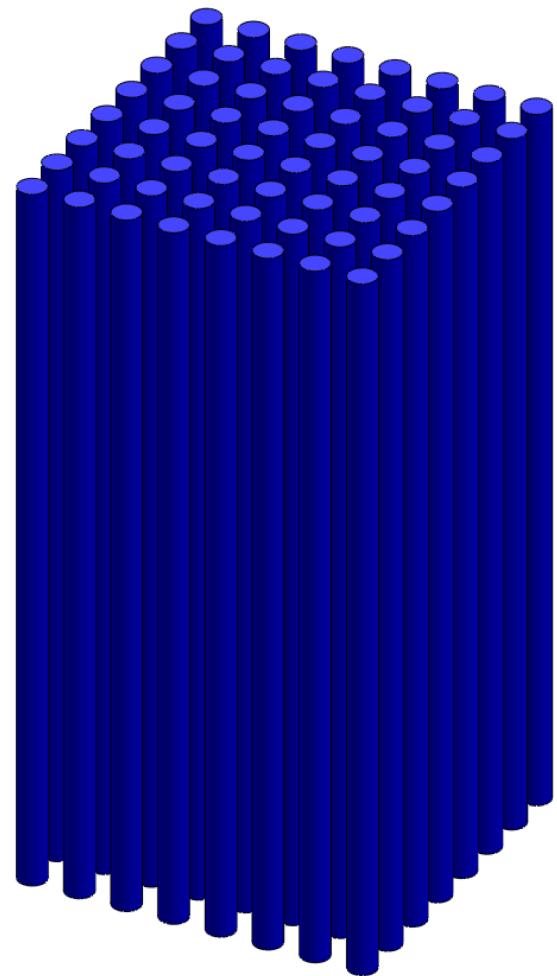
adjust design so electrical and magnetic resonances coincide



(adjustable parameters:  $n$ ,  $d$ , and  $a$ )

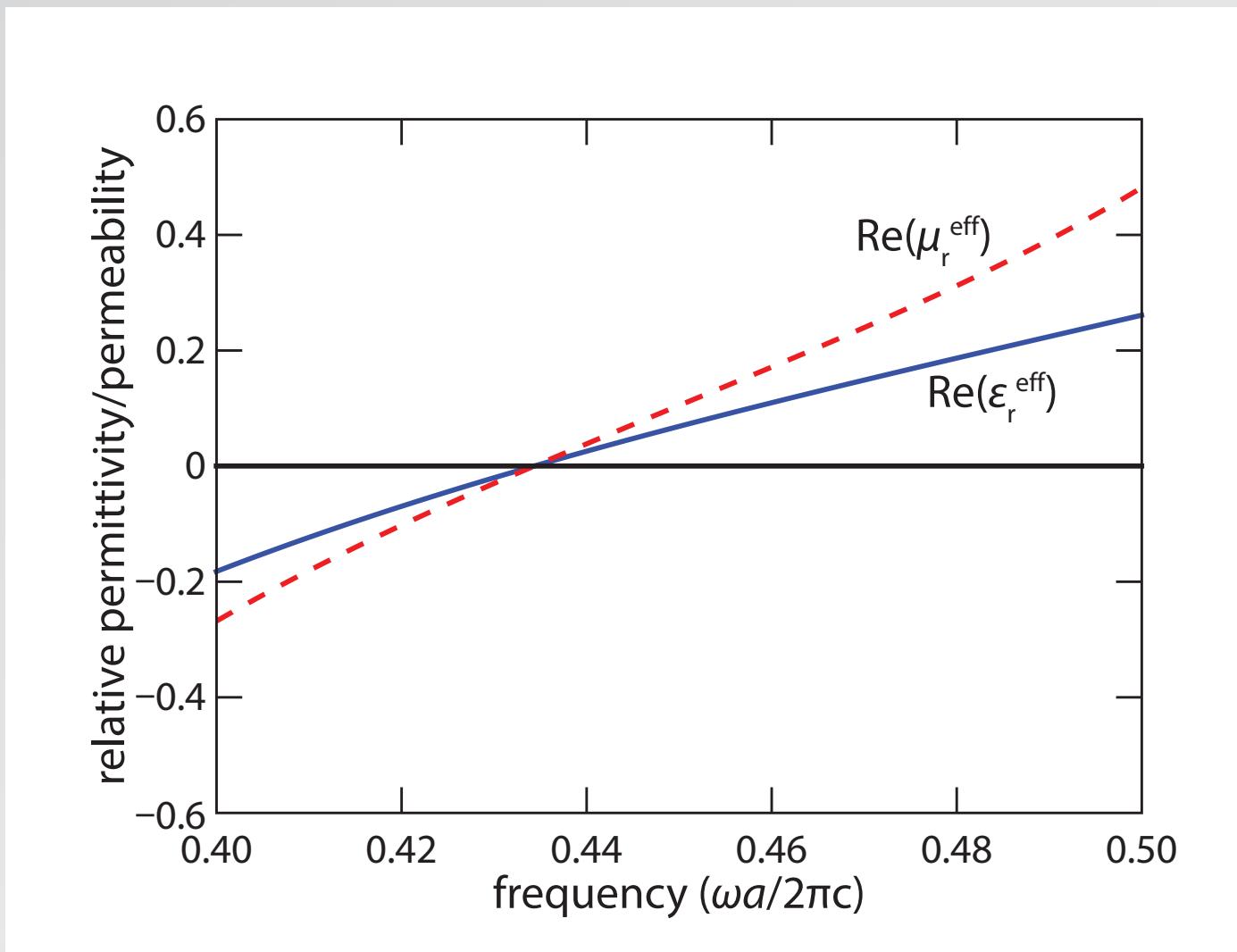
1 zero index

2 fabrication



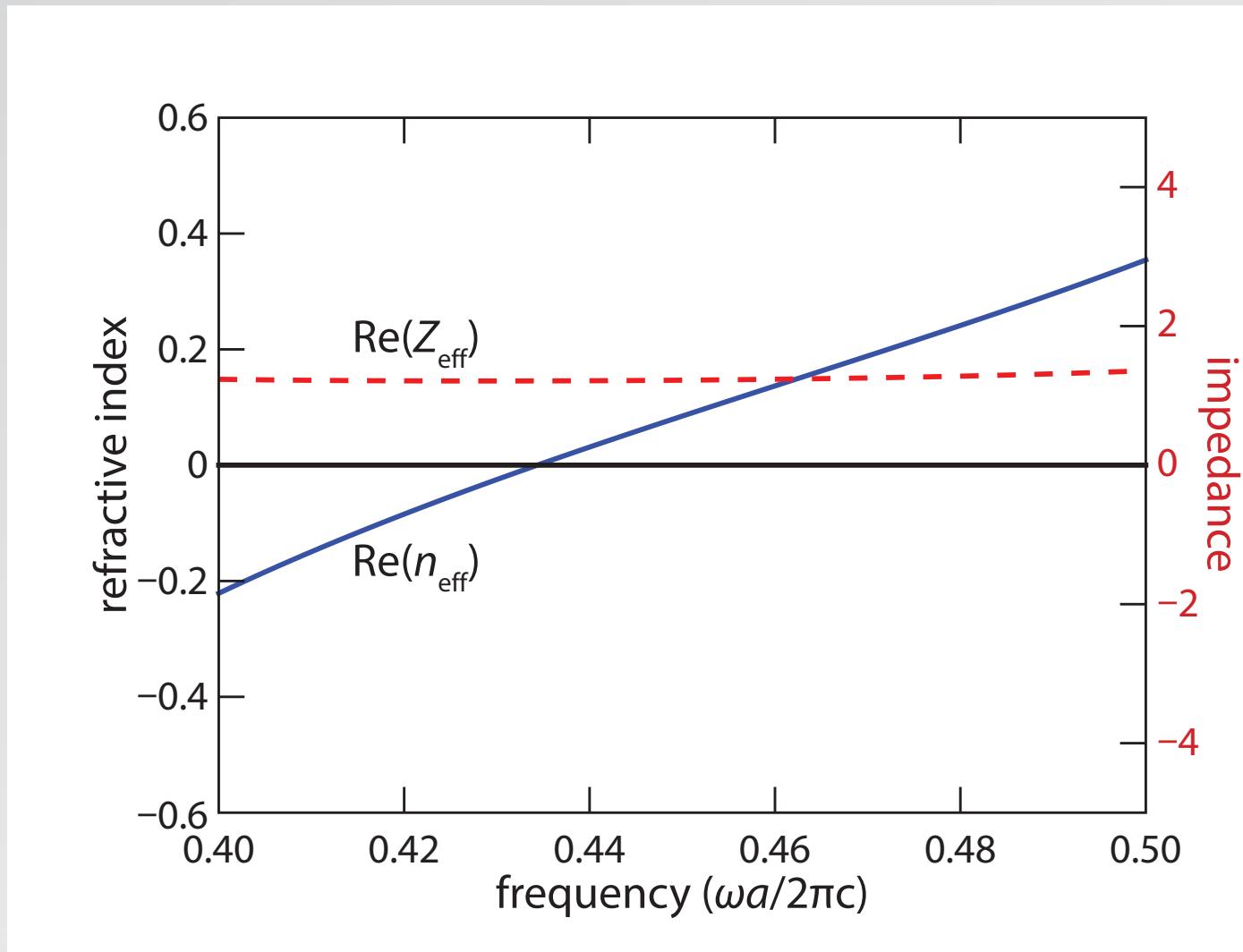
1 zero index

2 fabrication



1 zero index

2 fabrication



1 zero index

2 fabrication

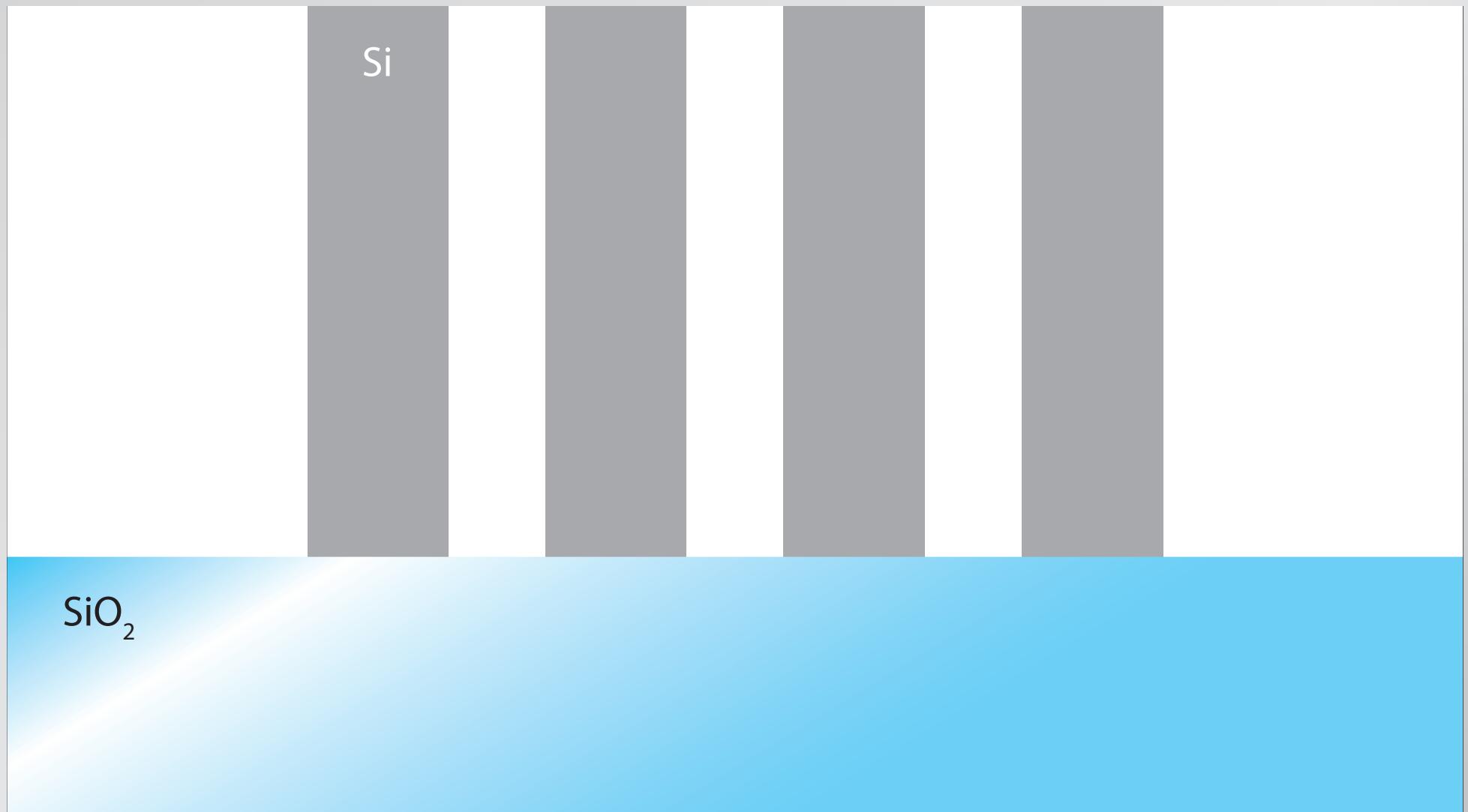
# On-chip zero-index fabrication



1 zero index

2 fabrication

# On-chip zero-index fabrication



1 zero index

2 fabrication

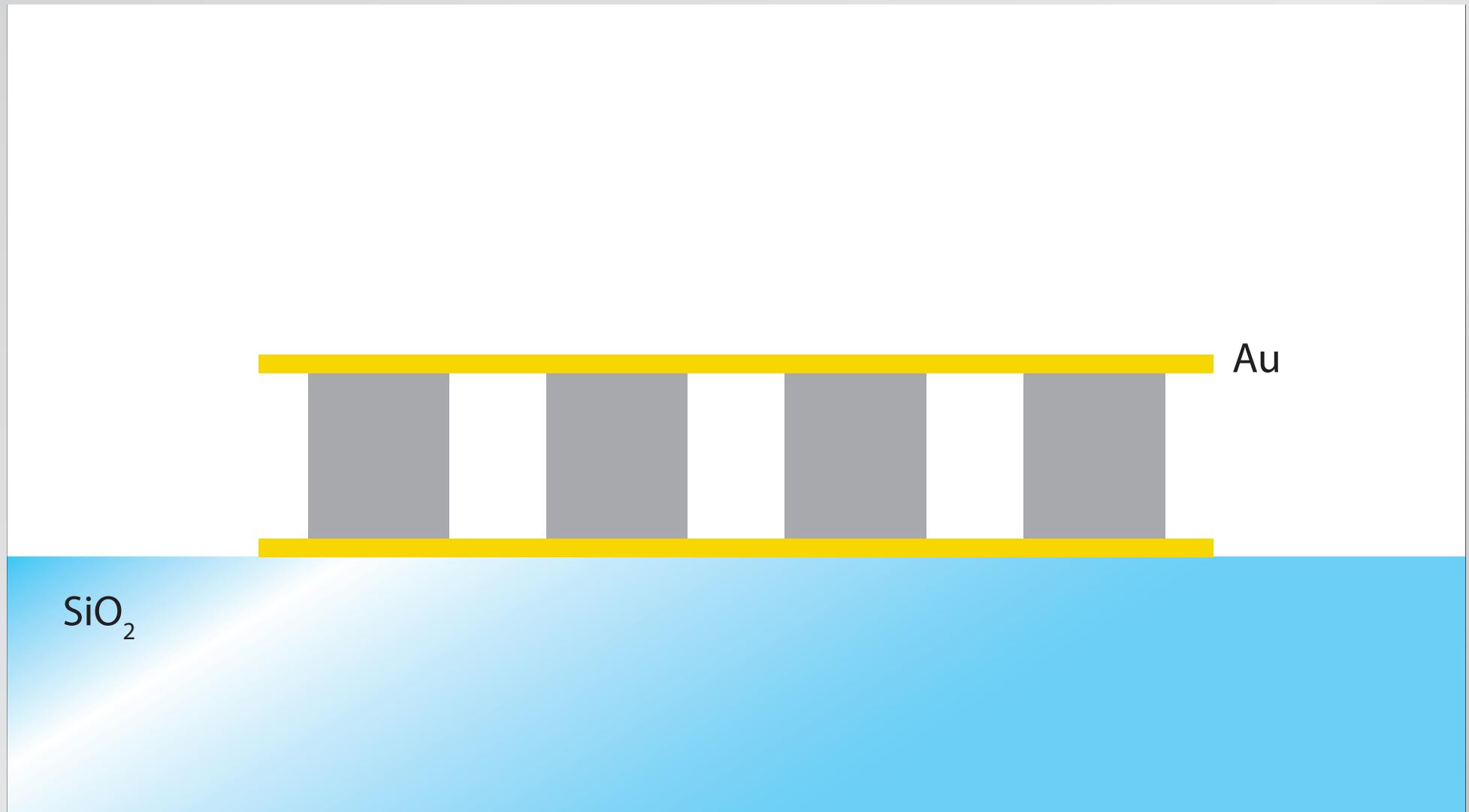
# On-chip zero-index fabrication



1 zero index

2 fabrication

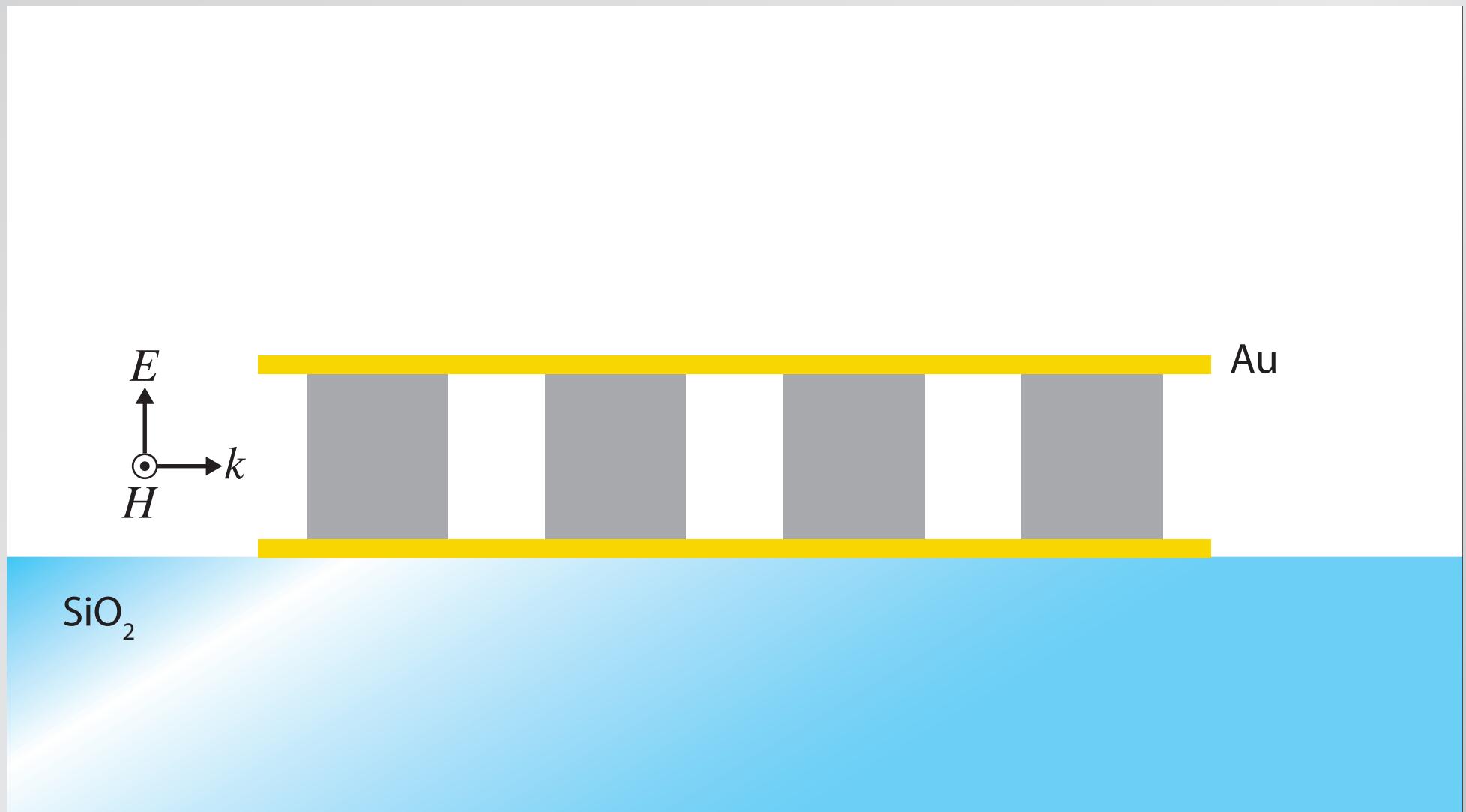
# On-chip zero-index fabrication



1 zero index

2 fabrication

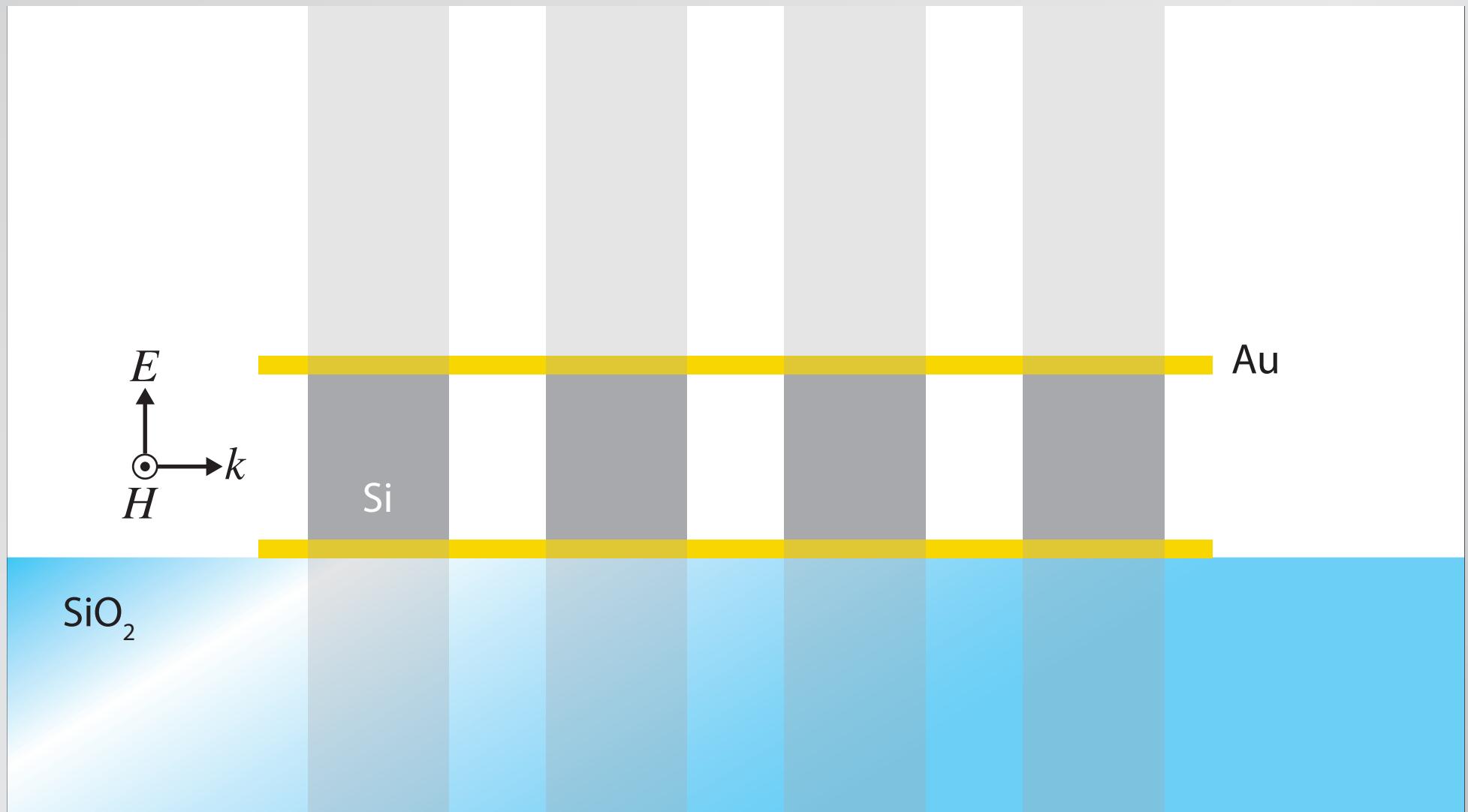
# On-chip zero-index fabrication



1 zero index

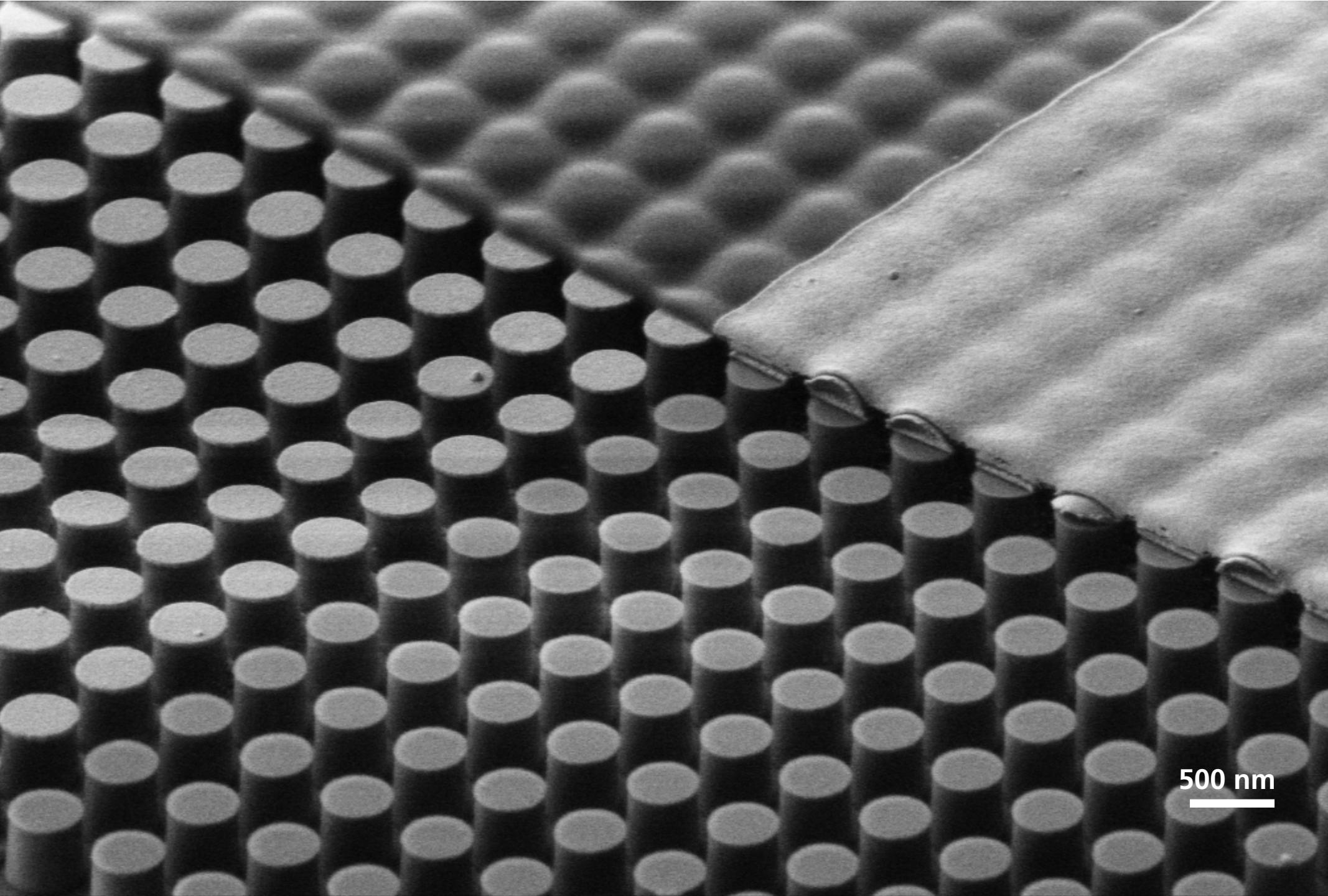
2 fabrication

# On-chip zero-index fabrication



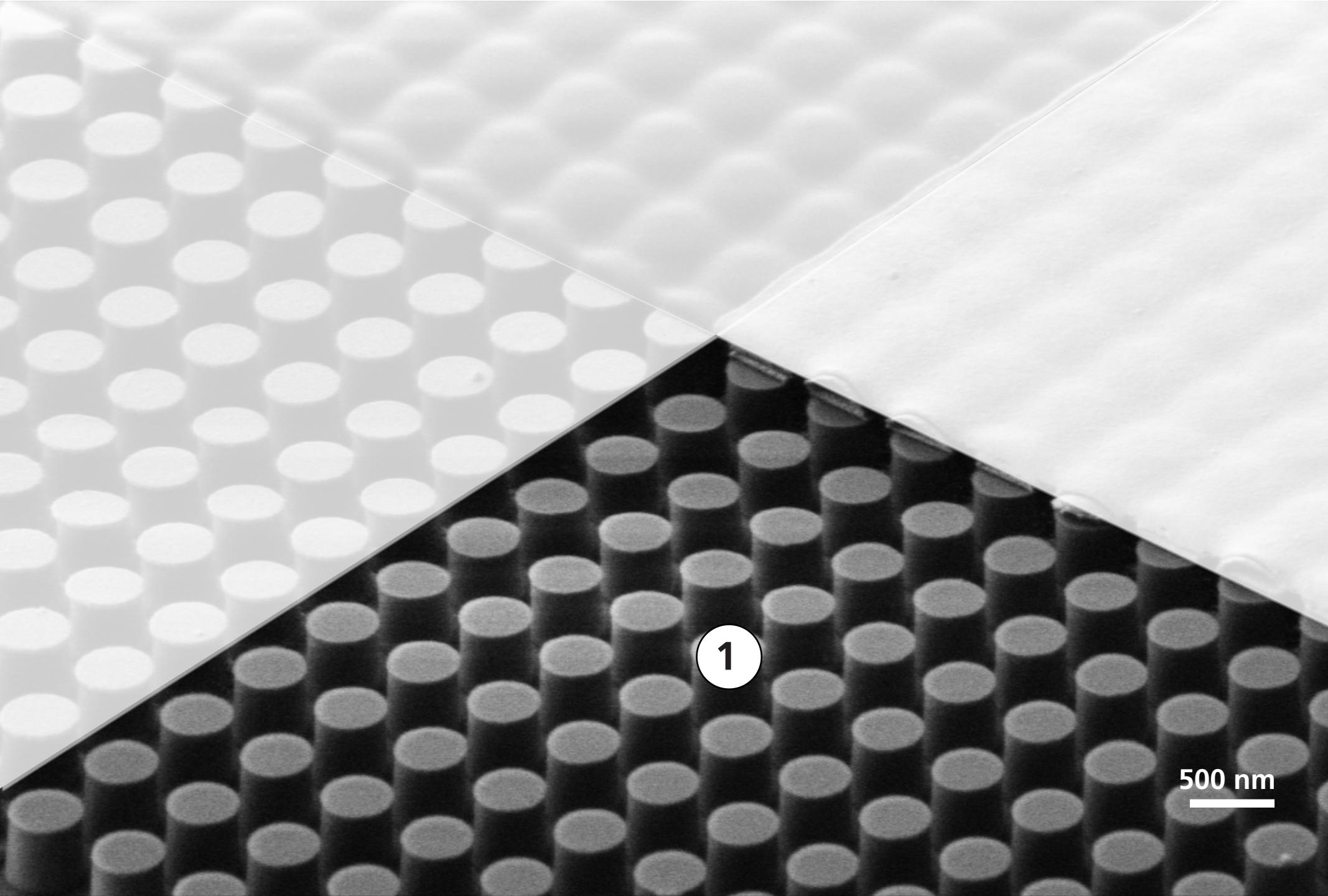
1 zero index

2 fabrication



1 zero index

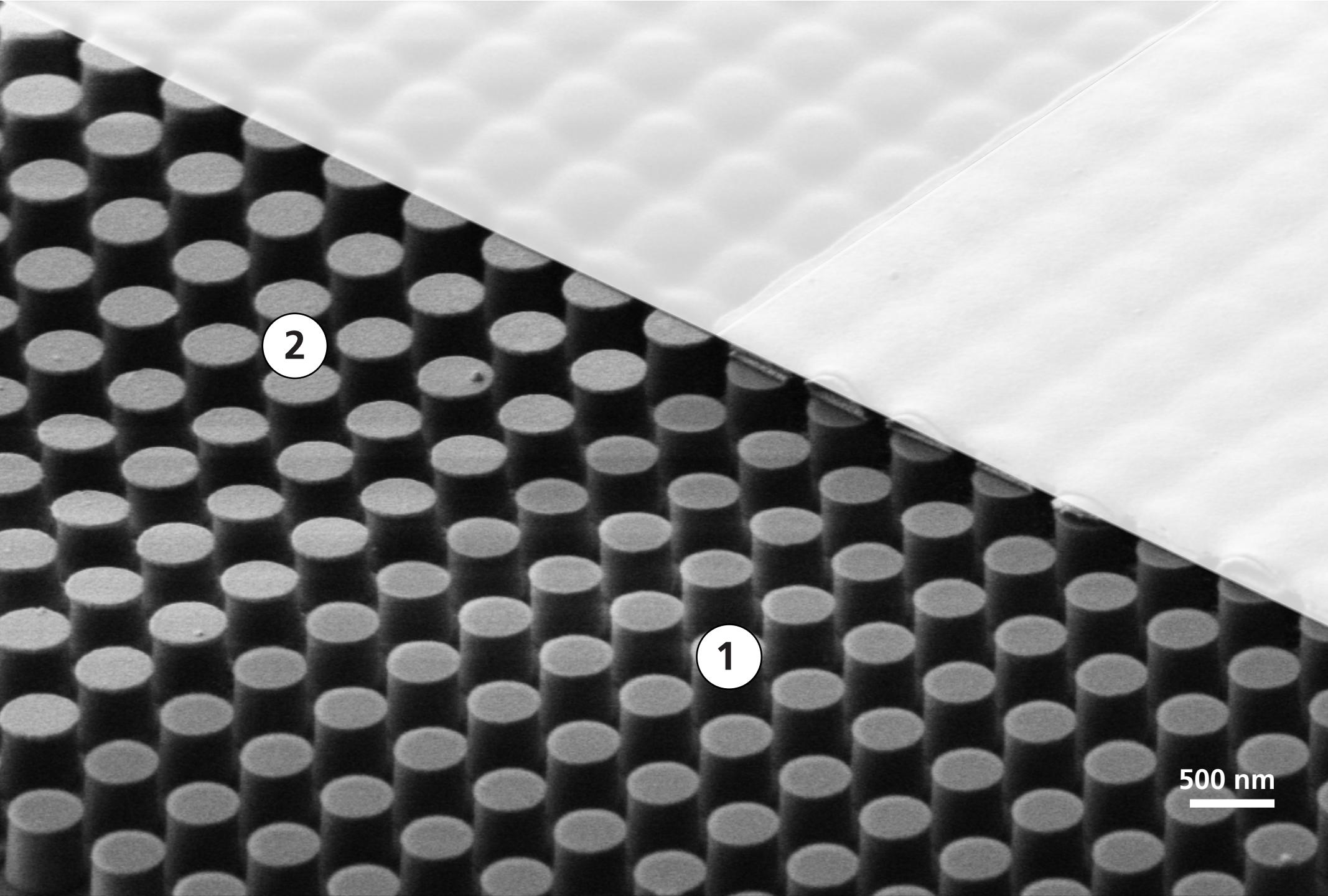
2 fabrication



1 zero index

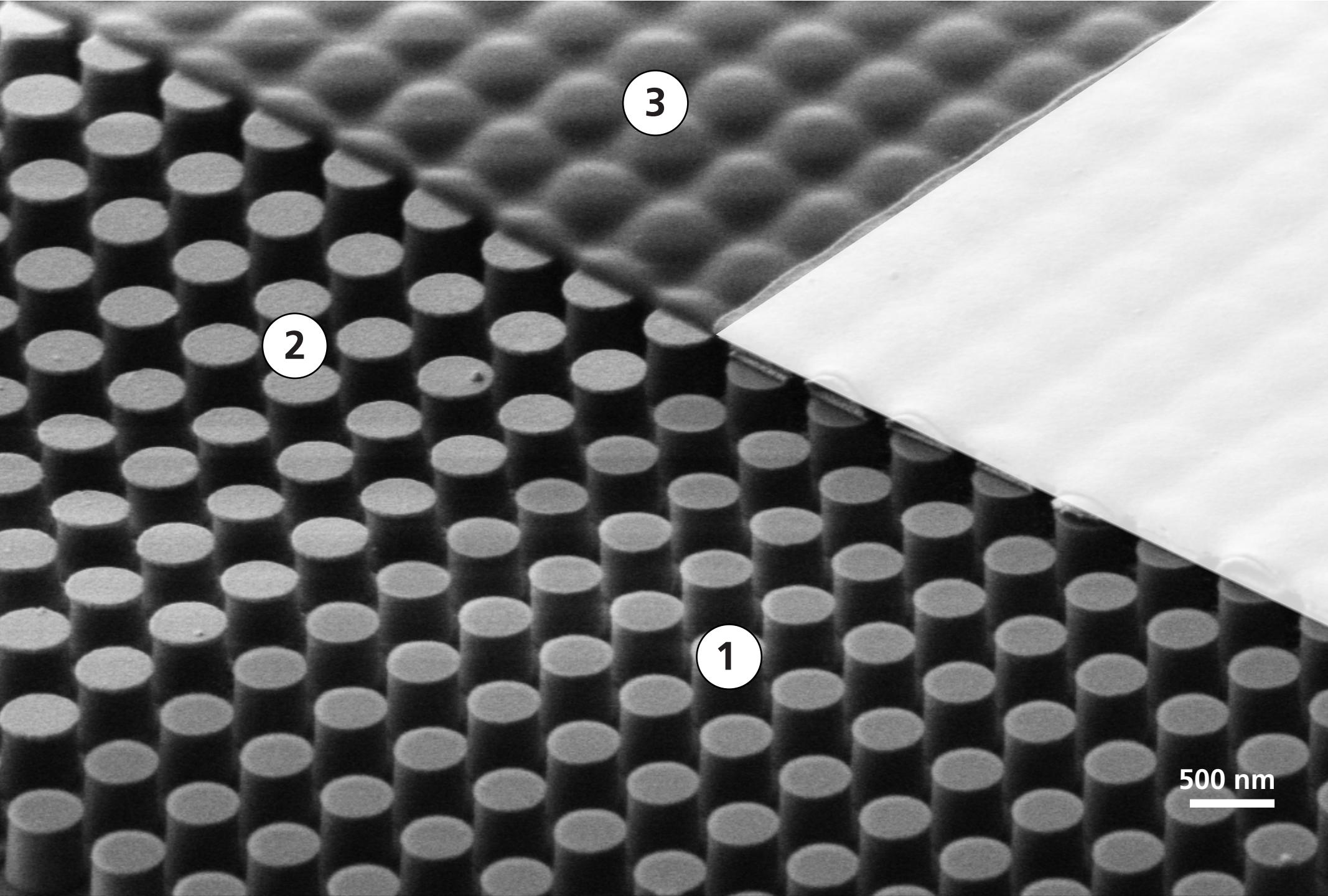
2 fabrication

500 nm



1 zero index

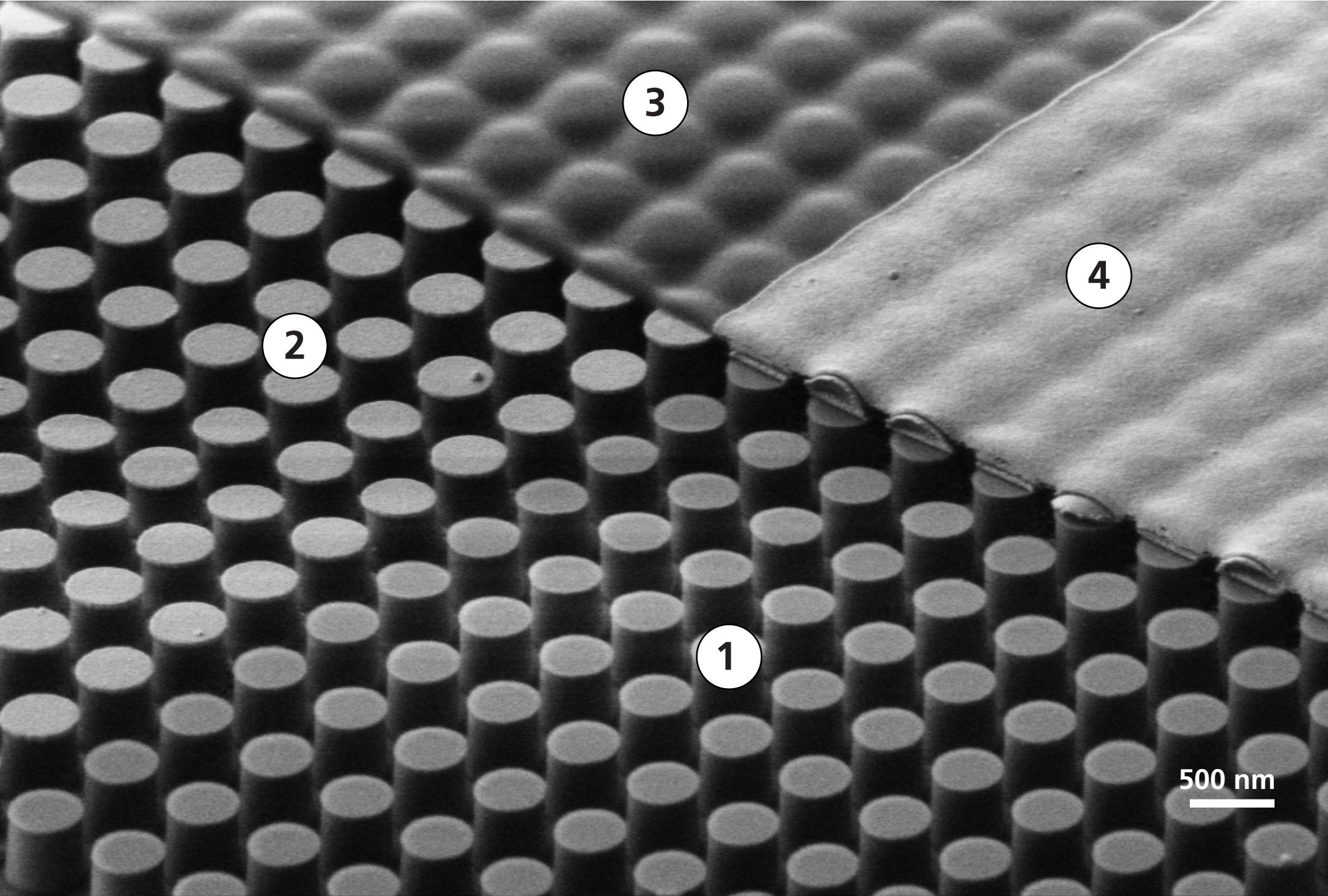
2 fabrication



1 zero index

2 fabrication

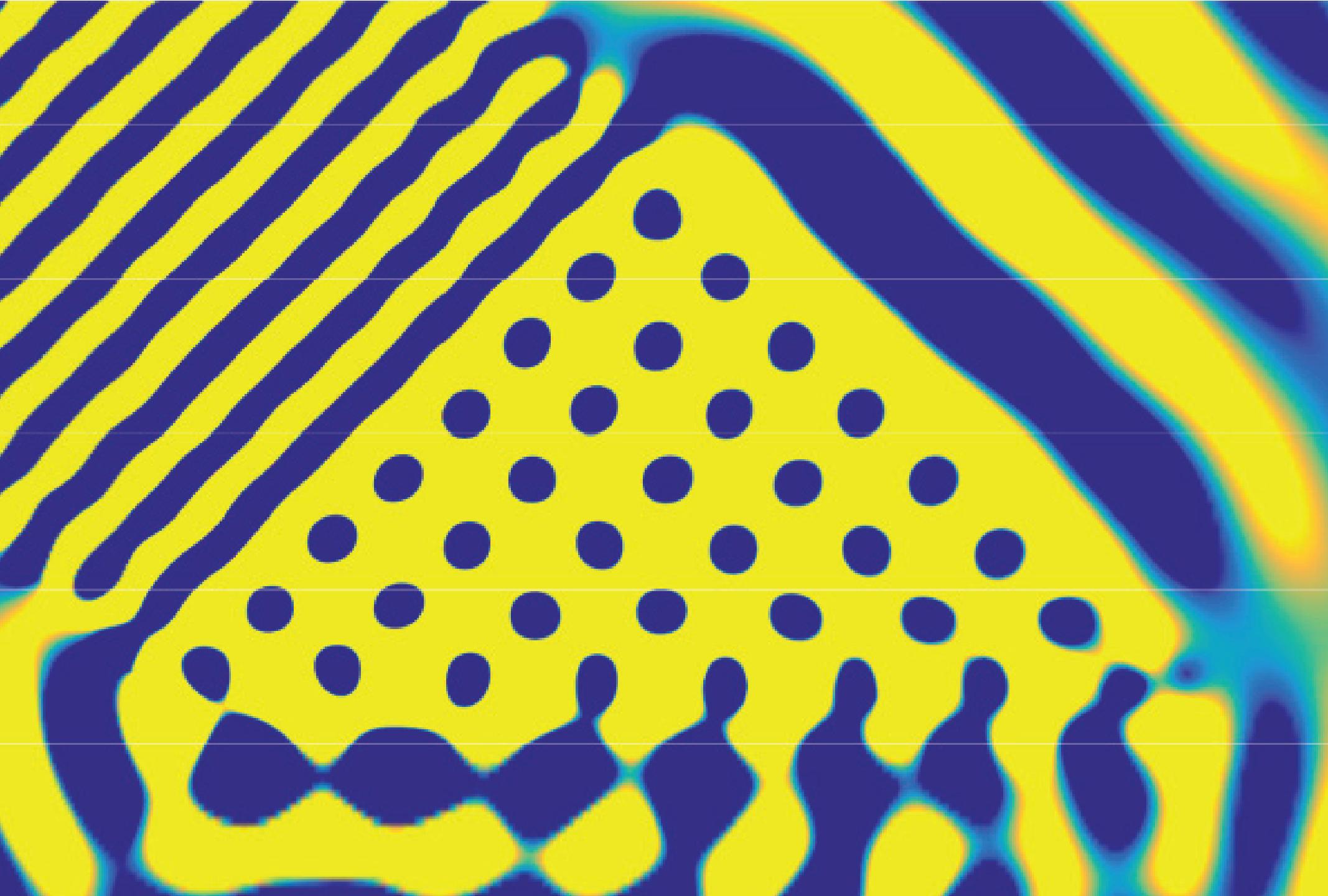
500 nm



1 zero index

2 fabrication

500 nm



1 zero index

2 fabrication

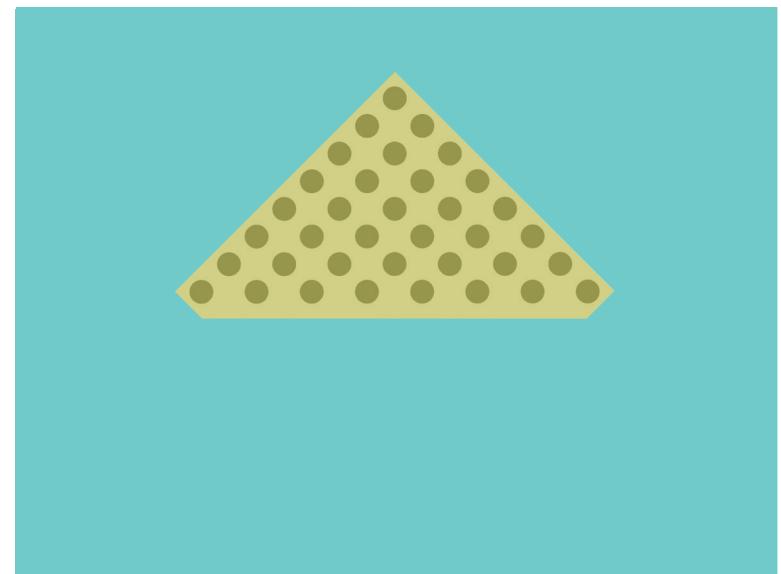
# On-chip zero-index prism



1 zero index

2 fabrication

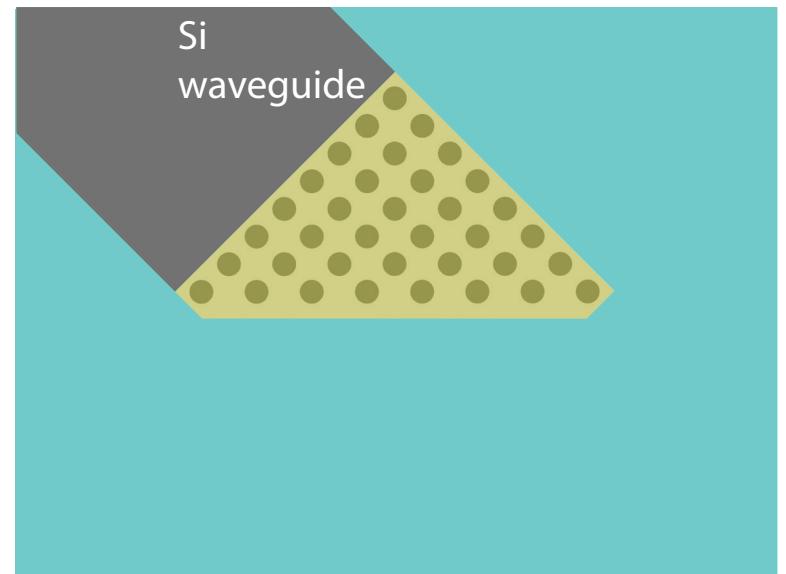
# On-chip zero-index prism



1 zero index

2 fabrication

# On-chip zero-index prism

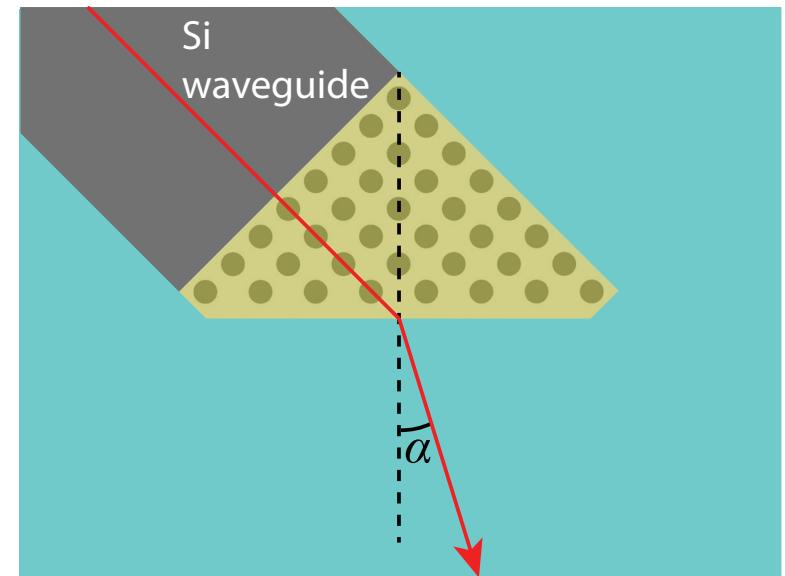


1 zero index

2 fabrication

3 results

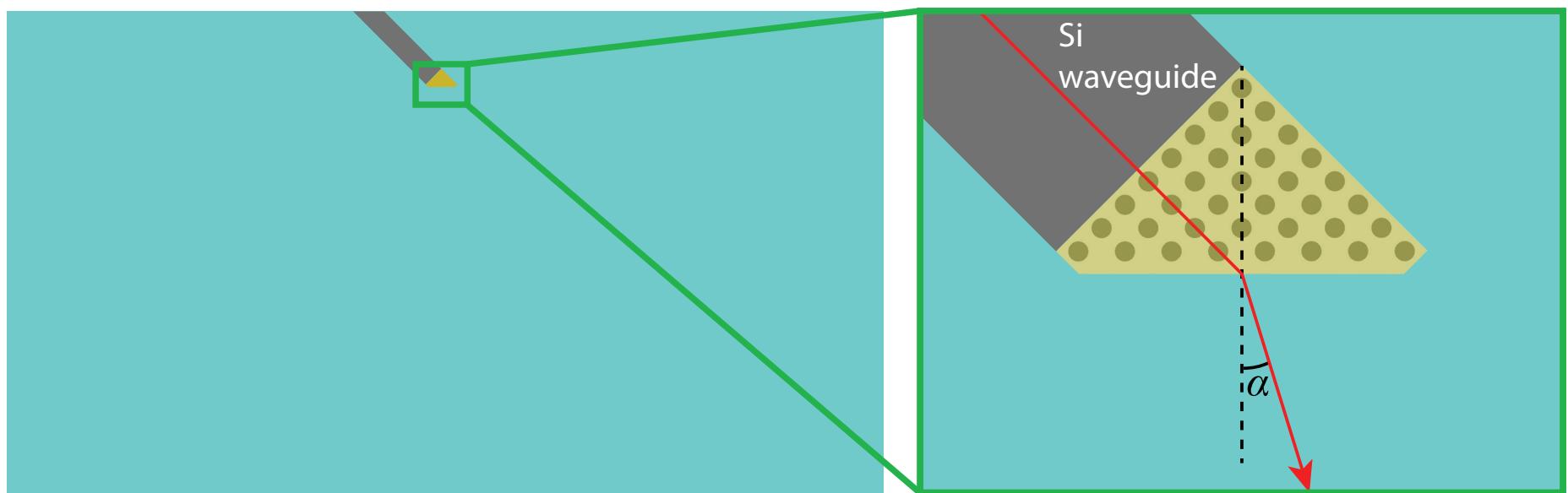
# On-chip zero-index prism



1 zero index

2 fabrication

# On-chip zero-index prism

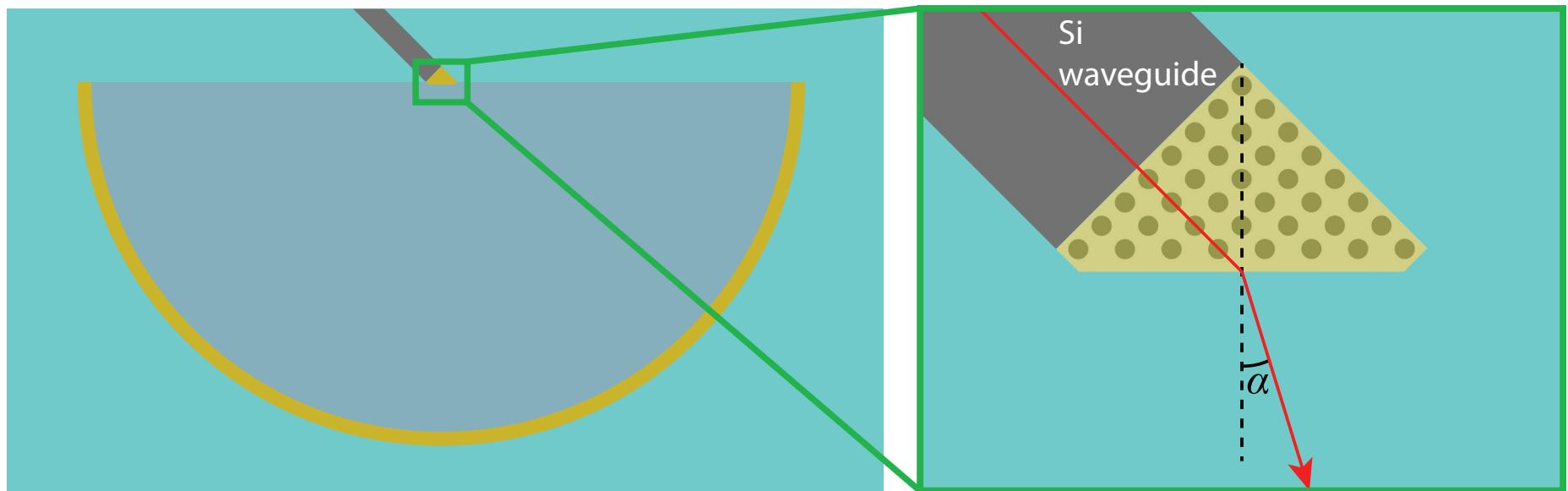


1 zero index

2 fabrication

3 results

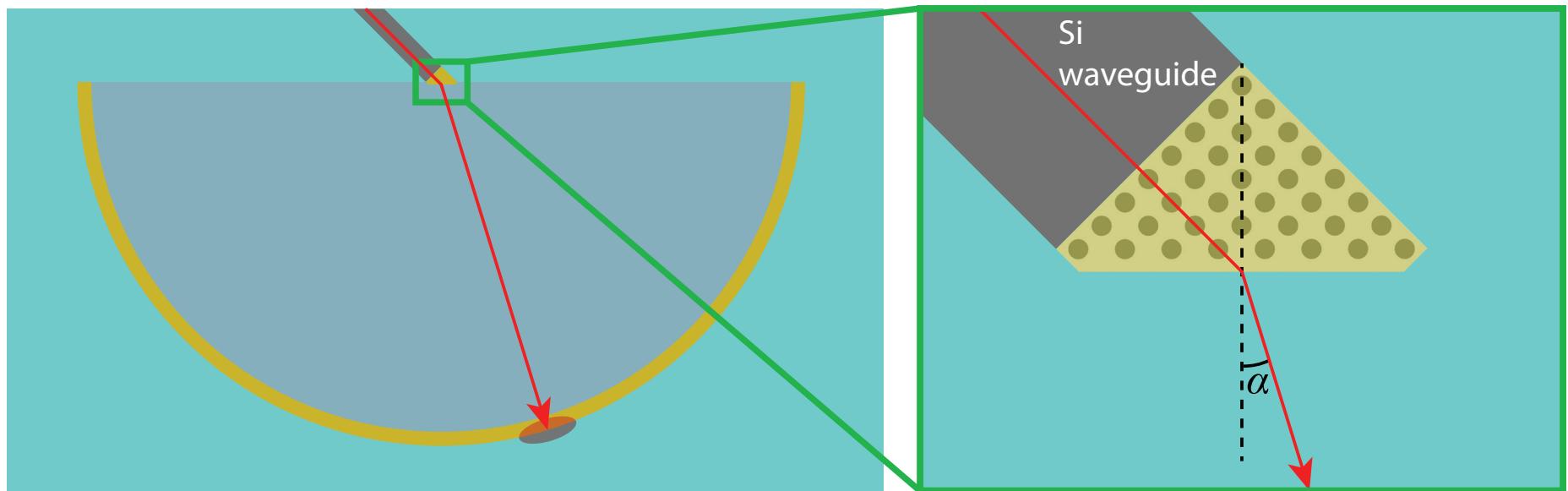
# On-chip zero-index prism



1 zero index

2 fabrication

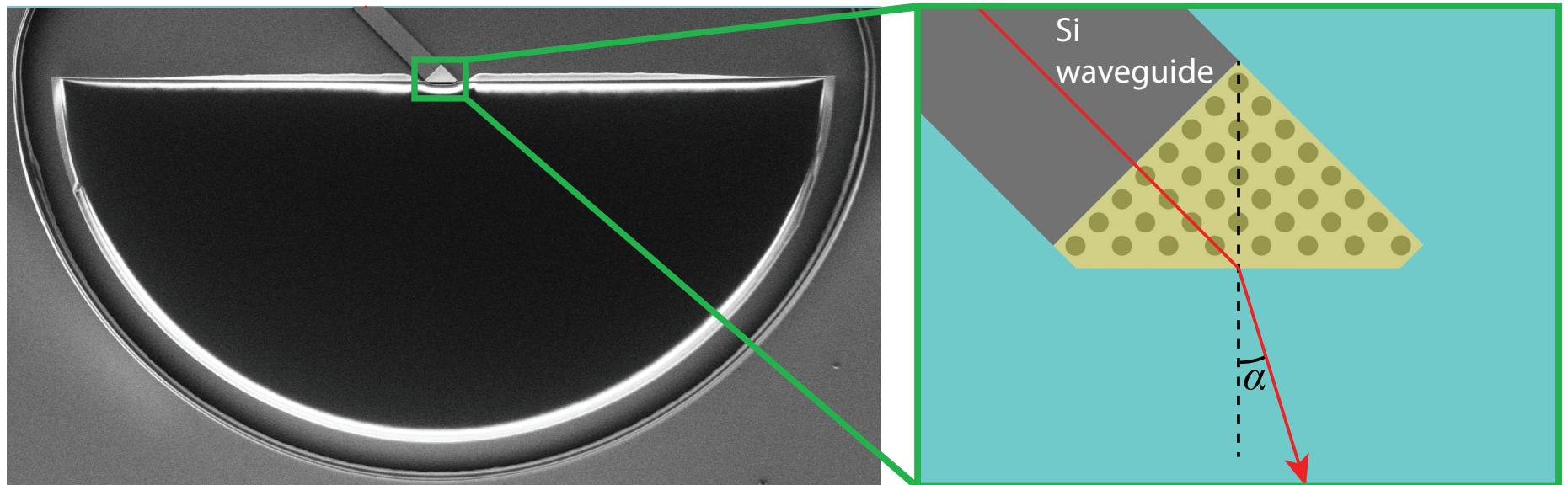
# On-chip zero-index prism



1 zero index

2 fabrication

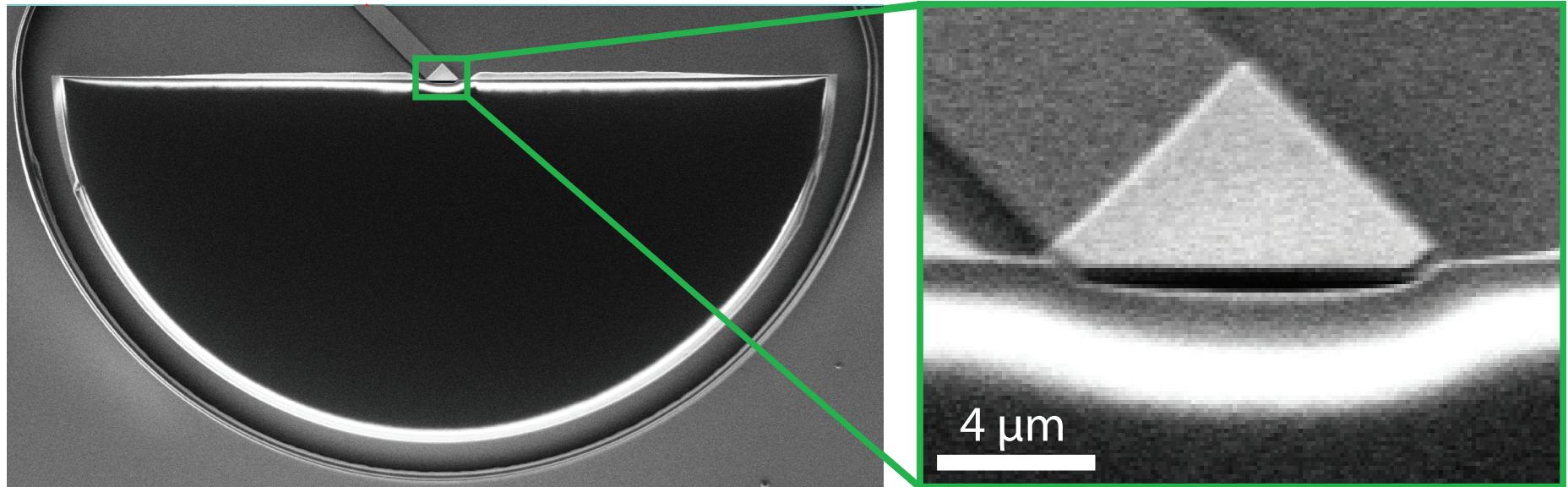
# On-chip zero-index prism



1 zero index

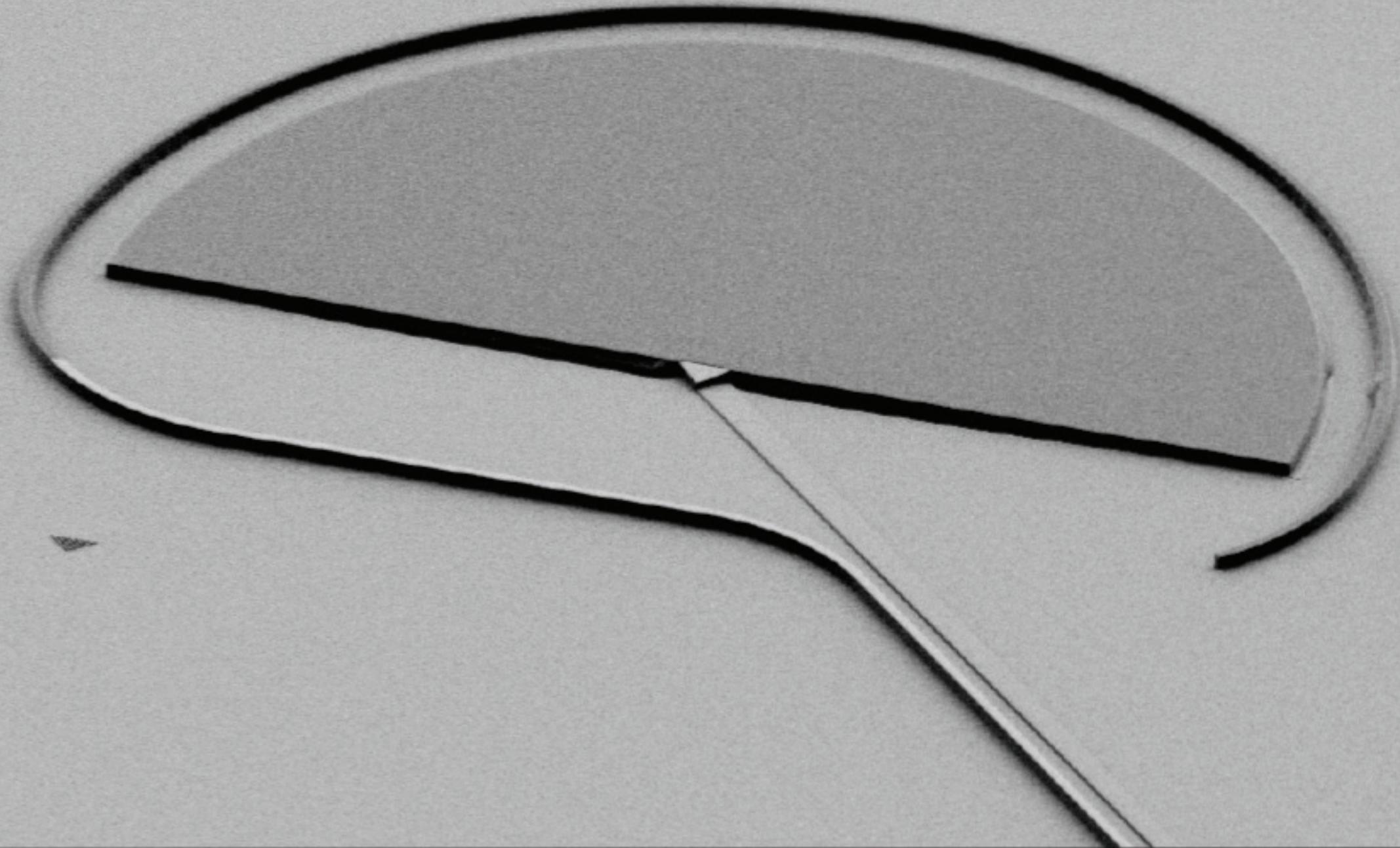
2 fabrication

# On-chip zero-index prism



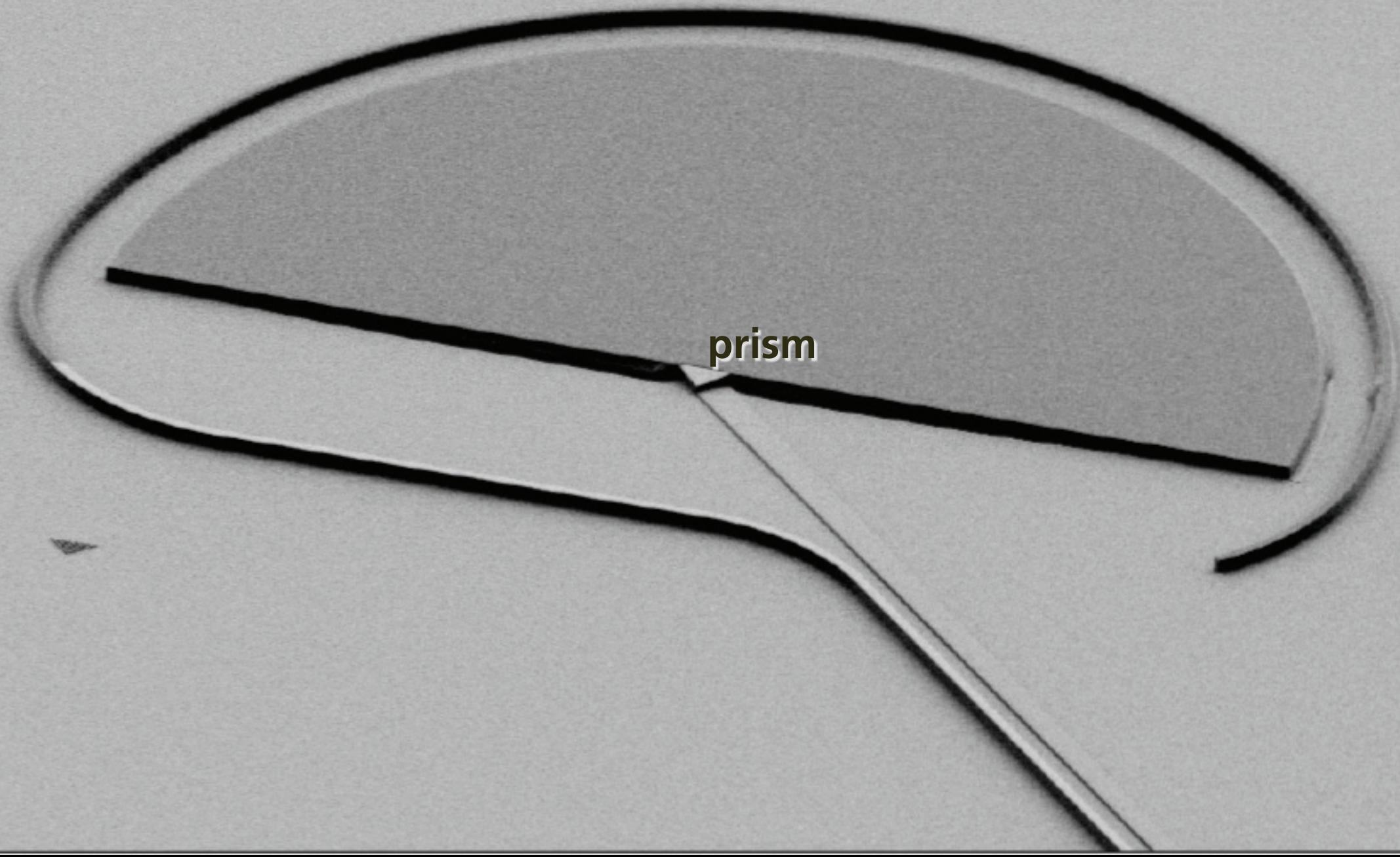
1 zero index

2 fabrication



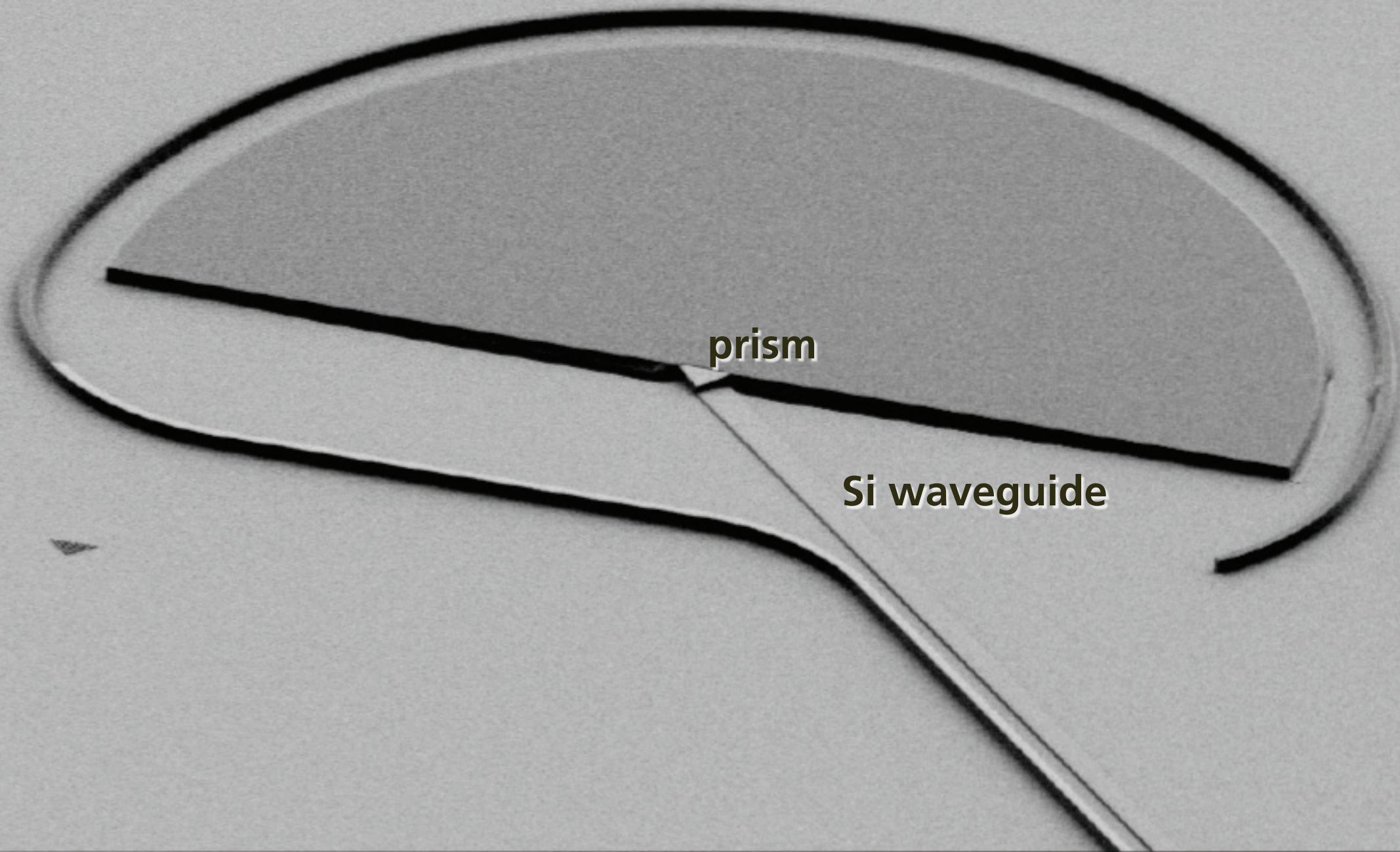
1 zero index

2 fabrication



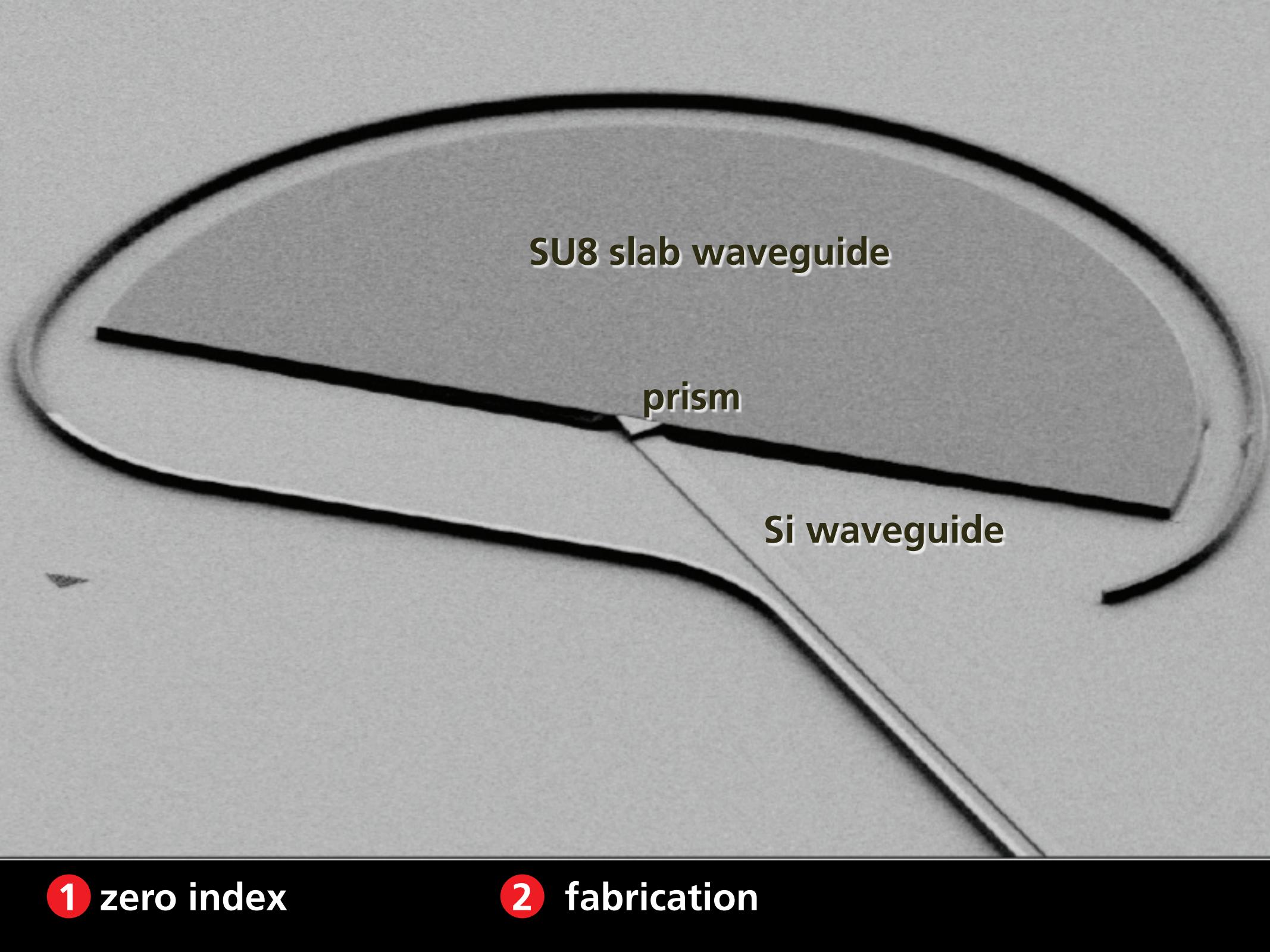
1 zero index

2 fabrication



1 zero index

2 fabrication

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, angled downwards. The two waveguides meet at a junction. A triangular prism is placed between the two waveguides. The entire structure is set against a dark background.

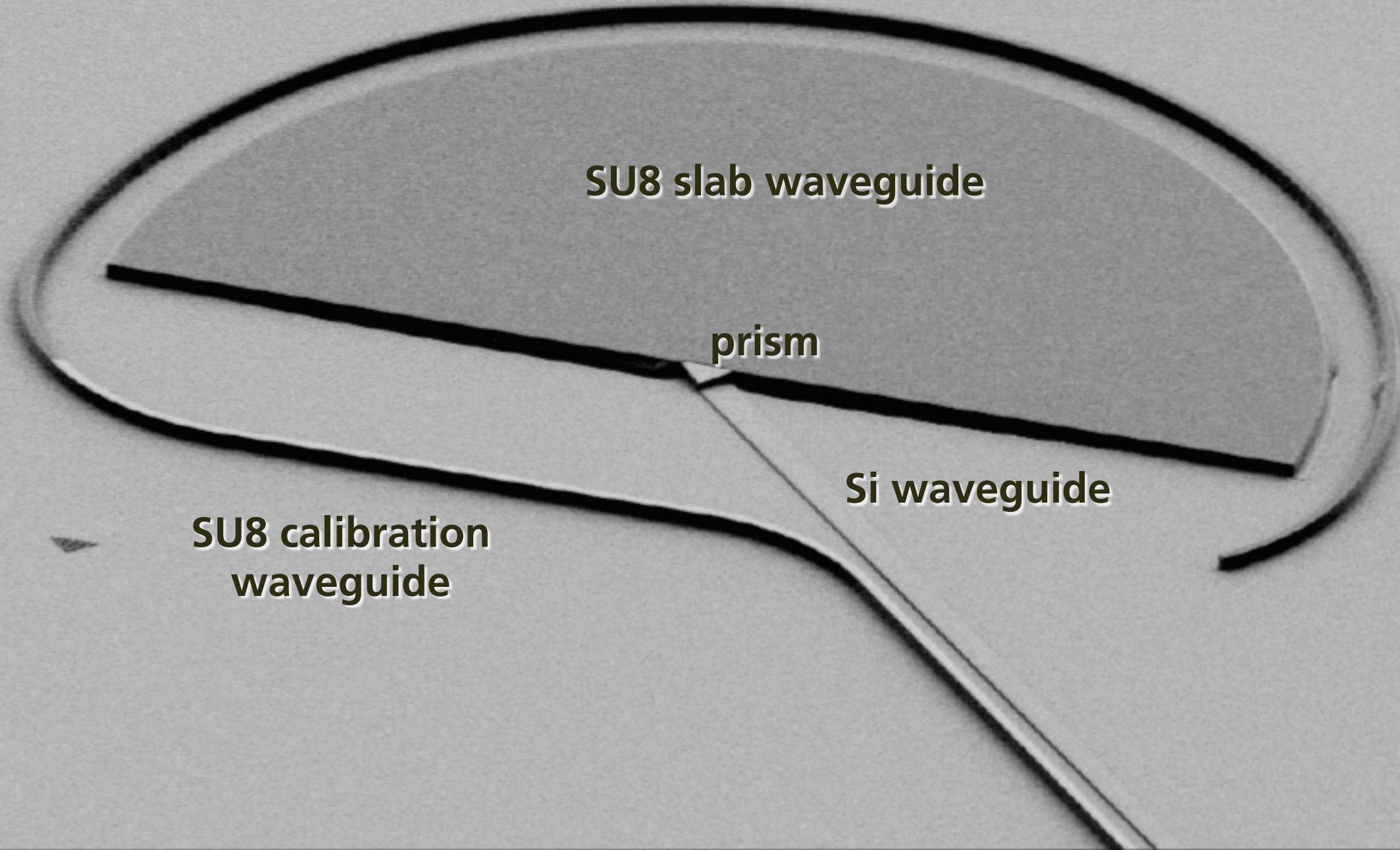
SU8 slab waveguide

prism

Si waveguide

1 zero index

2 fabrication



SU8 slab waveguide

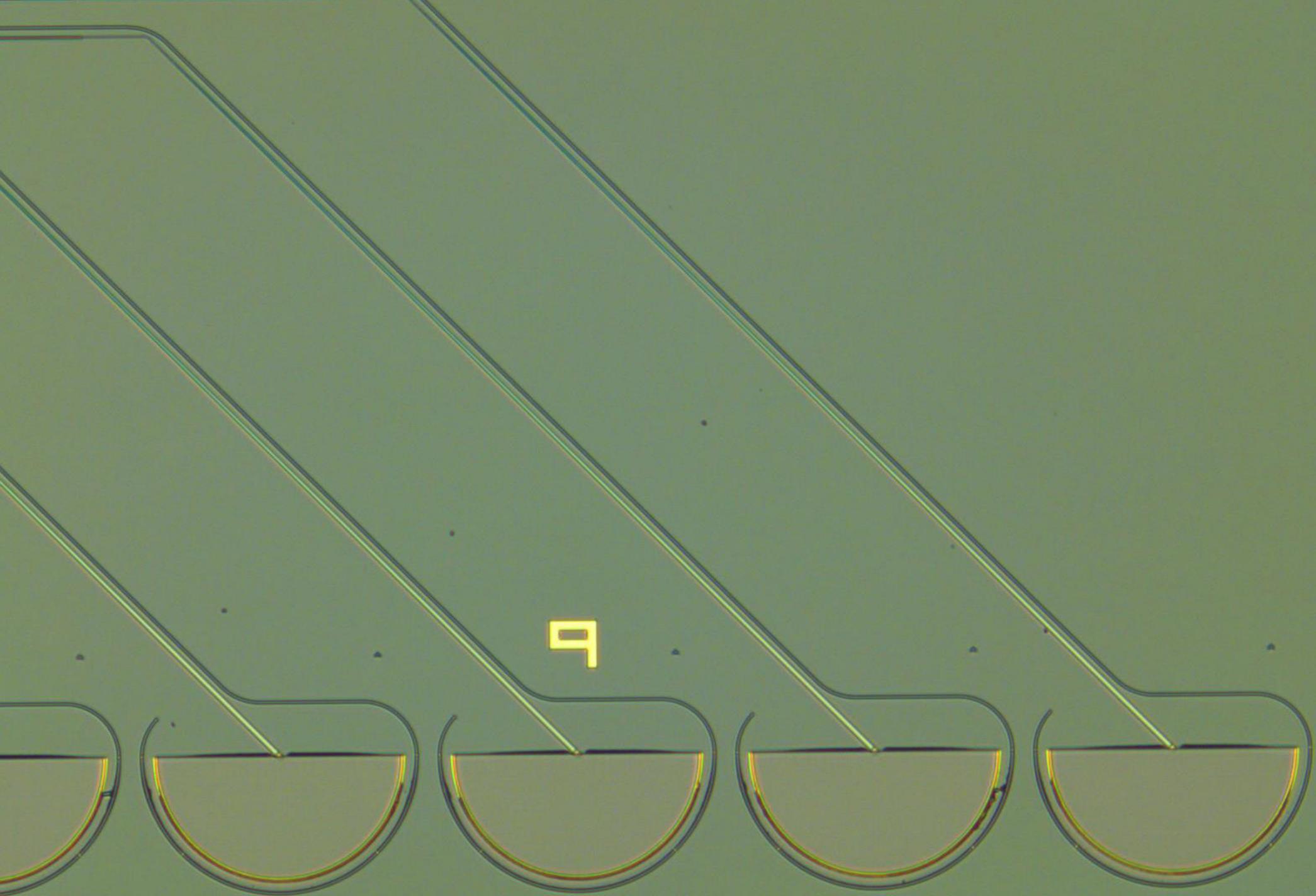
prism

Si waveguide

SU8 calibration  
waveguide

1 zero index

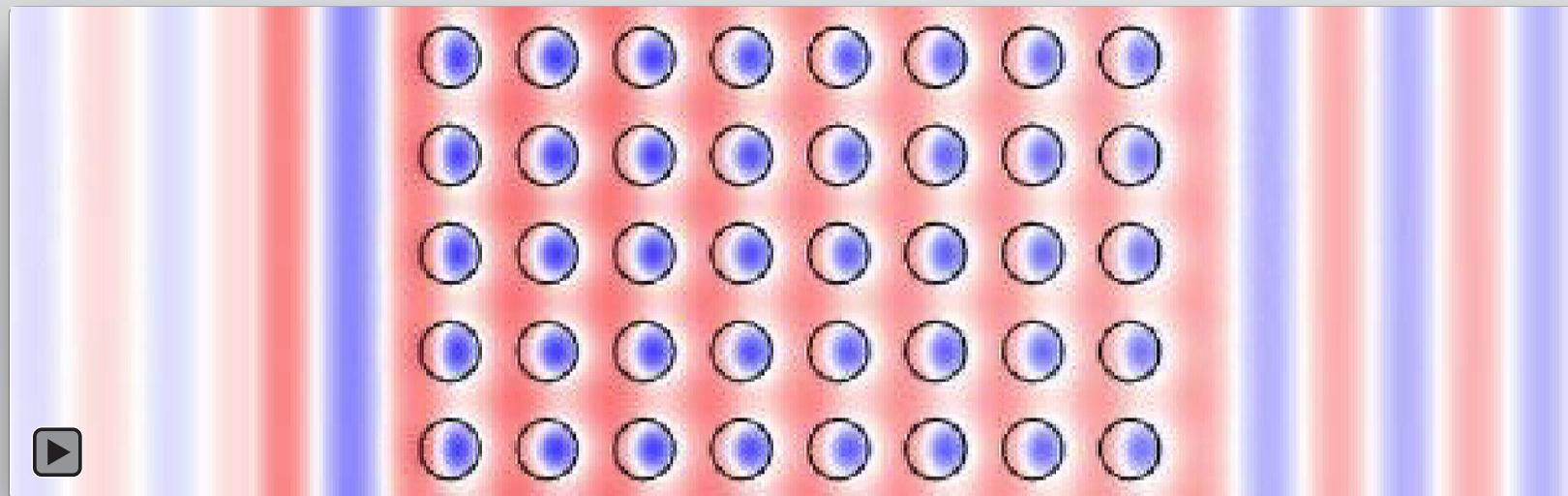
2 fabrication



1 zero index

2 fabrication

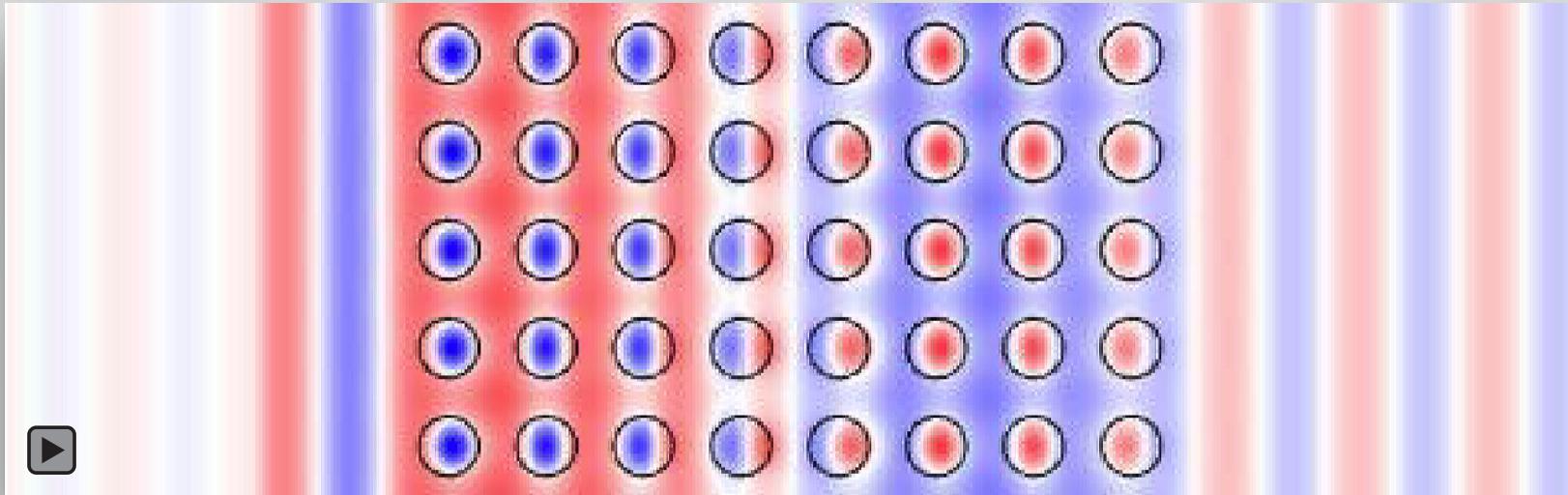
**at design wavelength (1590 nm)**



**1 zero index**

**2 fabrication**

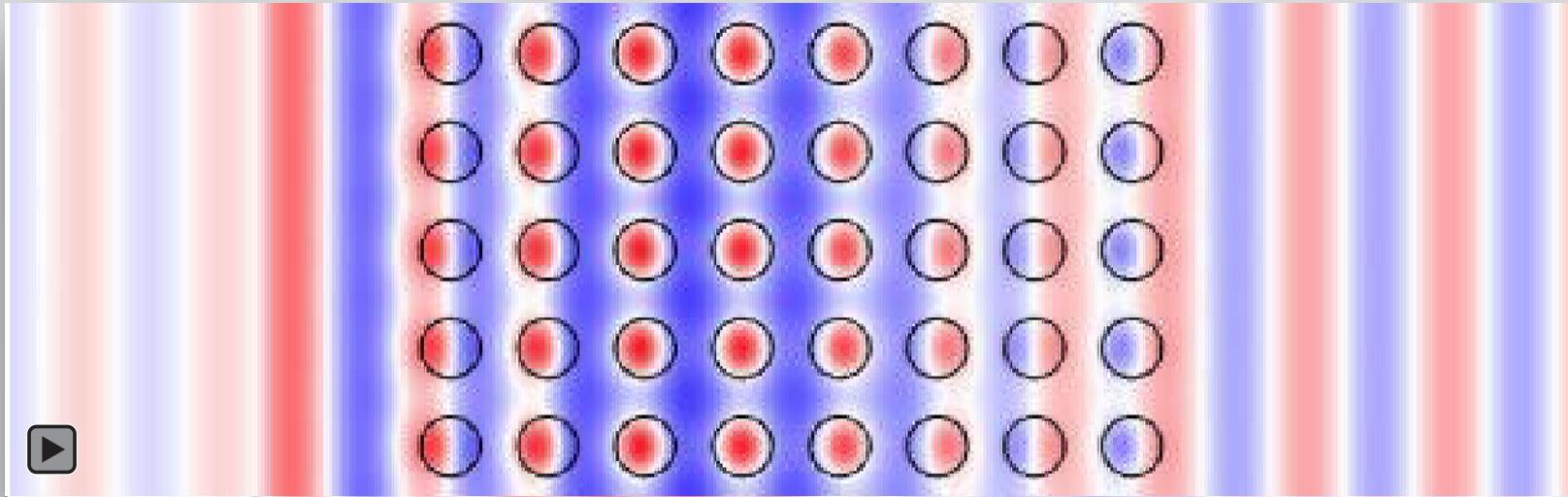
**below design wavelength (1530 nm)**



**1 zero index**

**2 fabrication**

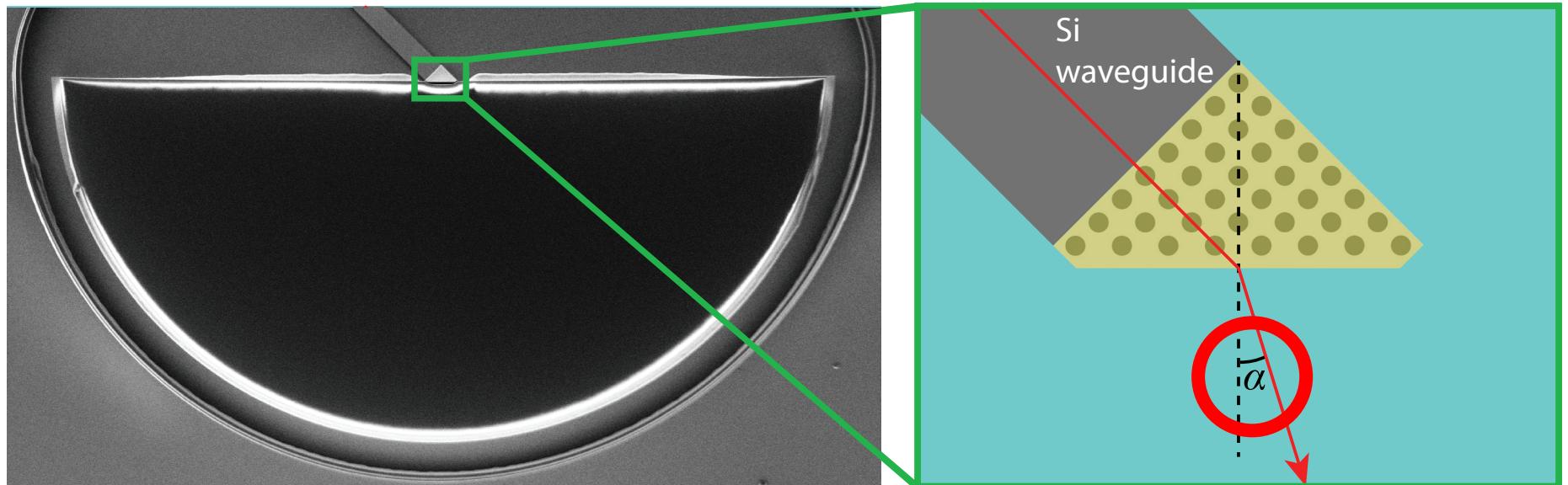
**above design wavelength (1650 nm)**



**1 zero index**

**2 fabrication**

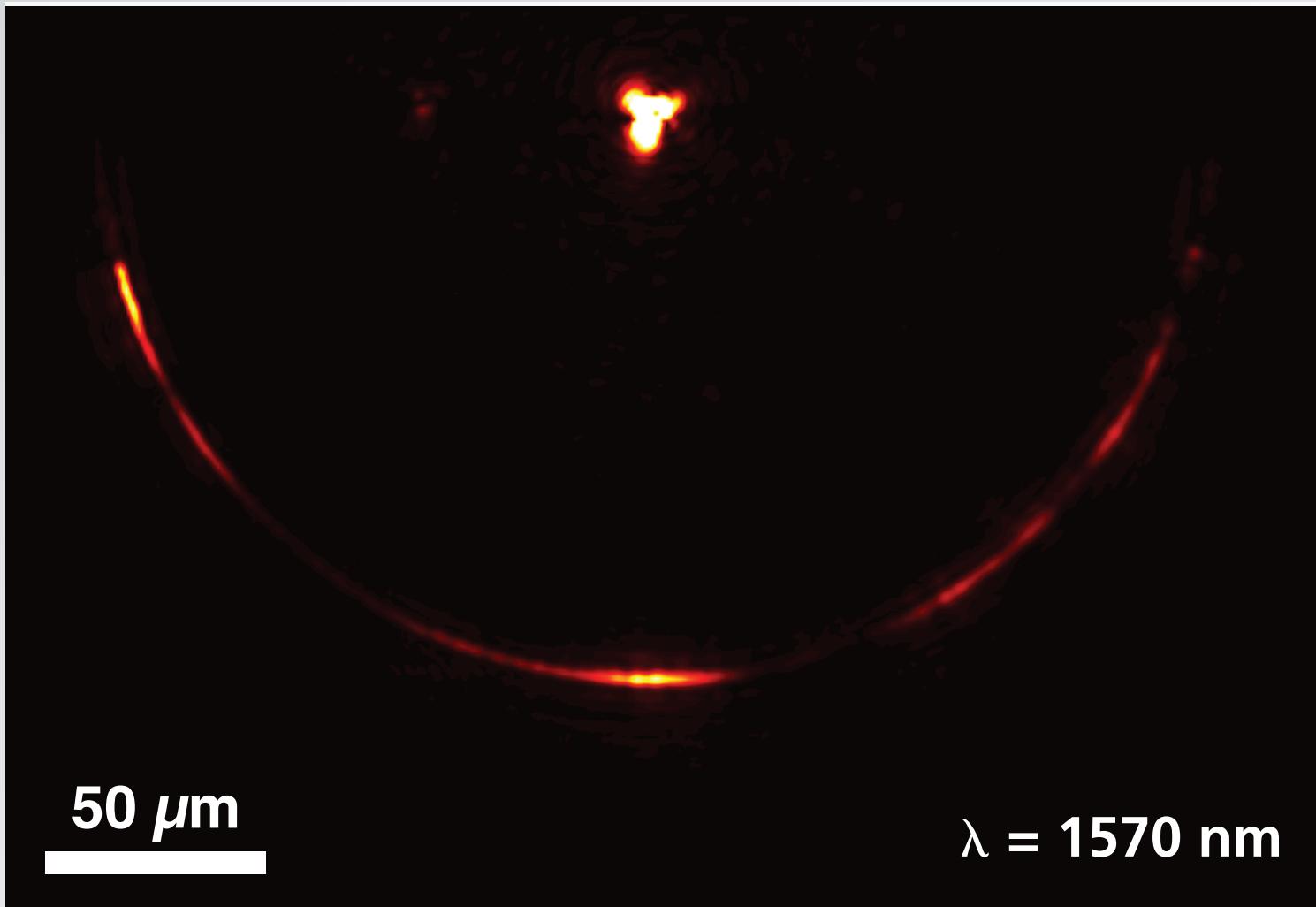
# On-chip zero-index prism



1 zero index

2 fabrication

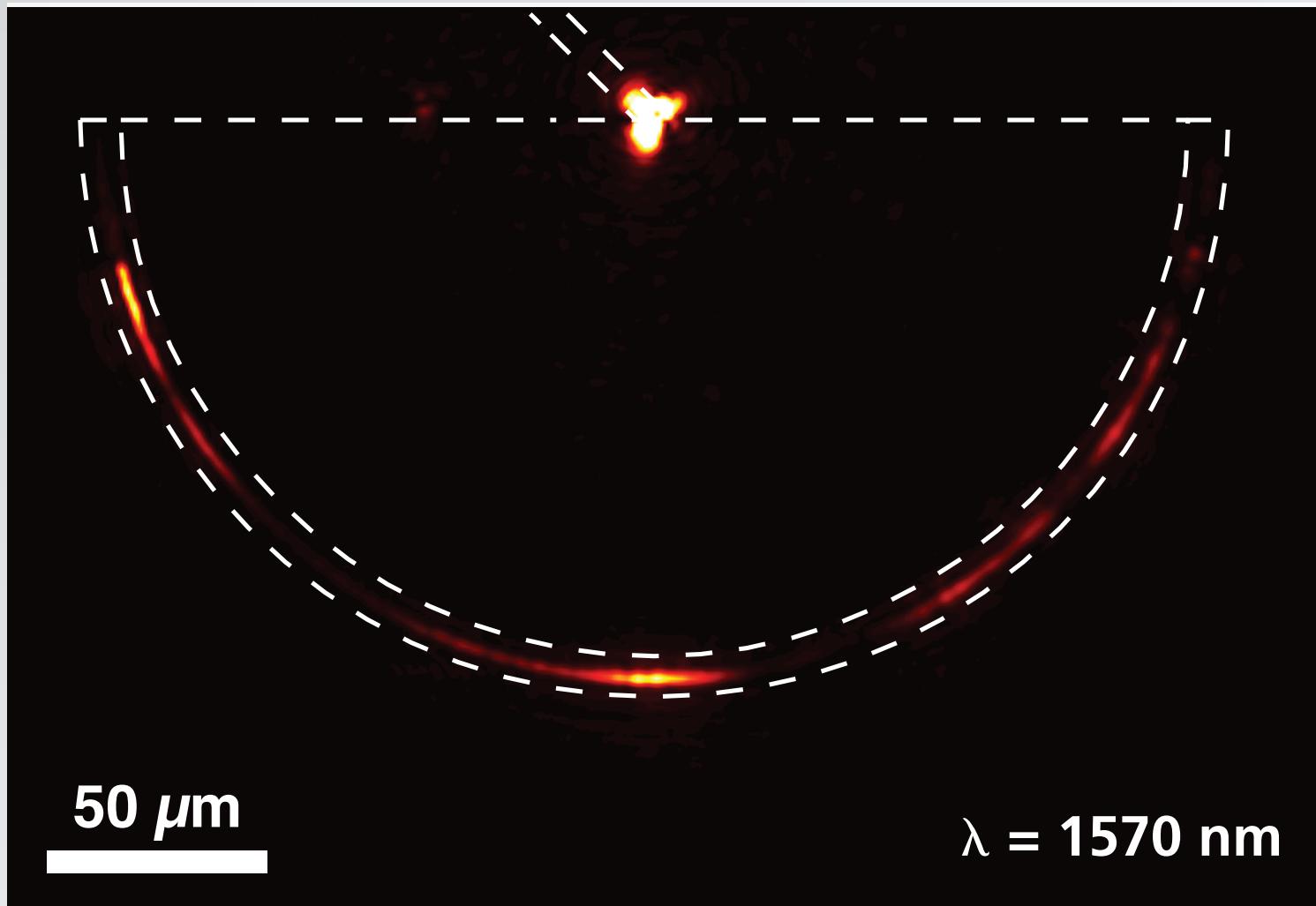
3 results



1 zero index

2 fabrication

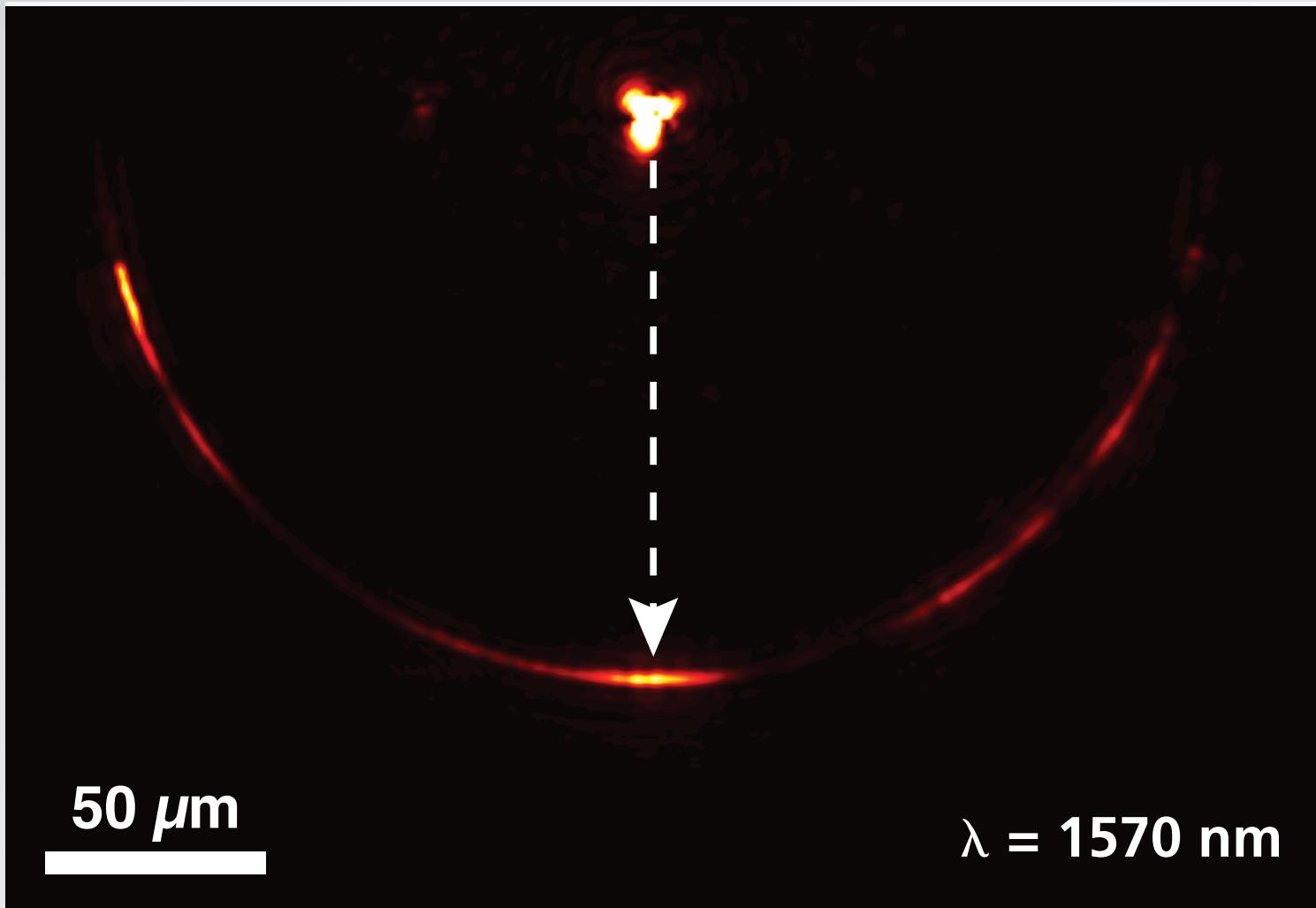
3 results



1 zero index

2 fabrication

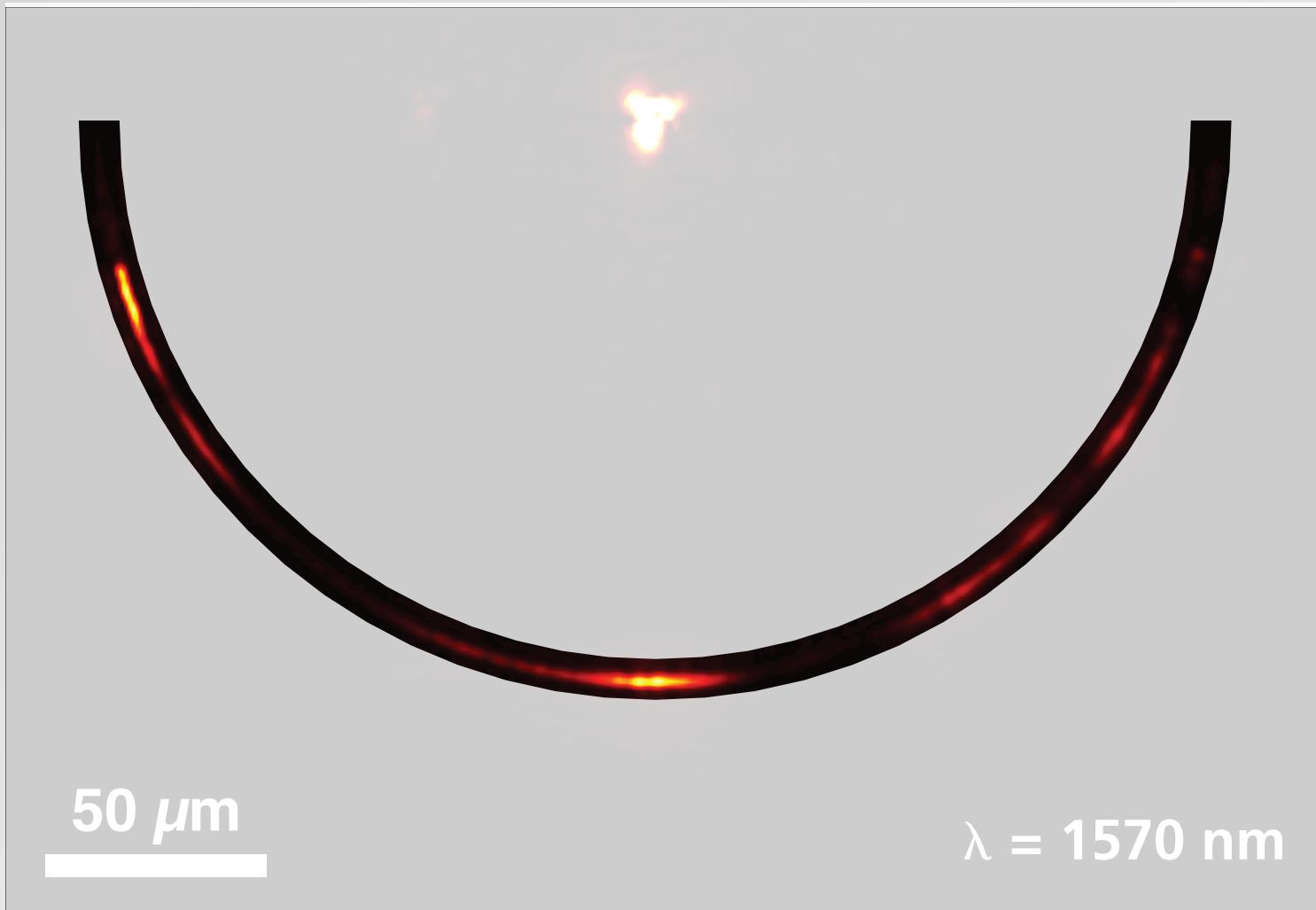
3 results



1 zero index

2 fabrication

3 results

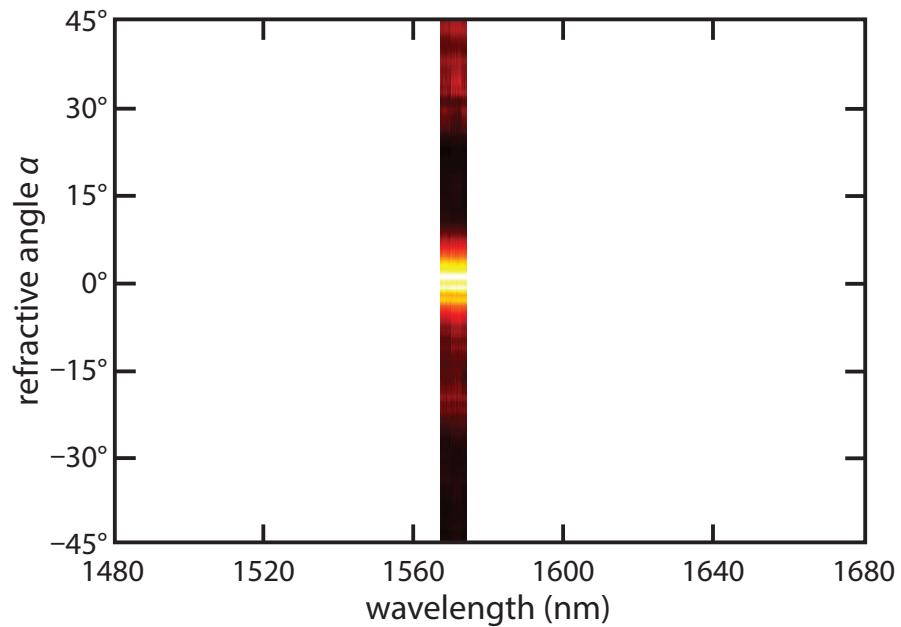


1 zero index

2 fabrication

3 results

# Wavelength dependence of refraction angle

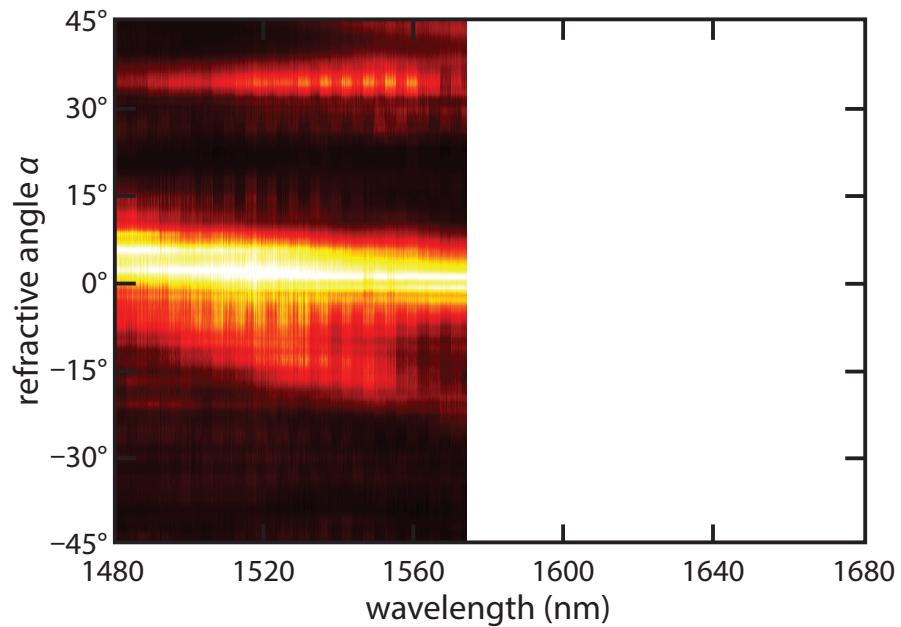


1 zero index

2 fabrication

3 results

# Wavelength dependence of refraction angle

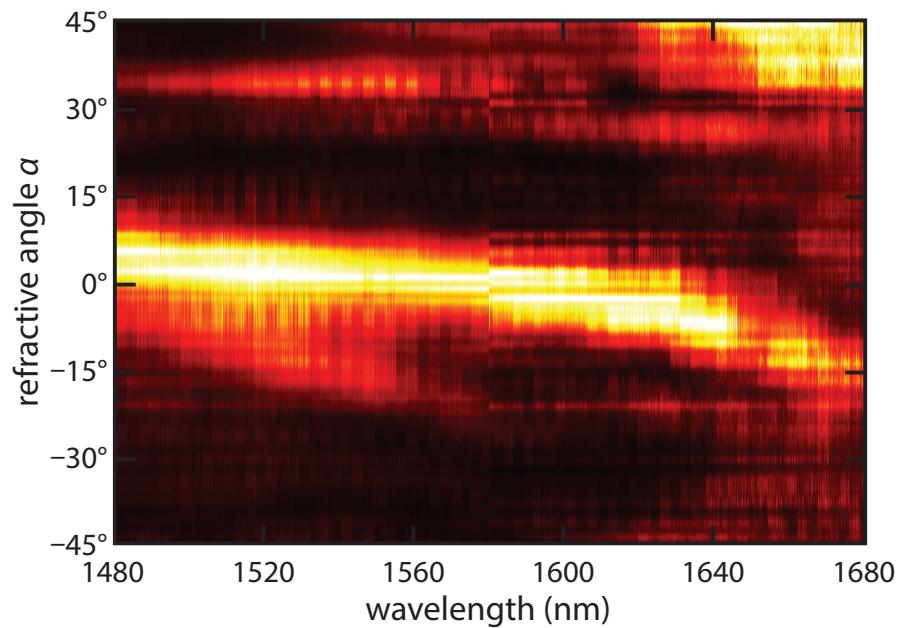


1 zero index

2 fabrication

3 results

# Wavelength dependence of refraction angle

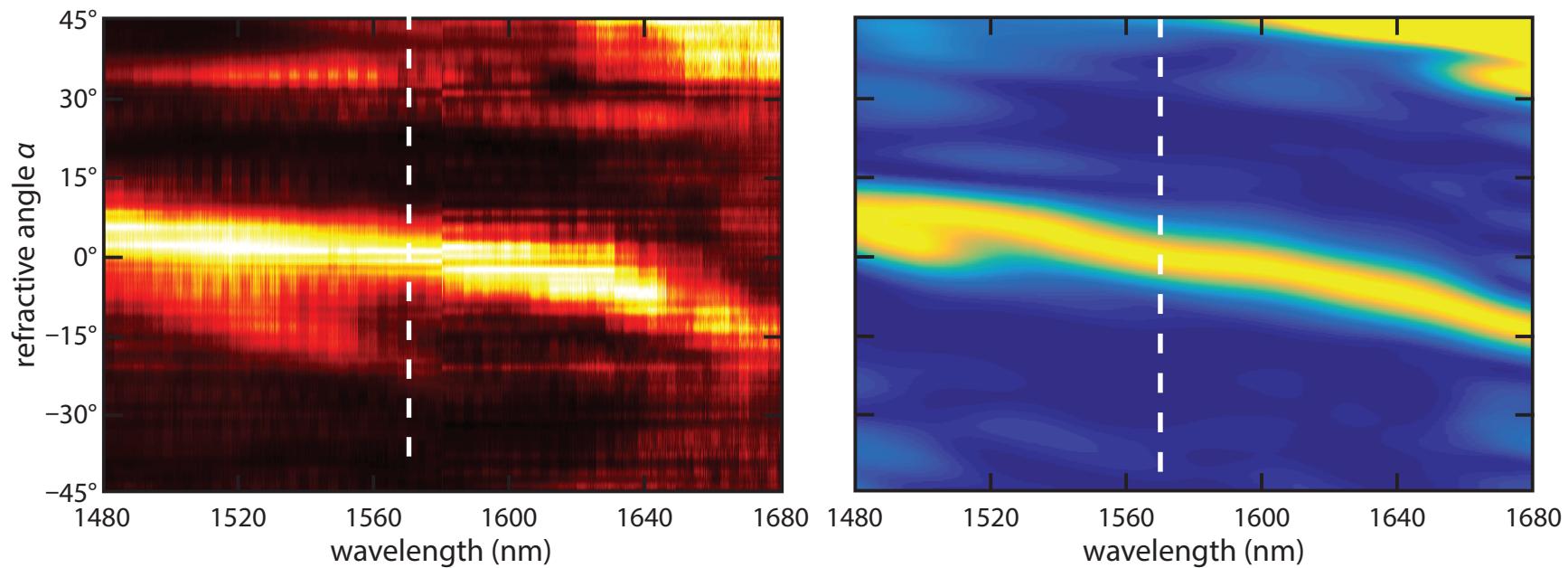


1 zero index

2 fabrication

3 results

# Wavelength dependence of refraction angle

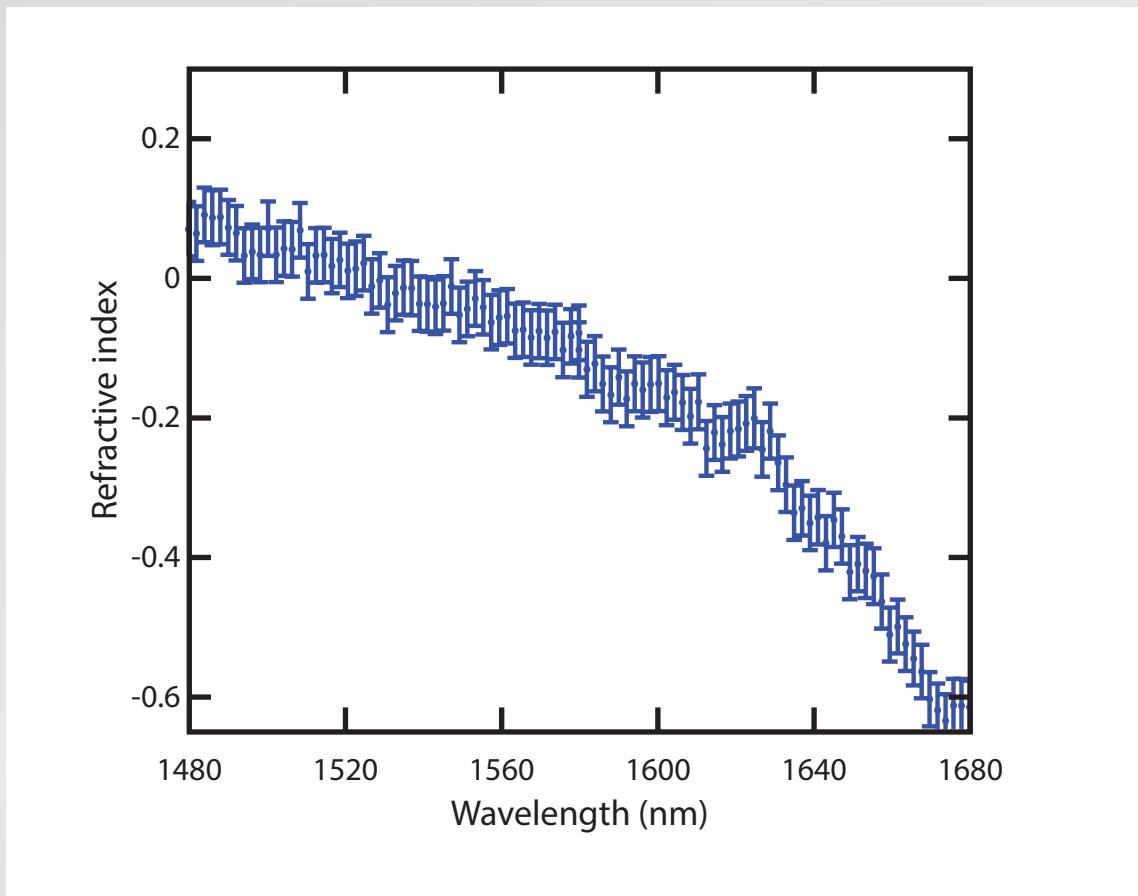


1 zero index

2 fabrication

3 results

# Wavelength dependence of index

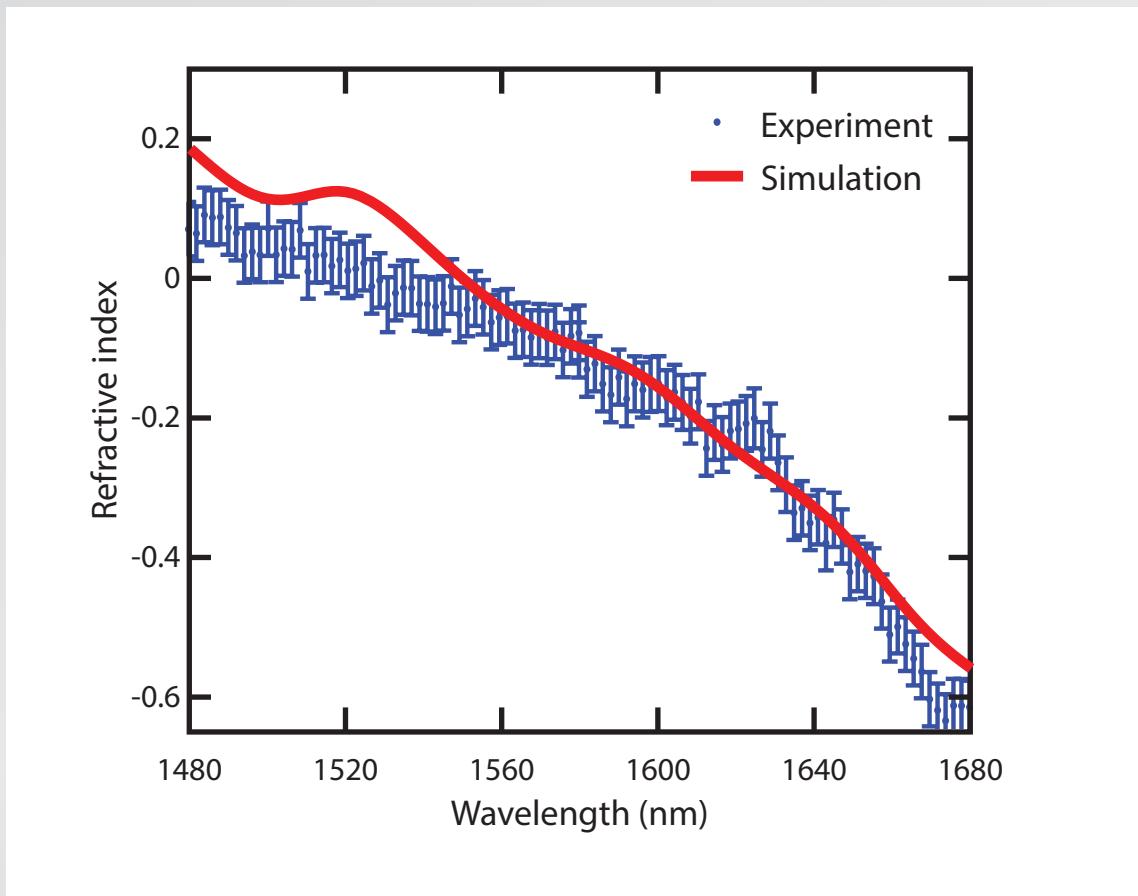


1 zero index

2 fabrication

3 results

# Wavelength dependence of index



1 zero index

2 fabrication

3 results

**unambiguous demonstration of on-chip zero-index material!**

**1** zero index

**2** fabrication

**3** results

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

**Funding: National Science Foundation**

**for a copy of this presentation:**

**<http://ericmazur.com>**

**Follow me!**



**eric\_mazur**

**1 zero index**

**2 fabrication**

**3 results**