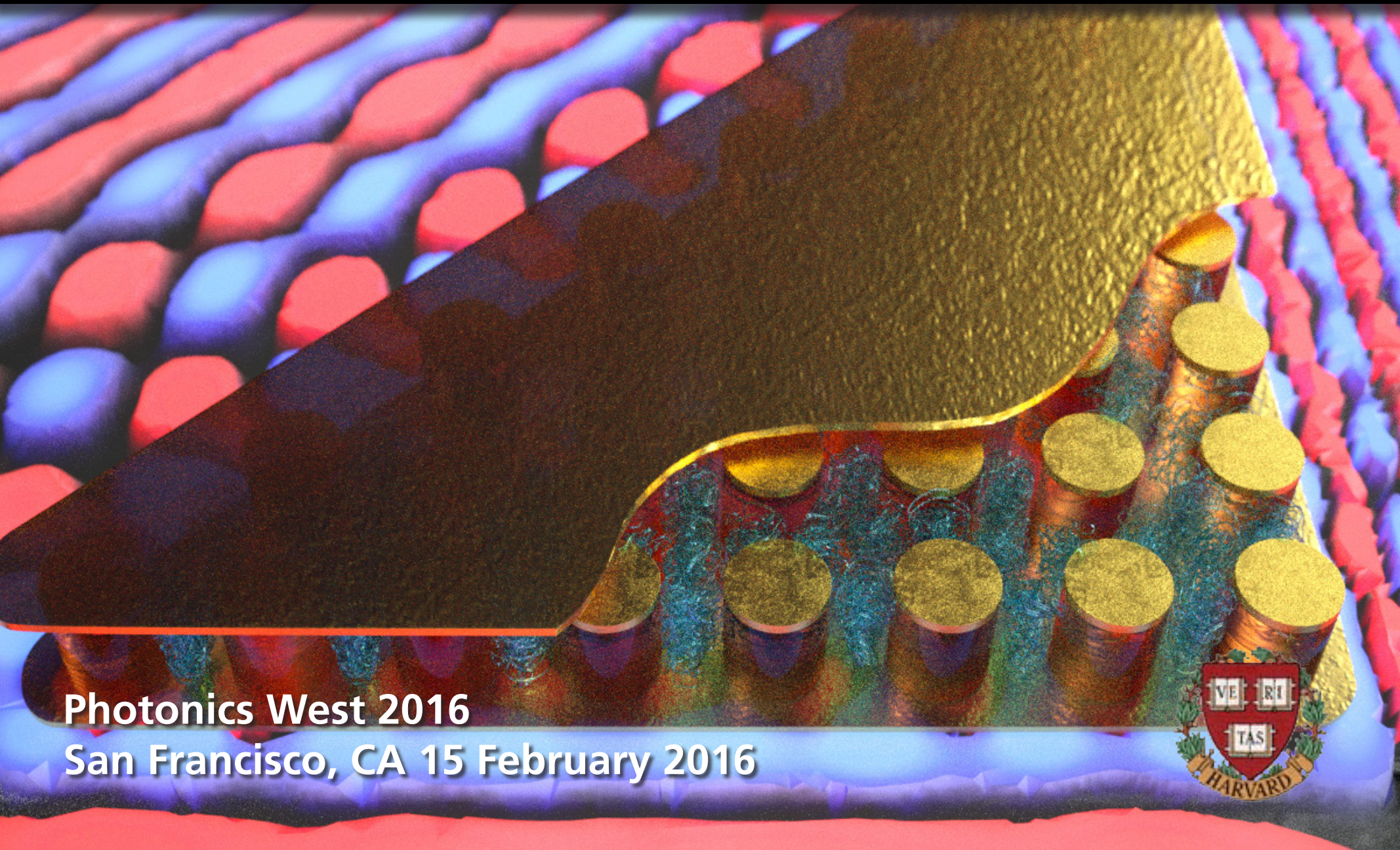
Less is more:
Extreme optics with zero refractive index



Photonics West 2016
San Francisco, CA 15 February 2016

Less is more:
Extreme optics with zero refractive index

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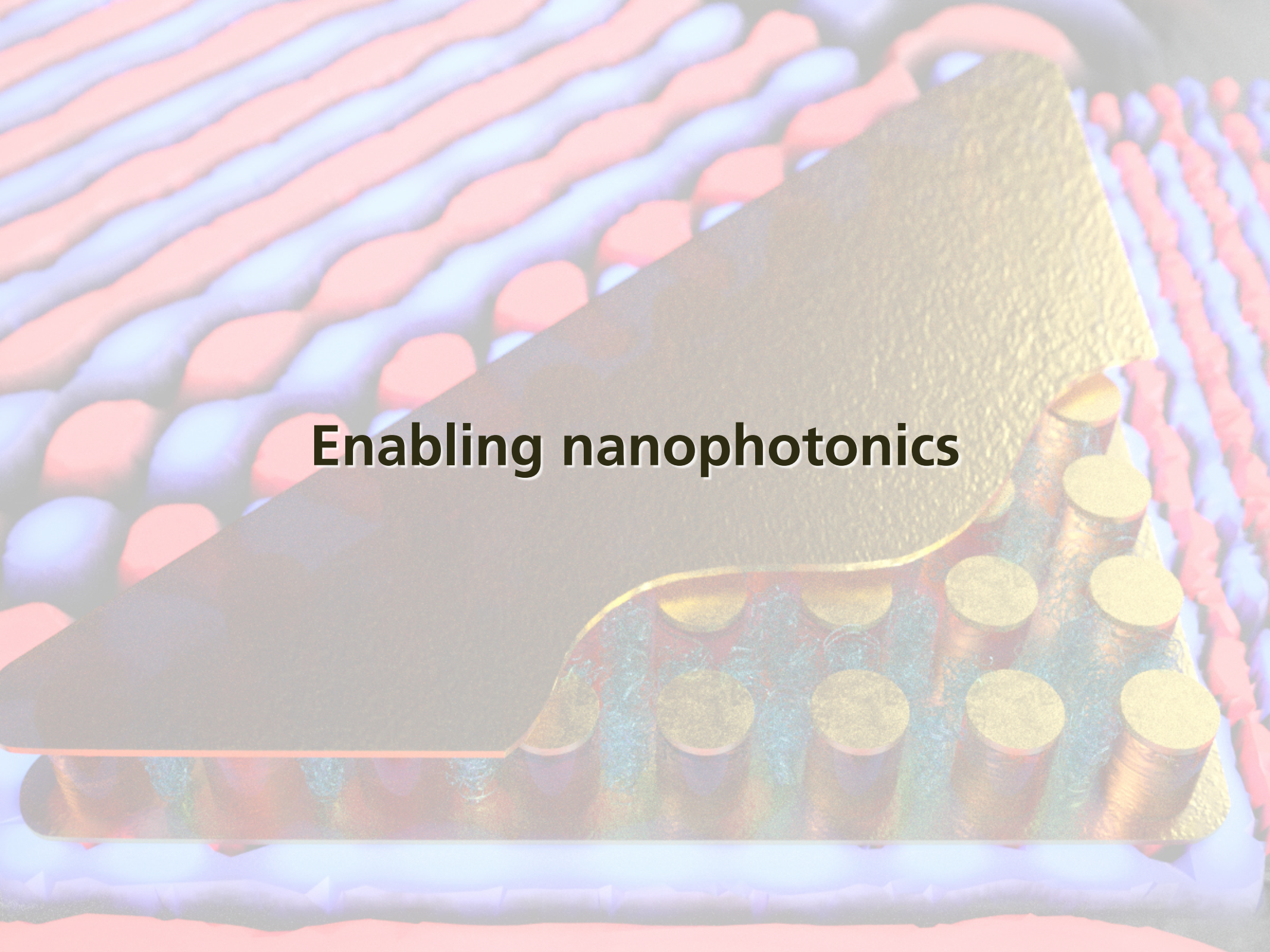
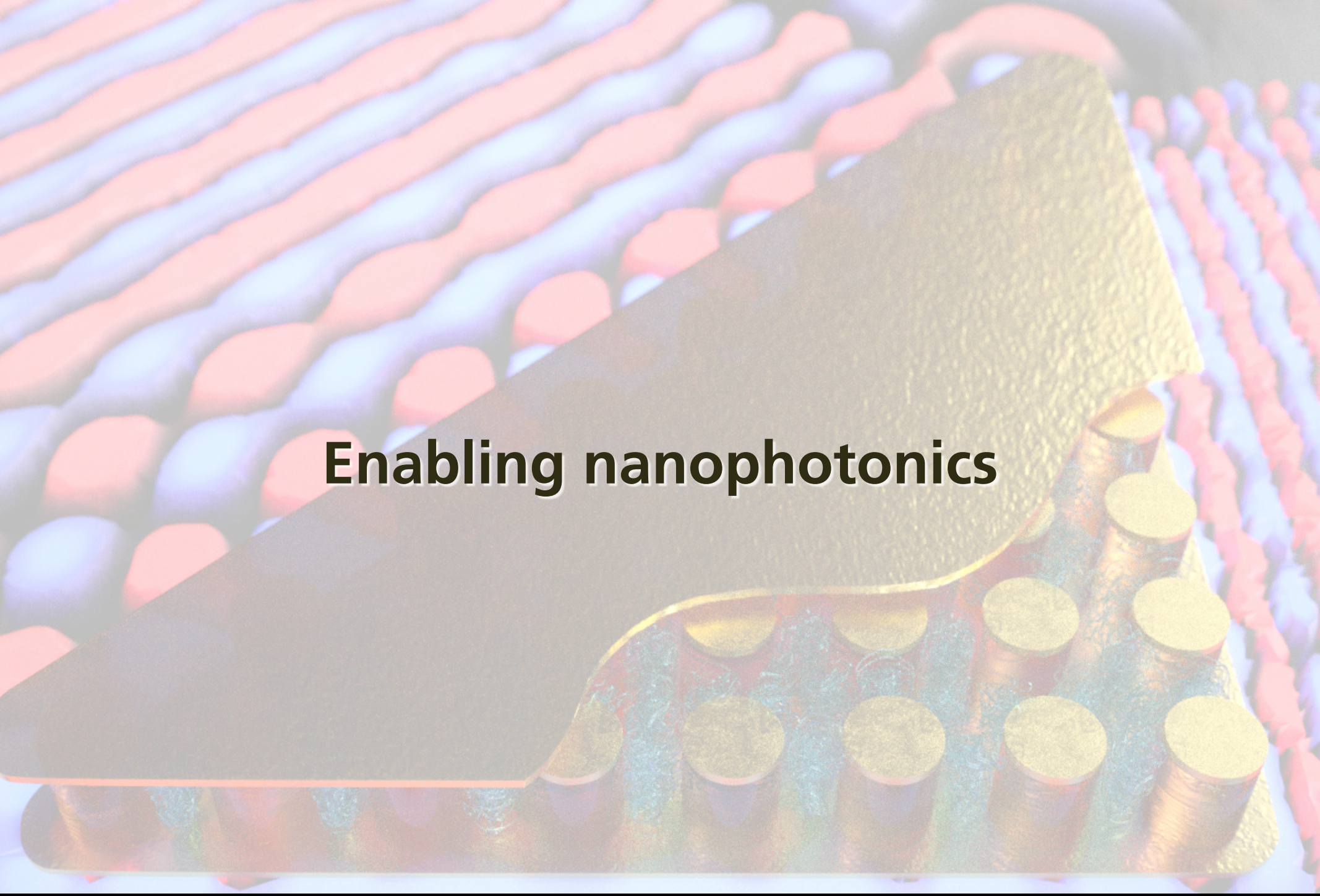
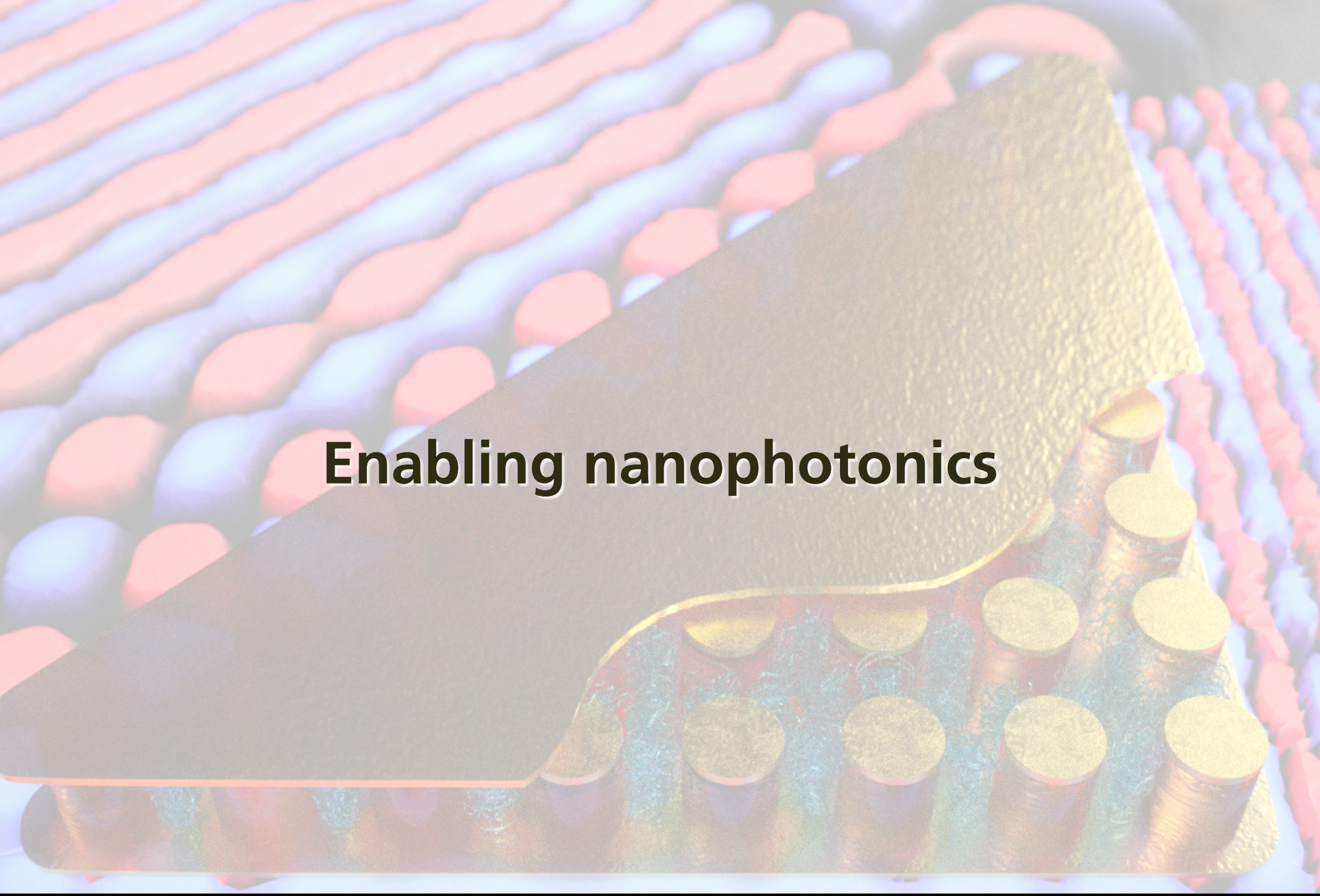


Enabling nanophotonics



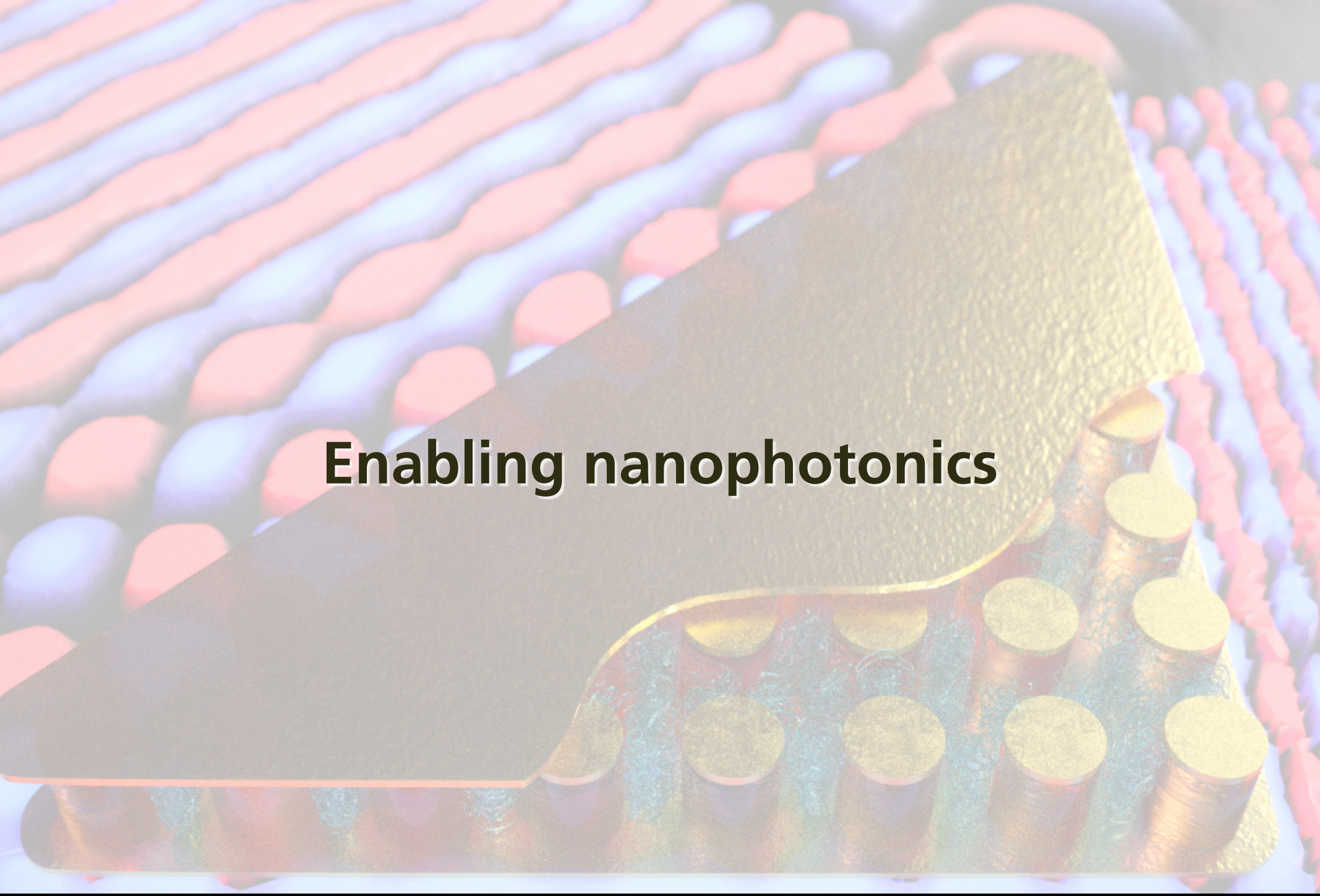
Enabling nanophotonics



Enabling nanophotonics

1 zero index

2 fabrication



Enabling nanophotonics

1 zero index

2 fabrication

3 results

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

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

wave equation

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

solution

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

where

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

wave equation

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

solution

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

where

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

wave equation

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

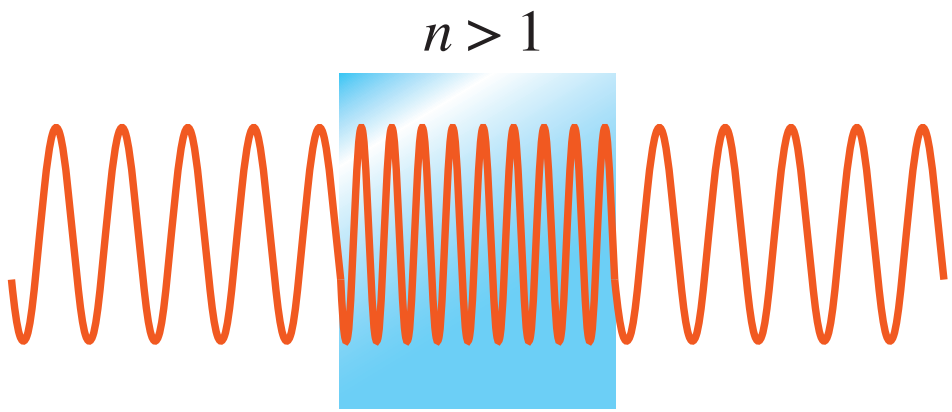
solution

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

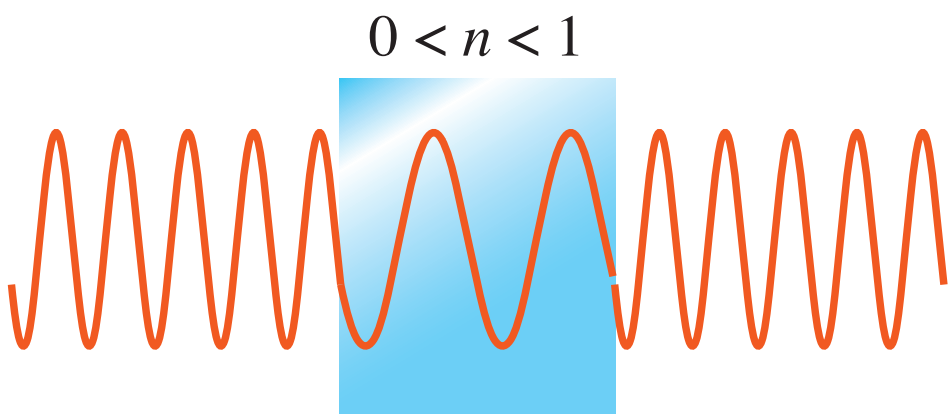
where

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

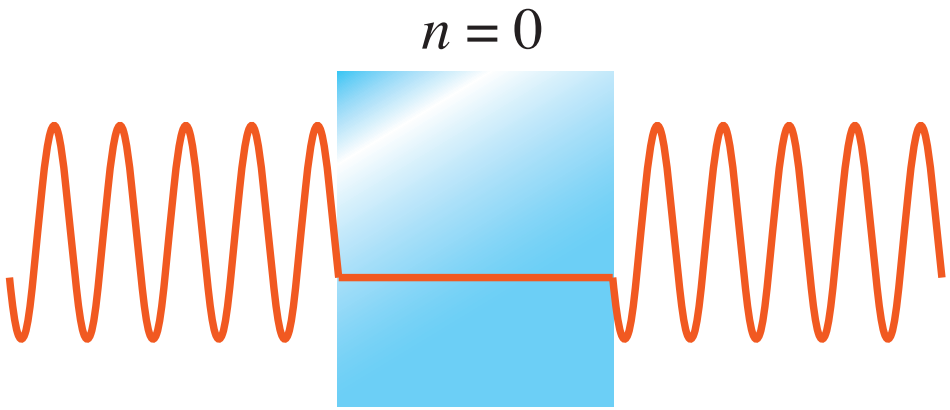
1 zero index



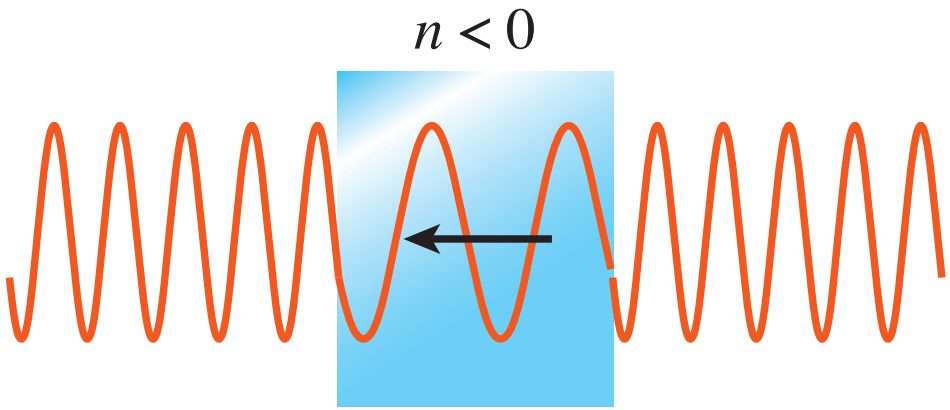
1 zero index



1 zero index



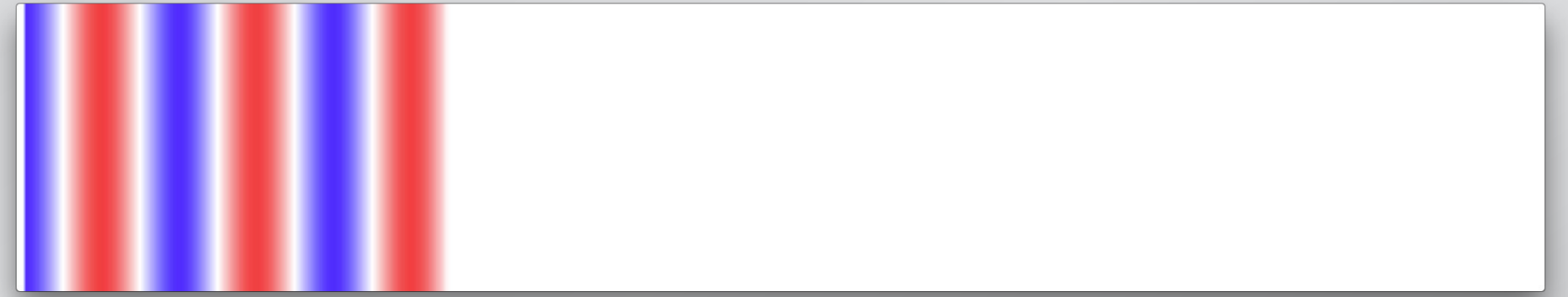
1 zero index



1 zero index

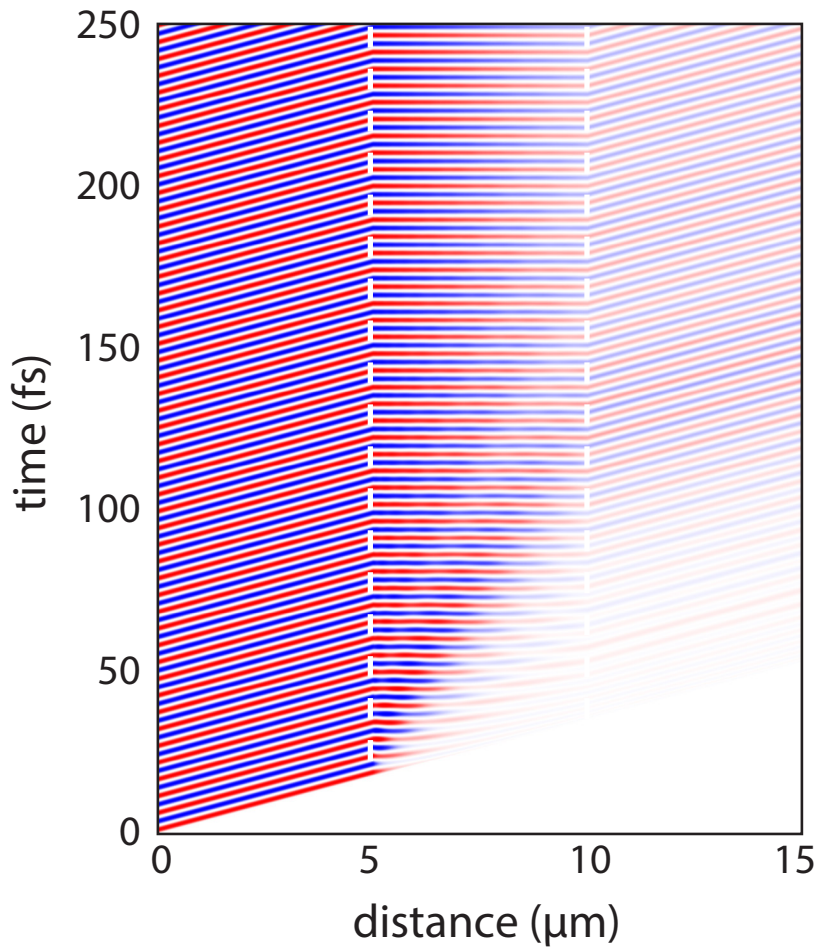
1 zero index

What about causality?



What about causality?

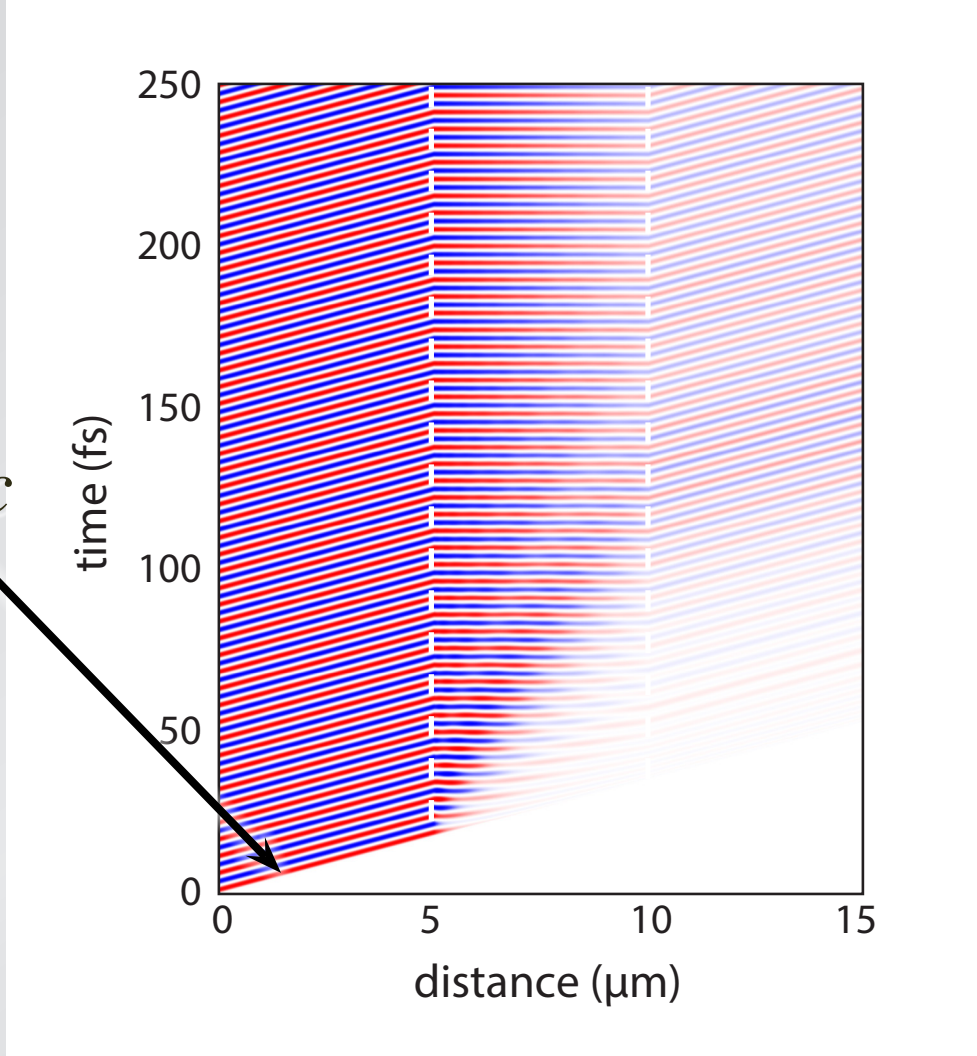
What about causality?



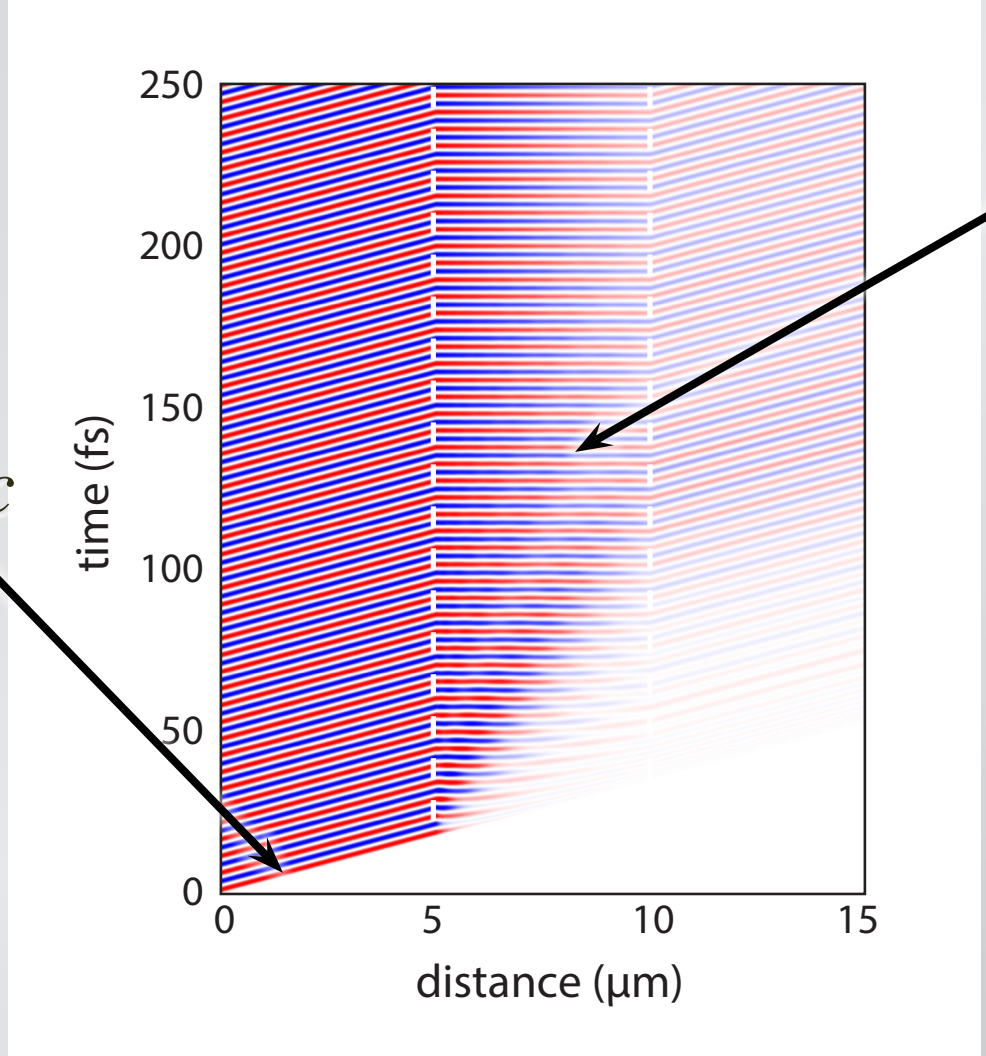
1 zero index

What about causality?

speed of light c



What about causality?



constant phase

speed of light c

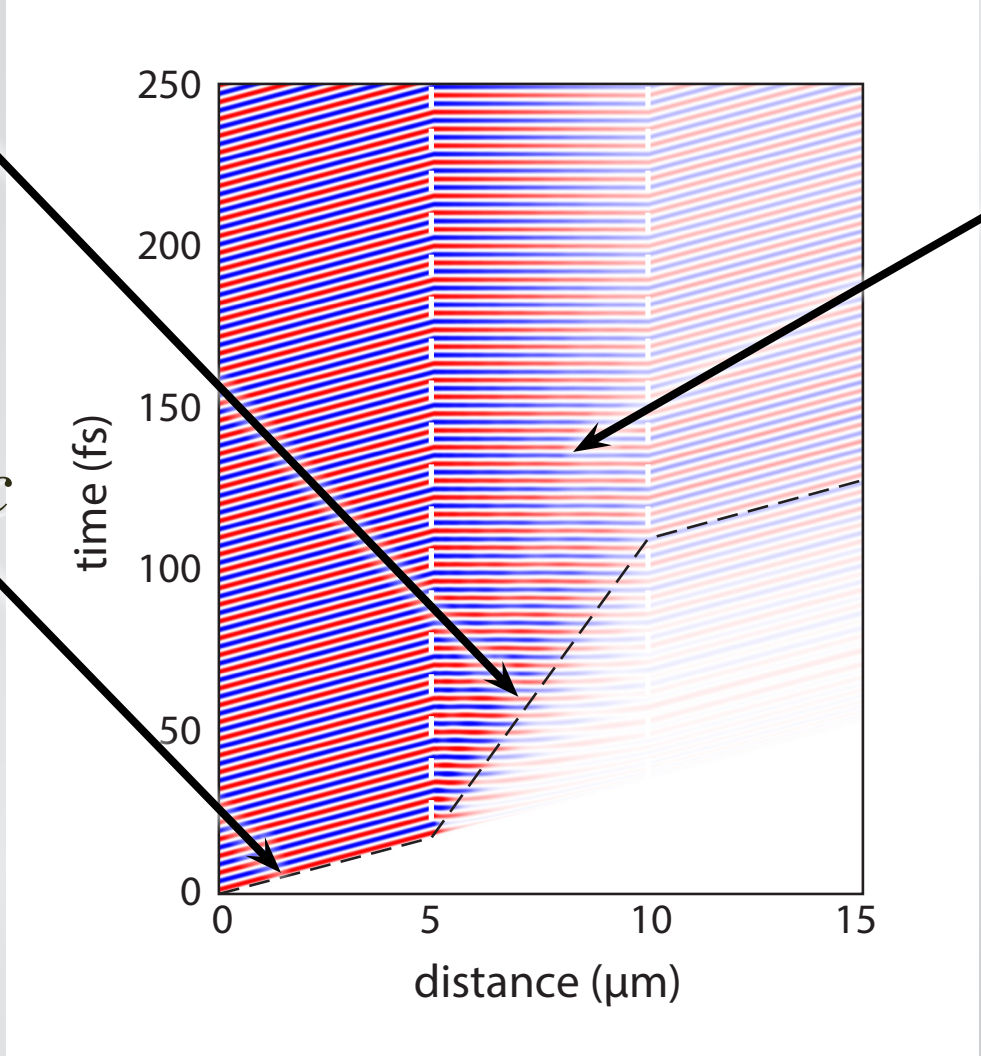
1 zero index

What about causality?

group velocity

$v_g > c$

speed of light c



constant phase

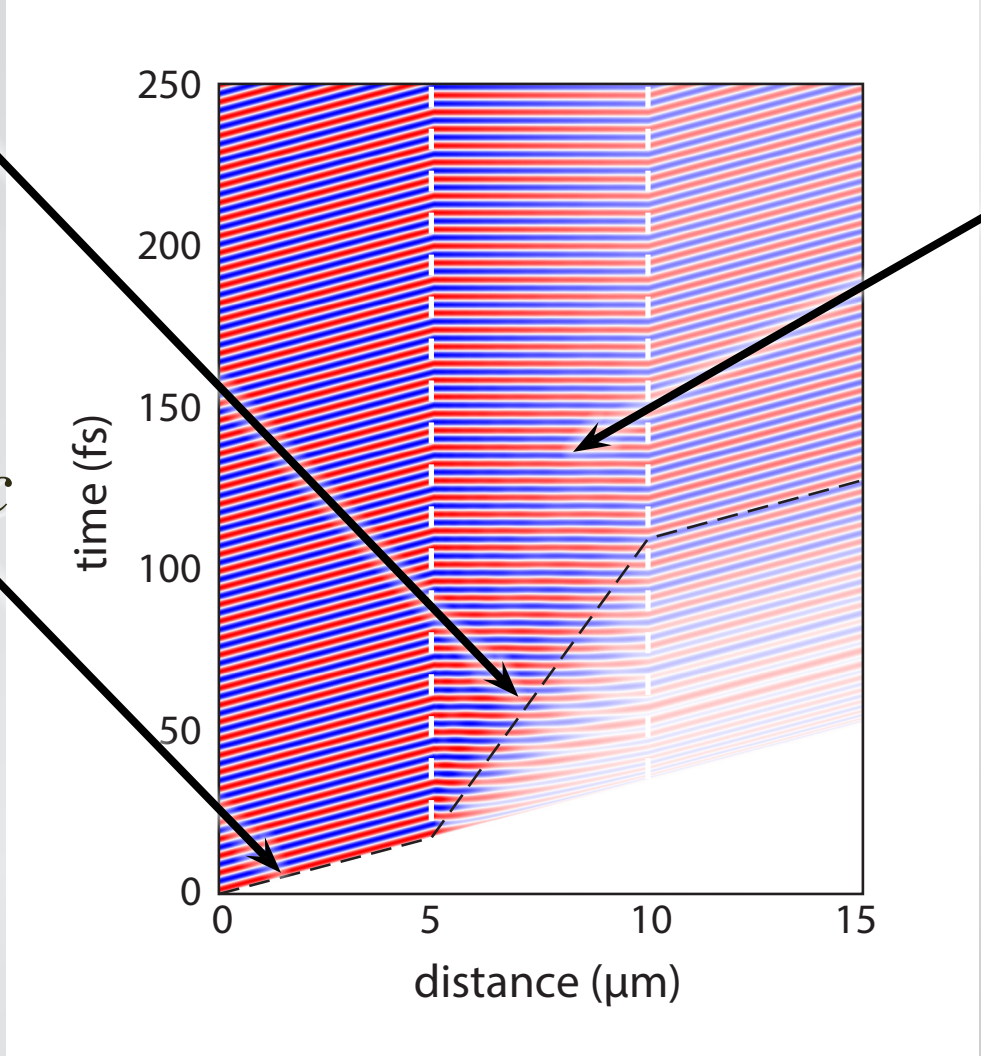
1 zero index

What about causality?

group velocity

$v_g > c$

speed of light c



constant phase

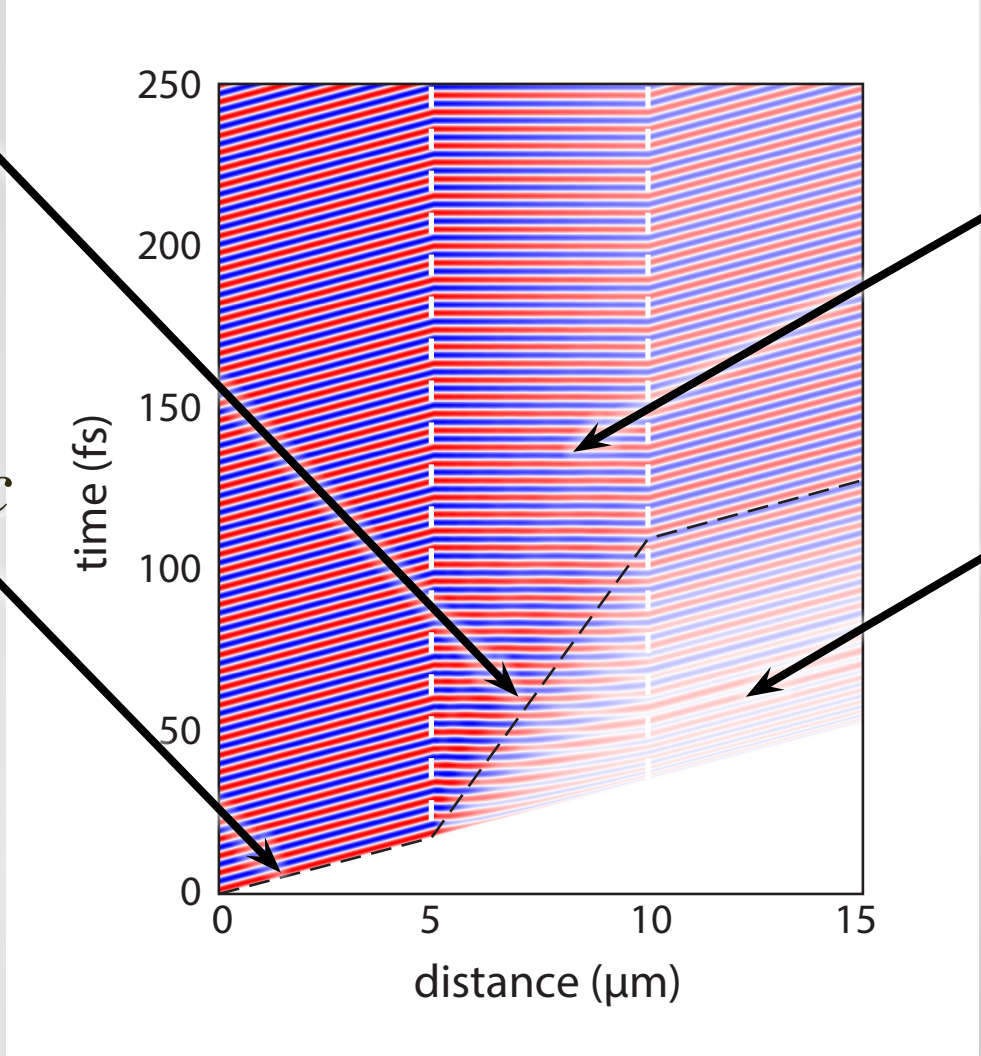
1 zero index

What about causality?

group velocity

$v_g > c$

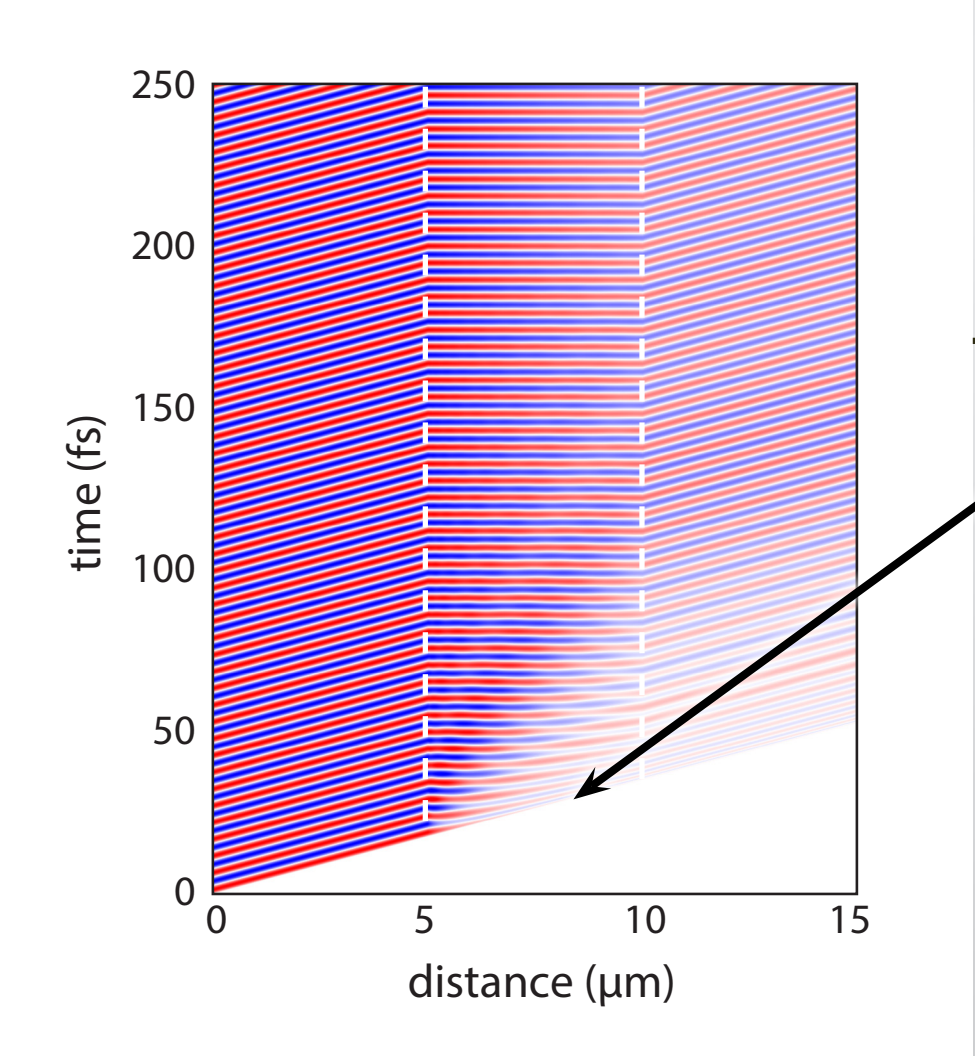
speed of light c



constant phase

high-frequency precursors

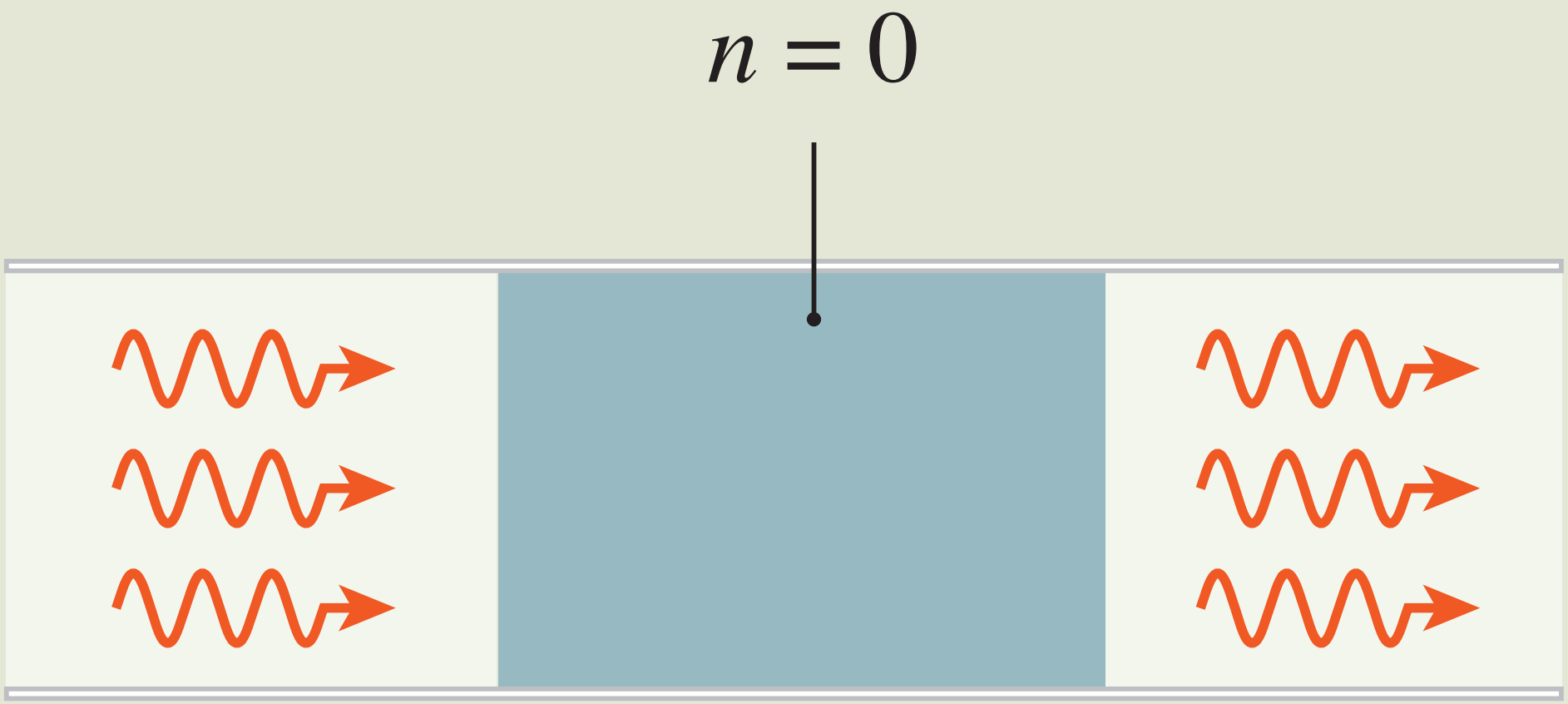
What about causality?



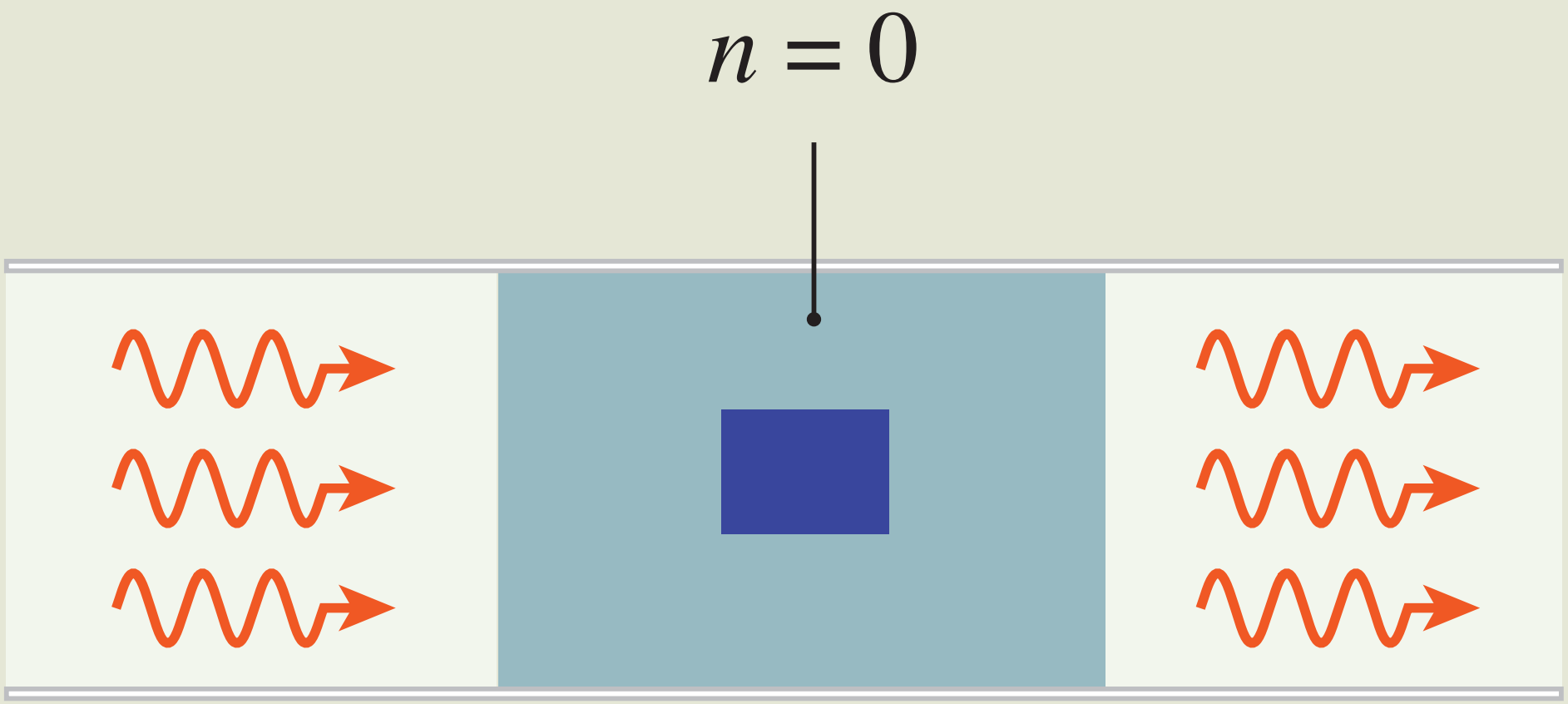
signal *always* travels at speed c!

What about causality?

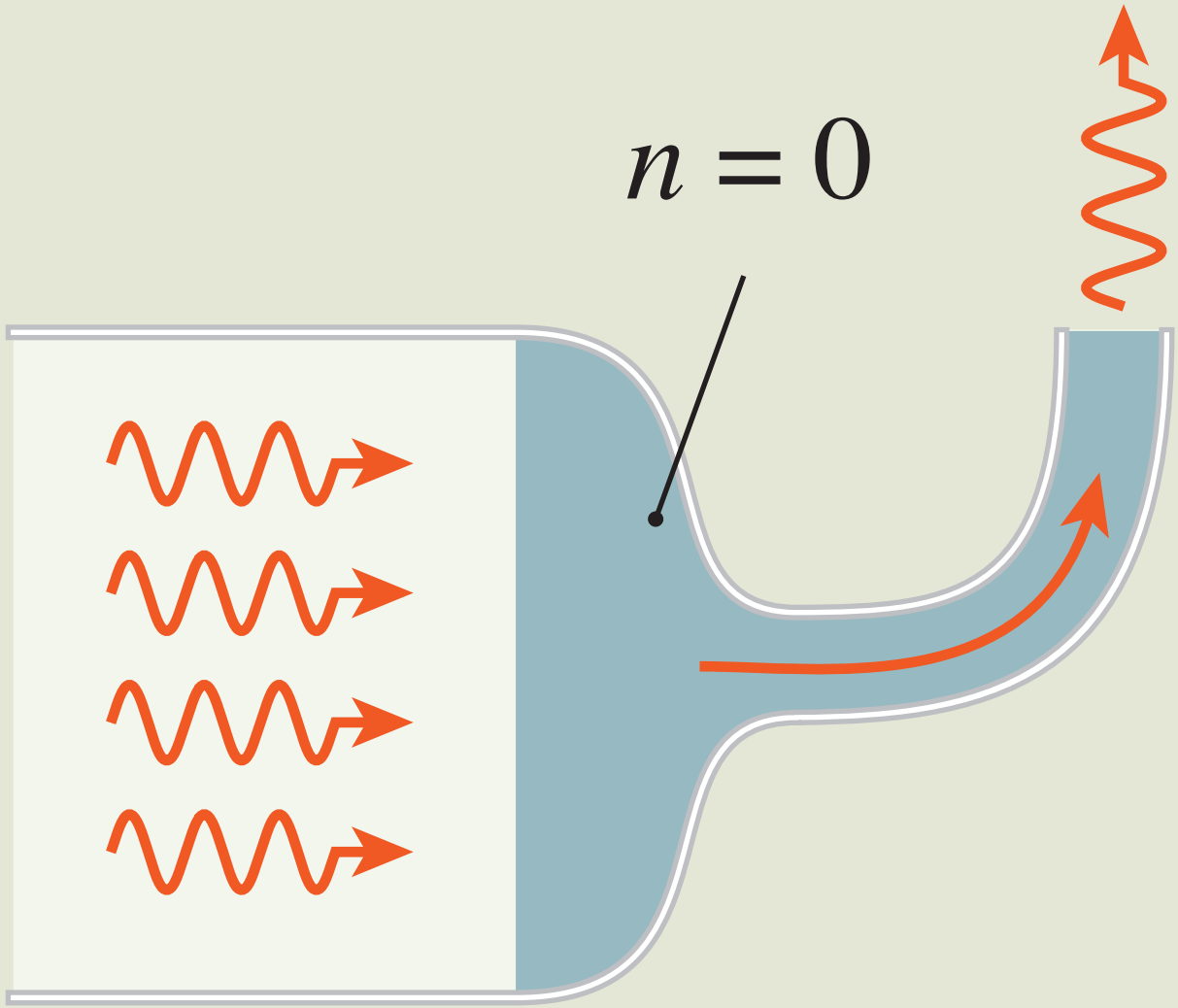
What can we do with uniform phase?



1 zero index

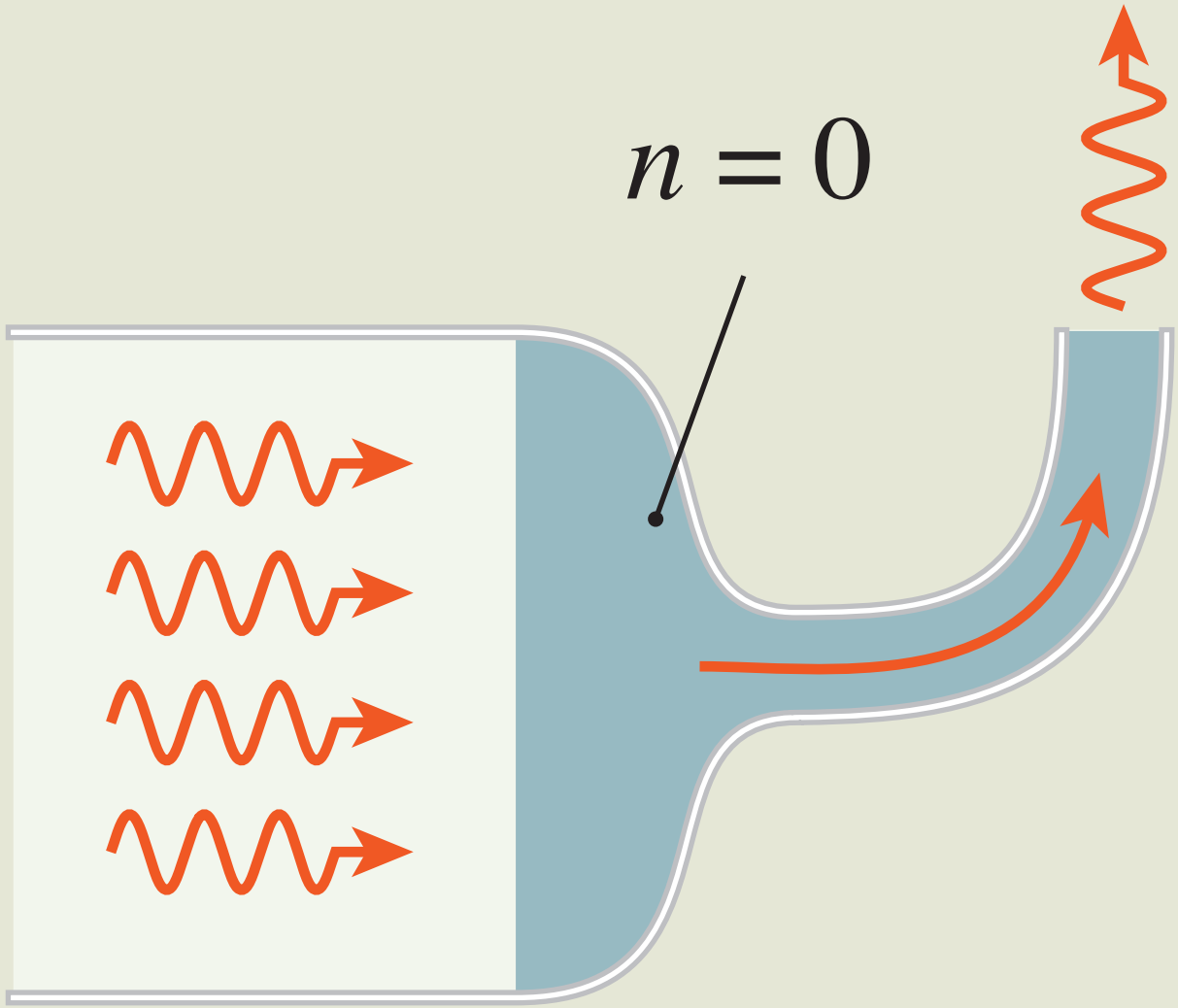


1 zero index



1 zero index

“tunneling with infinite decay length”



1 zero index

how?

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

how?

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

but ϵ and μ also determine reflectivity

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

how?

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

but ϵ and μ also determine reflectivity

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

where

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

how?

$$\varepsilon \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

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

how?

$$\varepsilon \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

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

how?

$$\varepsilon \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

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

how?

$$\mu \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

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

how?

$$\mu \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

$$Z = \sqrt{\frac{\mu}{\varepsilon}} \to 0$$

how?

$$\mu \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

$$Z = \sqrt{\frac{\mu}{\varepsilon}} \to 0$$

how?

$$\varepsilon, \mu \to 0 \qquad\qquad n = \sqrt{\varepsilon\mu} \to 0$$

but ϵ and μ also determine reflectivity

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

where

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

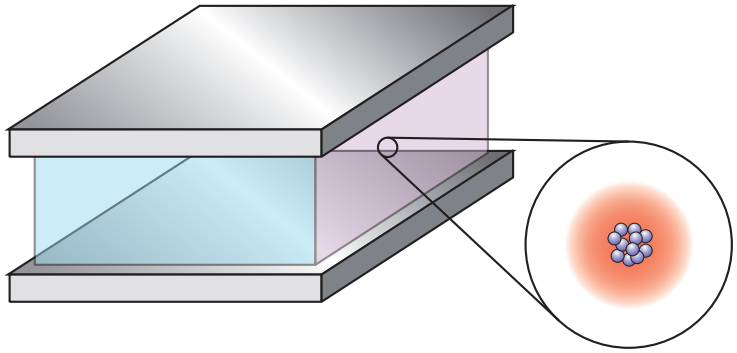
finite!

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

Engineering a magnetic response

Engineering a magnetic response

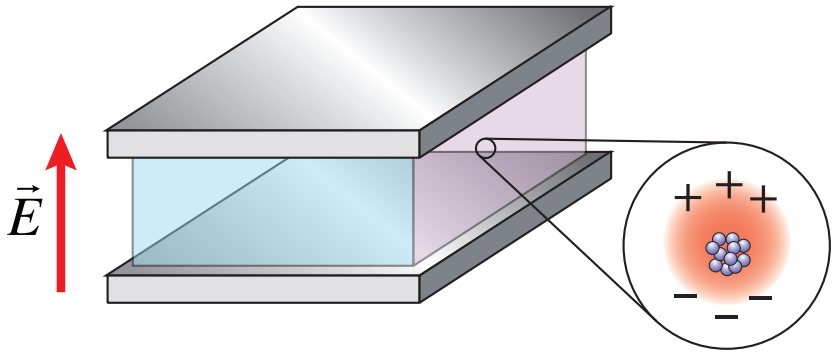
bulk material



properties derive from
constituent atoms

Engineering a magnetic response

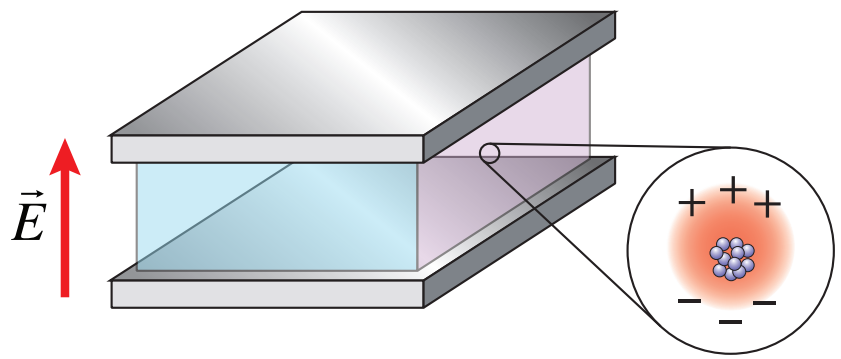
bulk material



properties derive from constituent atoms

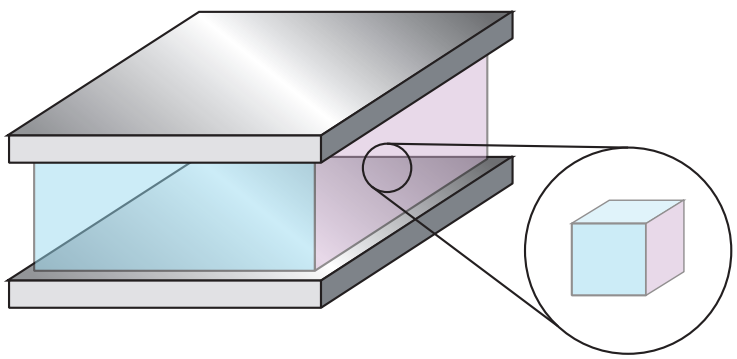
Engineering a magnetic response

bulk material



properties derive from constituent atoms

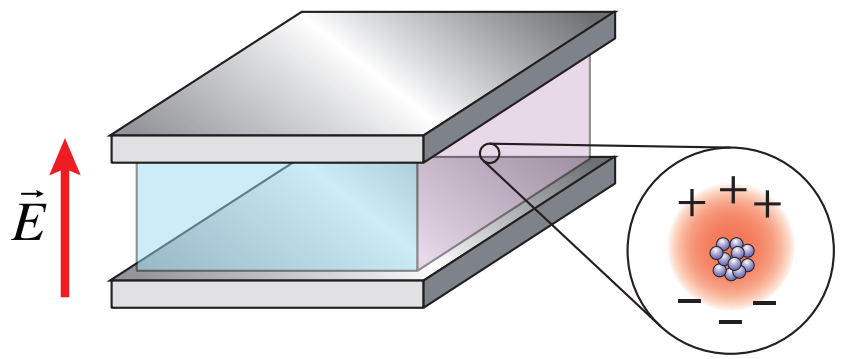
composite material



properties derive from constituent units

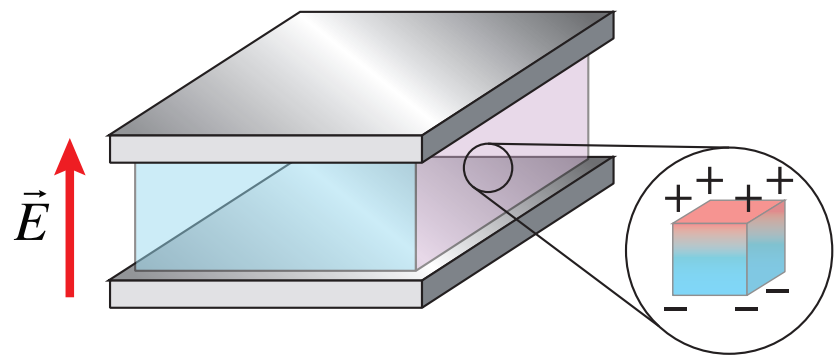
Engineering a magnetic response

bulk material



properties derive from constituent atoms

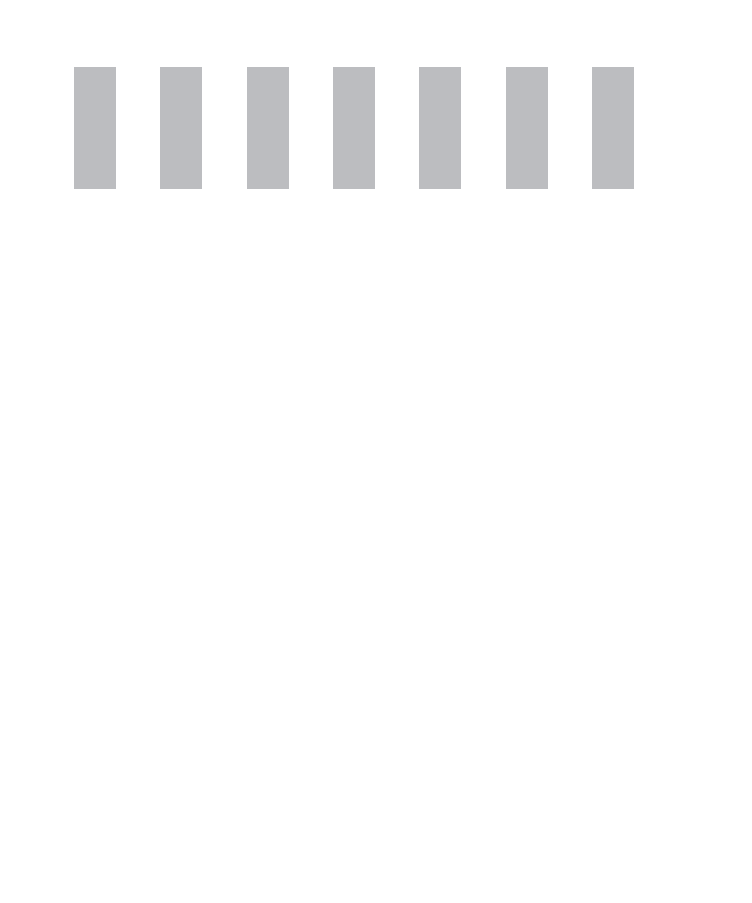
composite material



properties derive from constituent units

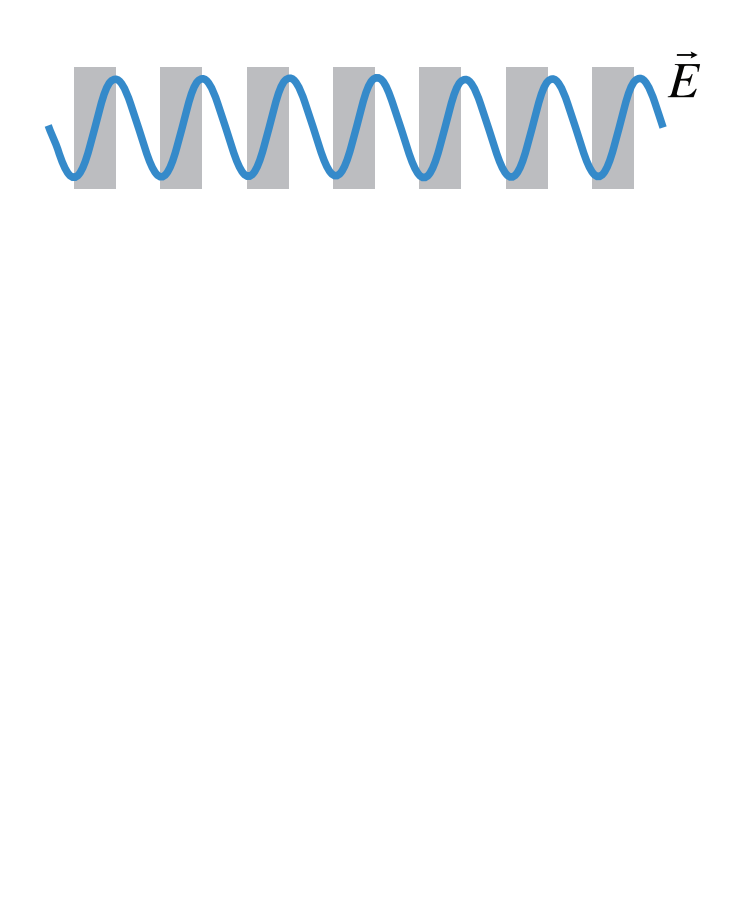
Engineering a magnetic response

use array of dielectric rods



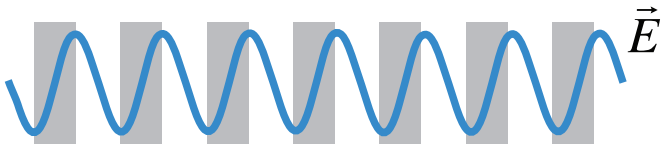
Engineering a magnetic response

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



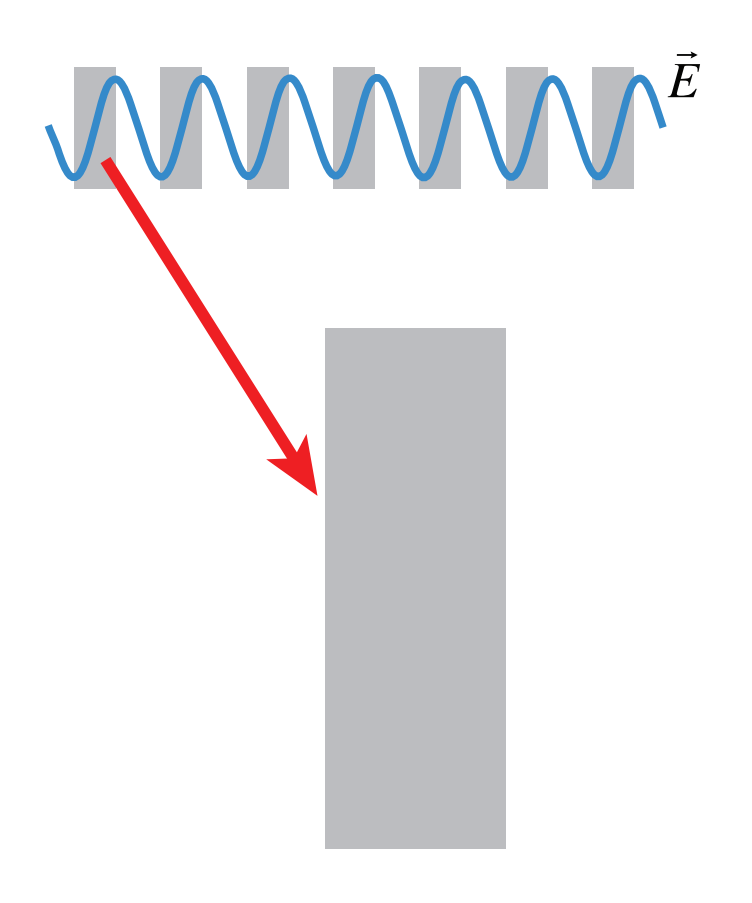
Engineering a magnetic response

produces an electric response…



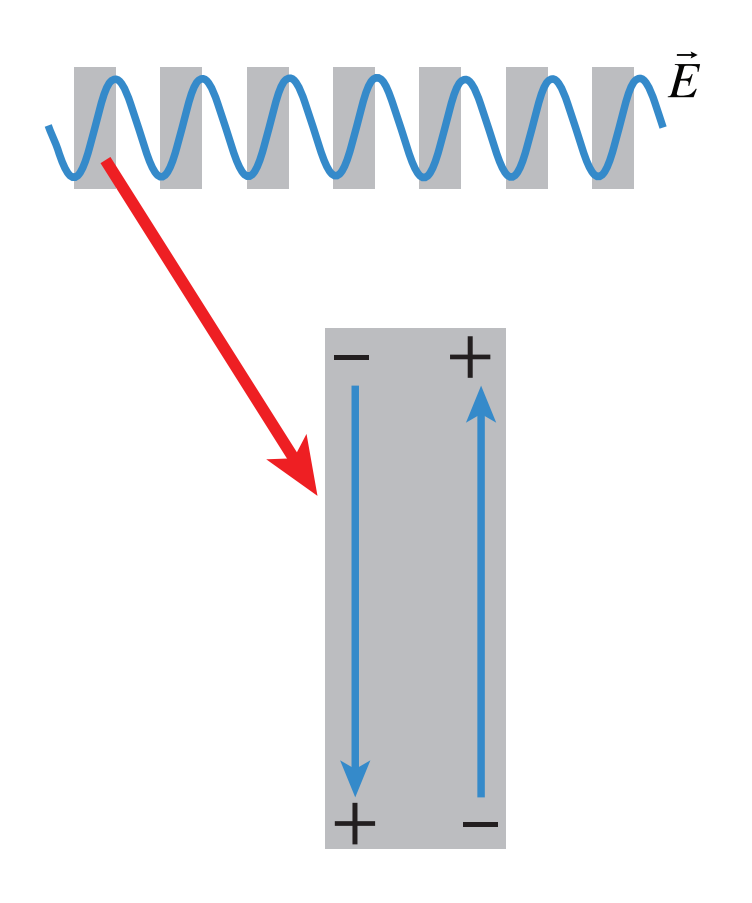
Engineering a magnetic response

… but different electric fields front and back…



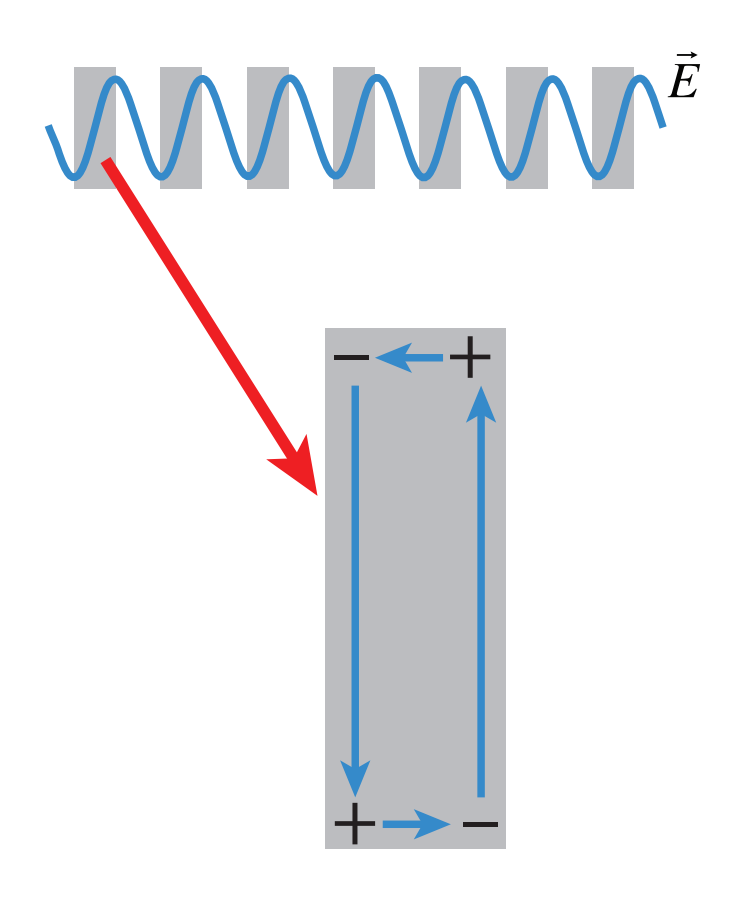
Engineering a magnetic response

…induce different polarizations on opposite sides…



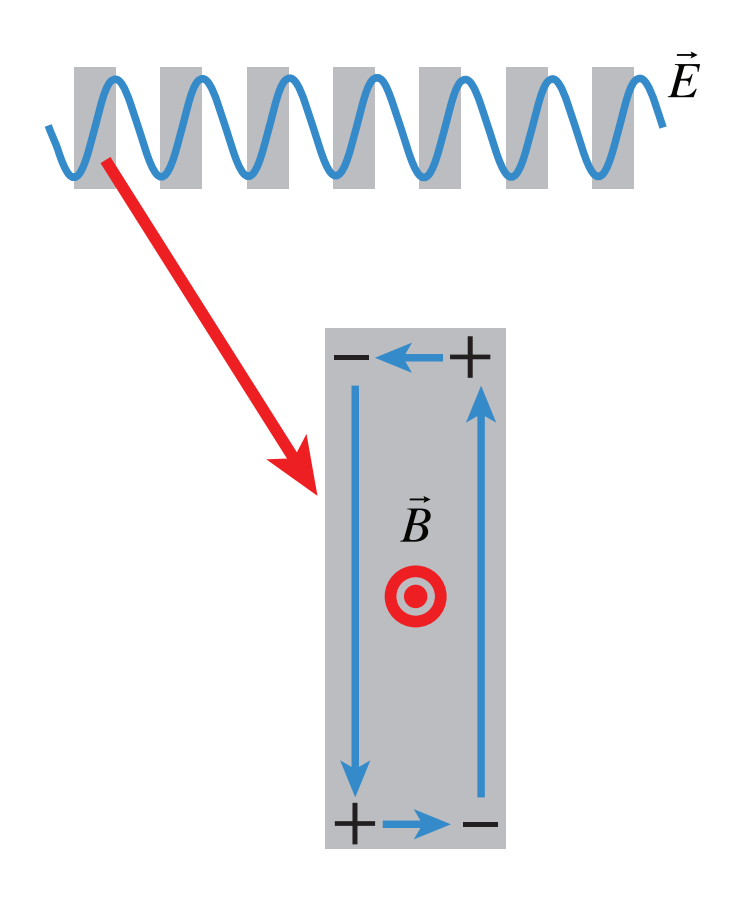
Engineering a magnetic response

…causing a current loop…



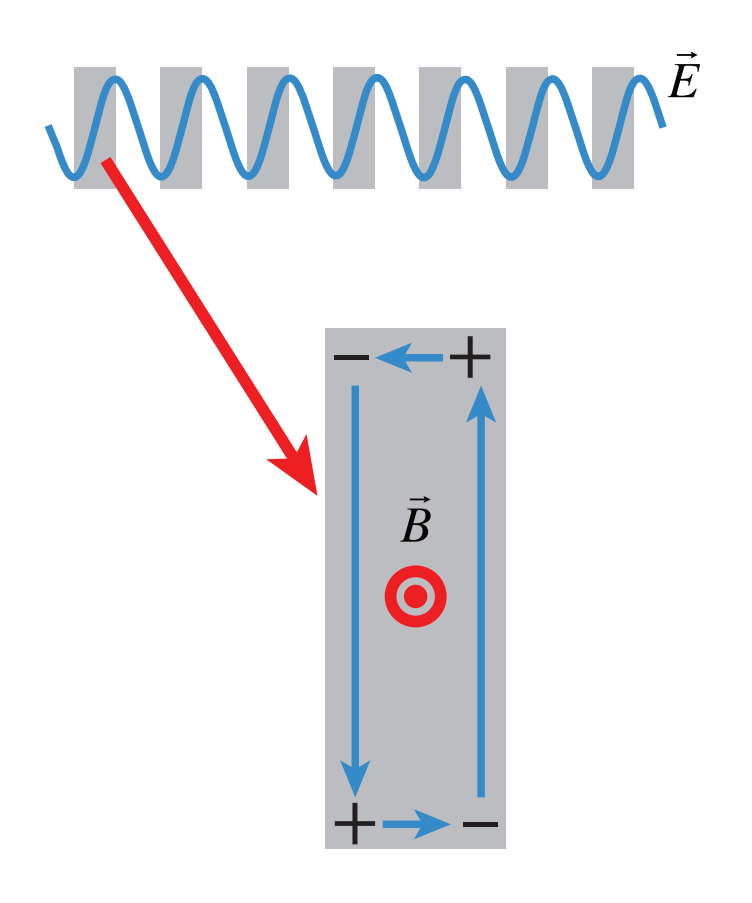
Engineering a magnetic response

…which, in turn, produces an induced magnetic field



Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide



Engineering a magnetic response

adjustable parameters

Engineering a magnetic response

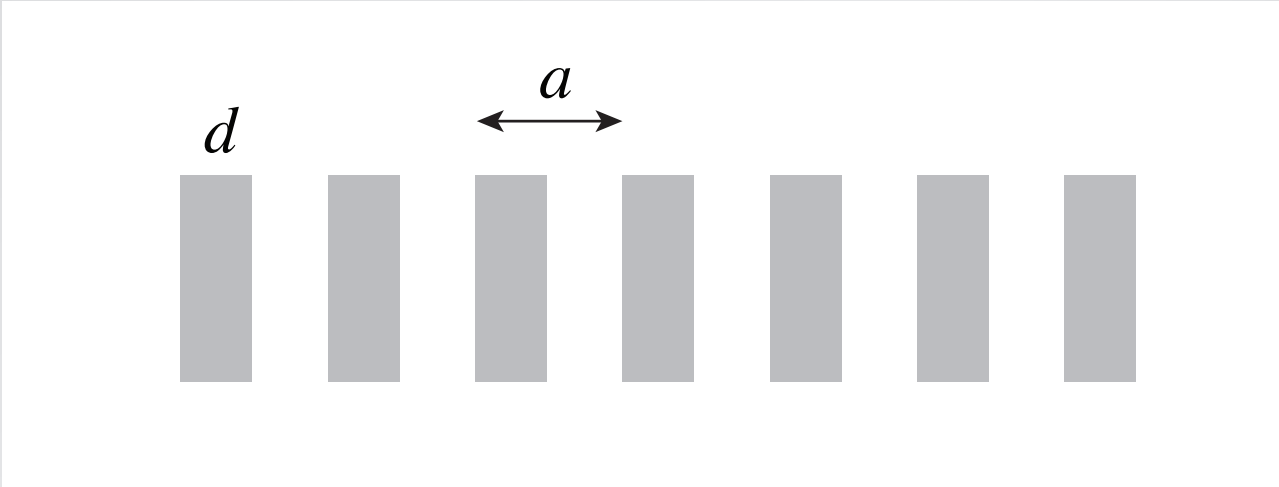
adjustable parameters

Engineering a magnetic response

adjustable parameters

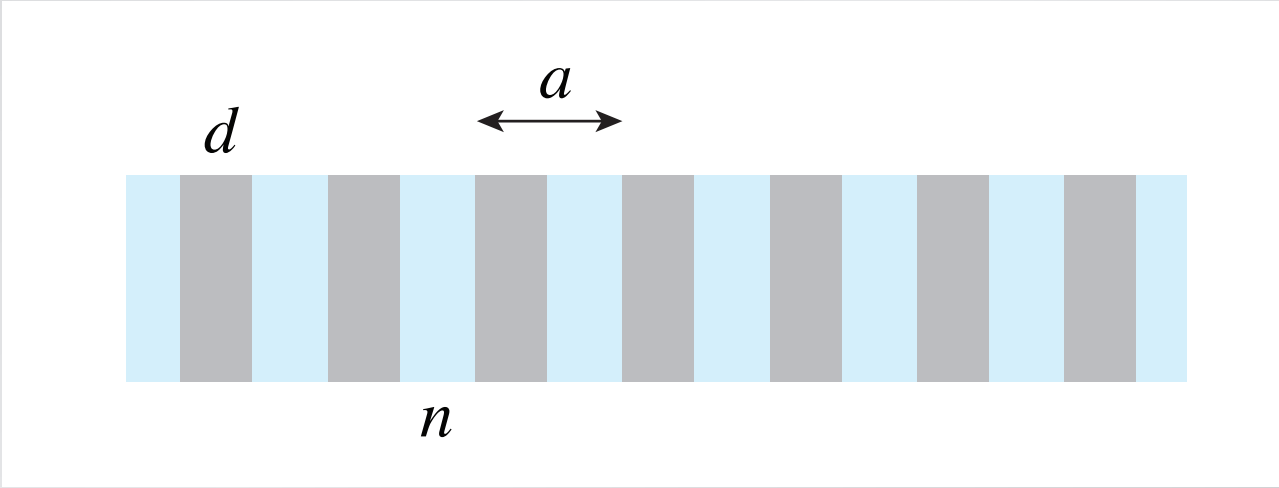
Engineering a magnetic response

adjustable parameters



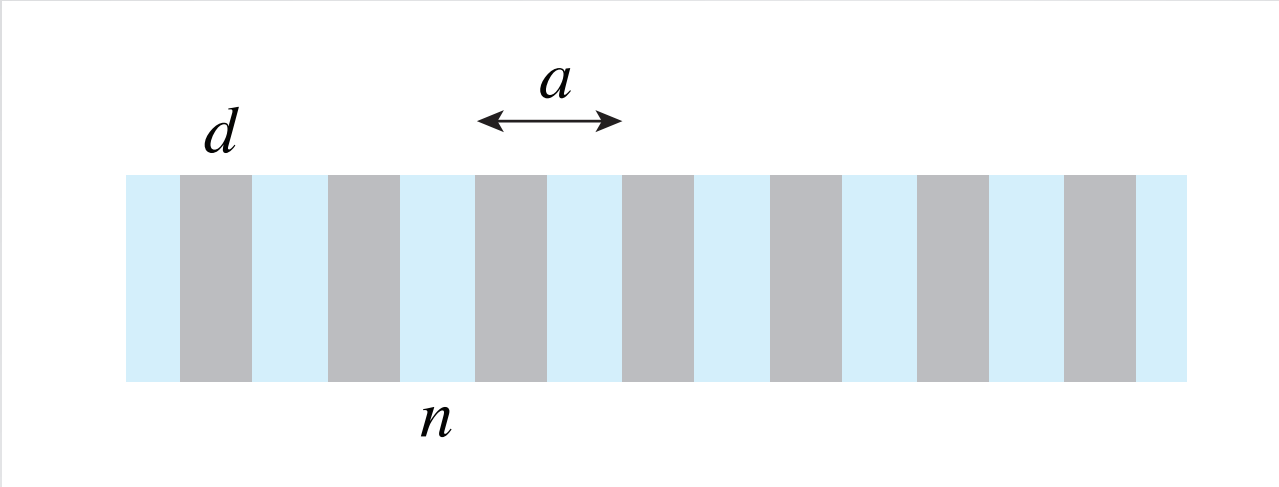
Engineering a magnetic response

adjustable parameters

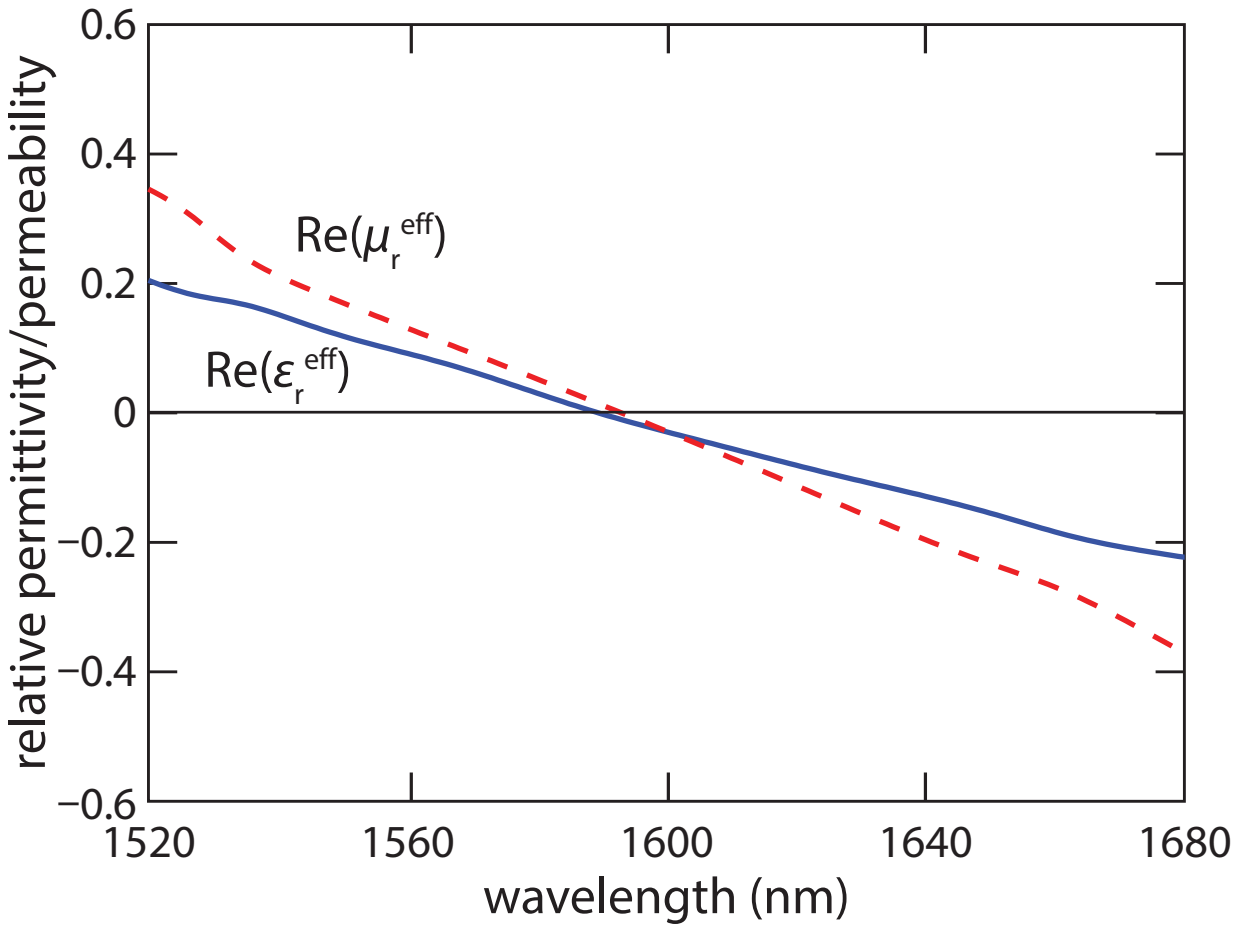


Engineering a magnetic response

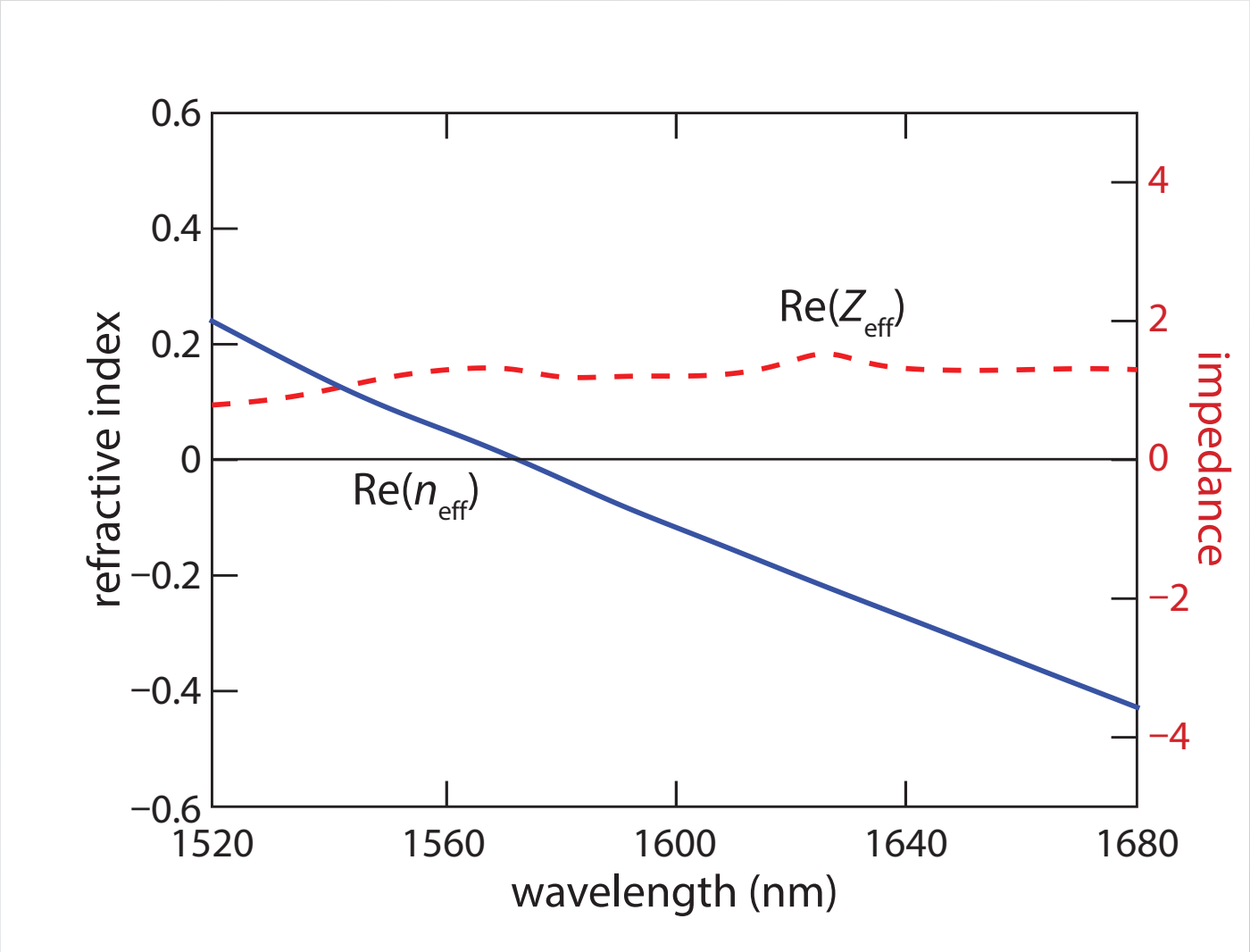
adjustable parameters



d = 422 nm, a = 690 nm, n = 1.57 (SU8)

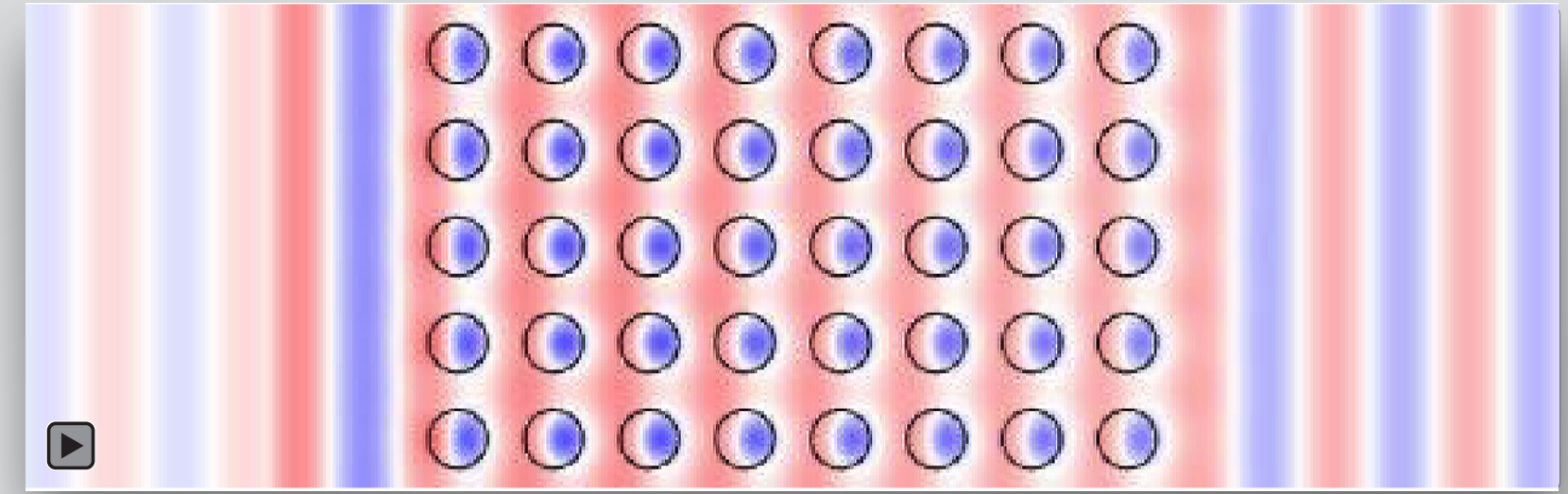

0.6
0.4
0.2
0
−0.2
−0.4
−0.6
relative permittivity/permeability
Re(μ_r^{eff})
Re(ε_r^{eff})
1520
1560
1600
1640
1680
wavelength (nm)

1 zero index


0.6
0.4
0.2
0
−0.2
−0.4
−0.6
refractive index
4
2
0
−2
−4
impedance
Re(Z_{eff})
Re(n_{eff})
1520
1560
1600
1640
1680
wavelength (nm)

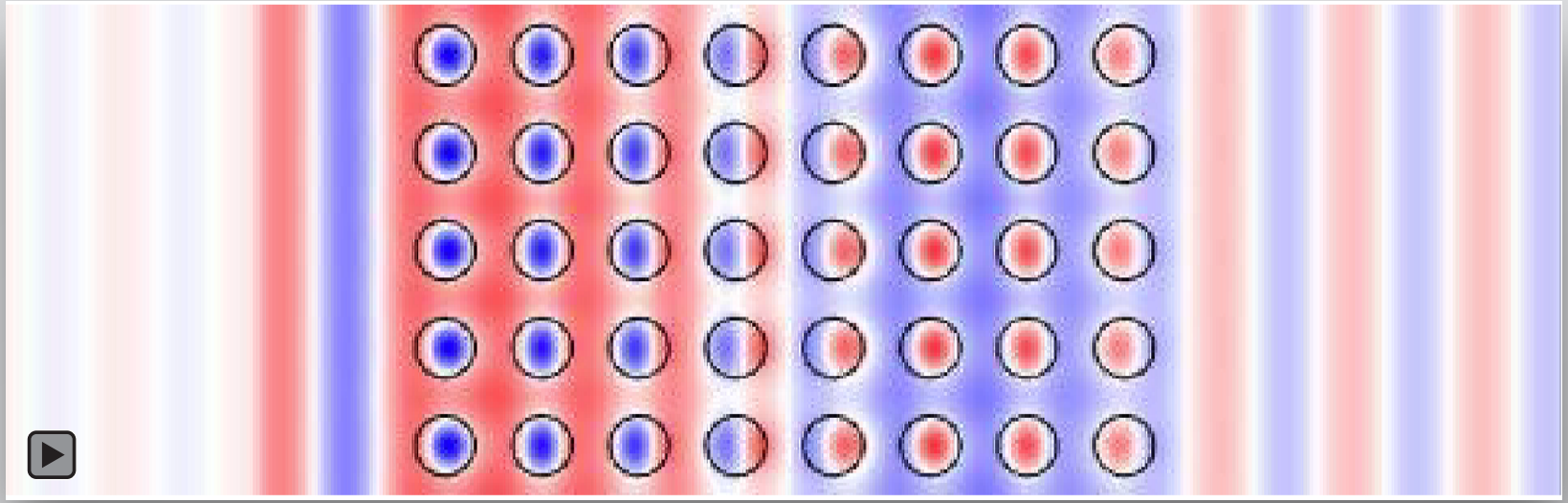
1 zero index

at design wavelength (1590 nm)



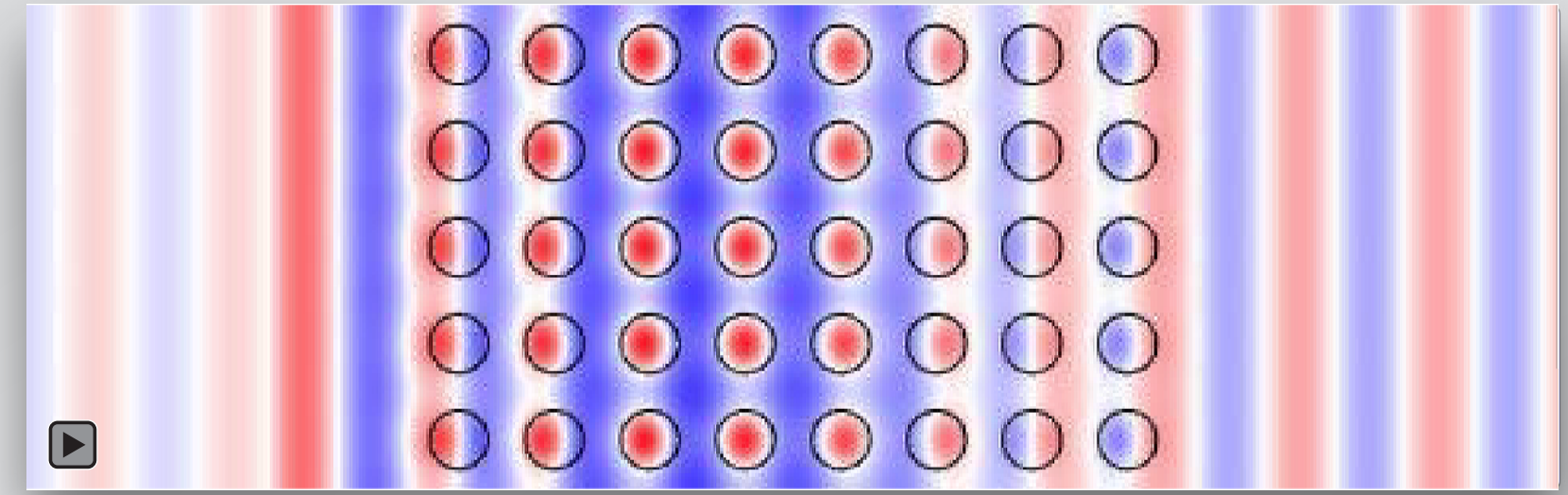
1 zero index

below design wavelength (1530 nm)



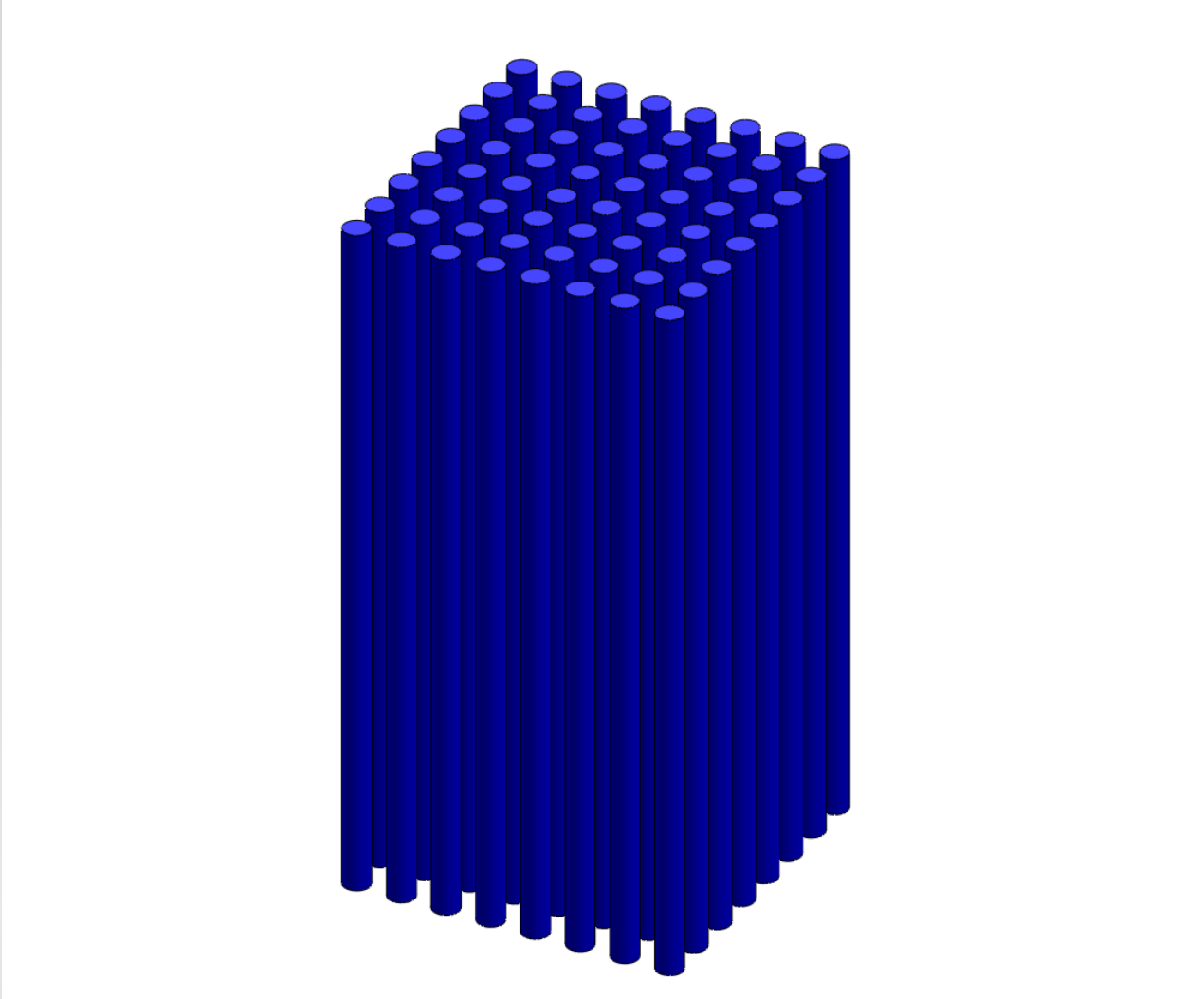
1 zero index

above design wavelength (1650 nm)



1 zero index

How to fabricate?



1 zero index

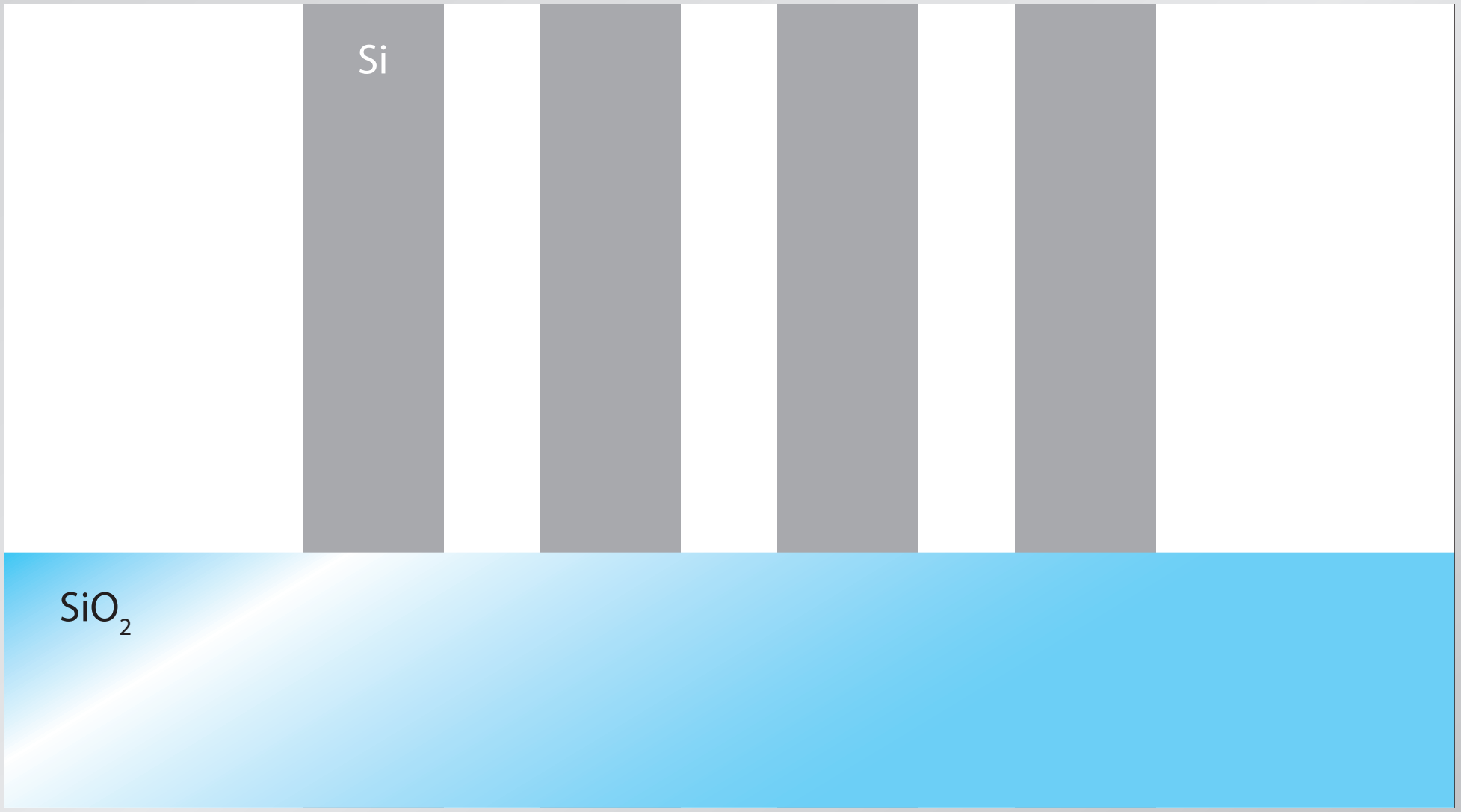
2 fabrication

On-chip zero-index fabrication

1 zero index

2 fabrication

On-chip zero-index fabrication



1 zero index

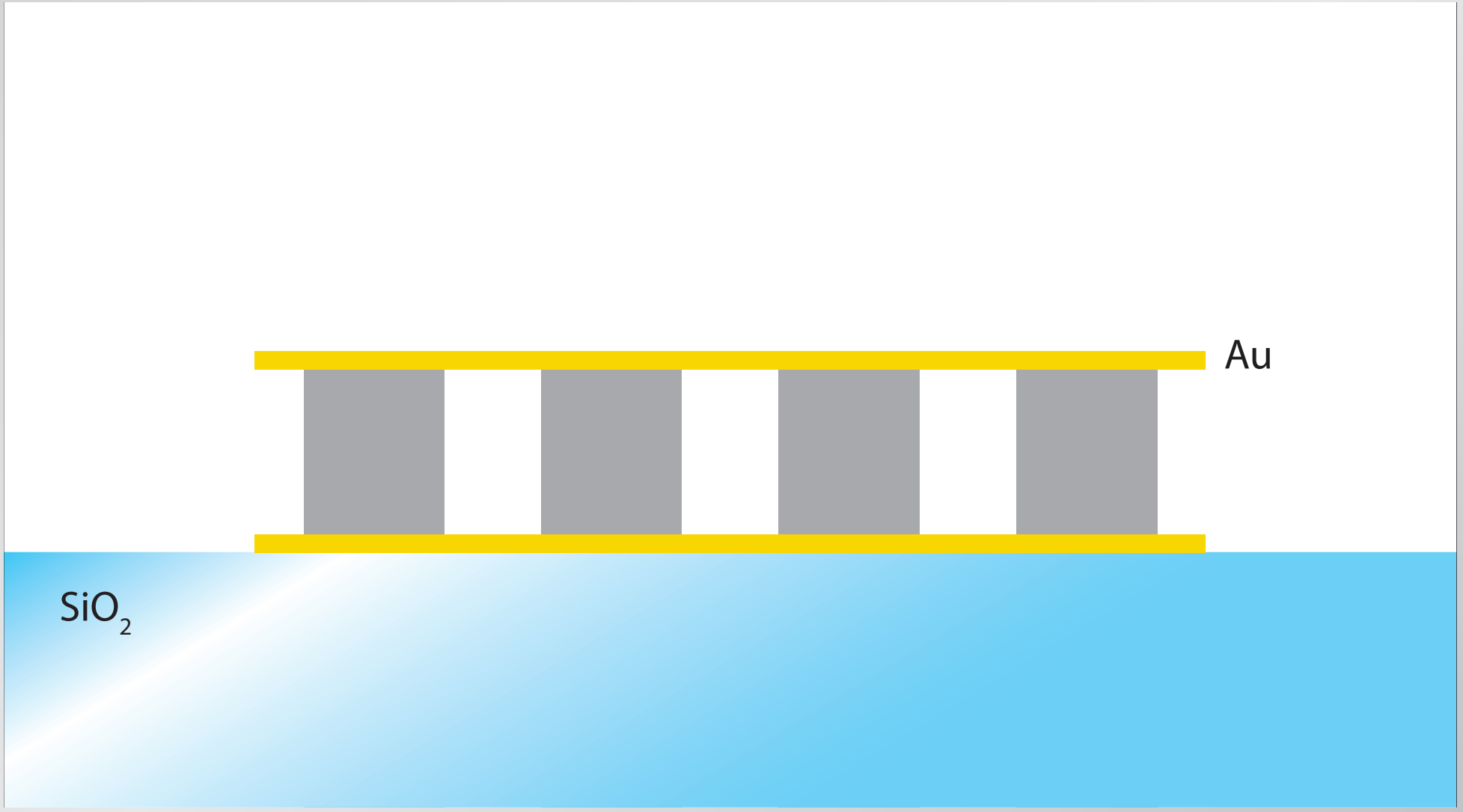
2 fabrication

On-chip zero-index fabrication

1 zero index

2 fabrication

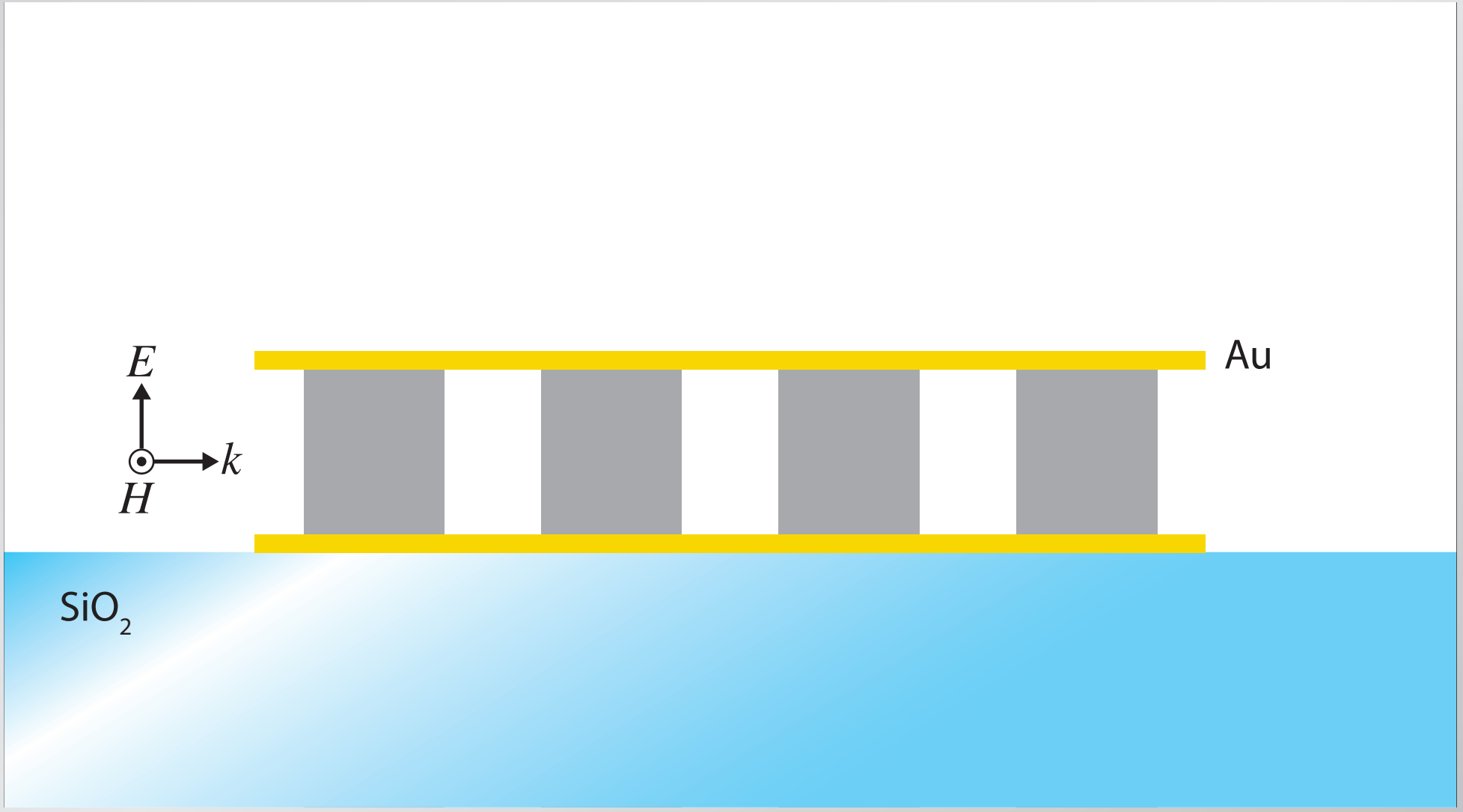
On-chip zero-index fabrication



1 zero index

2 fabrication

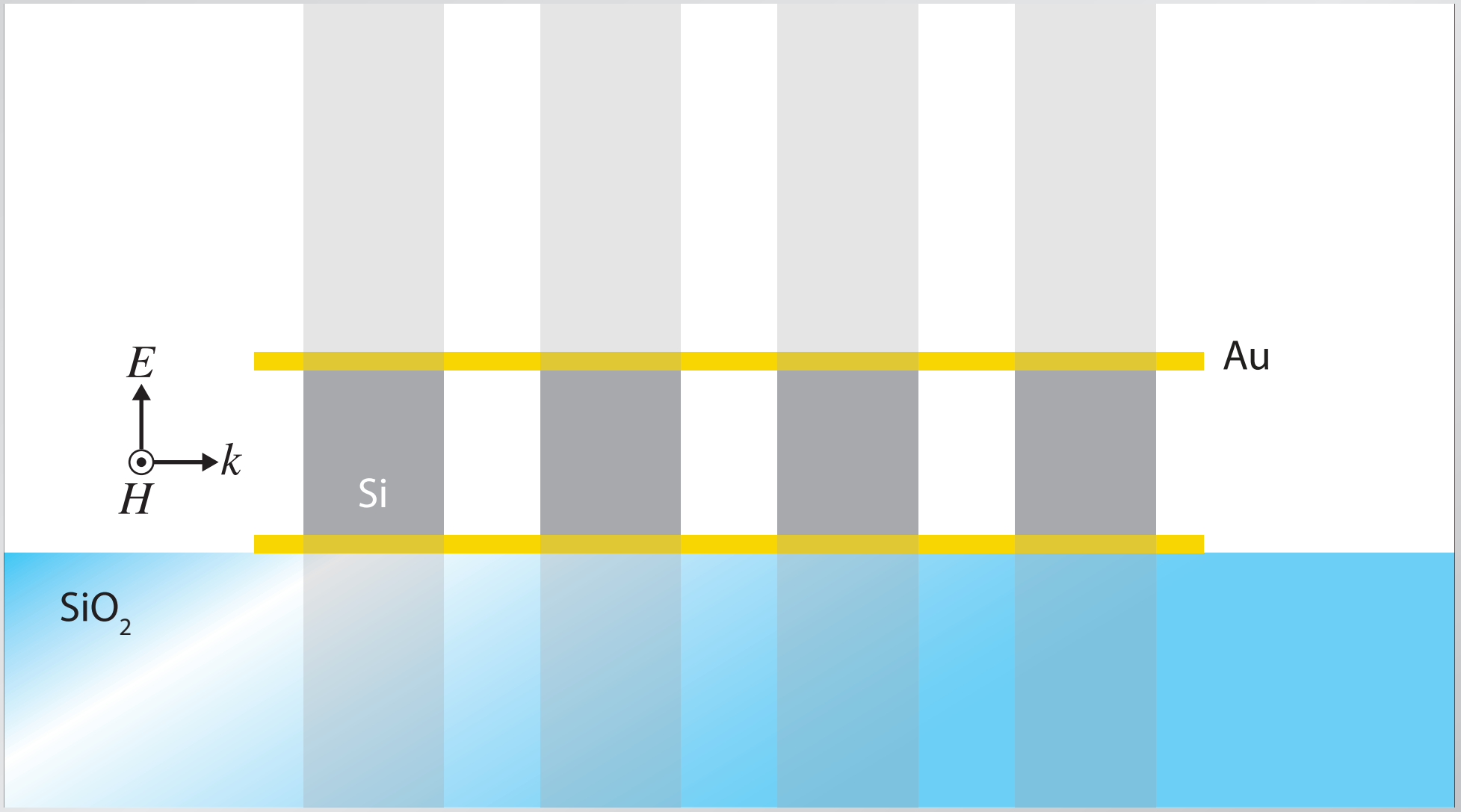
On-chip zero-index fabrication



1 zero index

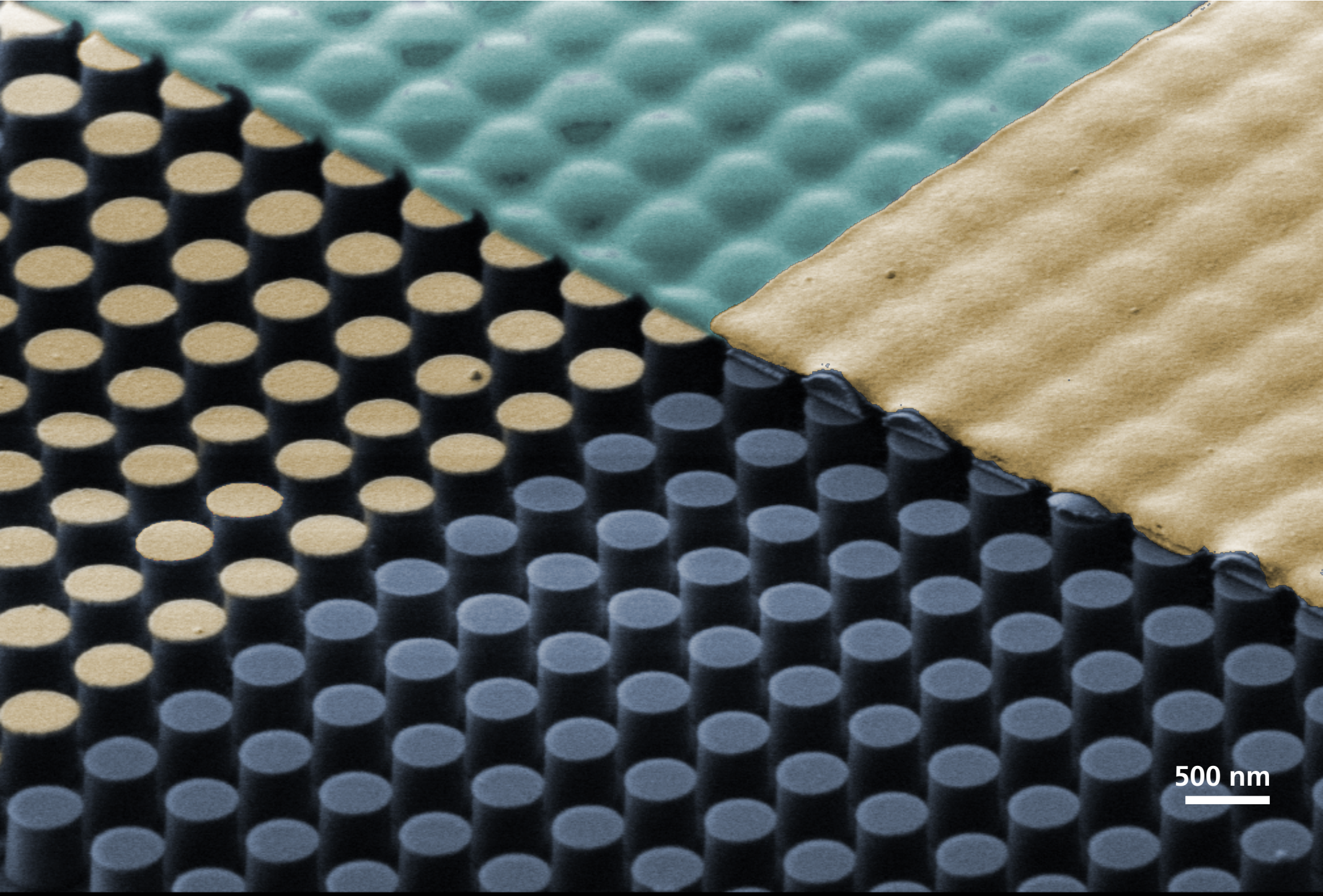
2 fabrication

On-chip zero-index fabrication



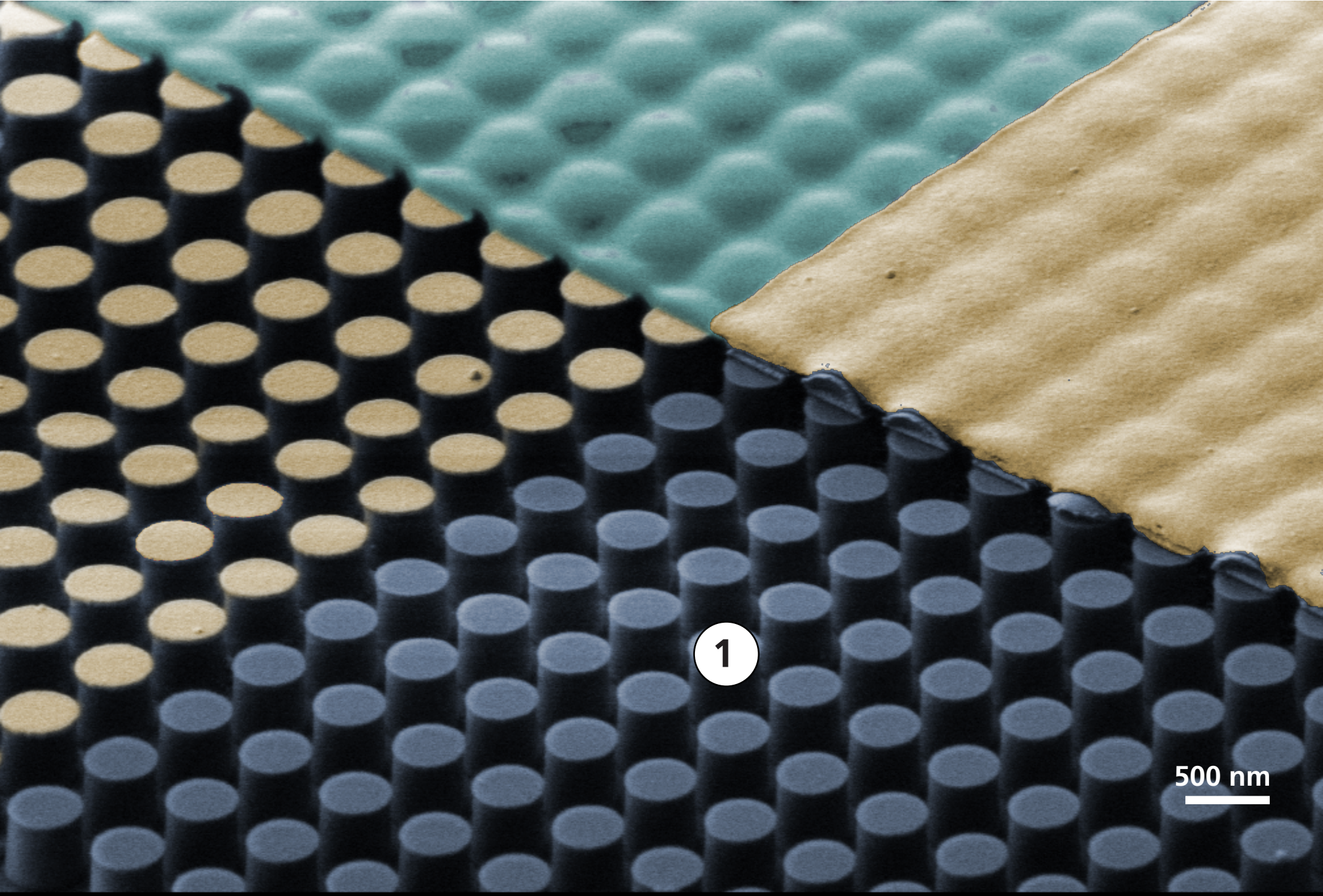
1 zero index

2 fabrication



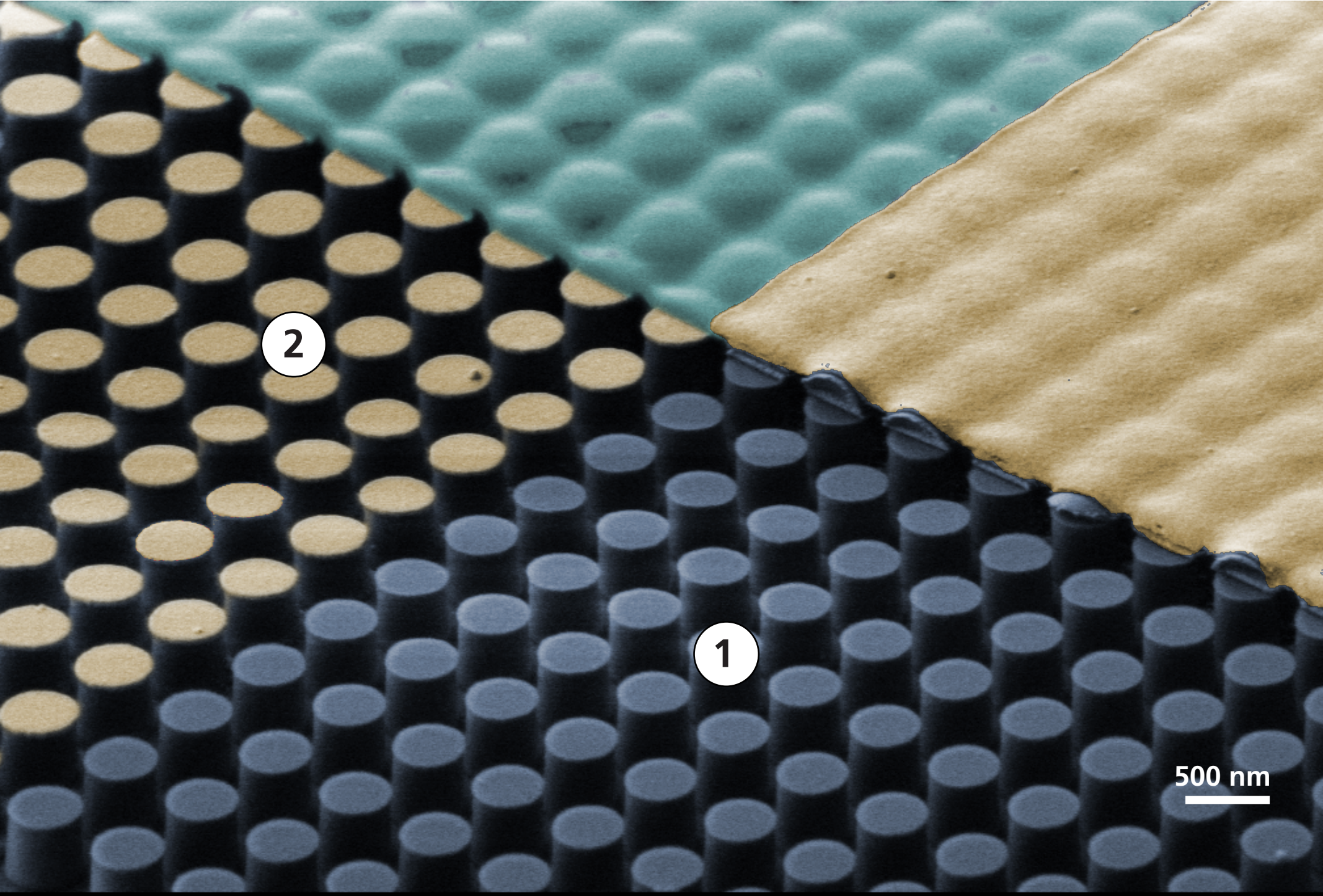
1 zero index

2 fabrication



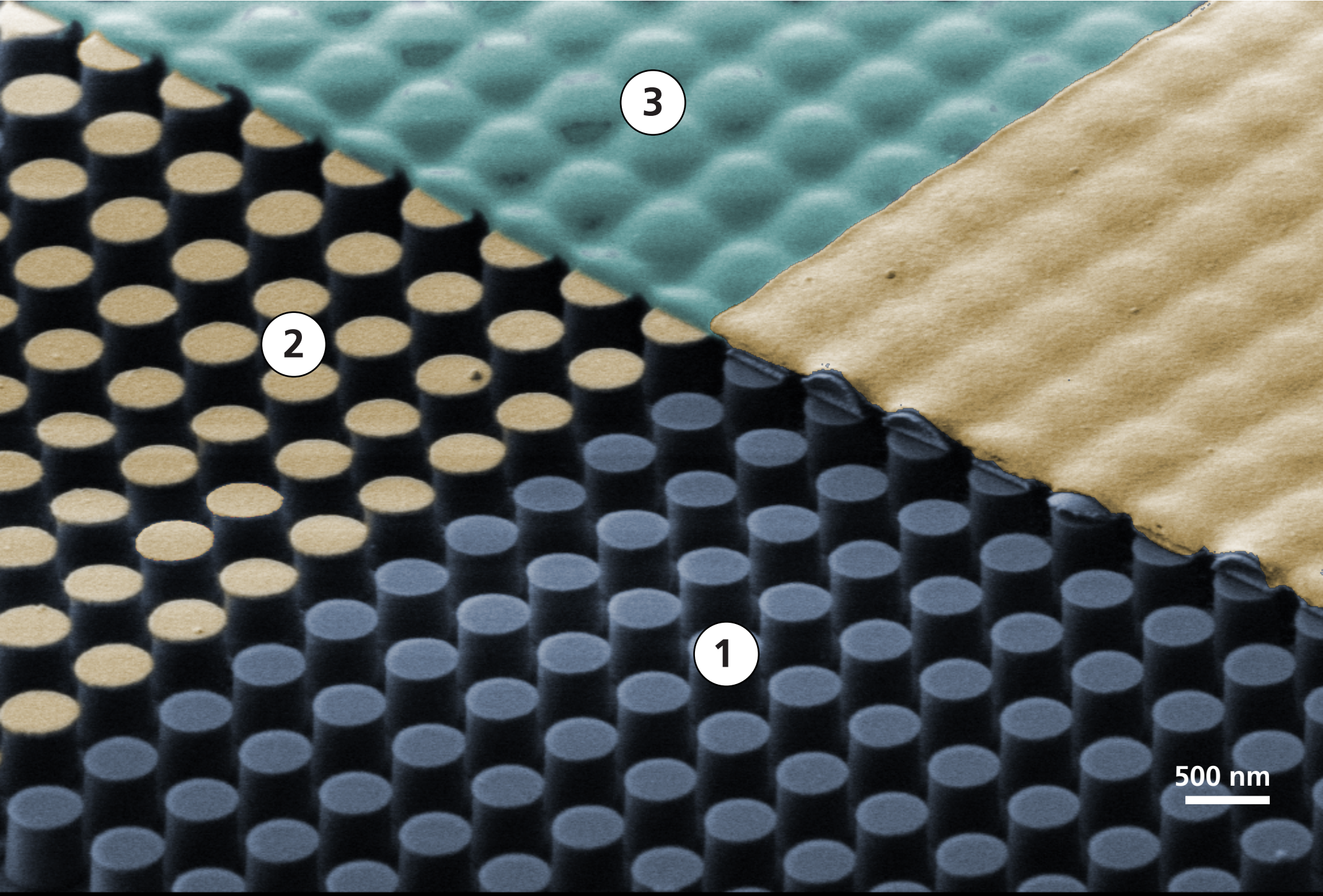
1 zero index

2 fabrication



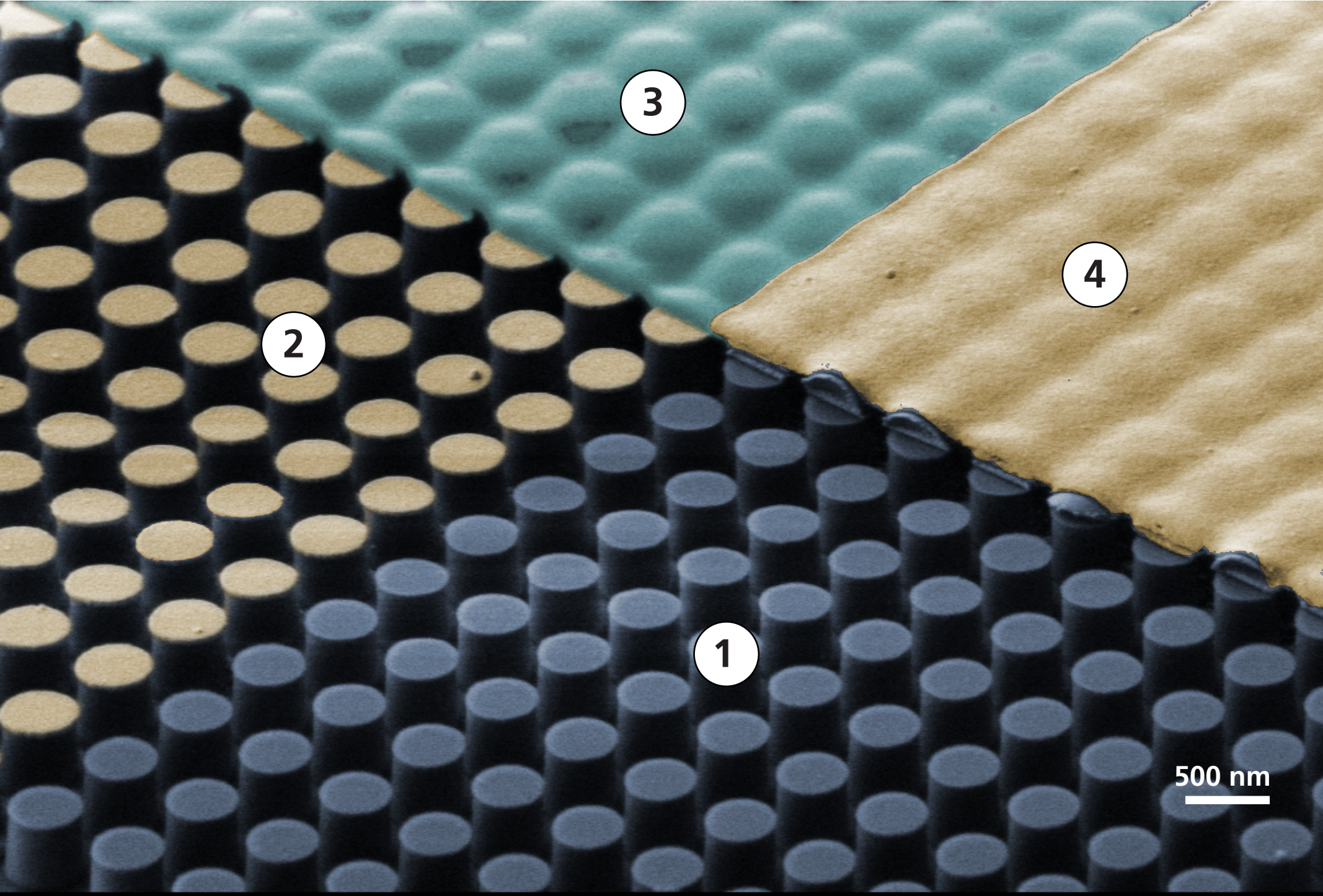
1 zero index

2 fabrication



1 zero index

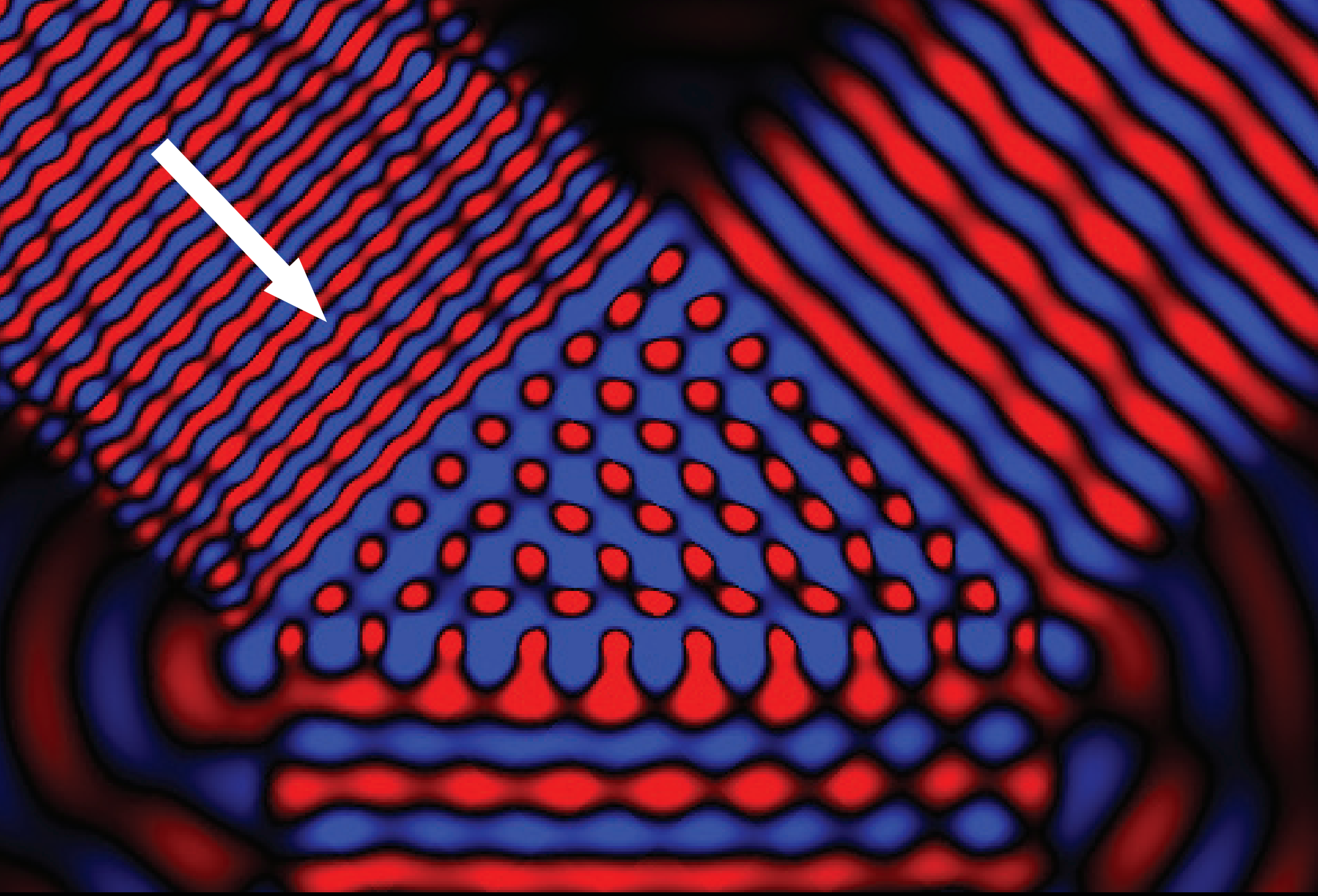
2 fabrication



1 zero index

2 fabrication

Can make this in any shape!



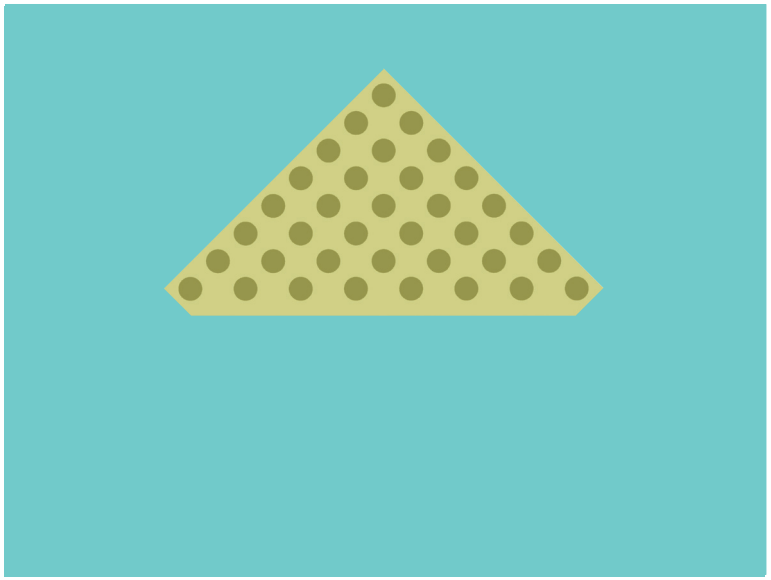
1 zero index

2 fabrication

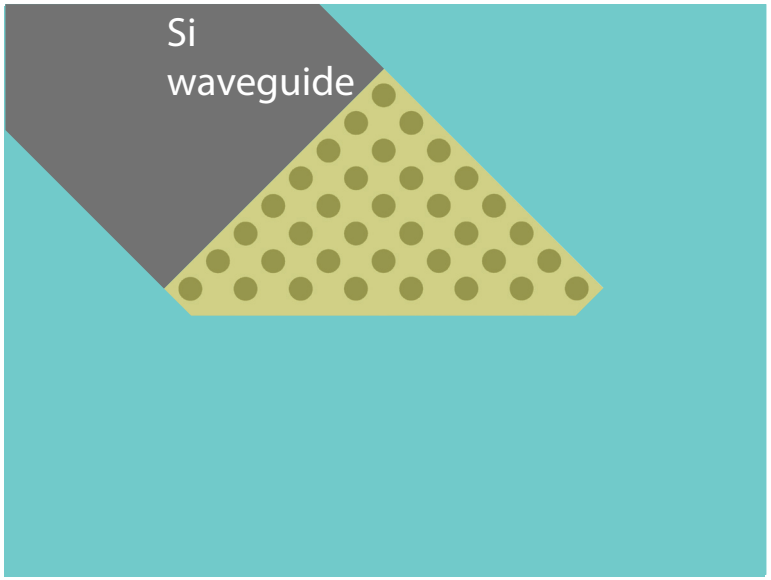
3 results

On-chip zero-index prism

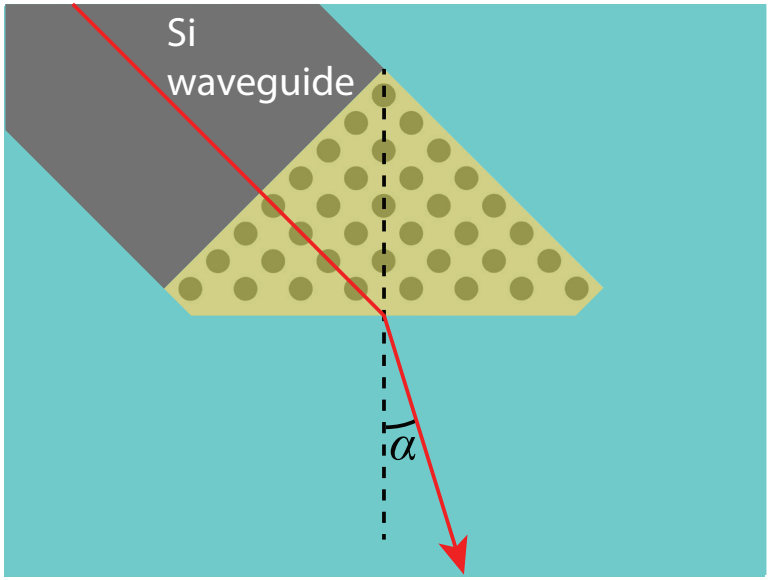
On-chip zero-index prism



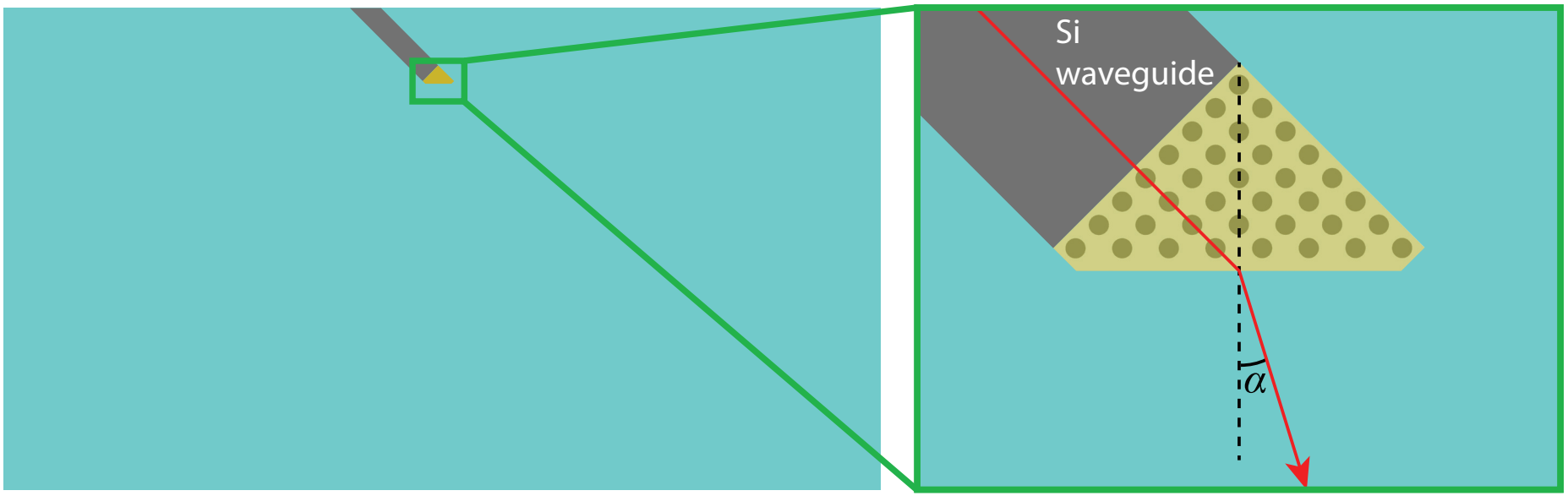
On-chip zero-index prism



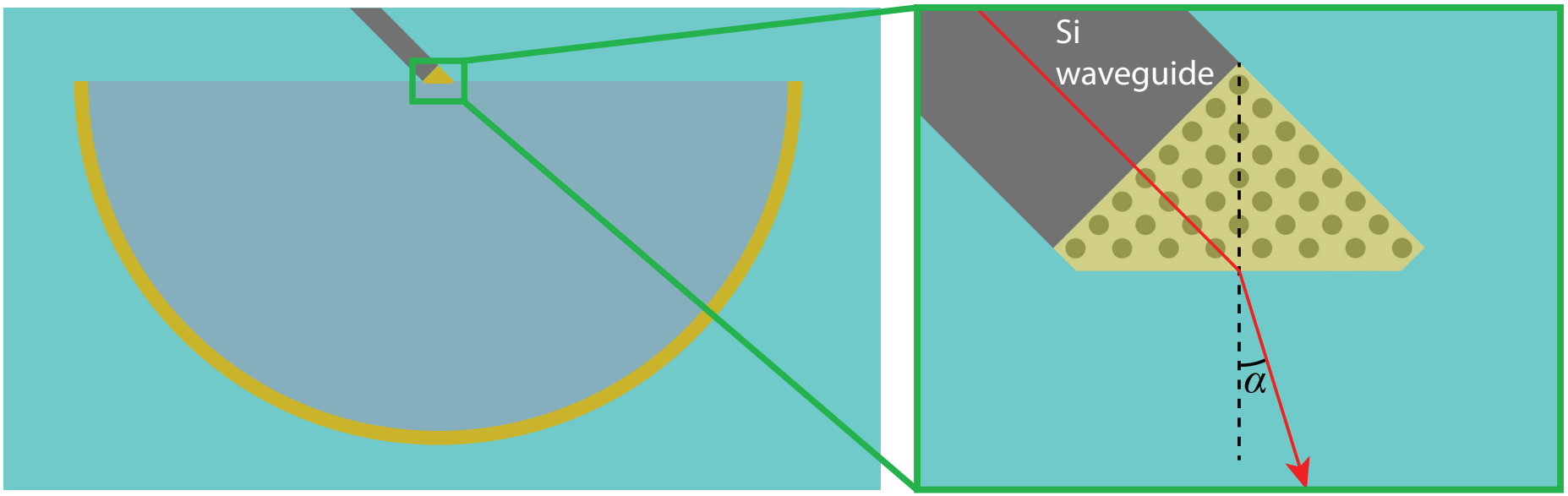
On-chip zero-index prism



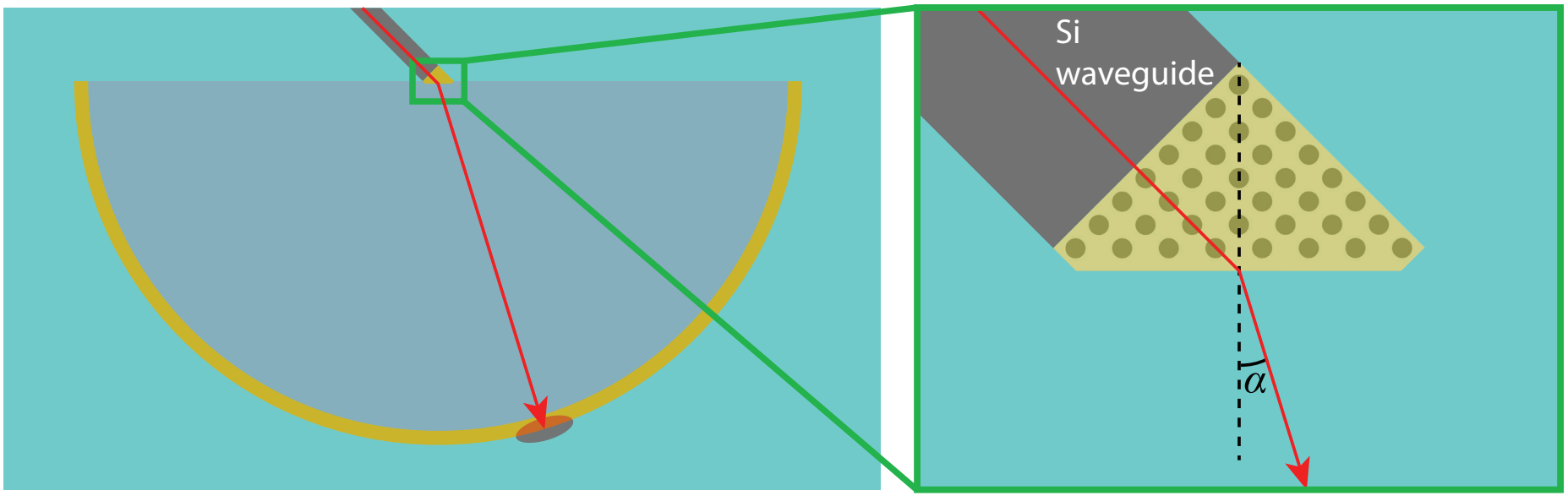
On-chip zero-index prism



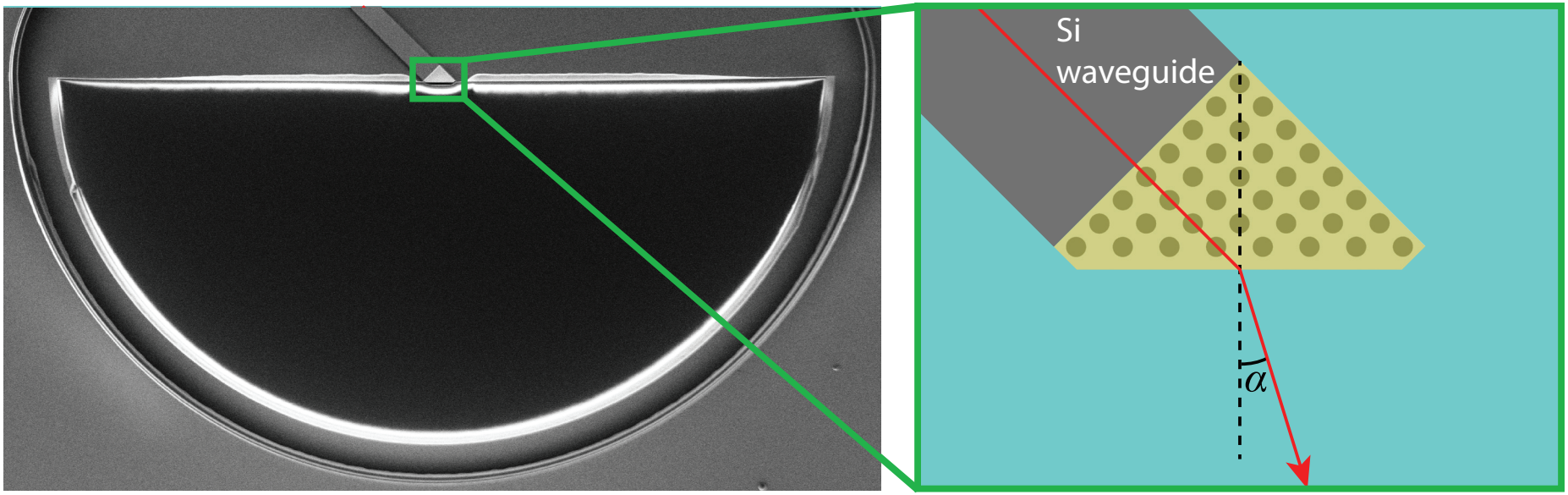
On-chip zero-index prism



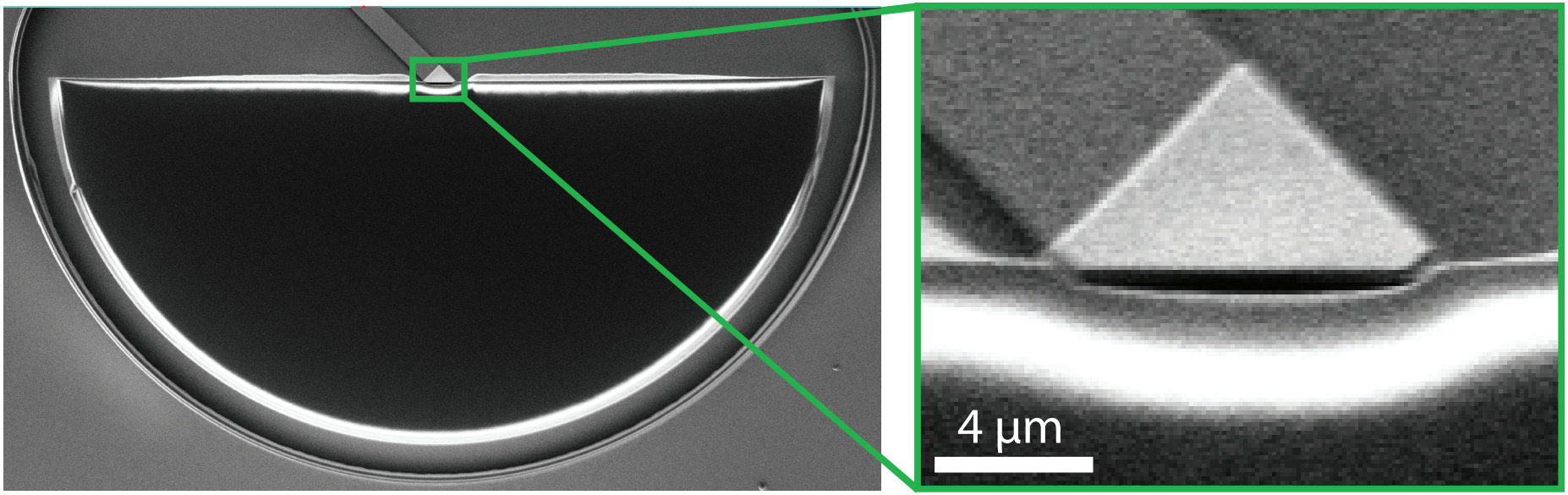
On-chip zero-index prism

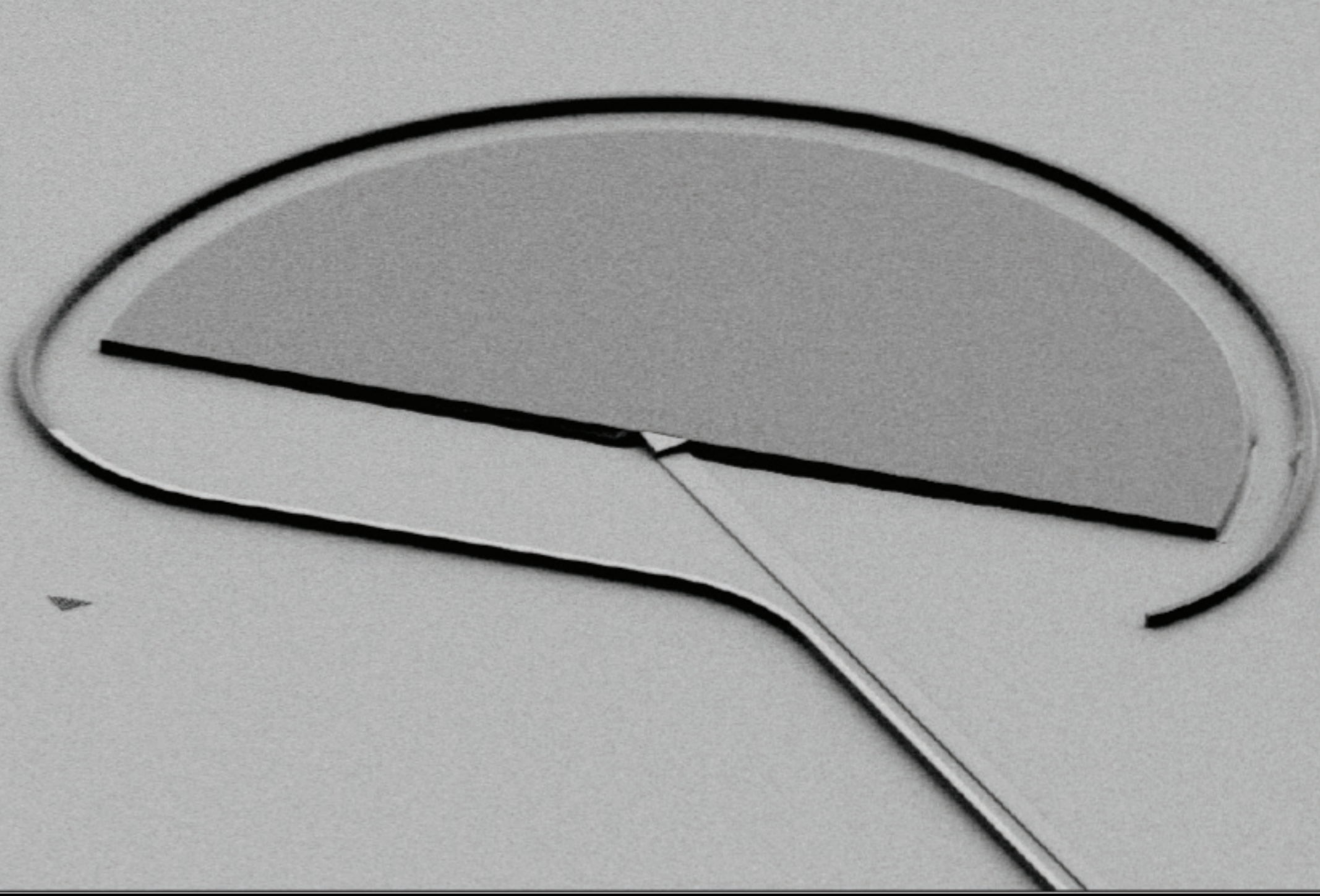


On-chip zero-index prism

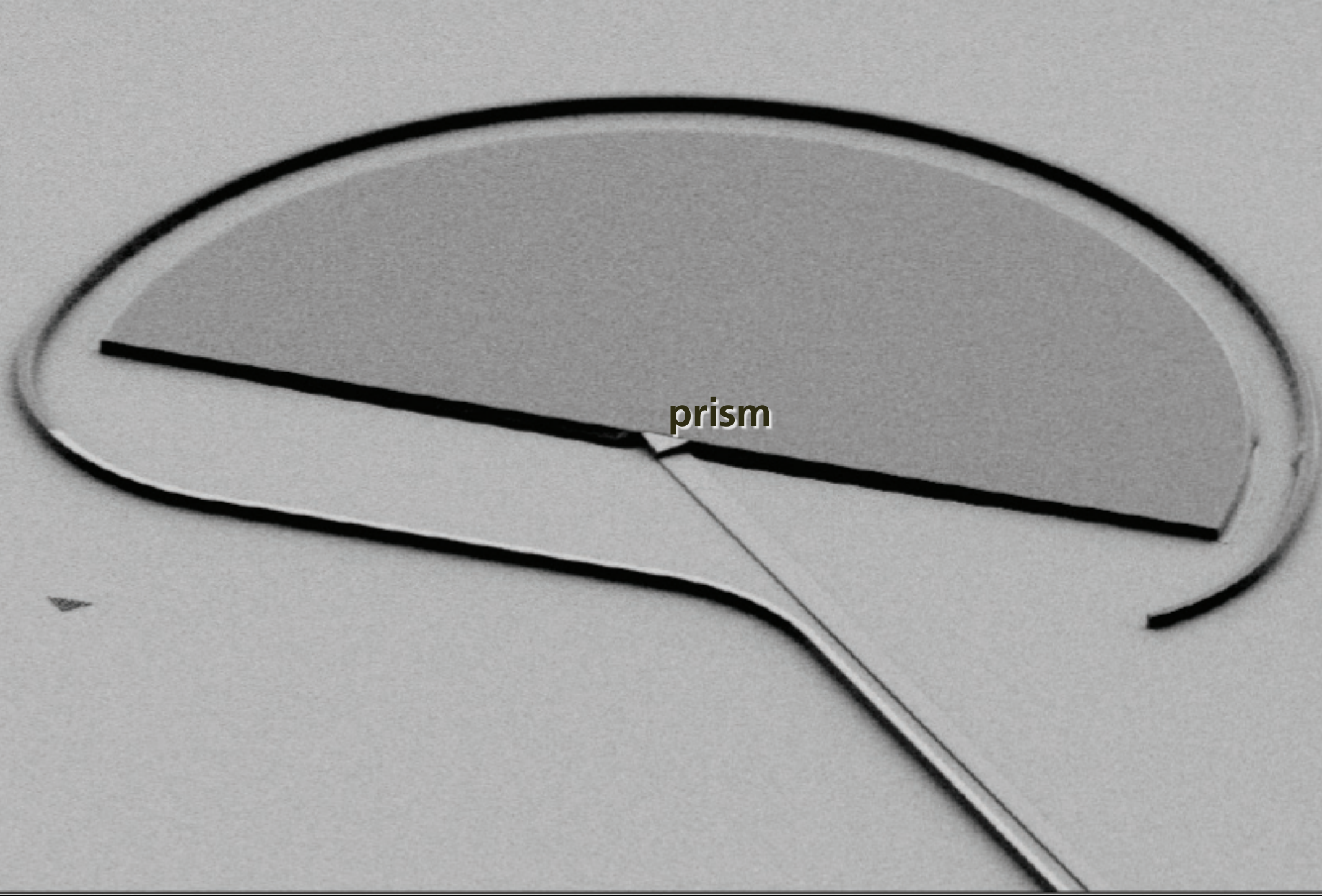


On-chip zero-index prism

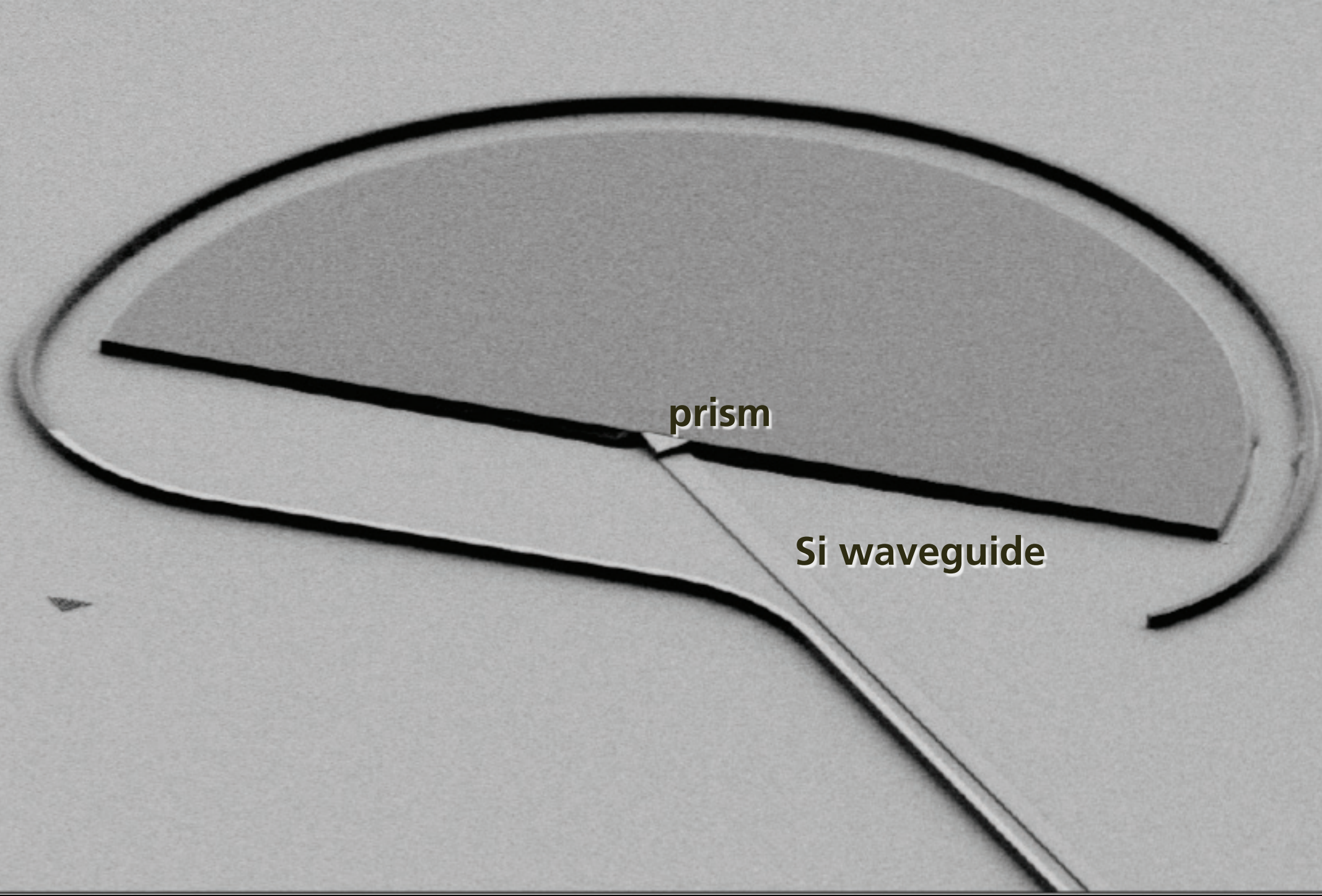


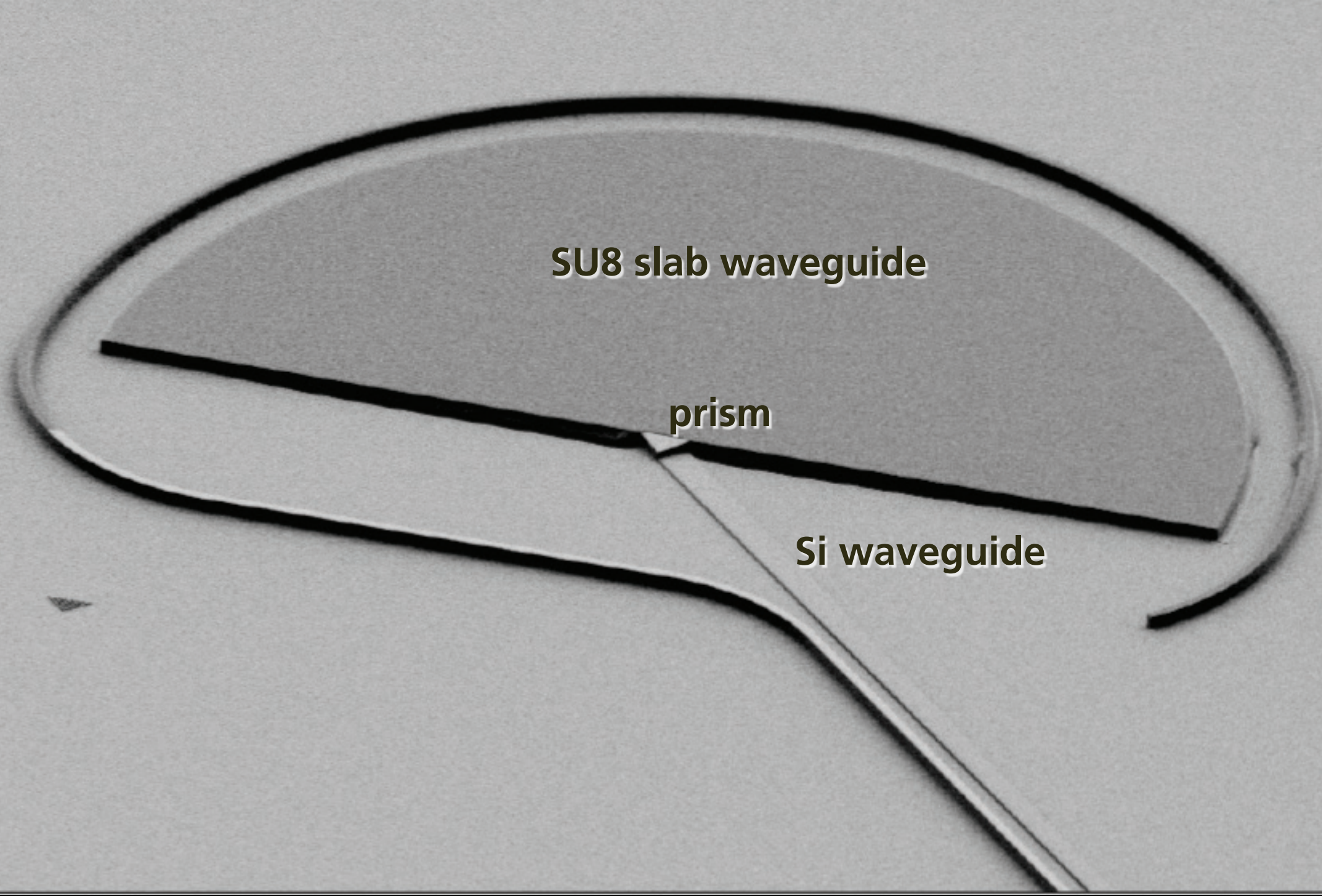


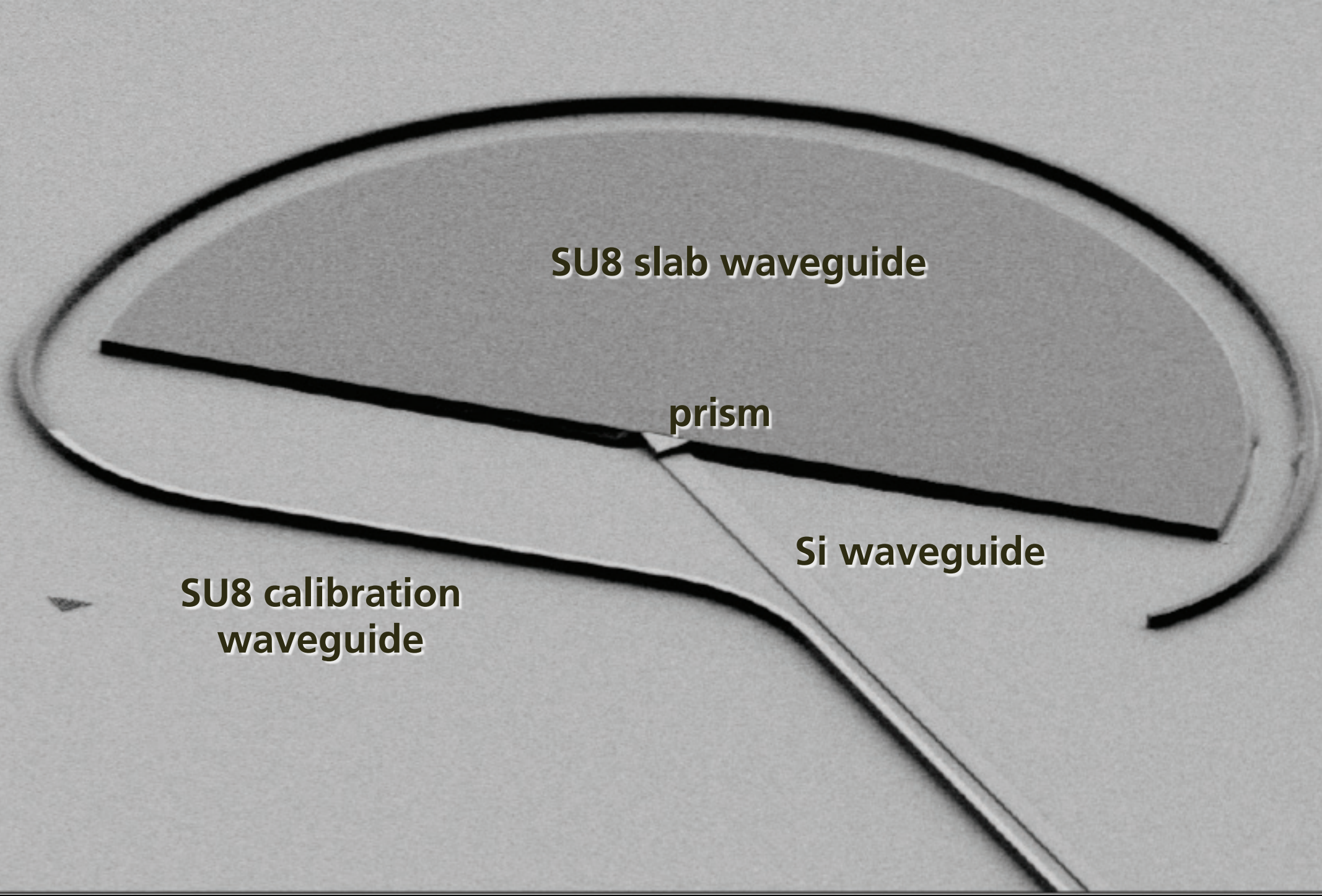
1 zero index 2 fabrication 3 results

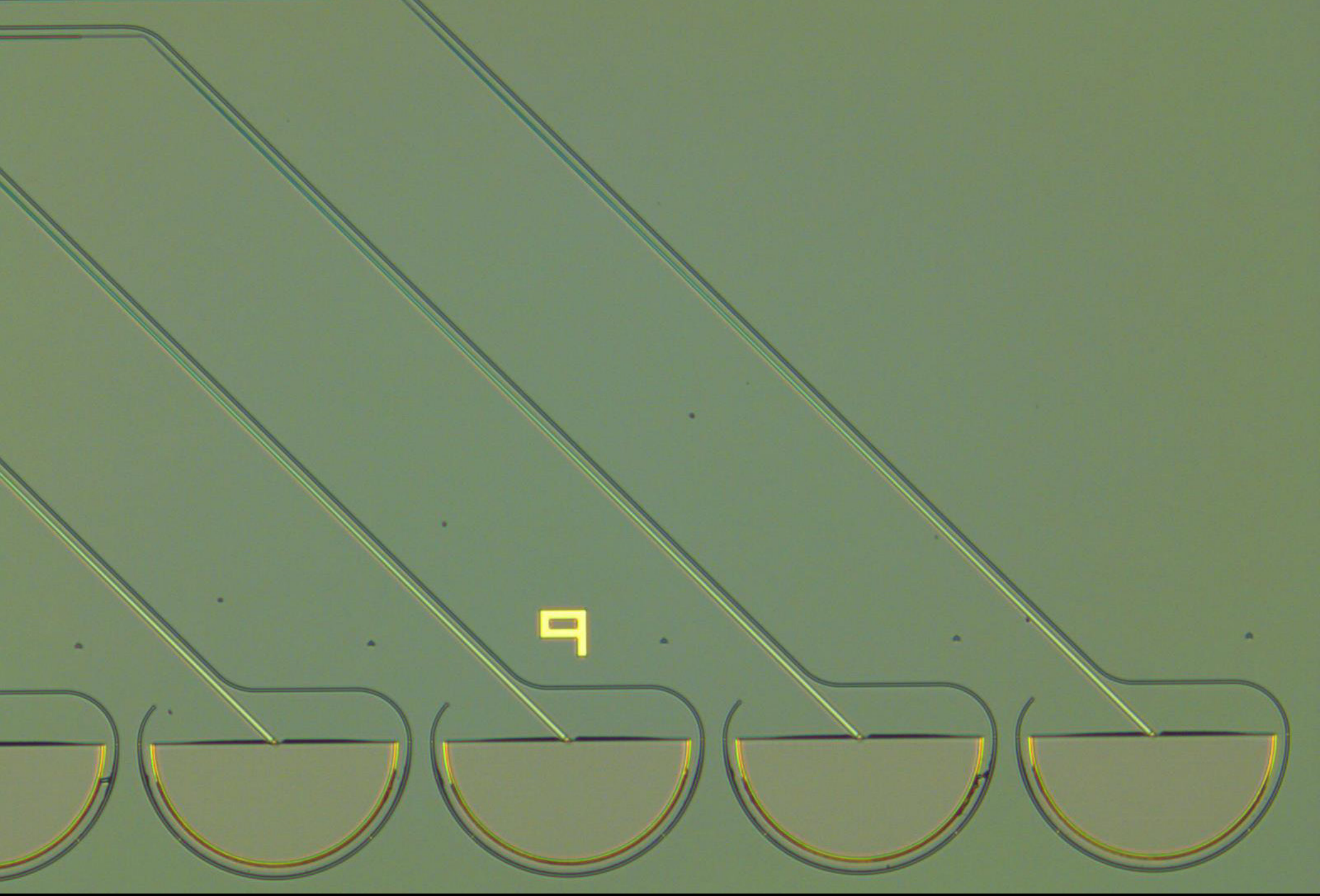


1 zero index 2 fabrication 3 results


prism
Si waveguide


SU8 slab waveguide
prism
Si waveguide


SU8 slab waveguide
prism
Si waveguide
SU8 calibration
waveguide

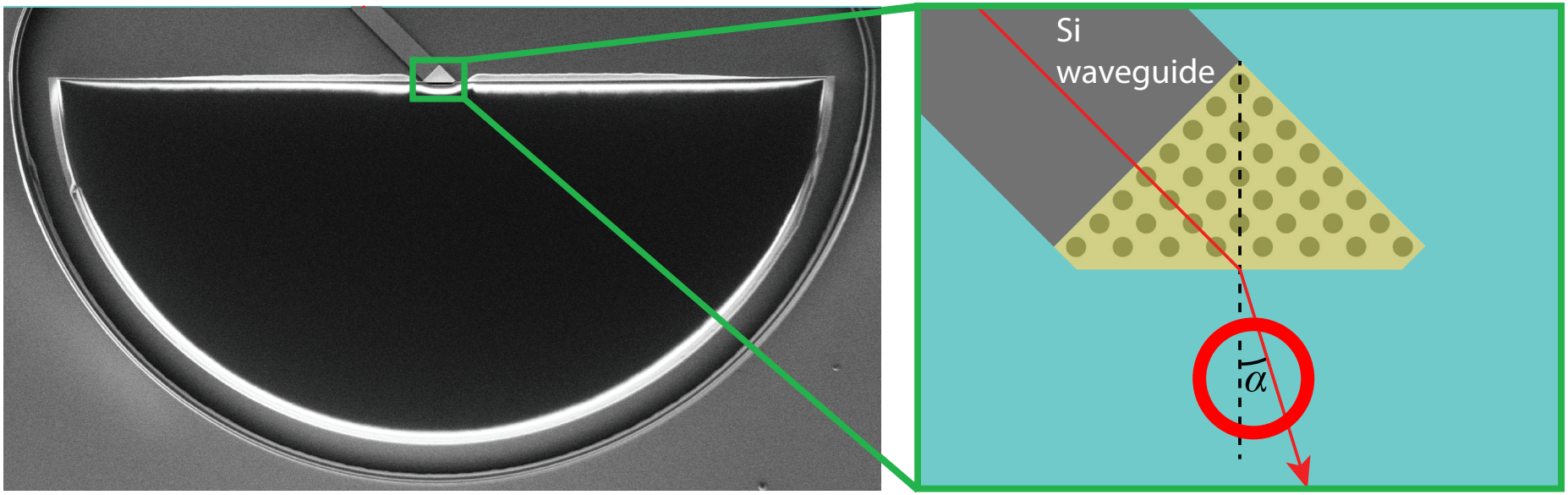


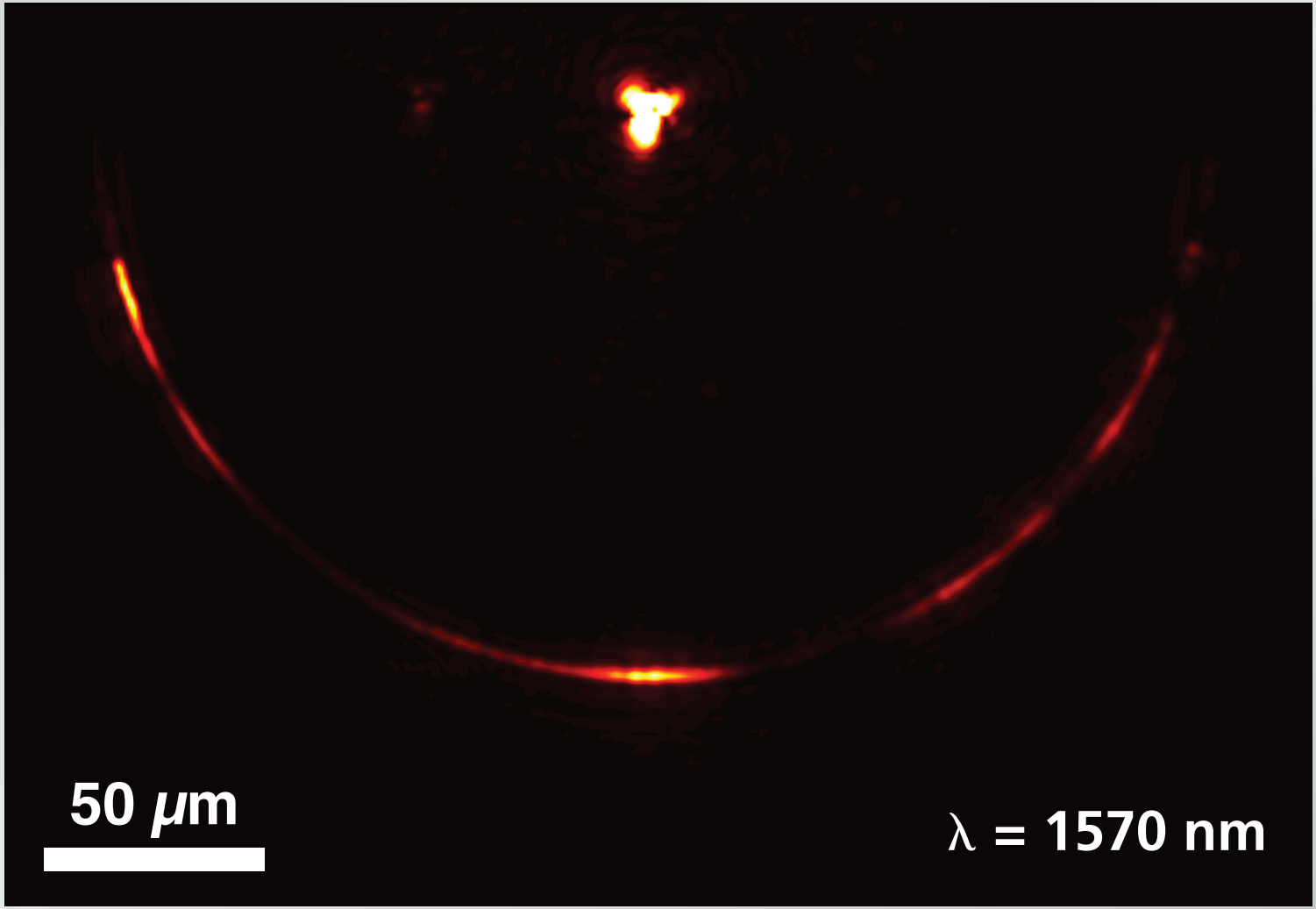
1 zero index

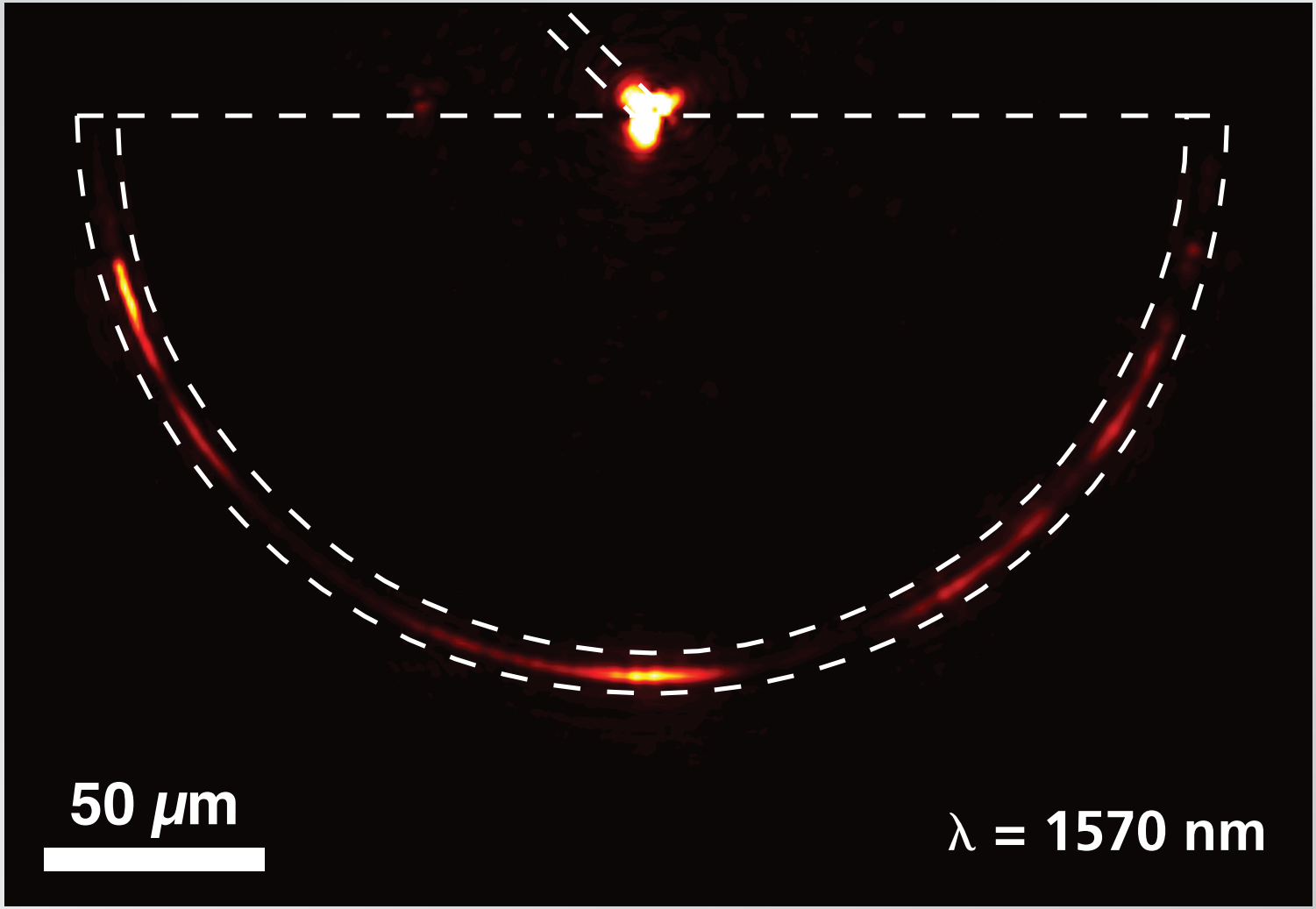
2 fabrication

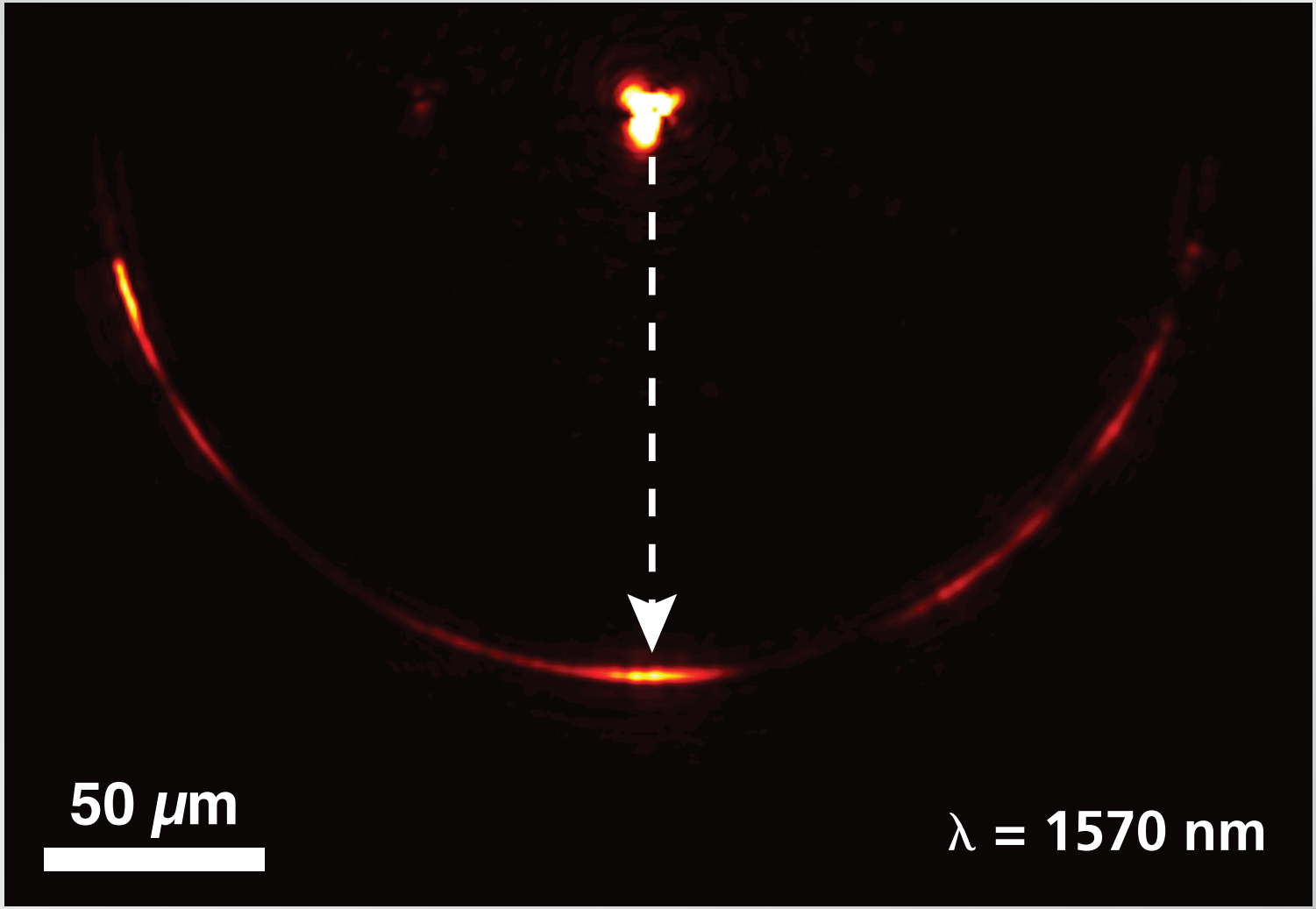
3 results

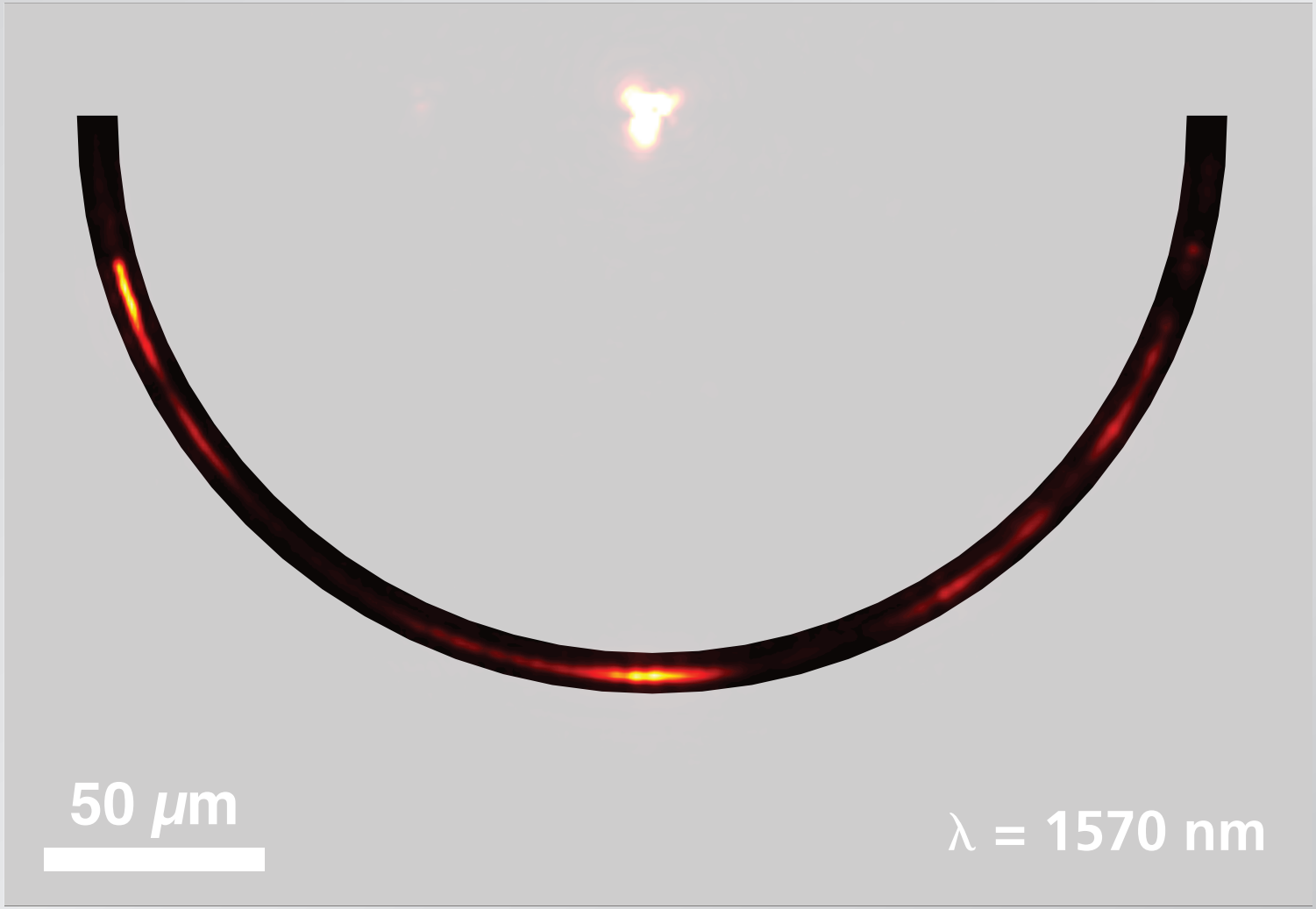
On-chip zero-index prism



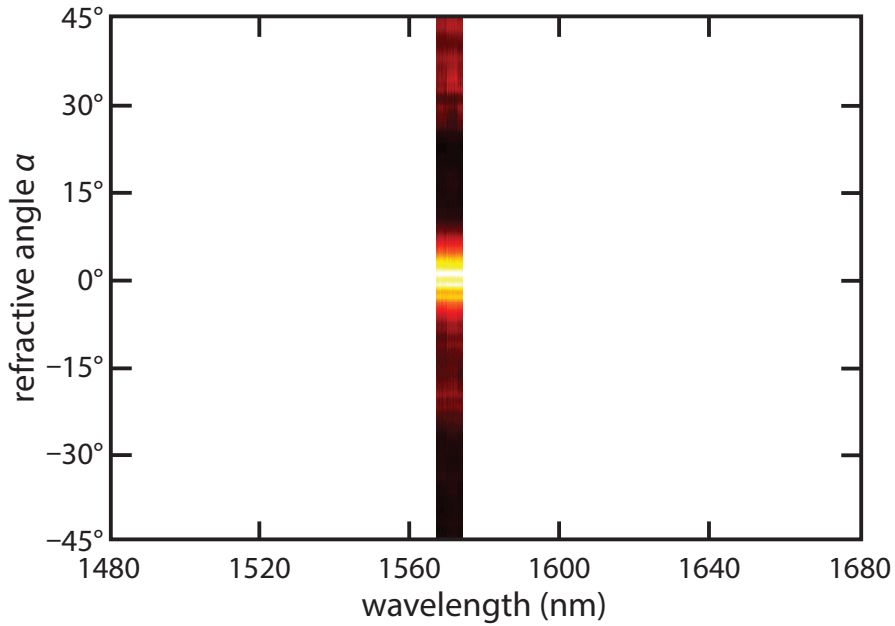

50 μm
λ = 1570 nm


50 μm
λ = 1570 nm

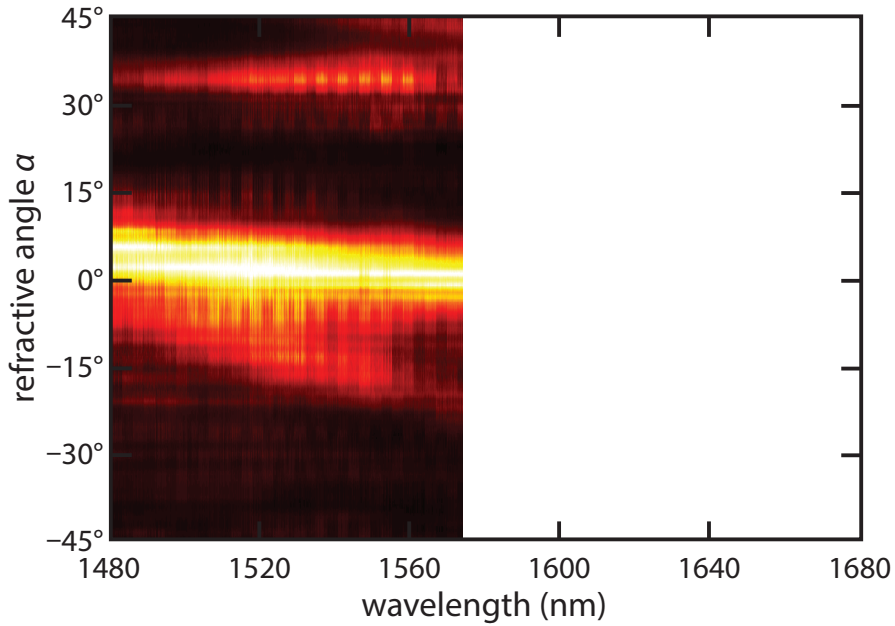

50 μm
λ = 1570 nm


50 μm
λ = 1570 nm

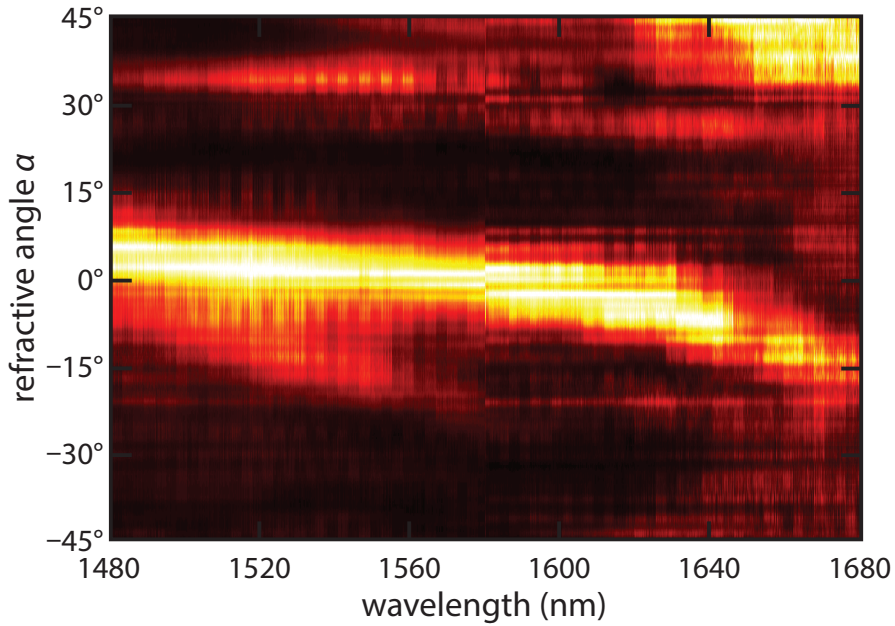
Wavelength dependence of refraction angle



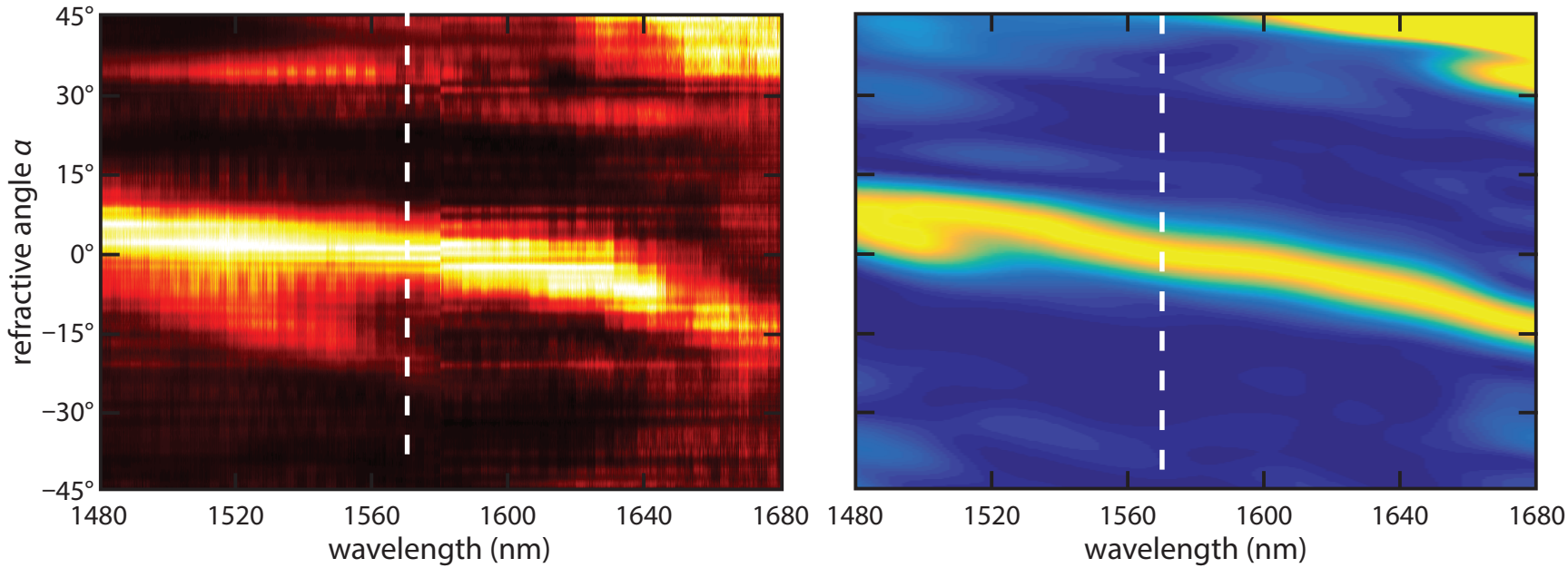
Wavelength dependence of refraction angle



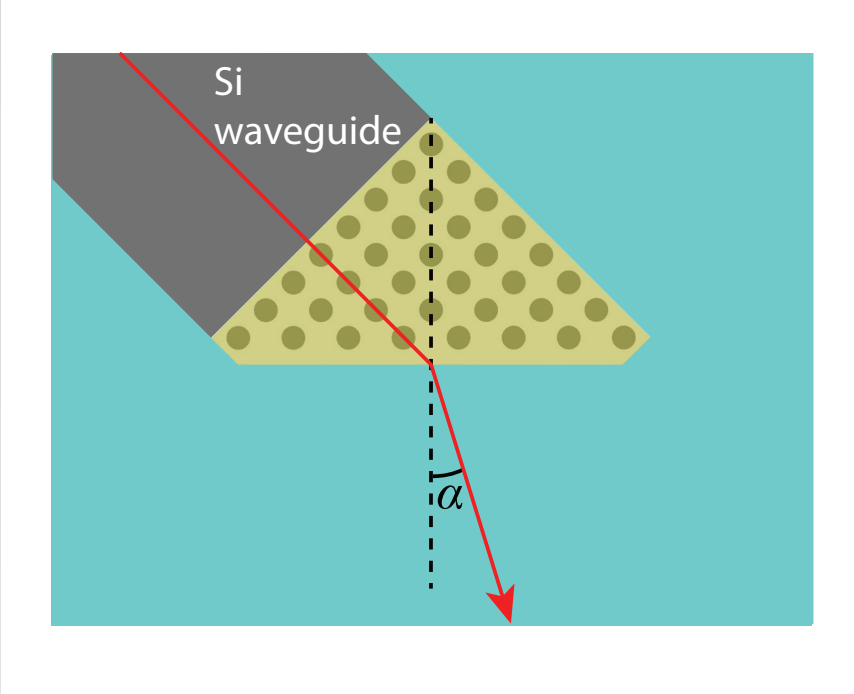
Wavelength dependence of refraction angle



Wavelength dependence of refraction angle

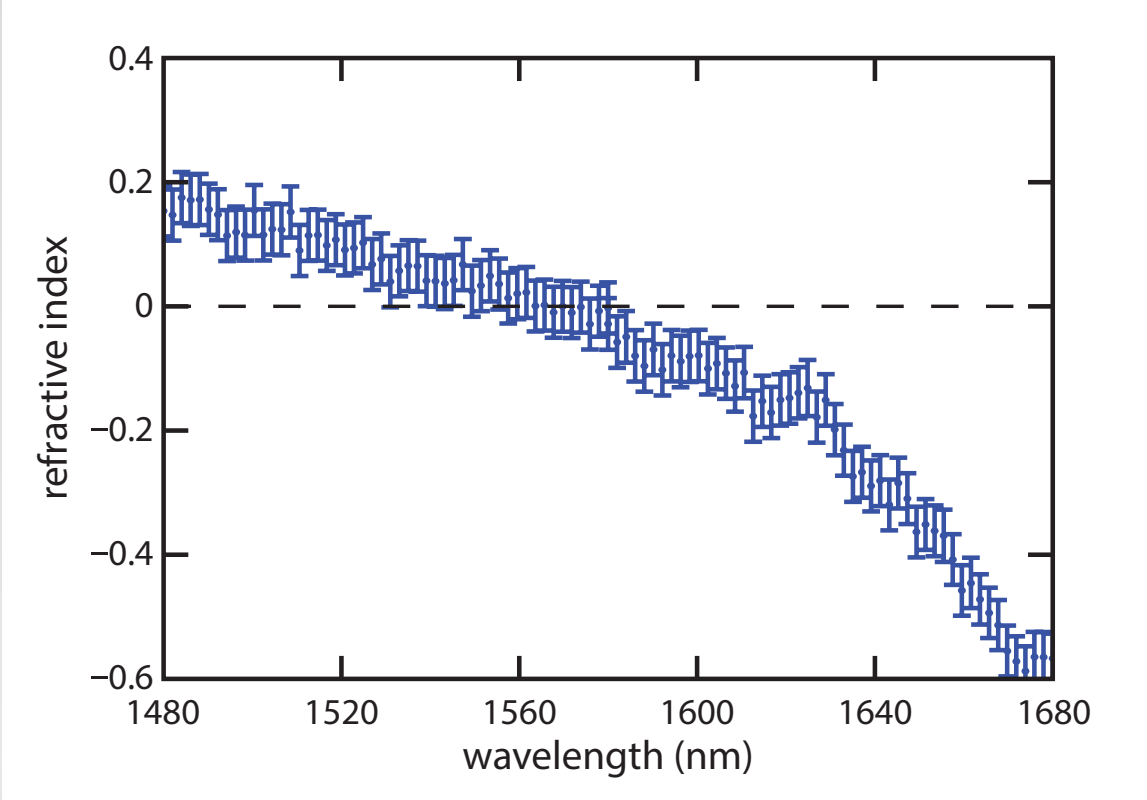


Wavelength dependence of index

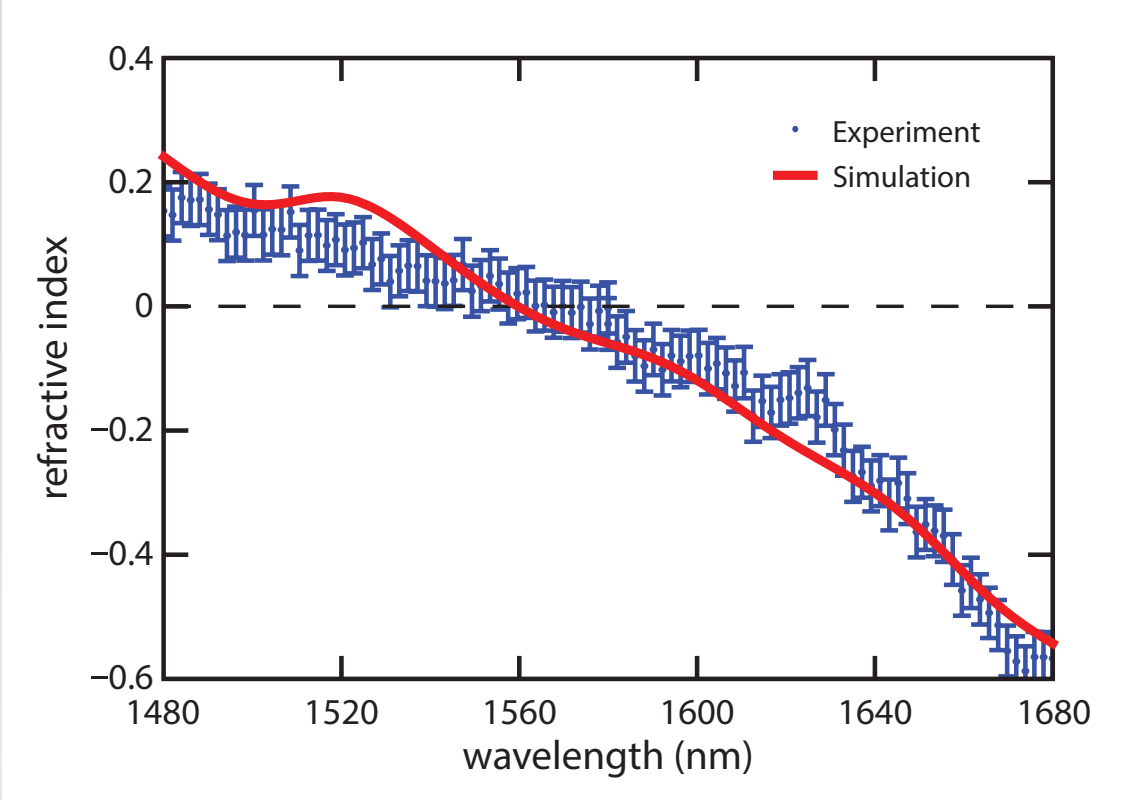


$$n_{\text{prism}} = n_{\text{slab}} \frac{\sin\alpha}{\sin 45^\circ}$$

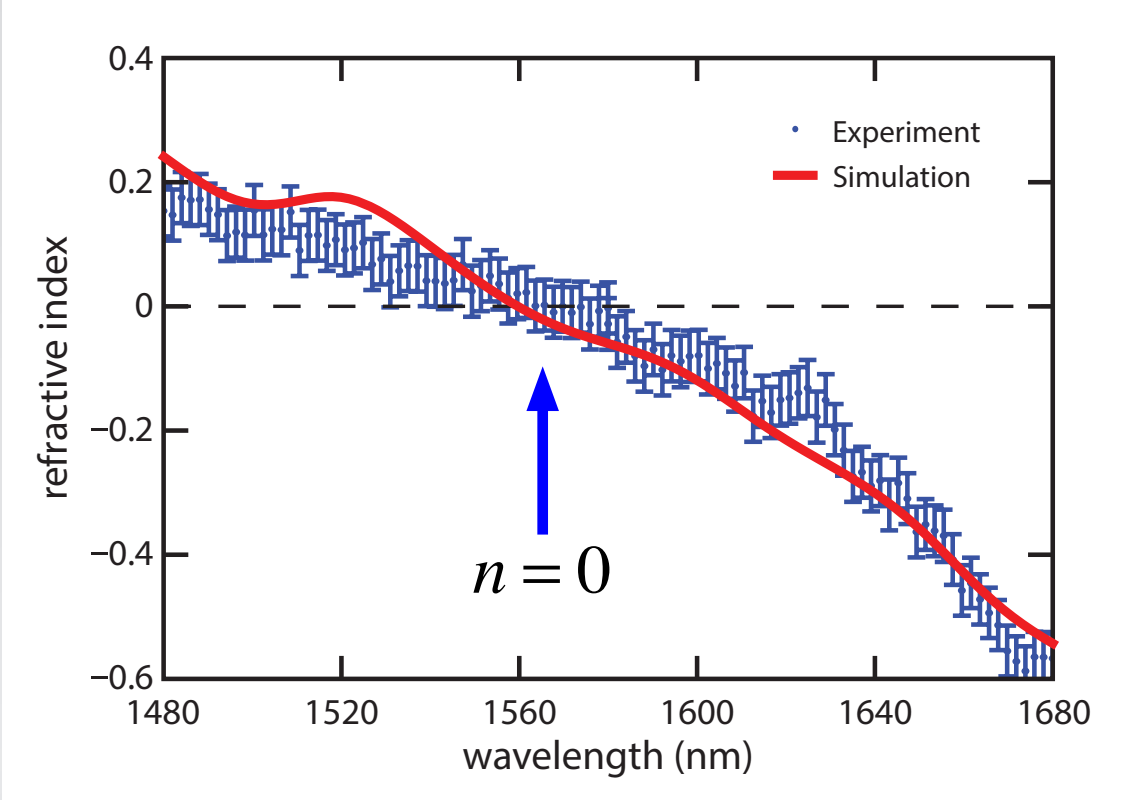
Wavelength dependence of index



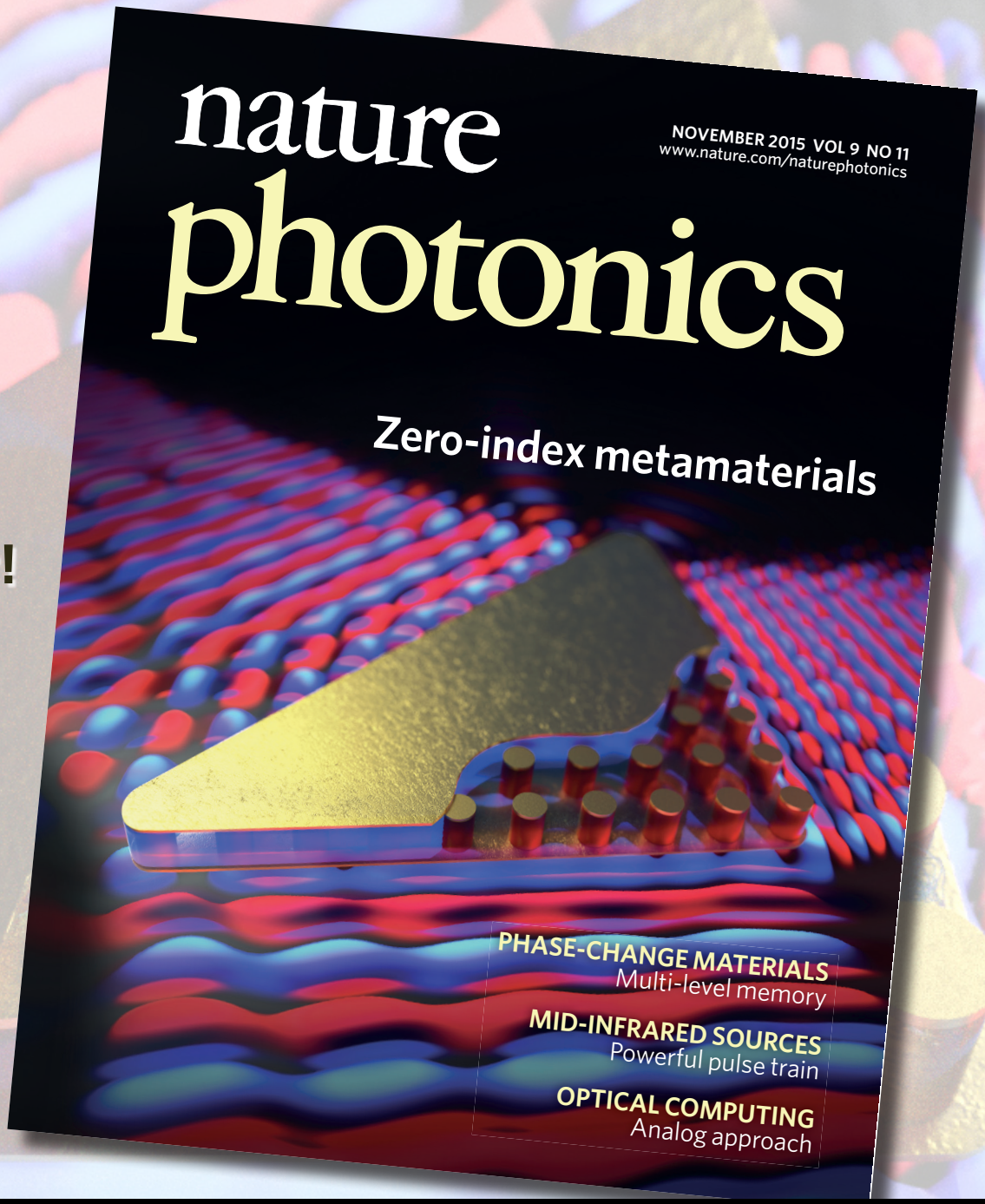
Wavelength dependence of index



Wavelength dependence of index



More info: download paper!



1 zero index

2 fabrication

3 results

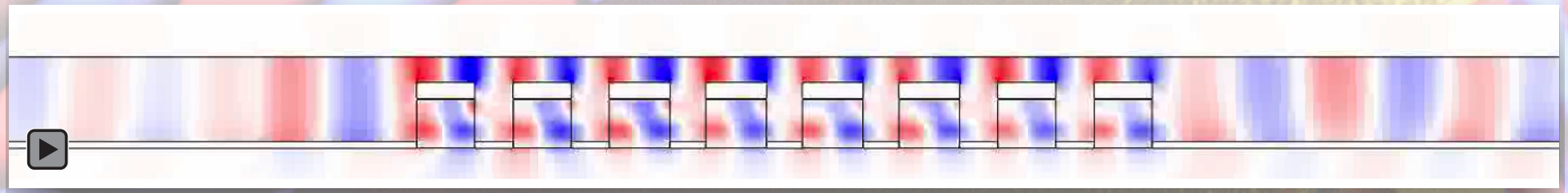
Where do we go from here?

1 zero index

2 fabrication

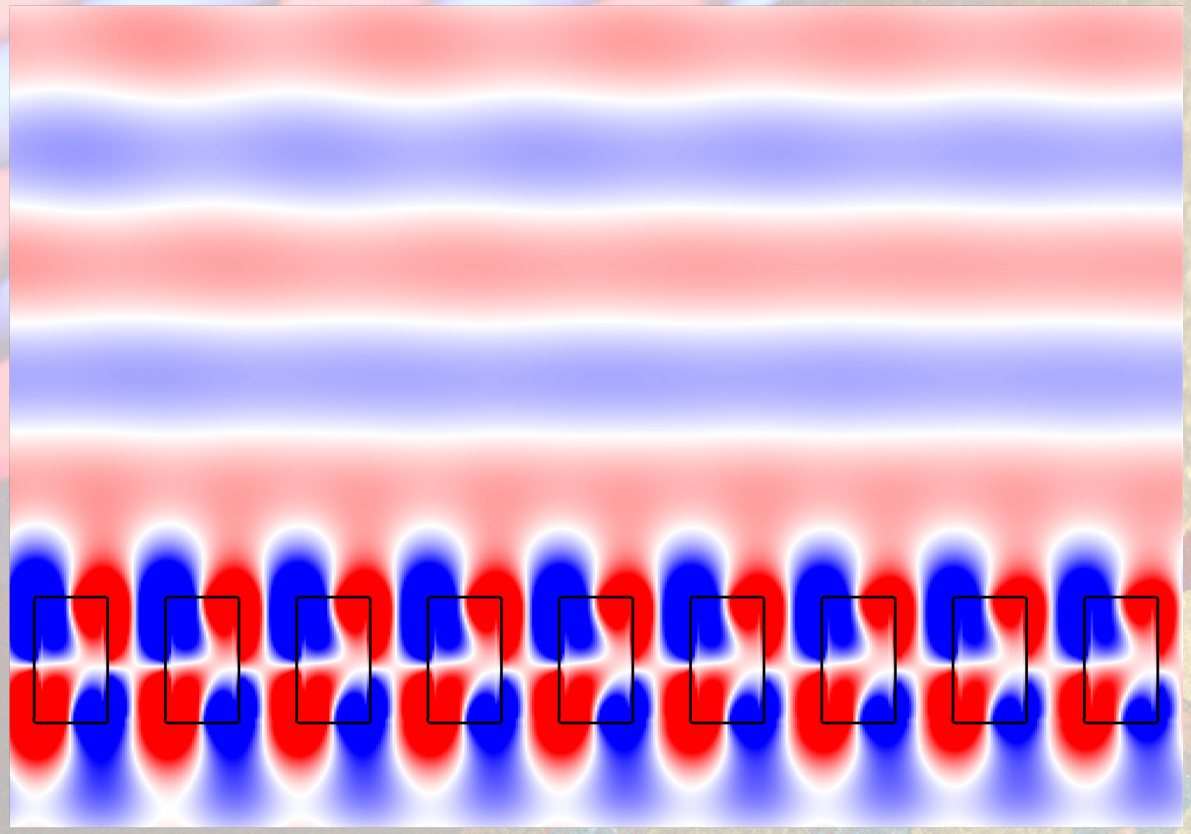
3 results

Where do we go from here?



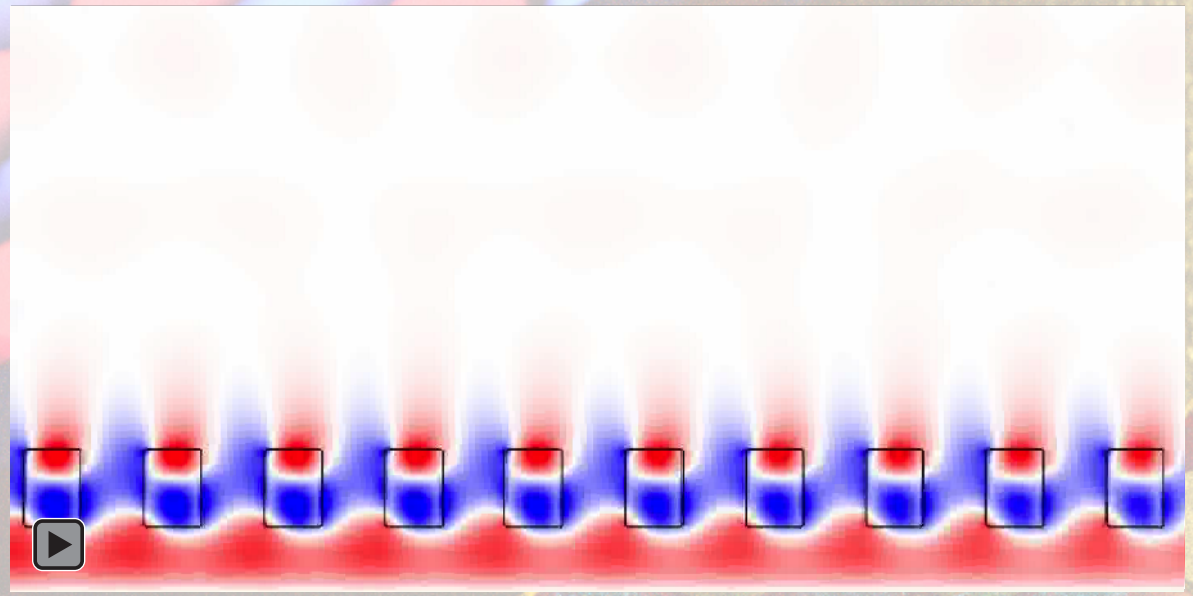
Need to eliminate losses in metal mirrors

Where do we go from here?



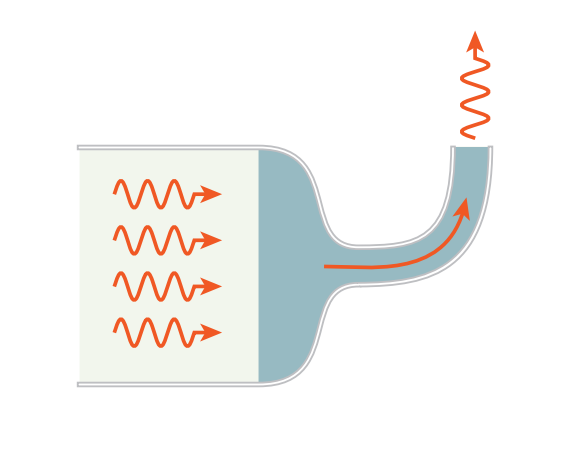
Removing mirrors causes radiative losses

Where do we go from here?



Eliminate losses using “bound in continuum” state

Exciting applications ahead



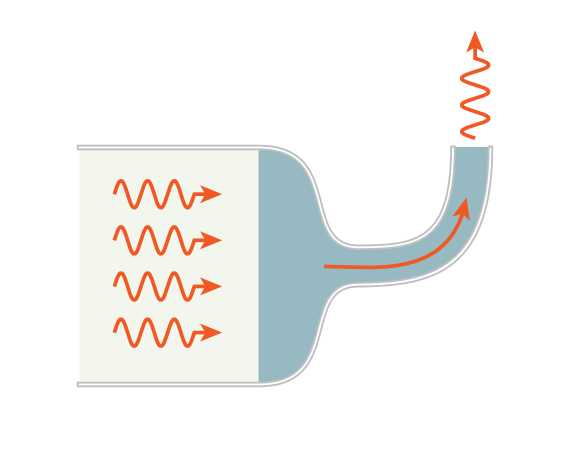
supercoupling

1 zero index

2 fabrication

3 results

Exciting applications ahead



supercoupling

NLO

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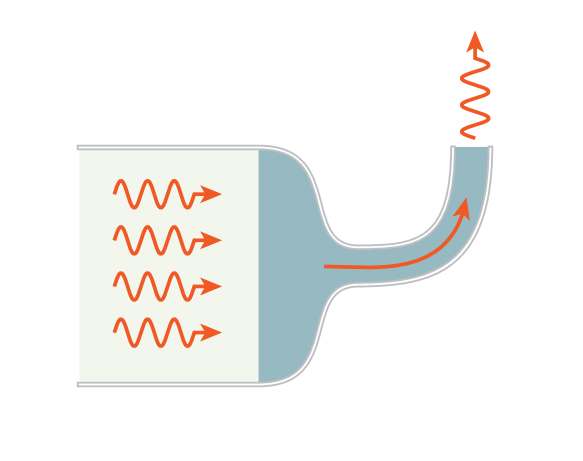
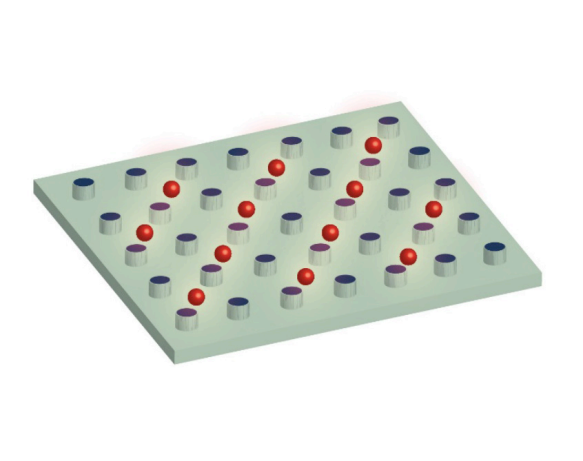
Exciting applications ahead



supercoupling

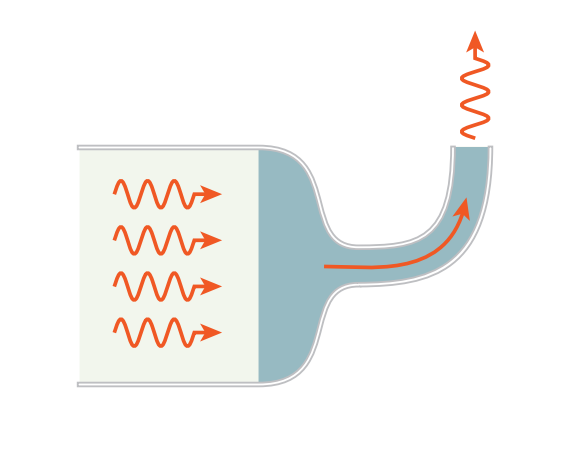
SHG $\omega' = 2\omega$

NLO

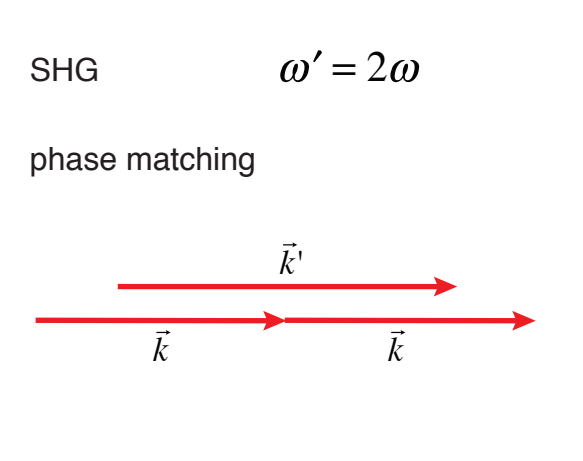


quantum optics

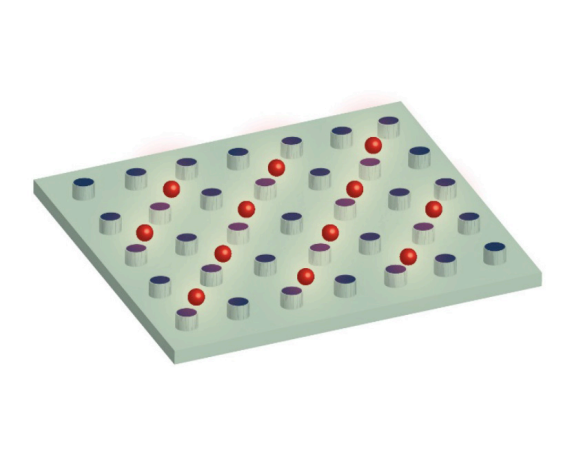
Exciting applications ahead



supercoupling



NLO



quantum optics

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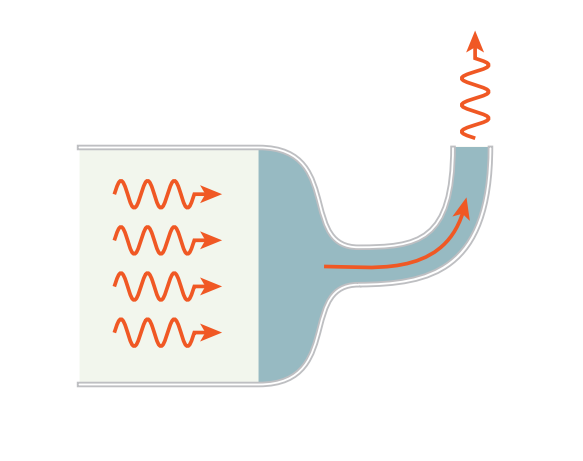
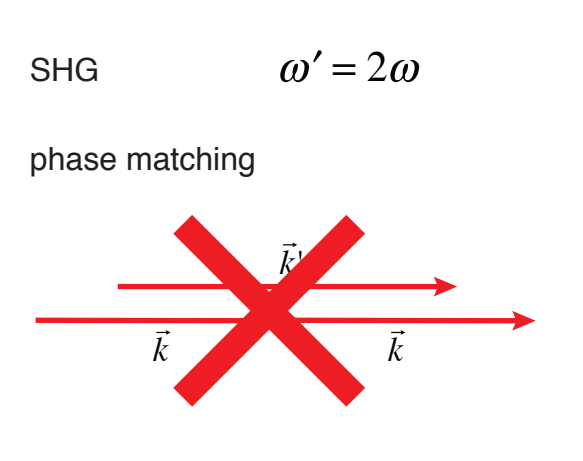
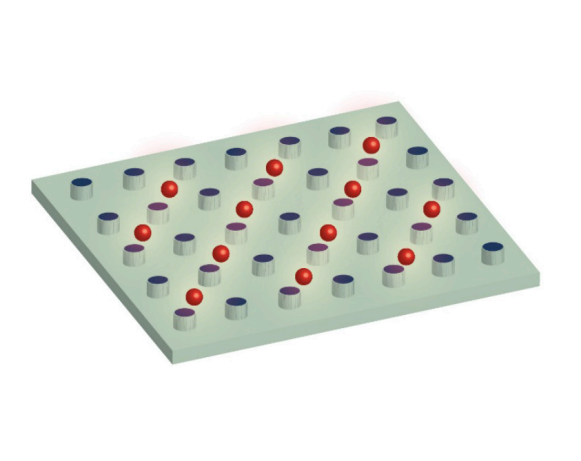


supercoupling



NLO



quantum optics

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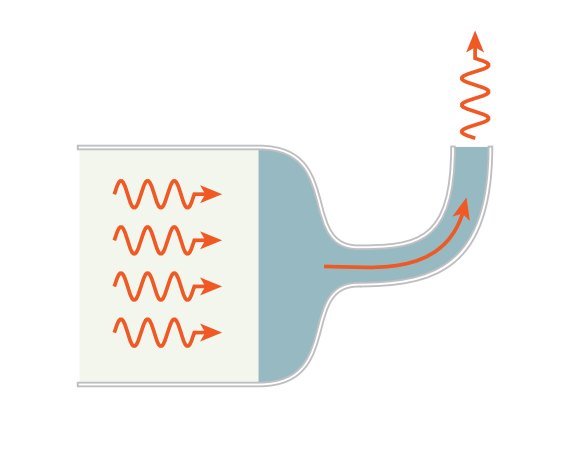
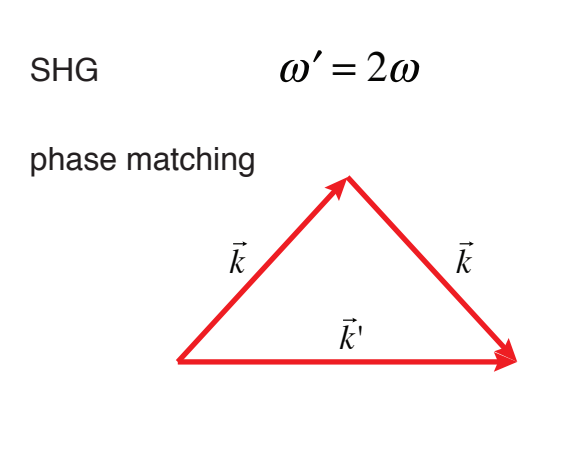
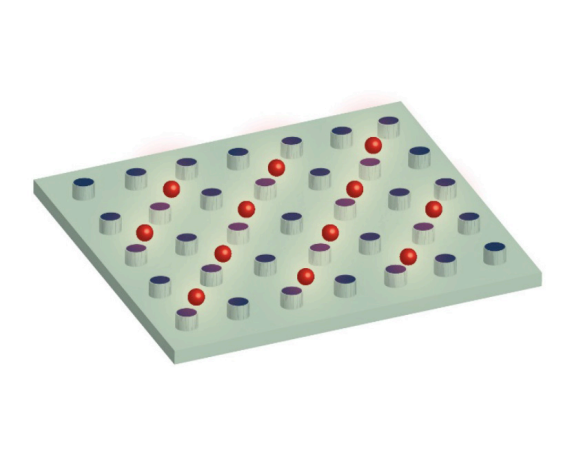
Exciting applications ahead



supercoupling



NLO



quantum optics

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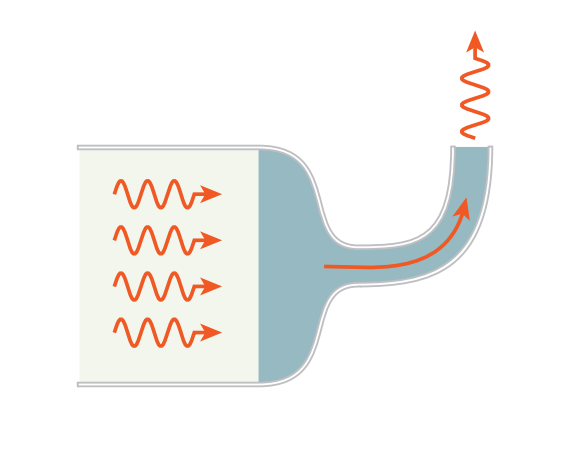
Exciting applications ahead



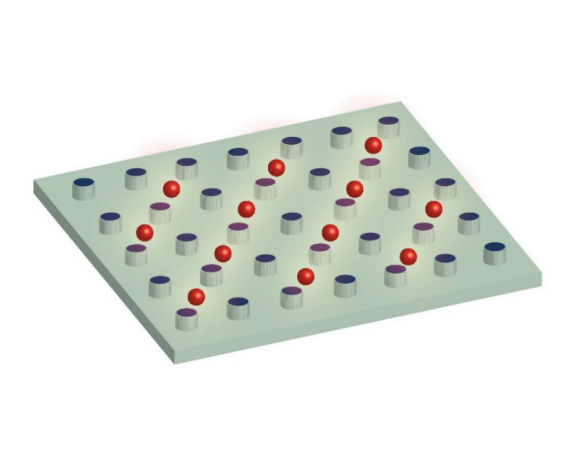
supercoupling

SHG $\omega' = 2\omega$

at zero index

$\vec{k} = 0$

NLO



quantum optics

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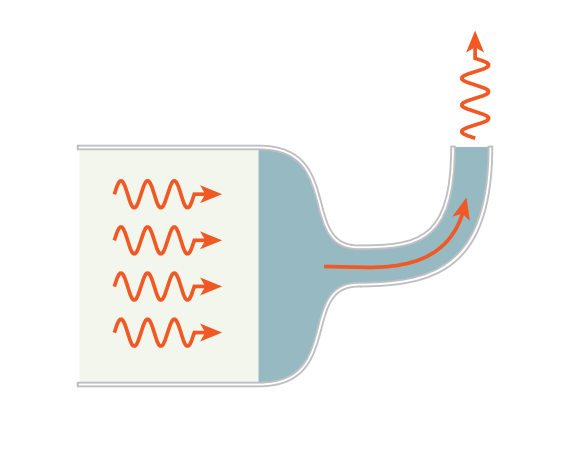
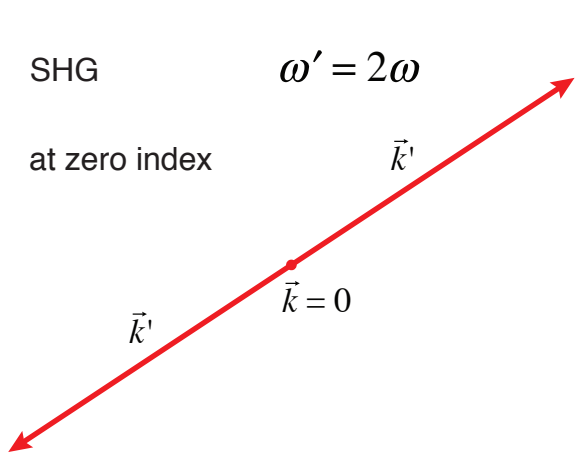
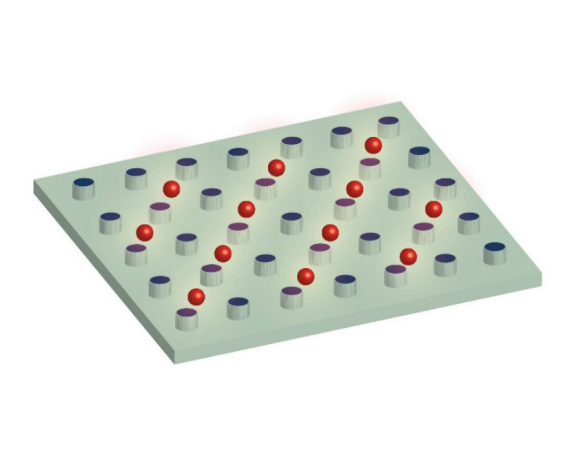


supercoupling



NLO



quantum optics

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

National Science Foundation
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