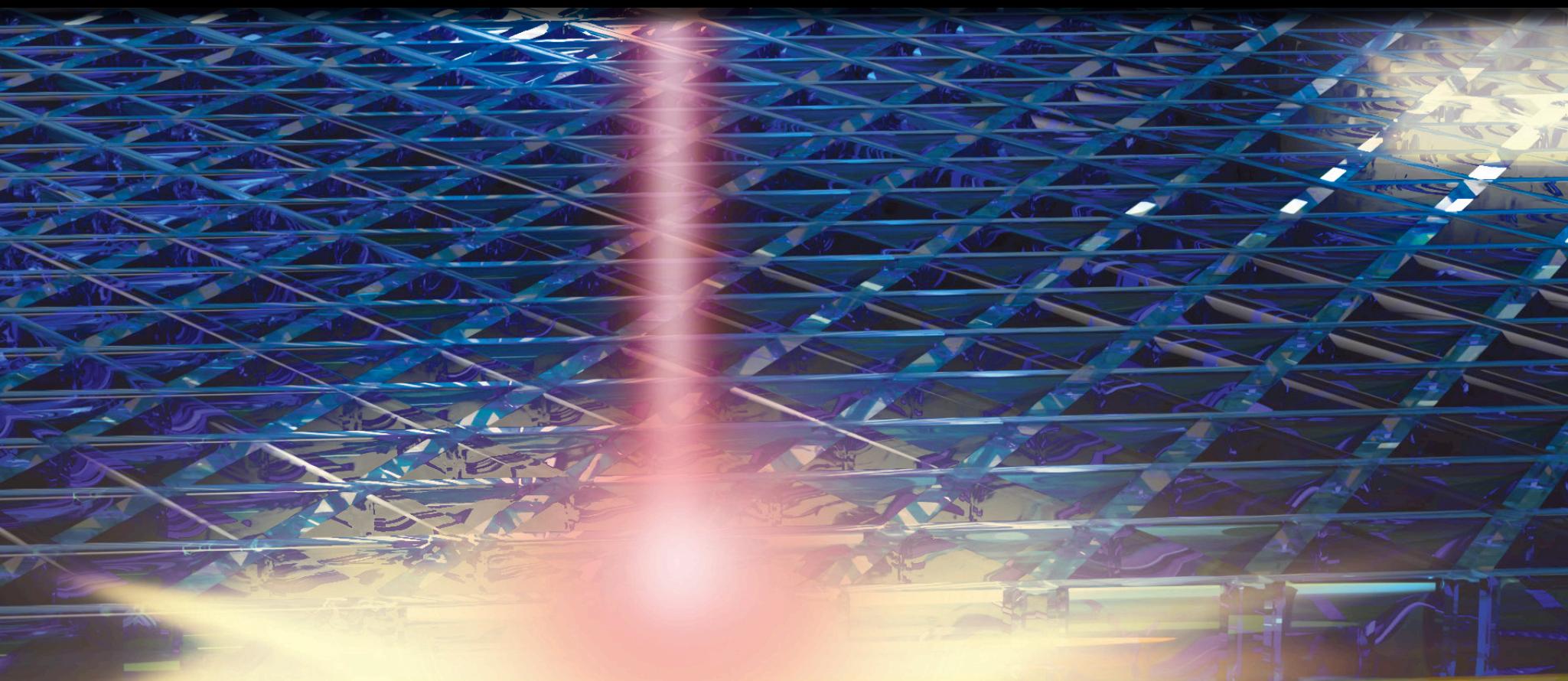


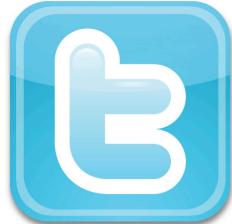
Metamaterials for extreme optics



SAIP2021
South-African Institute of Physics Conference
27 July 2021



Metamaterials for extreme optics

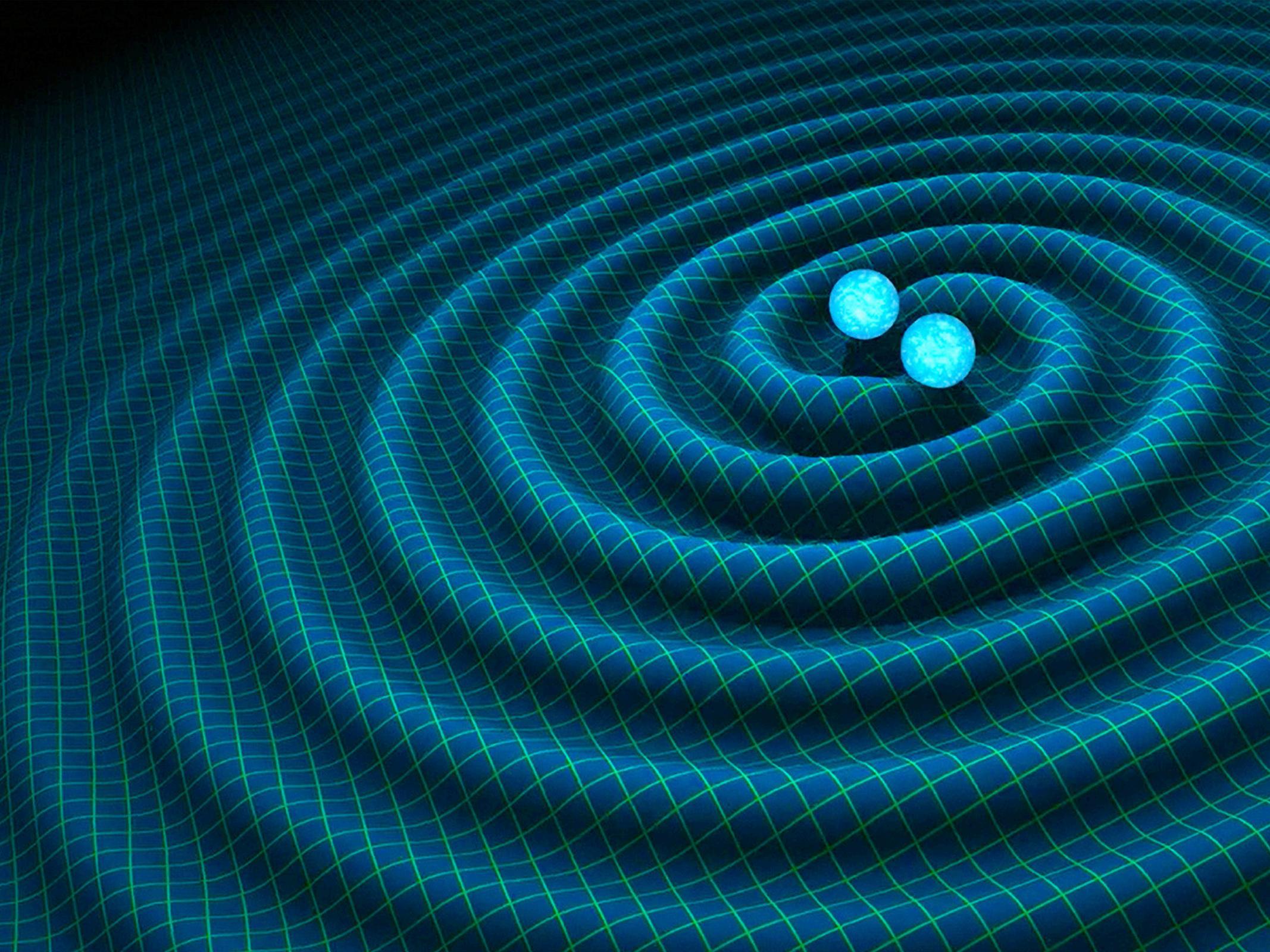


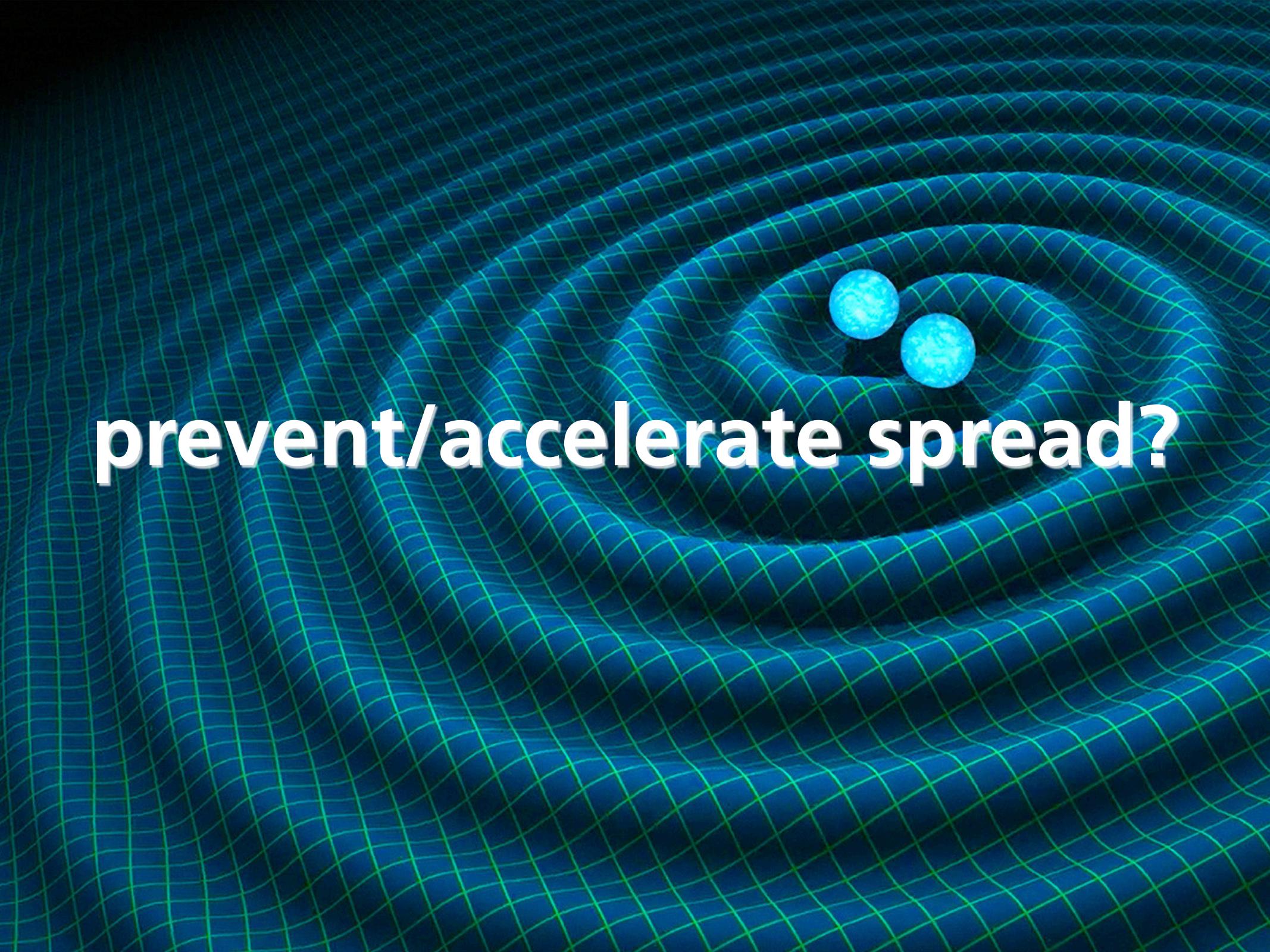
@eric_mazur

SAIP2021
South-African Institute of Physics Conference
27 July 2021

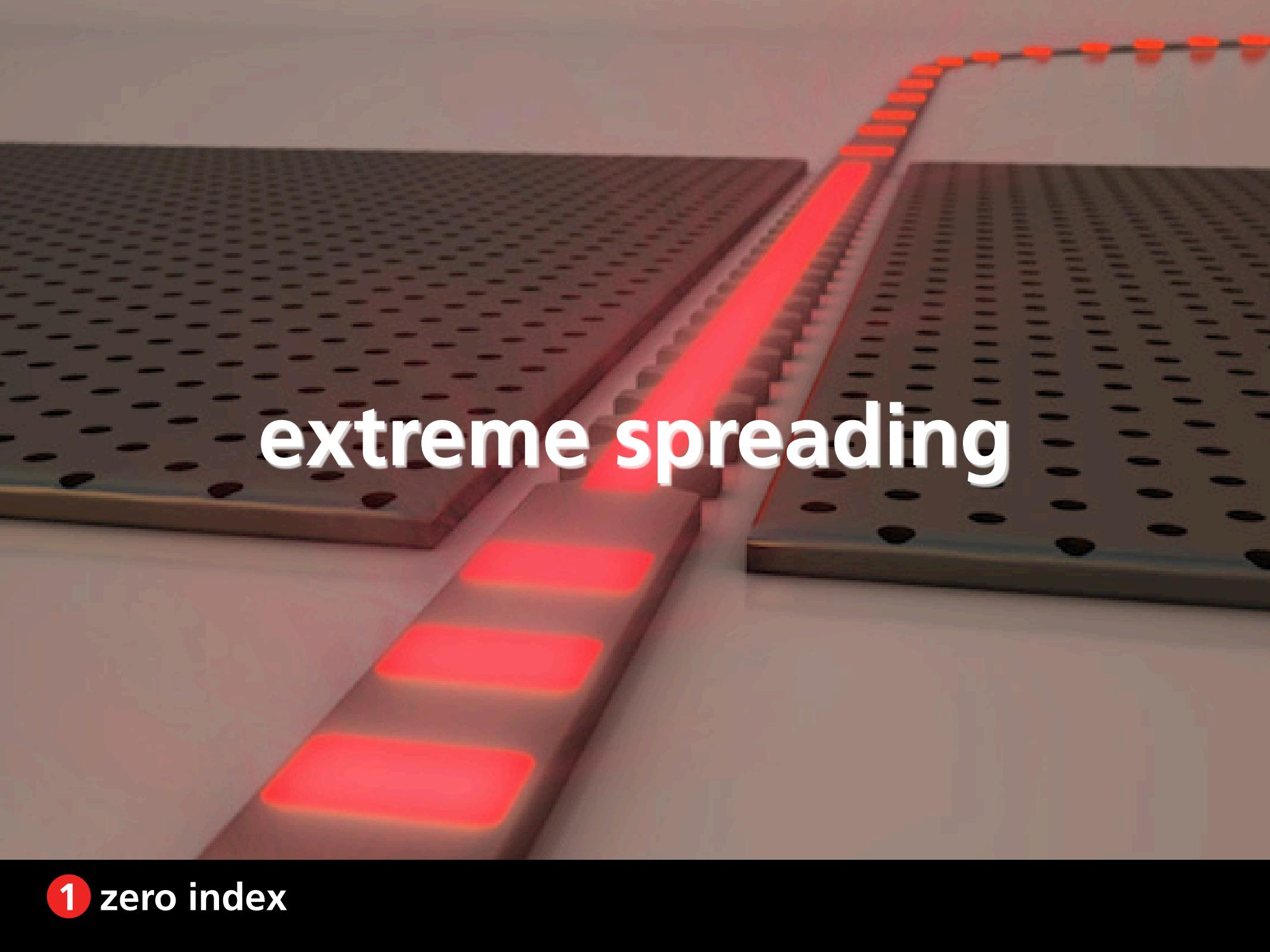






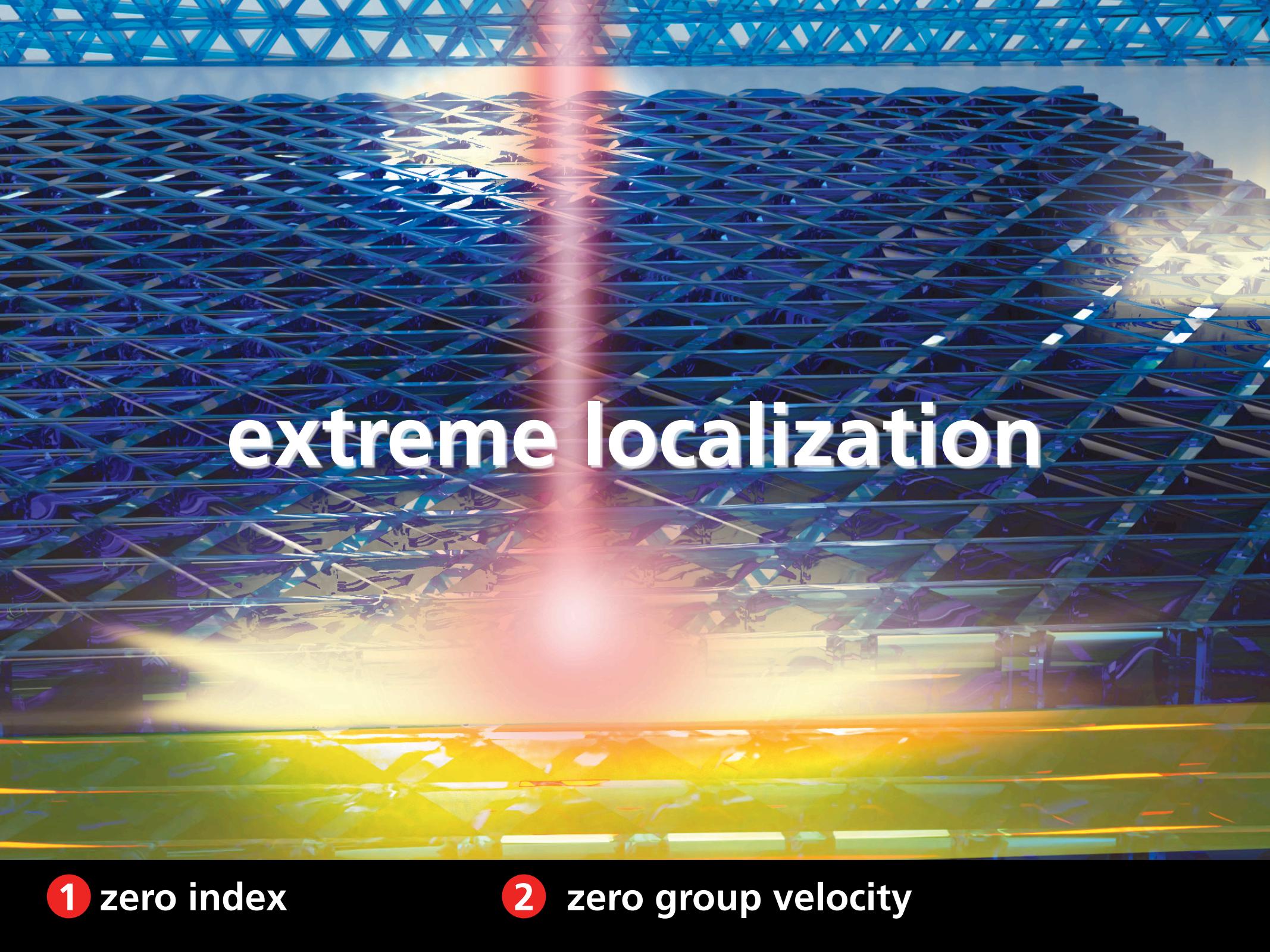
The background features a blue grid landscape that curves upwards towards the right. Two glowing blue spheres are positioned on the curve, one slightly above and to the left of the other. The grid consists of small squares of varying shades of blue.

prevent/accelerate spread?



extreme spreading

1 zero index



extreme localization

1 zero index

2 zero group velocity

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

1 zero index

wave equation

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

solution

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

where

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

1 zero index

wave equation

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

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

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

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

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

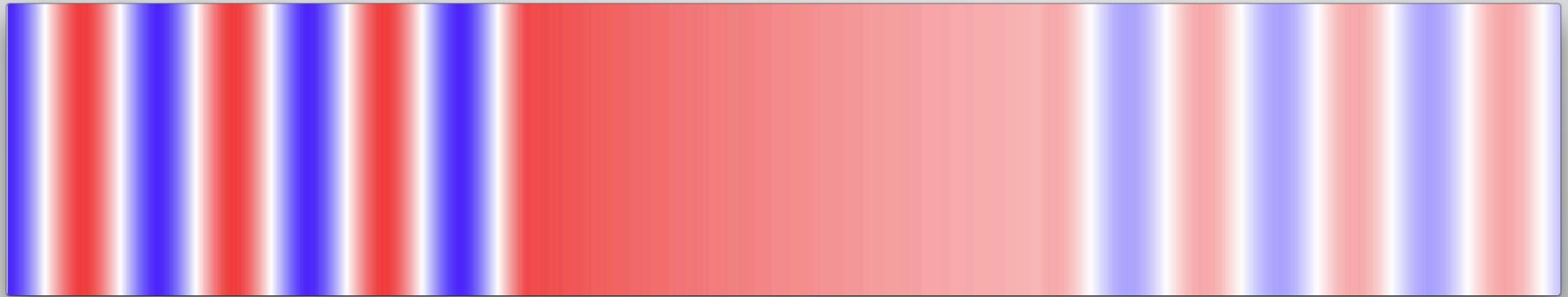
solution

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

where

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

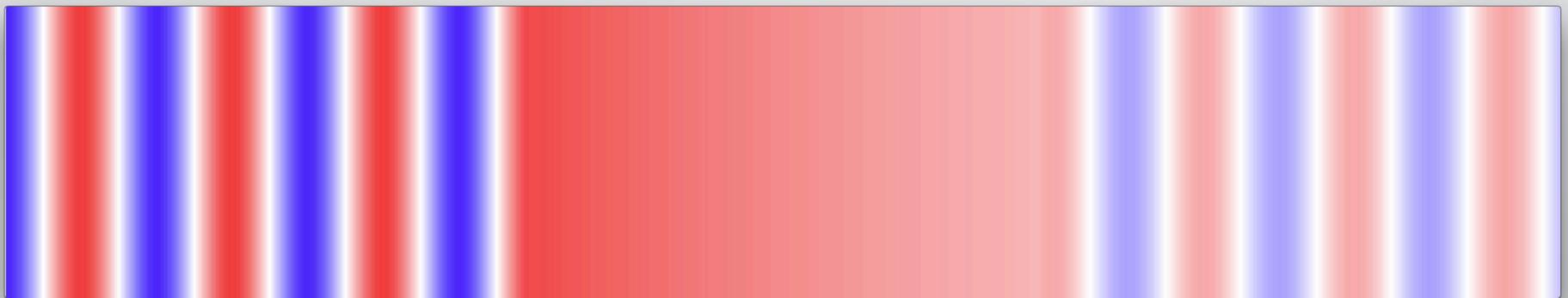
1 zero index



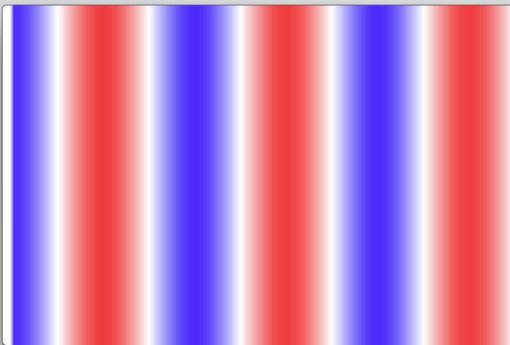
1 zero index

“Superluminal”?

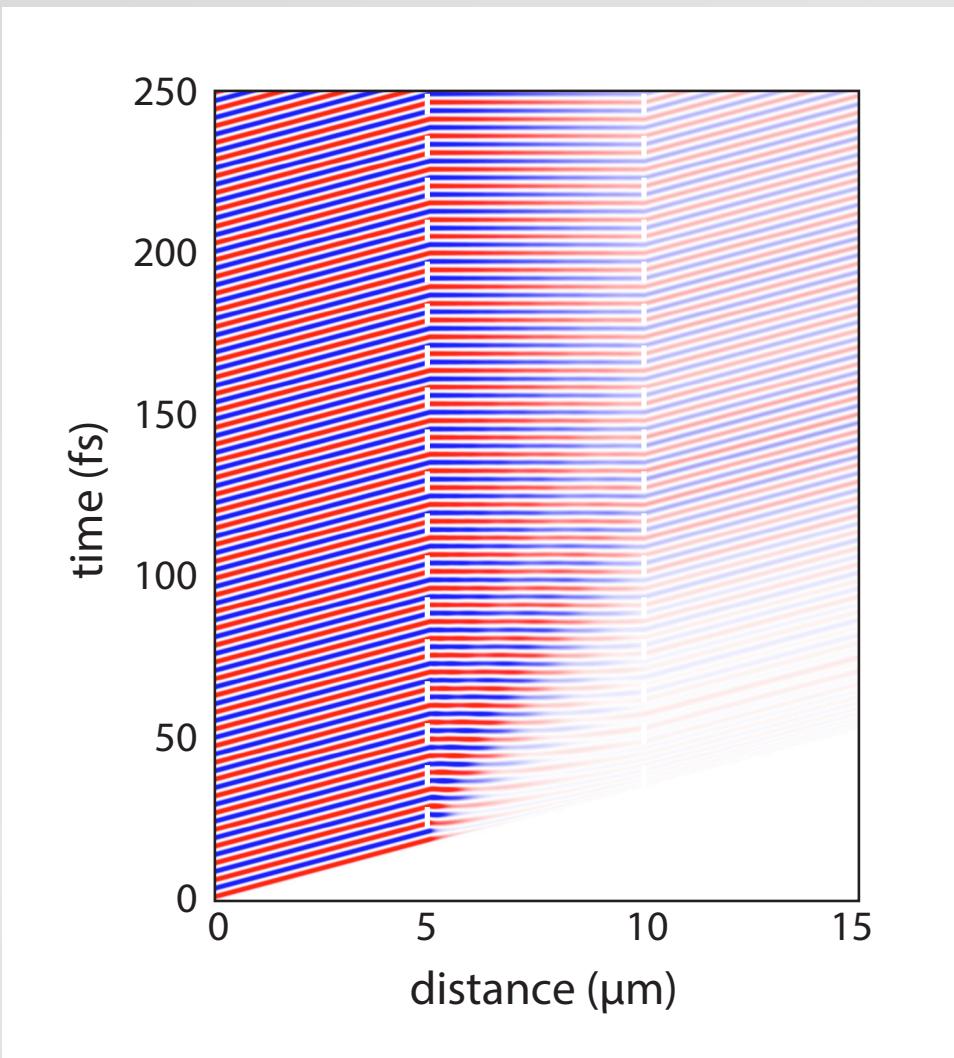
What about causality?



What about causality?



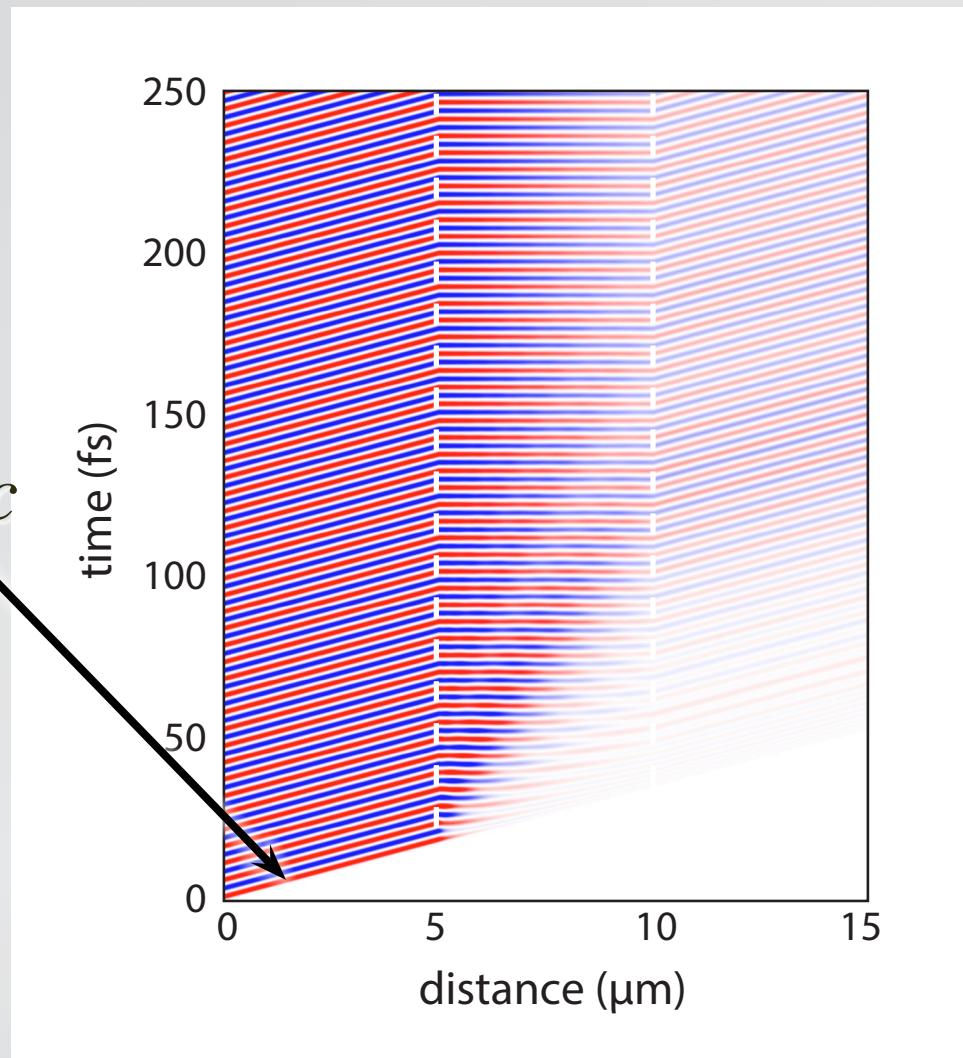
What about causality?



1 zero index

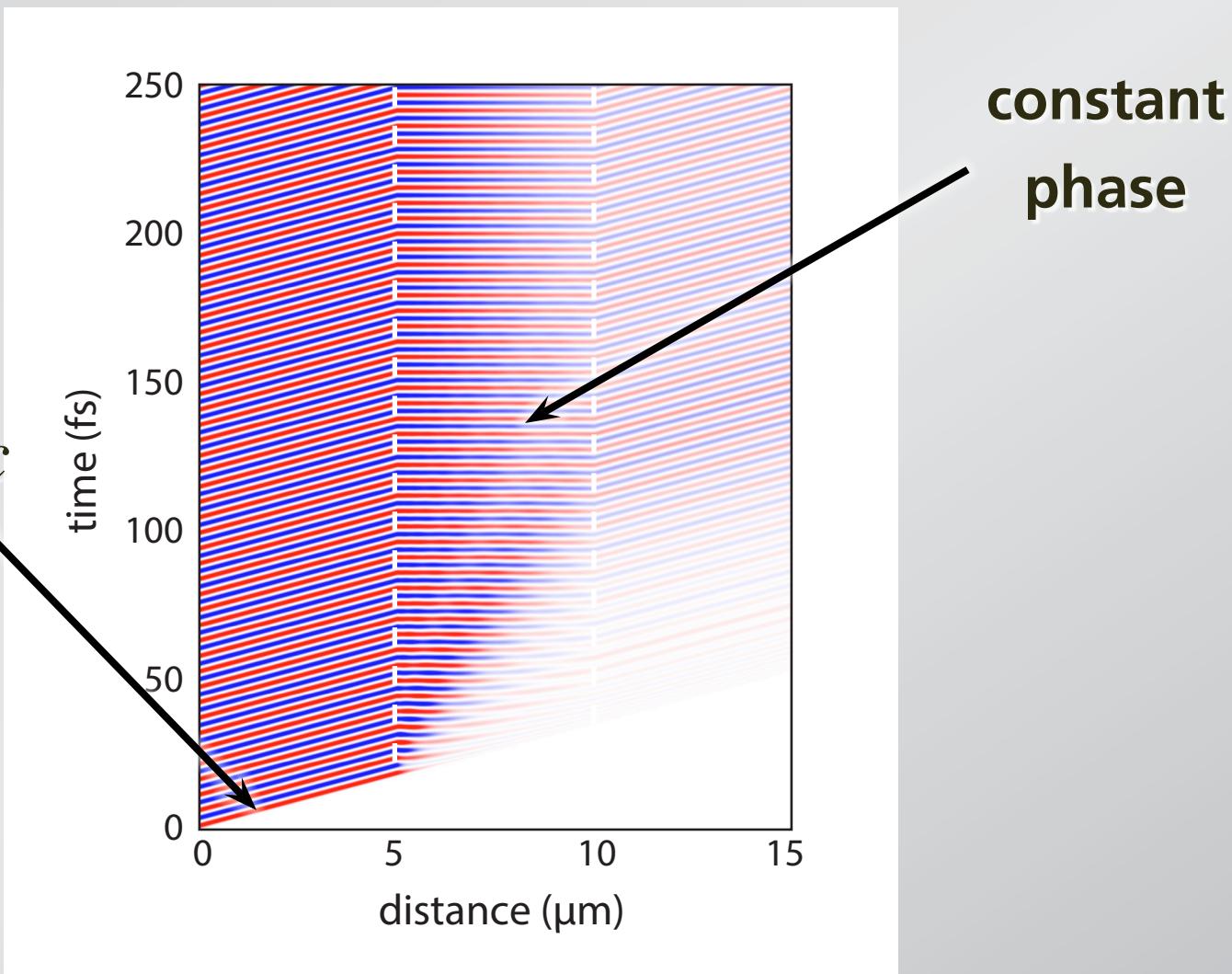
What about causality?

speed of light c



What about causality?

speed of light c



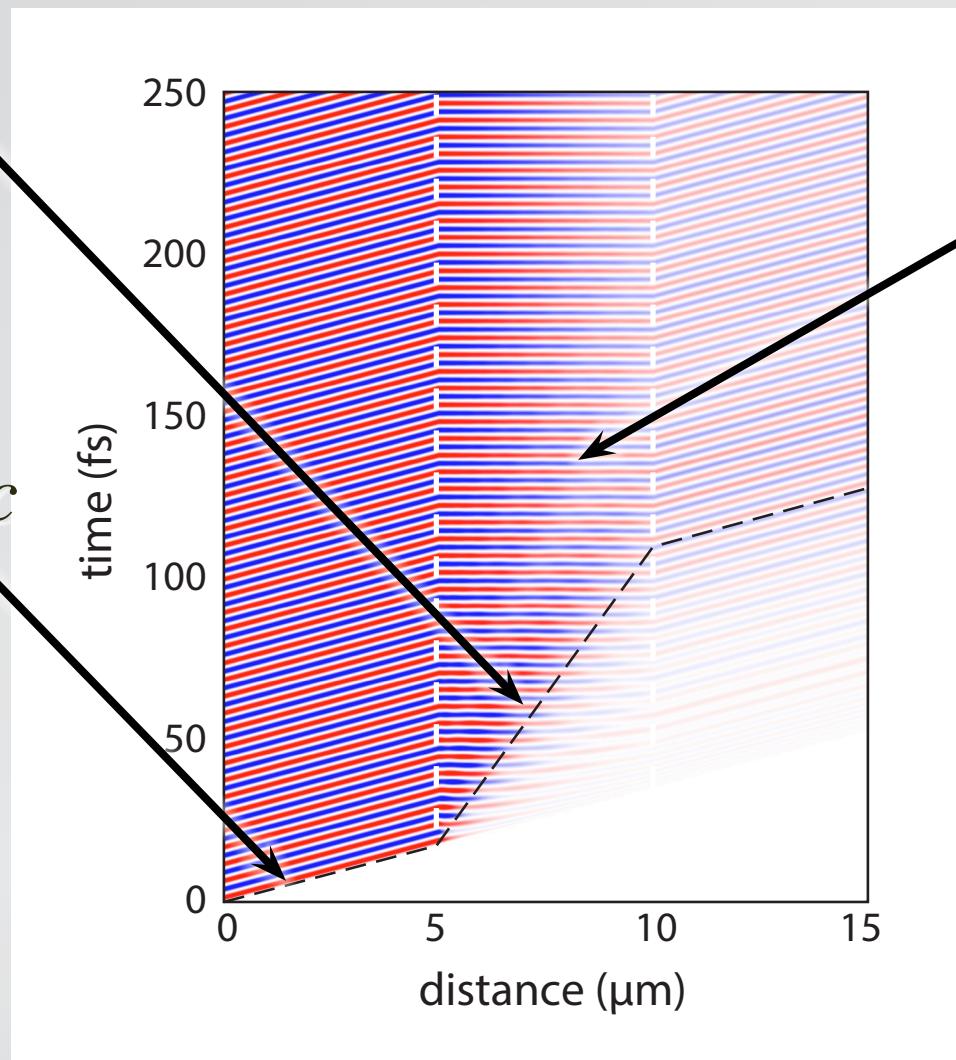
What about causality?

group velocity

$$v_g < c$$

speed of light c

constant
phase



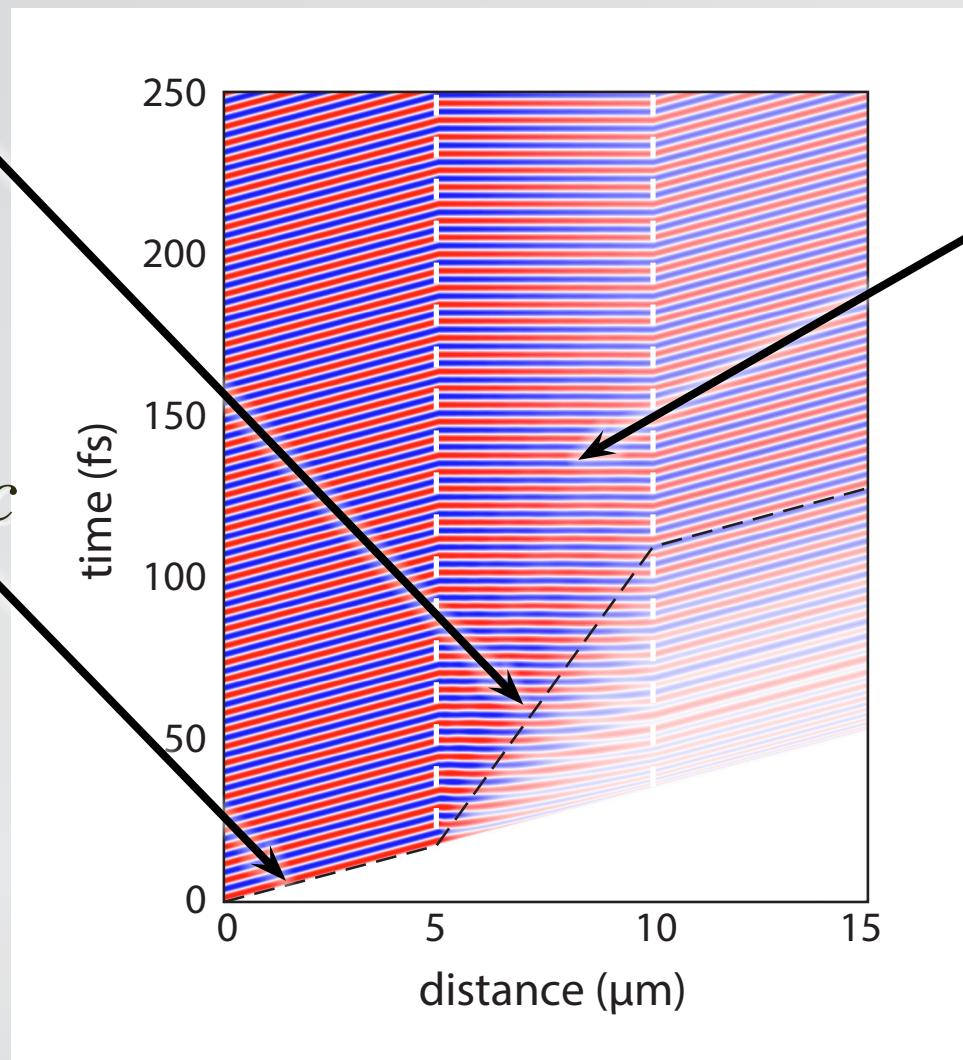
What about causality?

group velocity

$$v_g < c$$

speed of light c

constant
phase

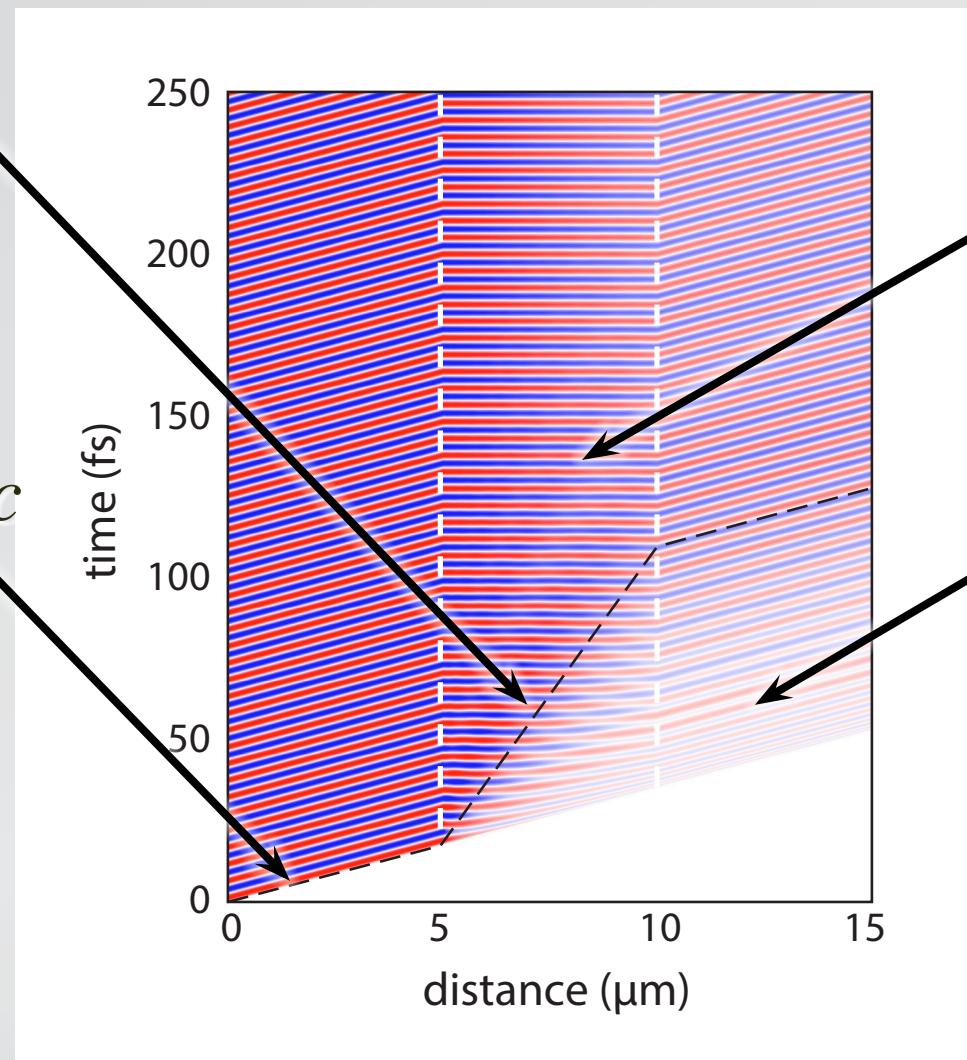


What about causality?

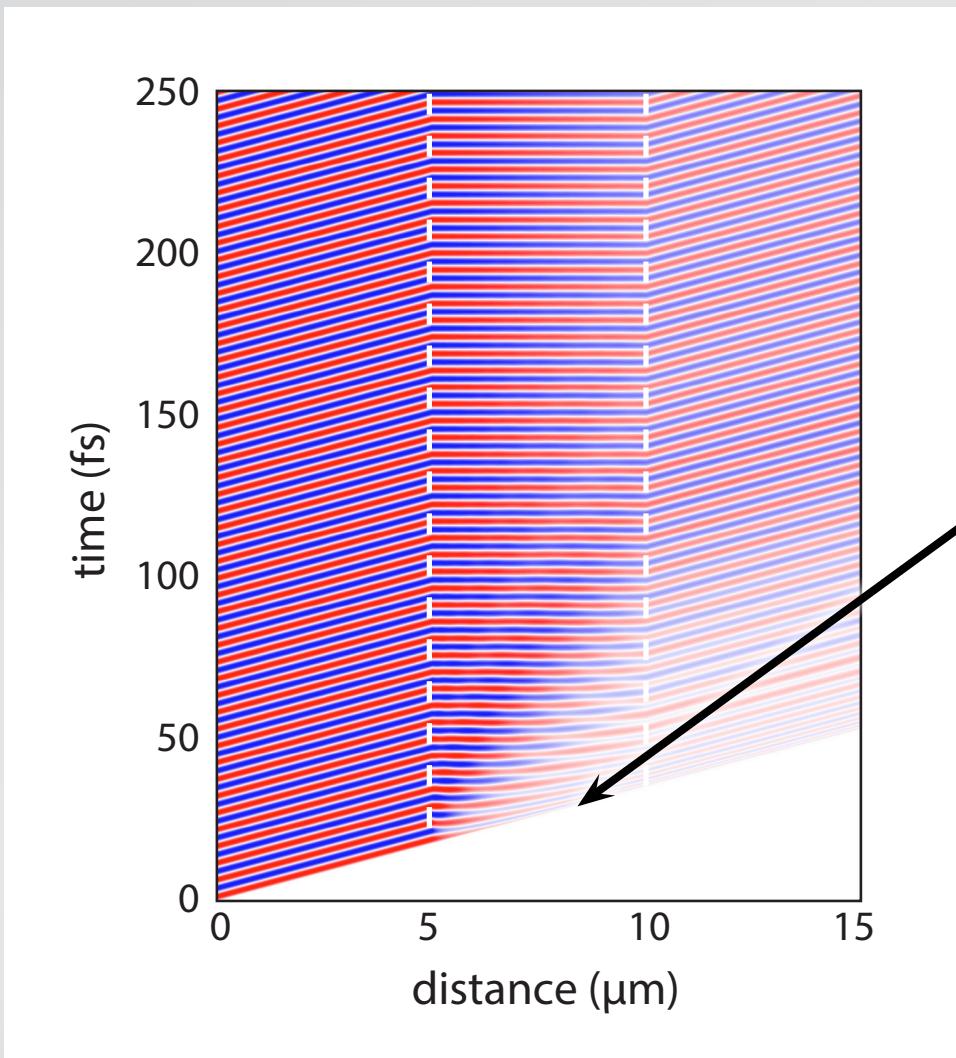
group velocity

$$v_g < c$$

speed of light c

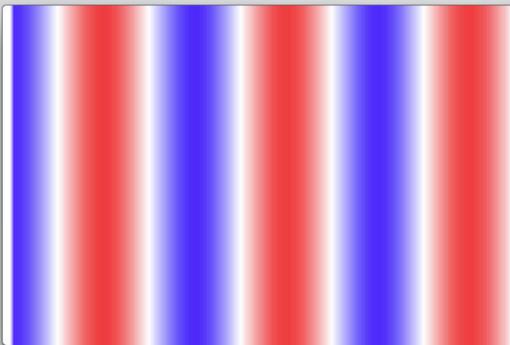


What about causality?



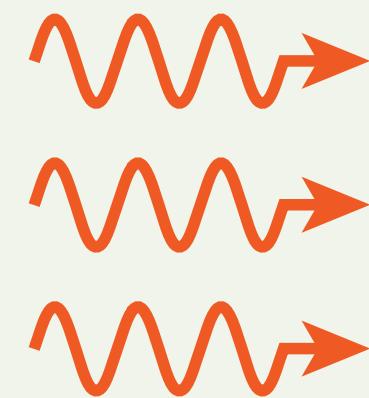
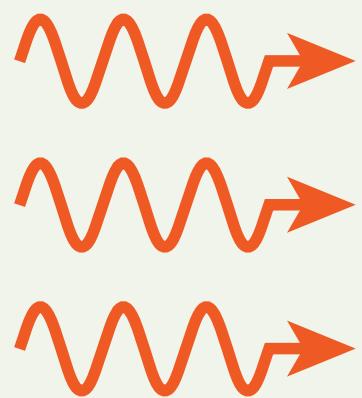
**signal *always*
travels at speed c !**

What about causality?

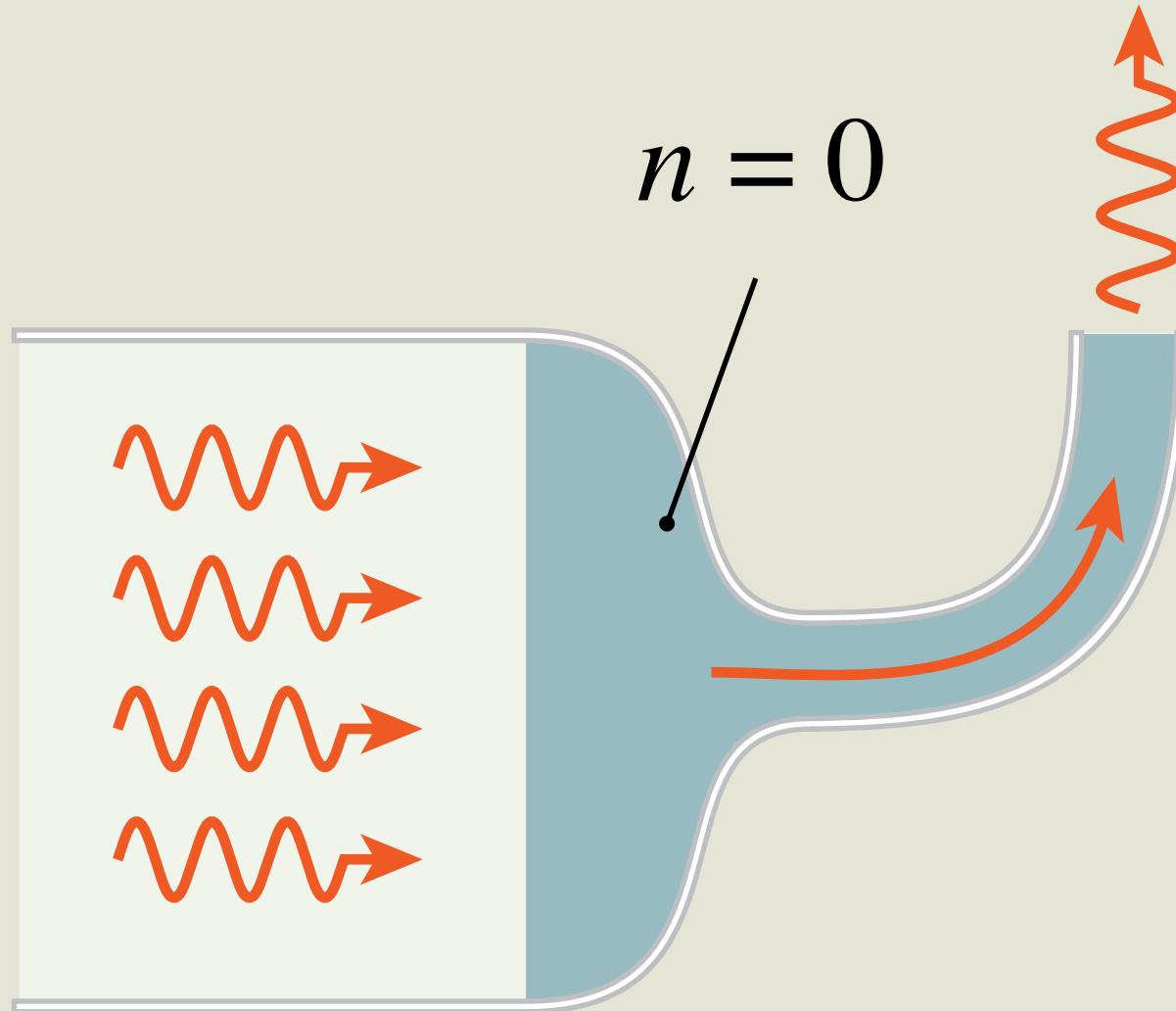


$n = 0$ 

1 zero index

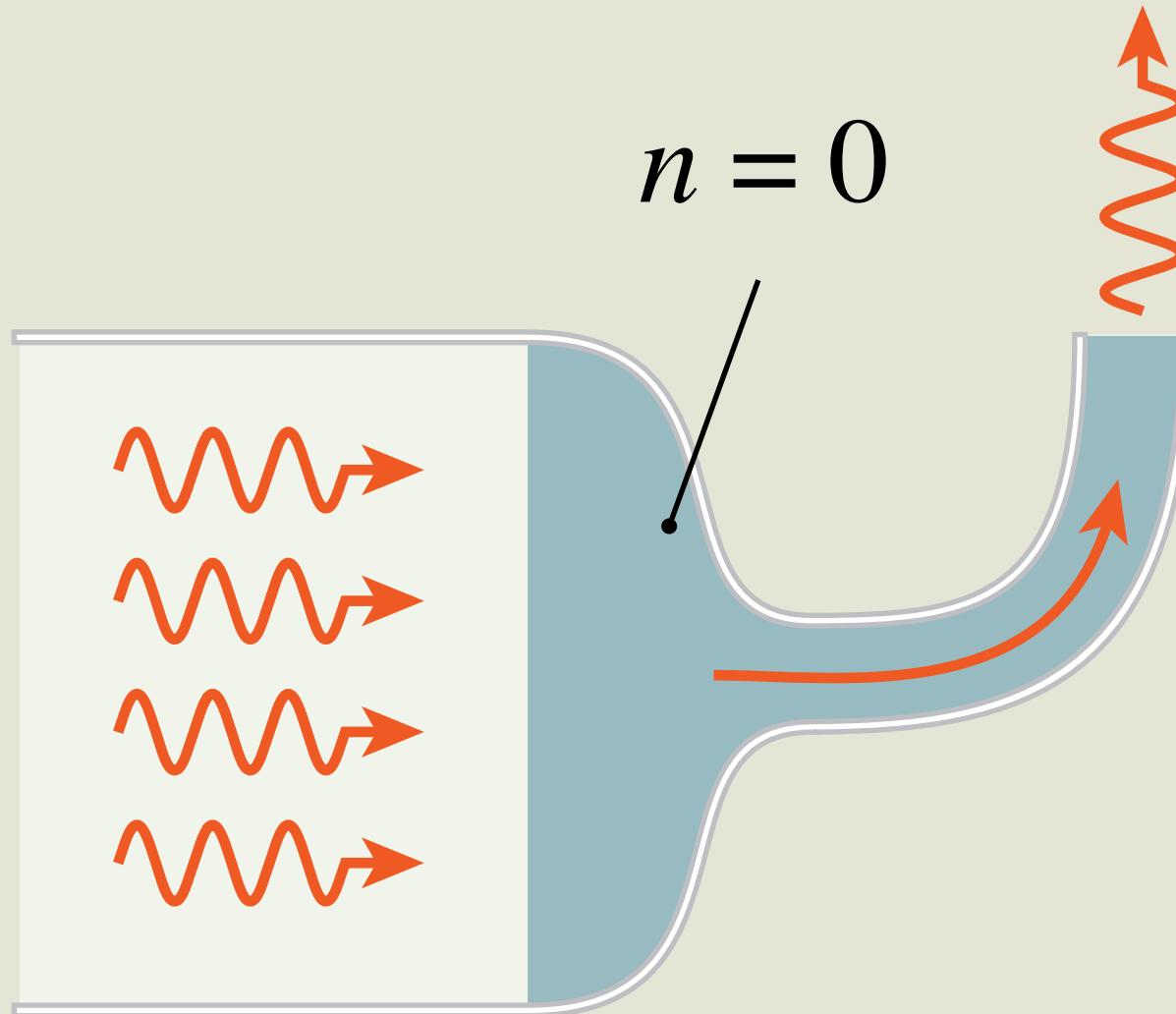
$n = 0$ 

1 zero index



1 zero index

“tunneling with infinite decay length”



$$n = 0$$

1 zero index

how?

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

but ϵ and μ also determine reflectivity

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

how?

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

but ϵ and μ also determine reflectivity

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

where

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

how?

$$\varepsilon, \mu \rightarrow 0$$

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

but ϵ and μ also determine reflectivity

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

where

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

1 zero index

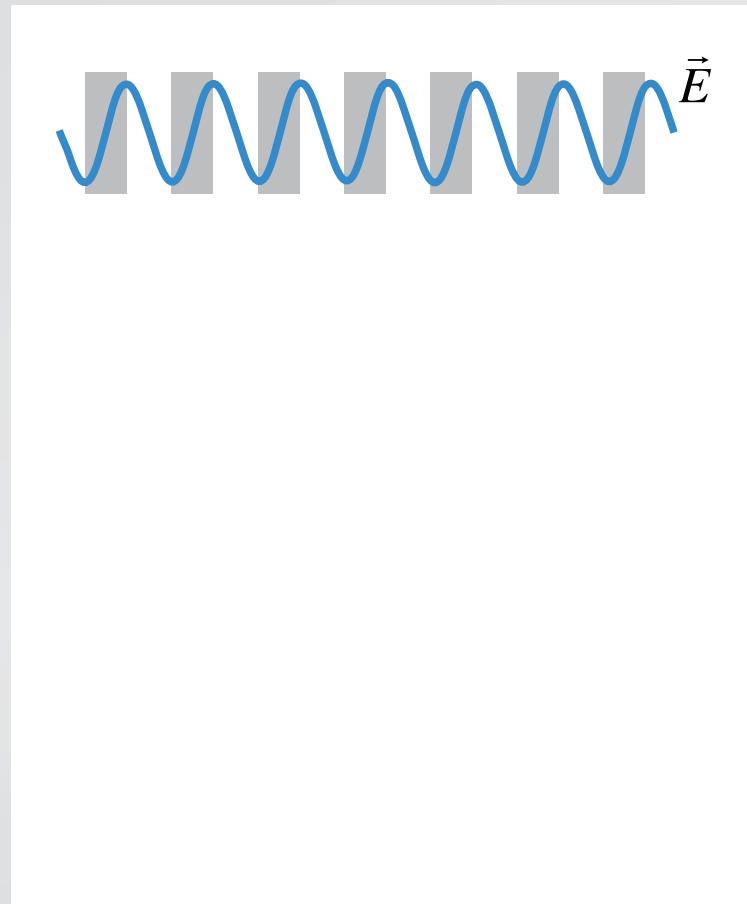
Engineering a magnetic response

use array of dielectric rods



Engineering a magnetic response

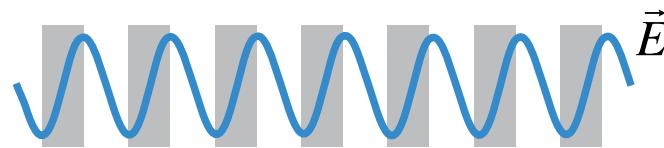
incident electromagnetic wave ($\lambda_{\text{eff}} \approx a$)



1 zero index

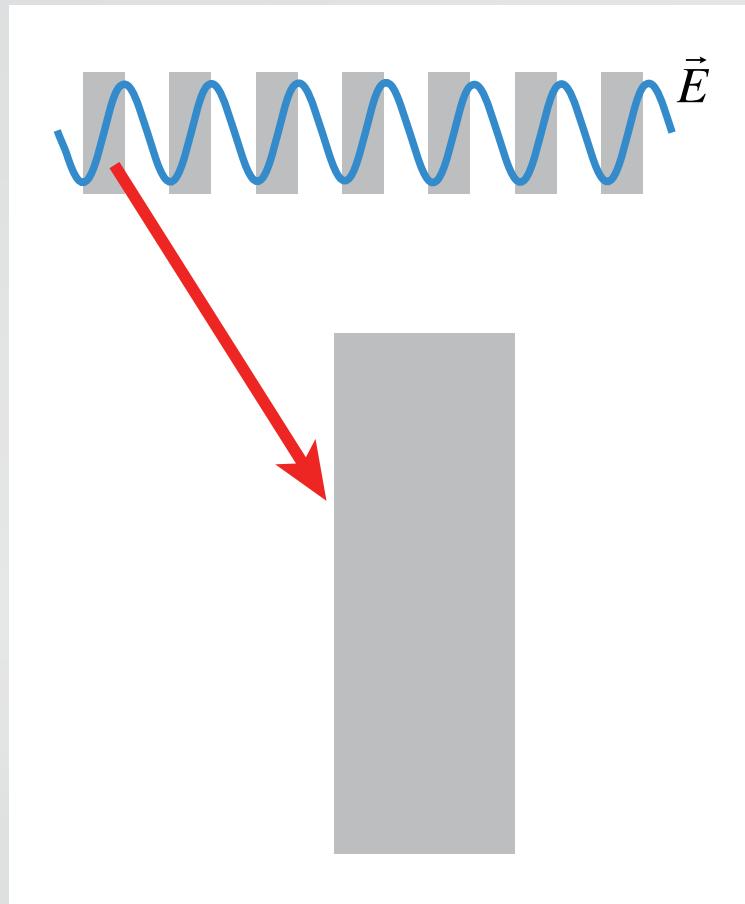
Engineering a magnetic response

produces an electric response...



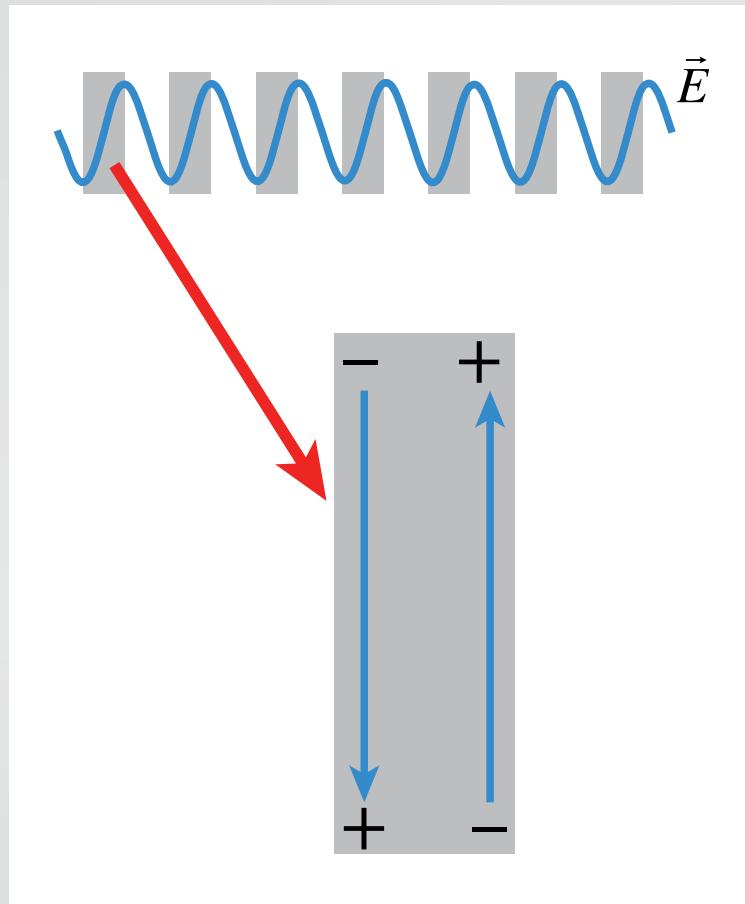
Engineering a magnetic response

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



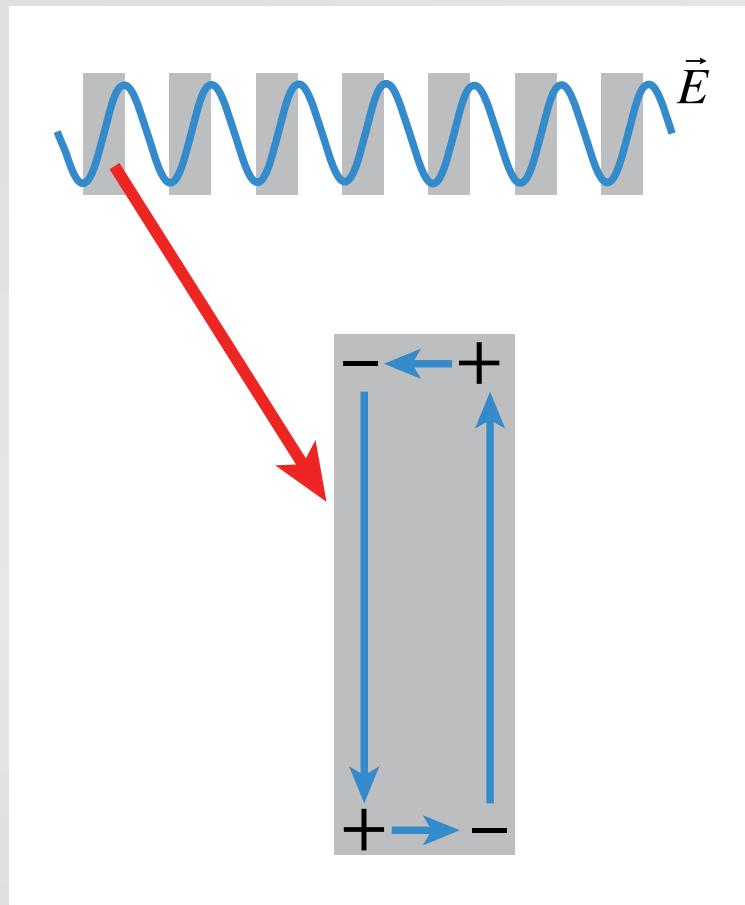
Engineering a magnetic response

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



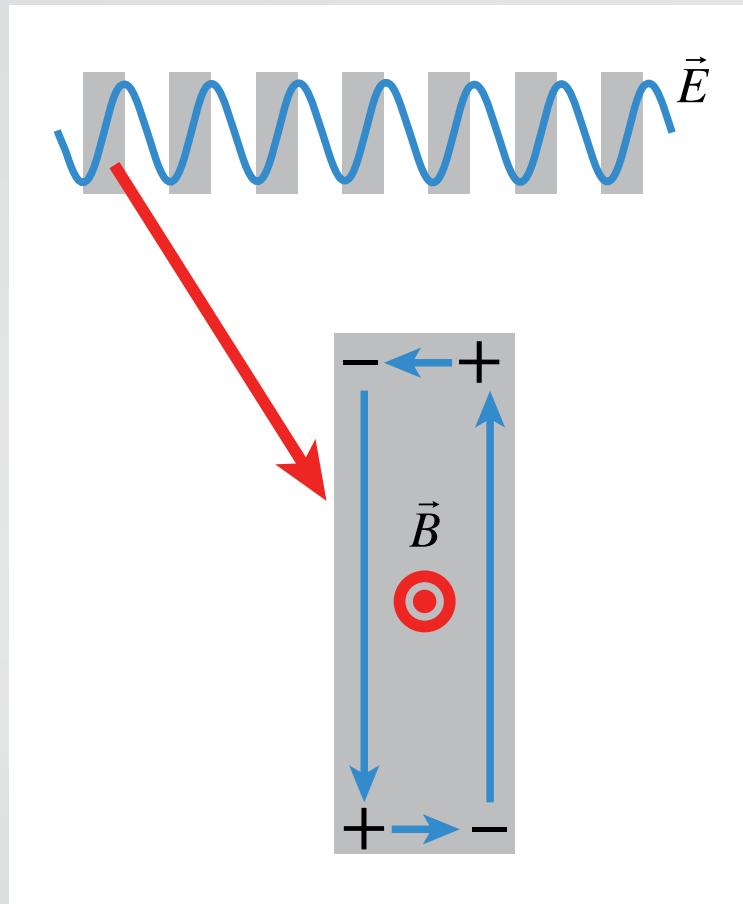
Engineering a magnetic response

...causing a current loop...



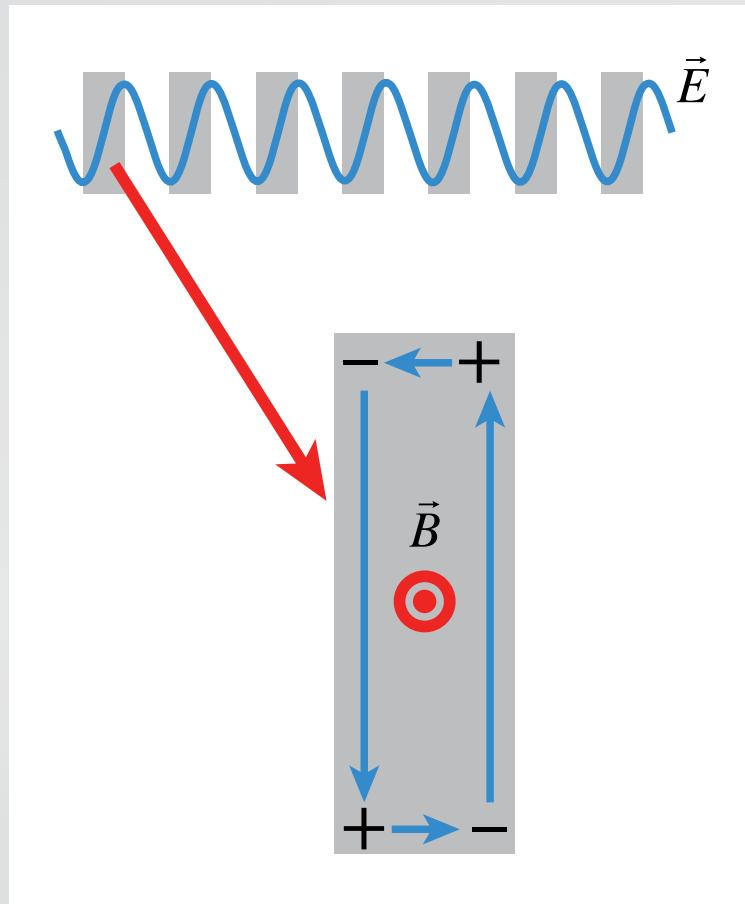
Engineering a magnetic response

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



Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide



1 zero index

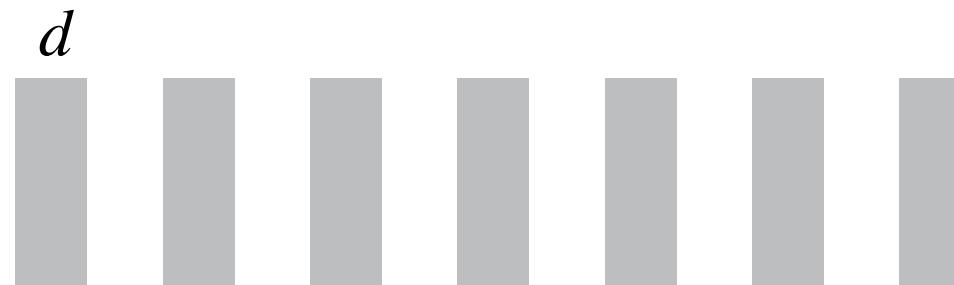
Engineering a magnetic response

adjustable parameters



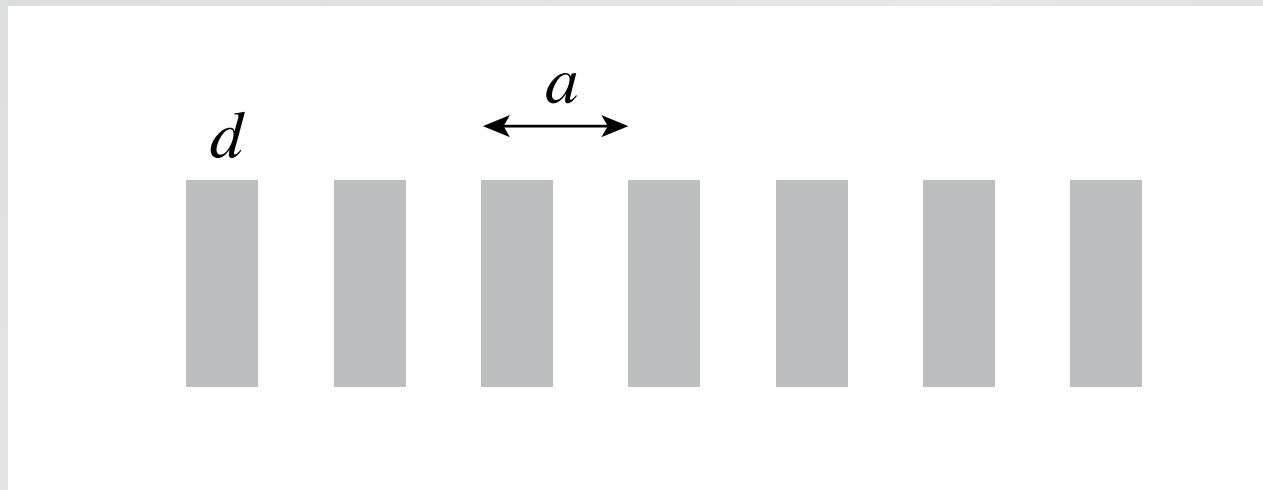
Engineering a magnetic response

adjustable parameters



Engineering a magnetic response

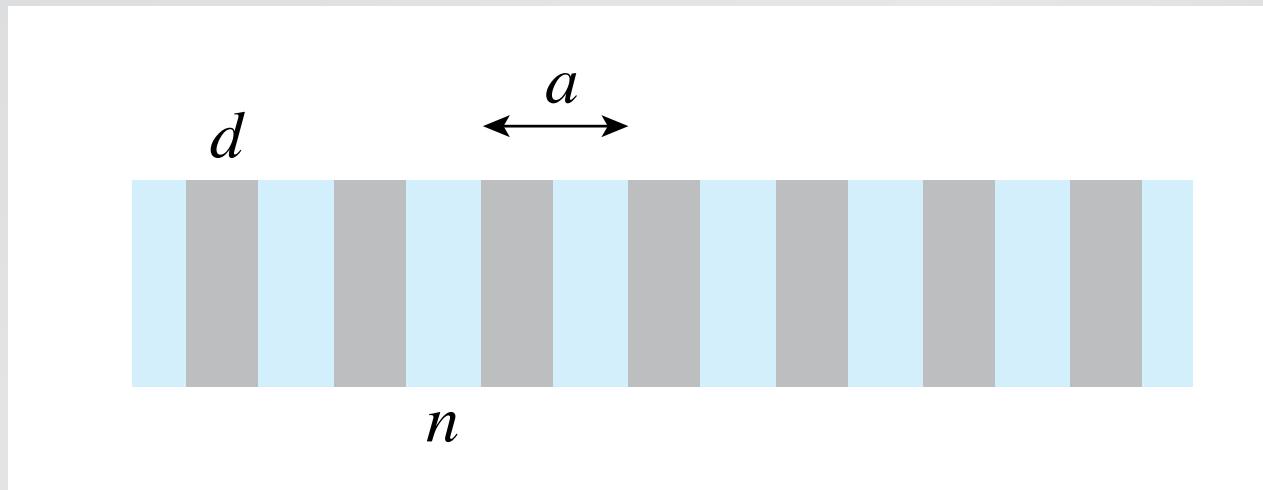
adjustable parameters



1 zero index

Engineering a magnetic response

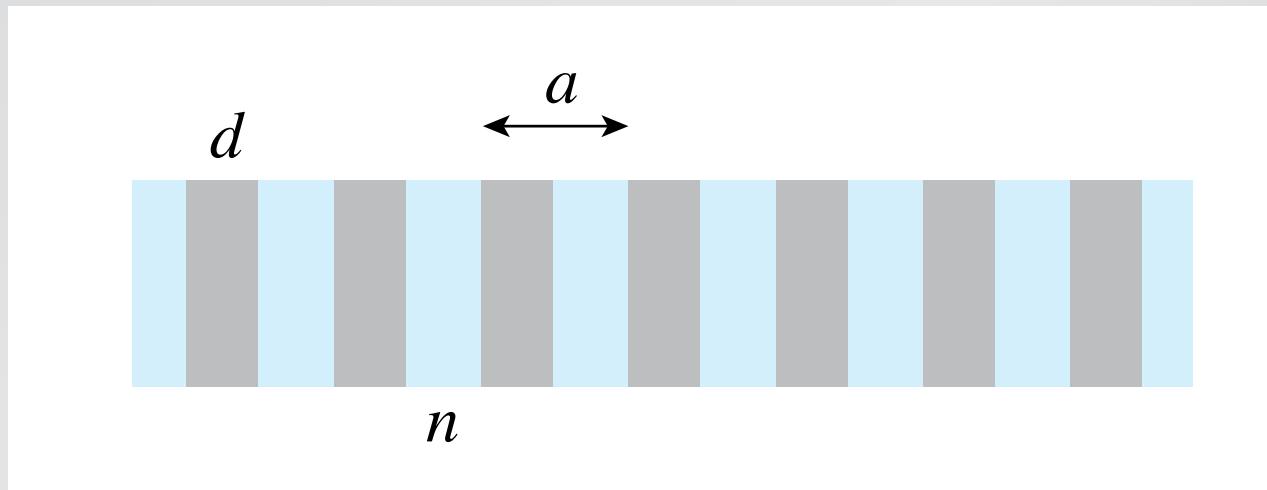
adjustable parameters



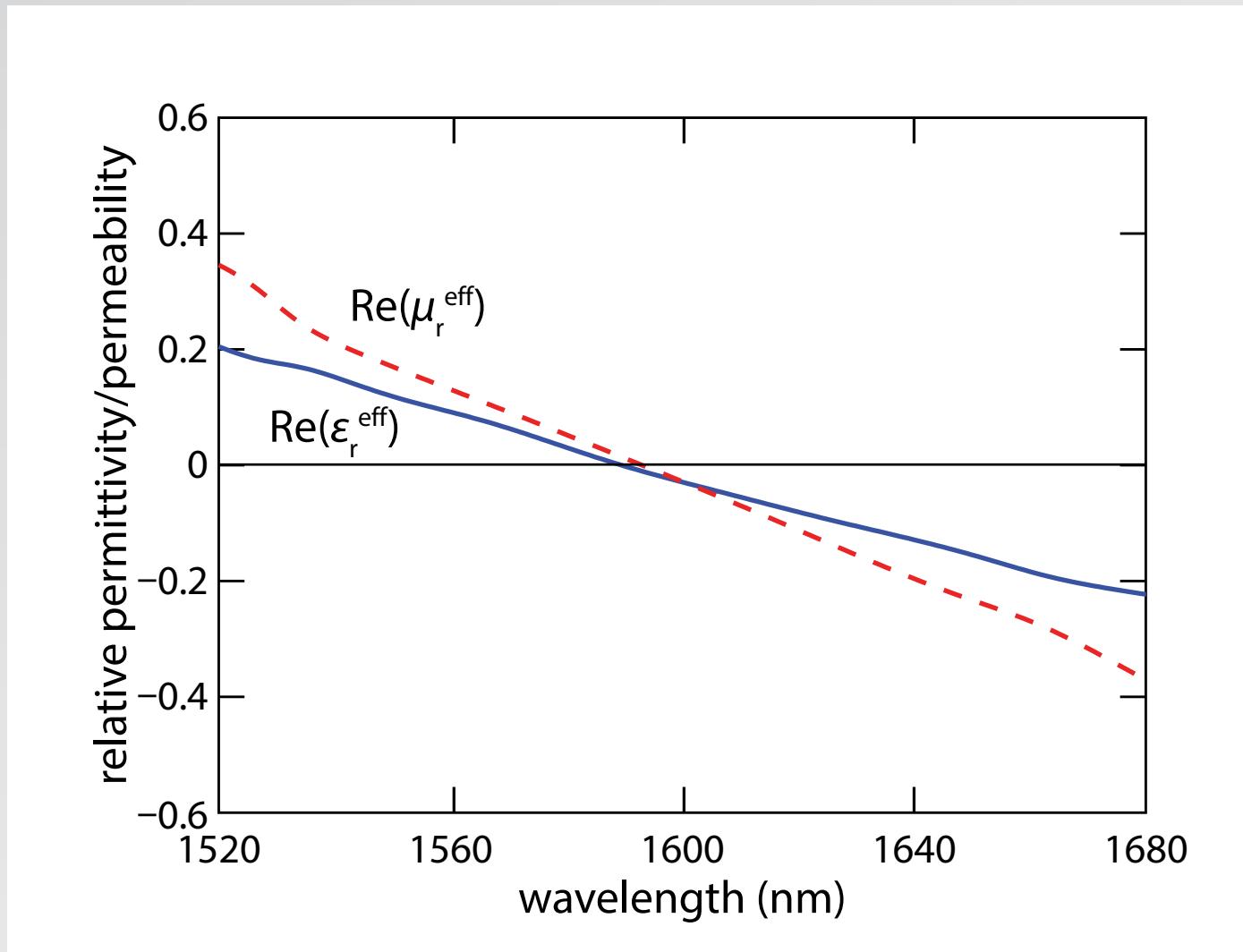
1 zero index

Engineering a magnetic response

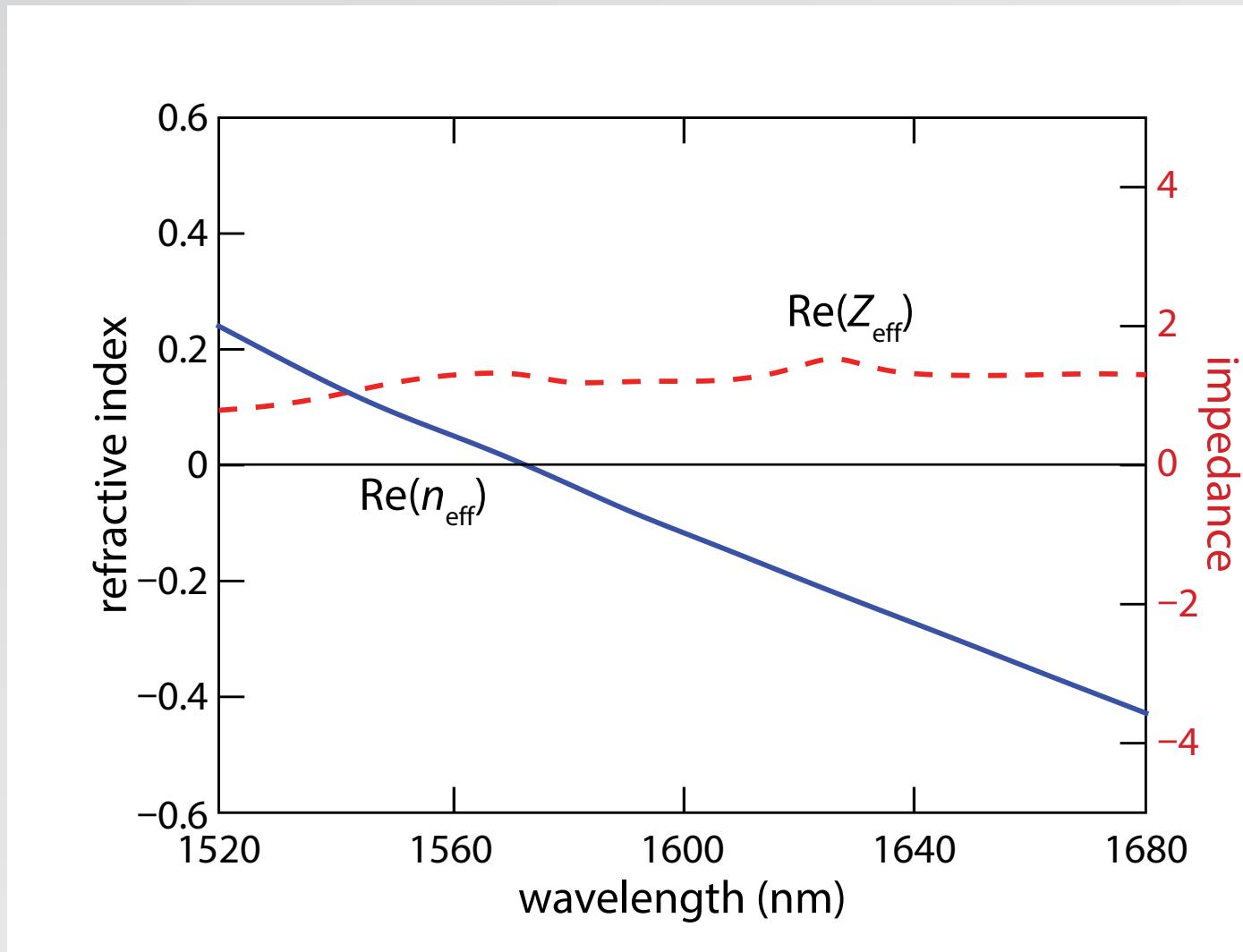
adjustable parameters



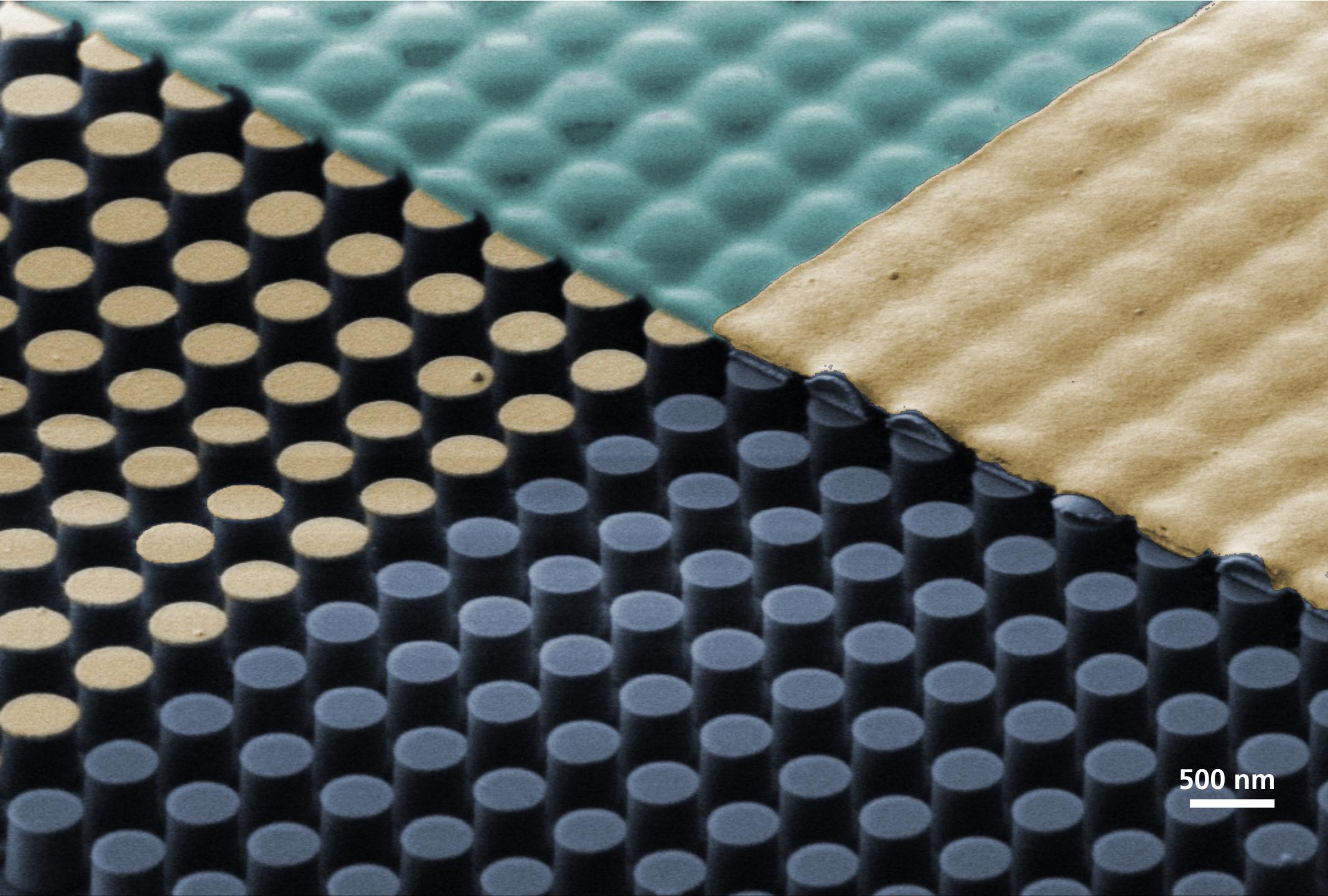
$$d = 422 \text{ nm}, \quad a = 690 \text{ nm}, \quad n = 1.57 \text{ (SU8)}$$



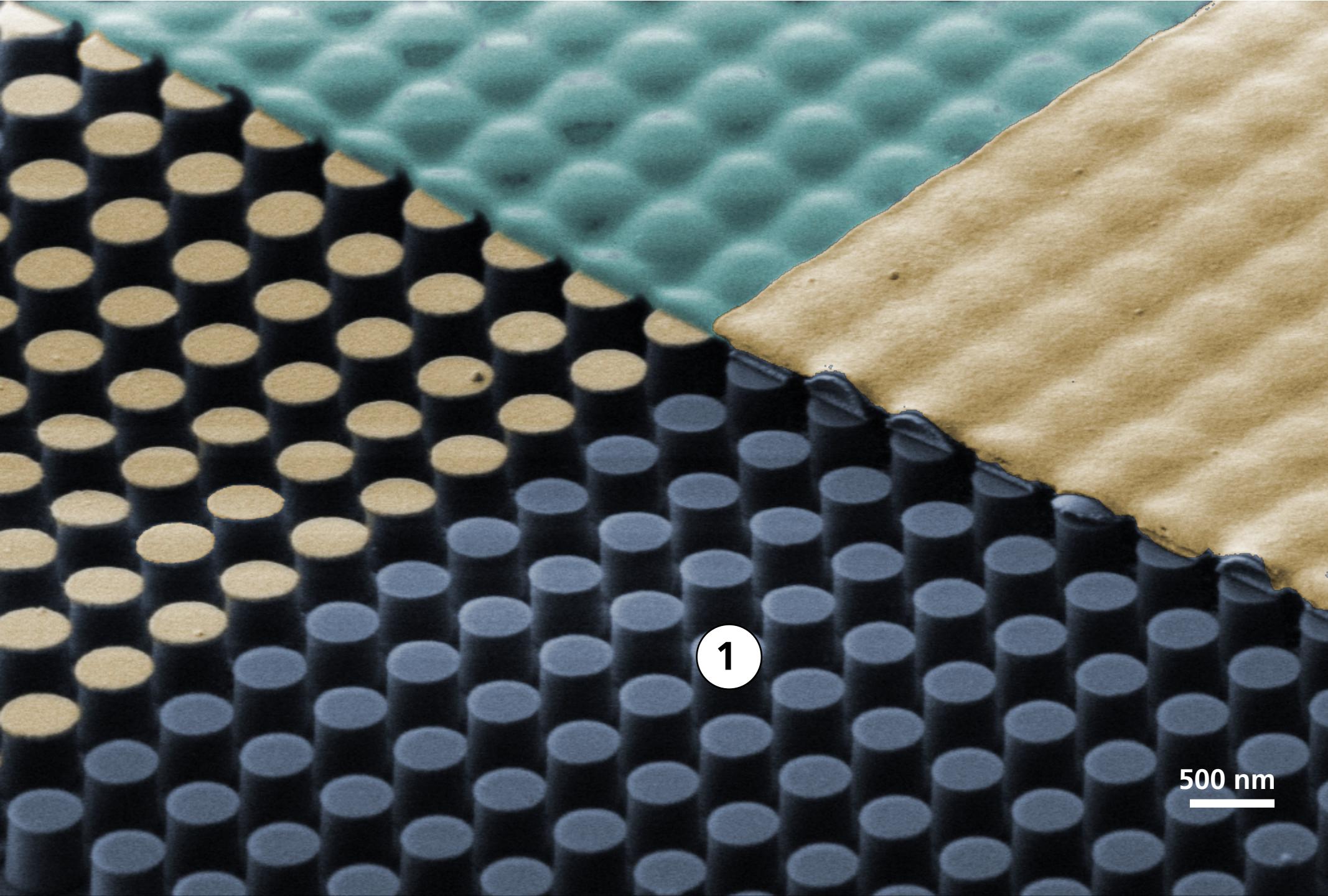
1 zero index



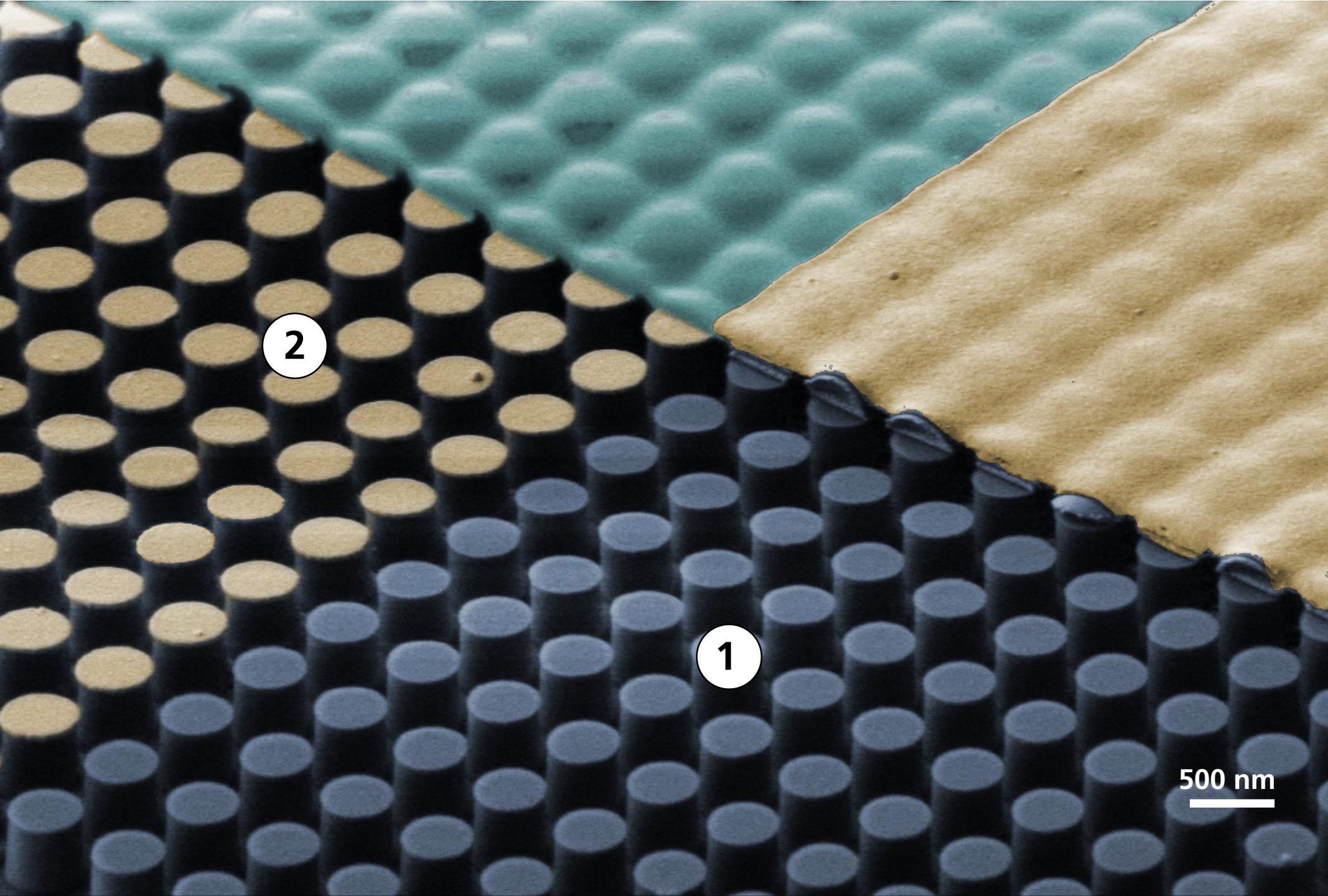
1 zero index



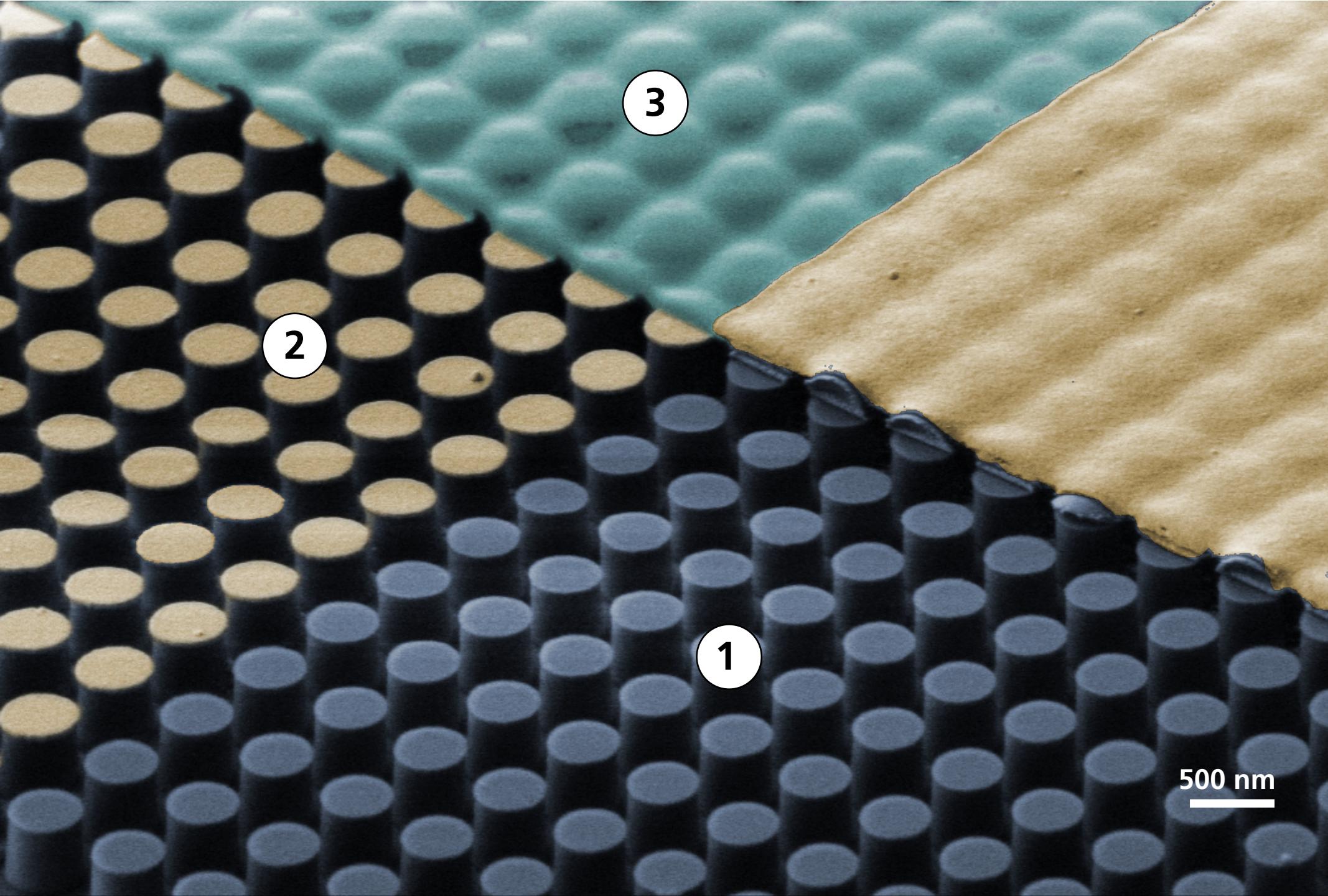
1 zero index



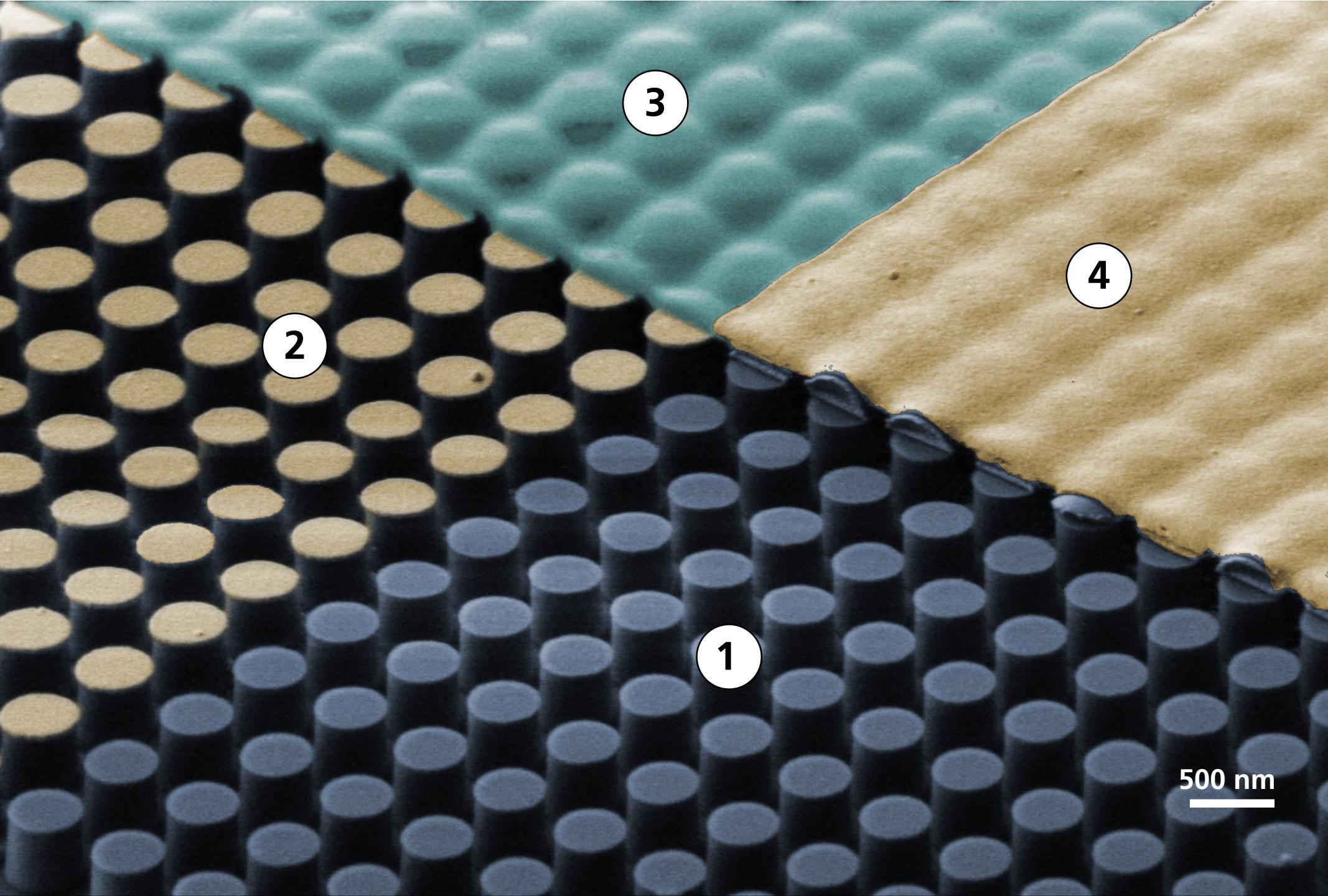
1 zero index



1 zero index

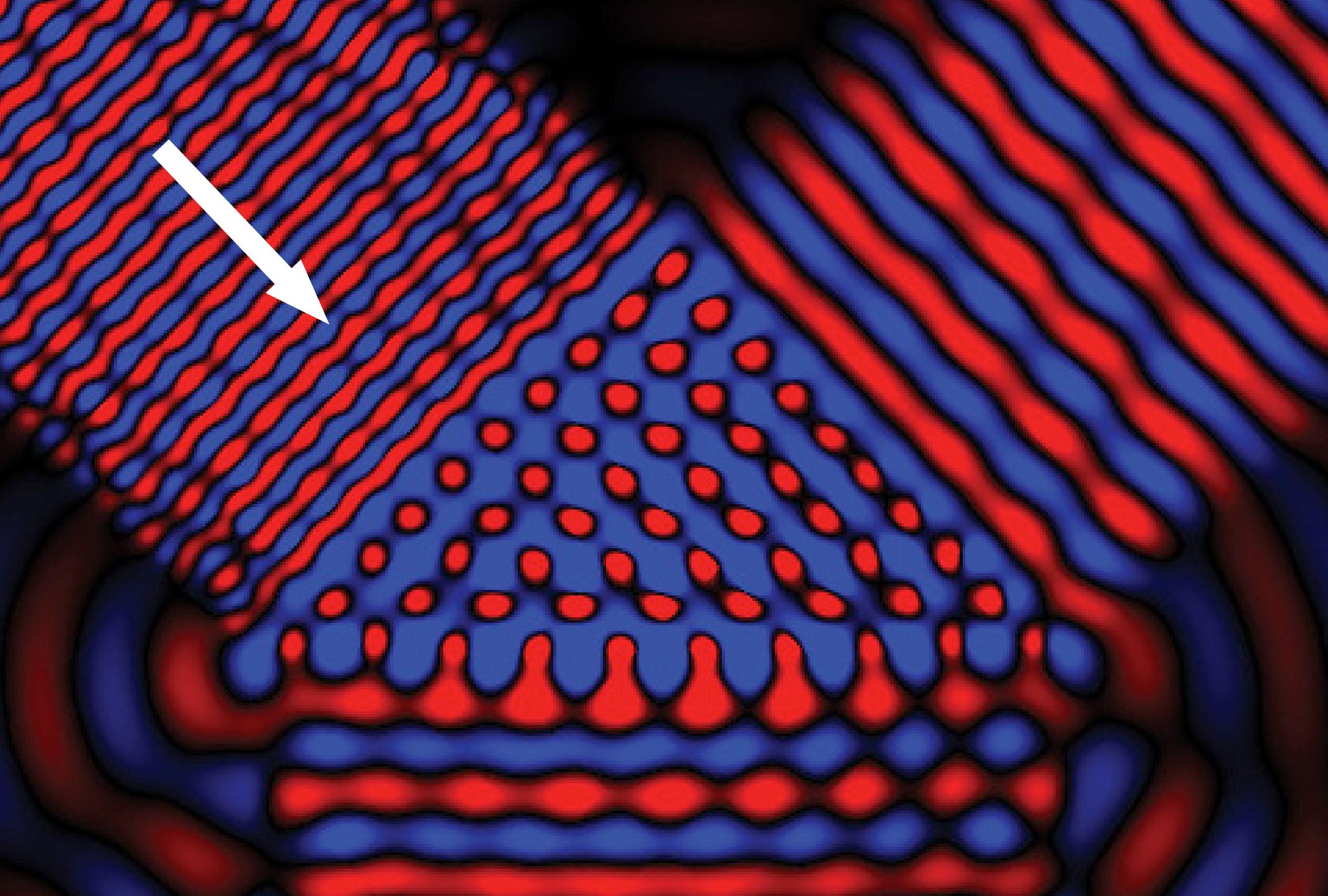


1 zero index

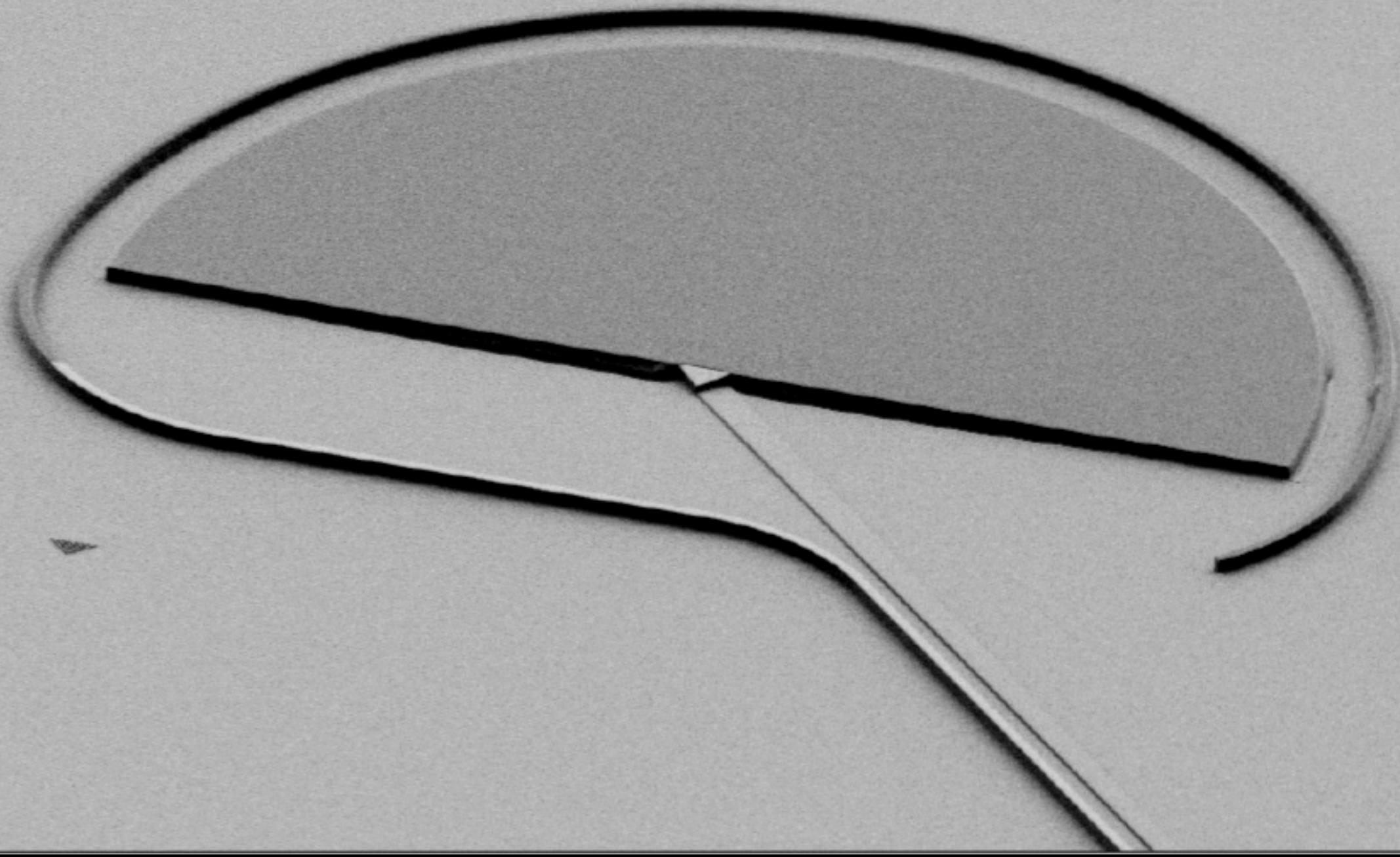


1 zero index

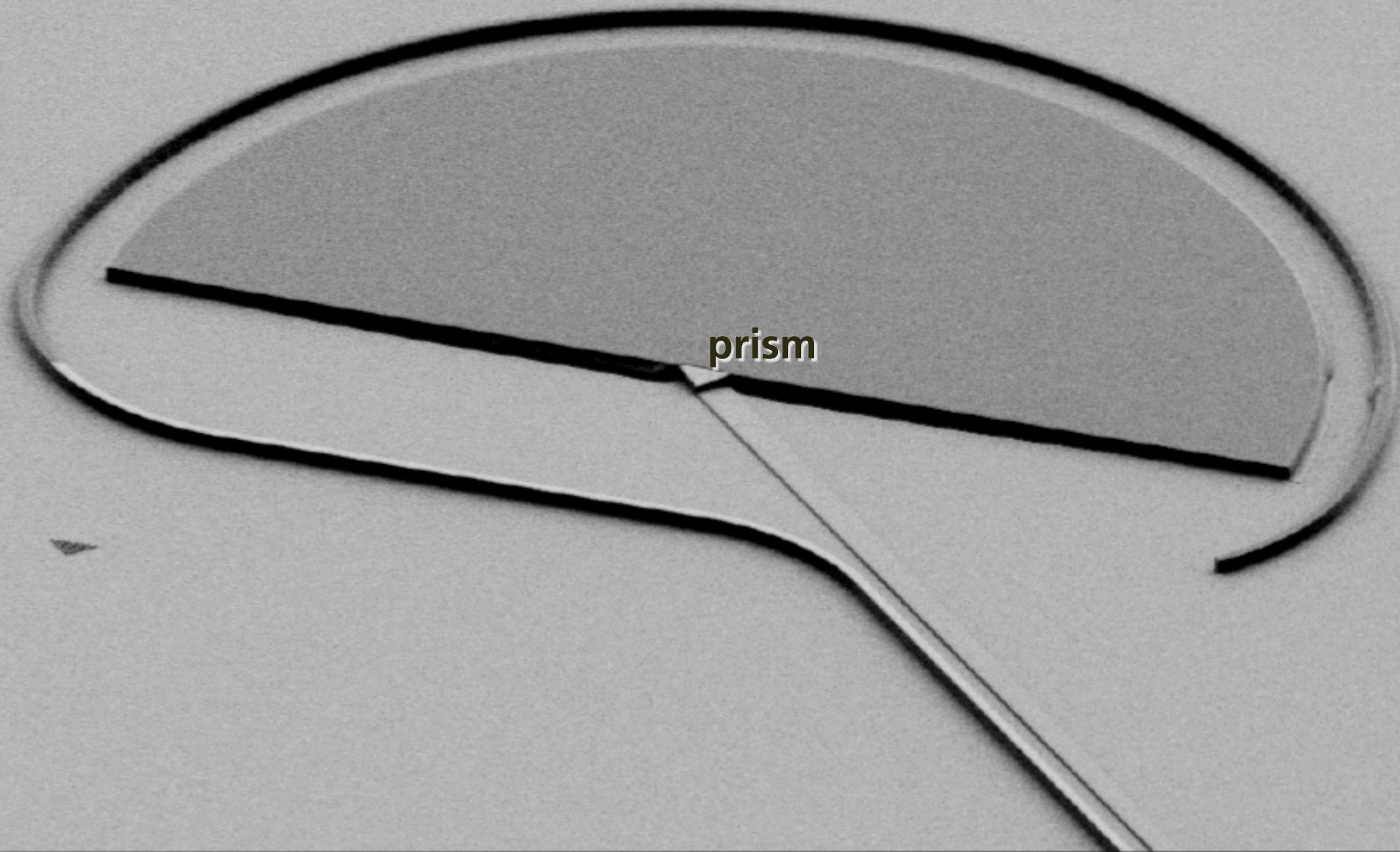
Can make this in any shape!



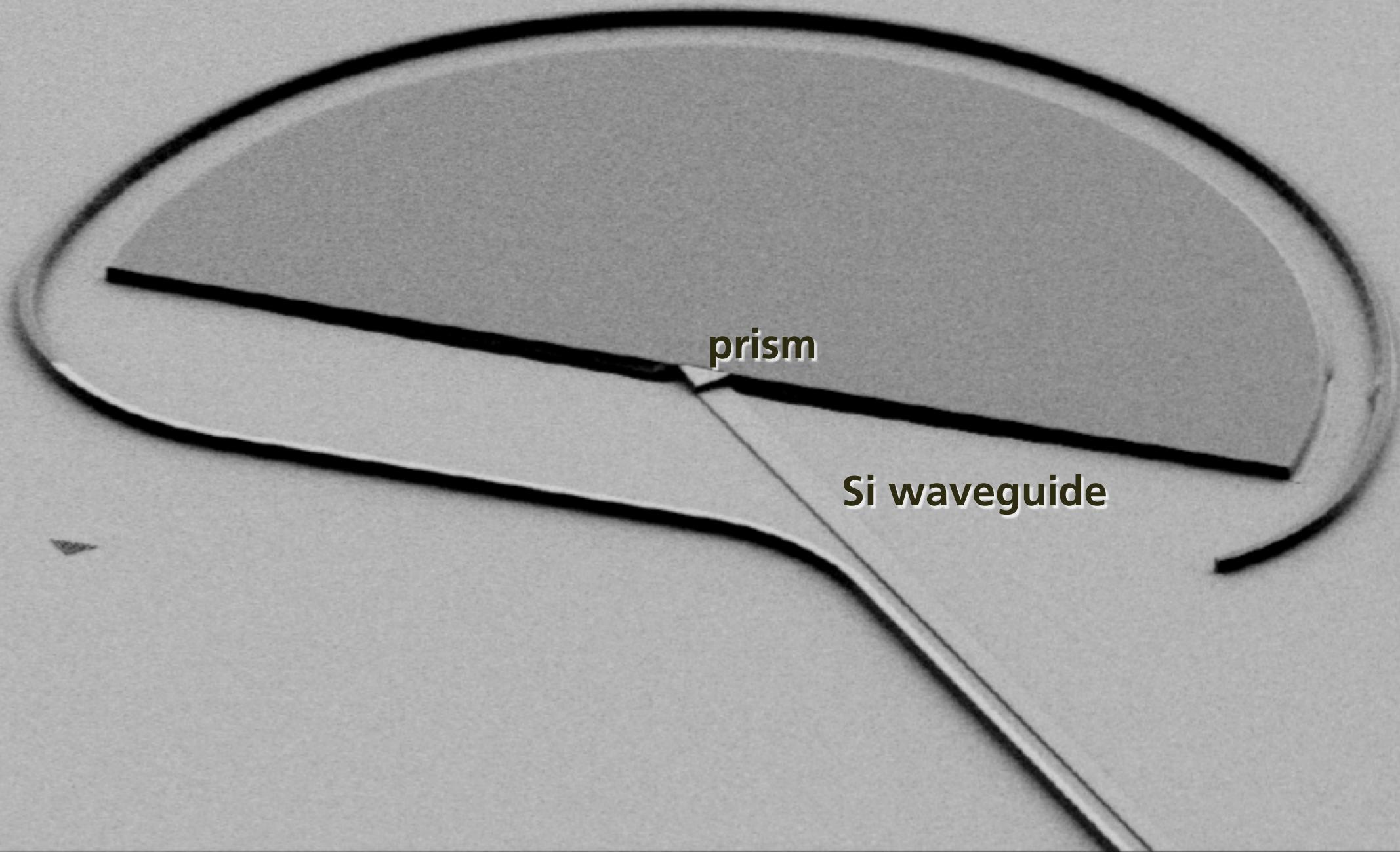
1 zero index



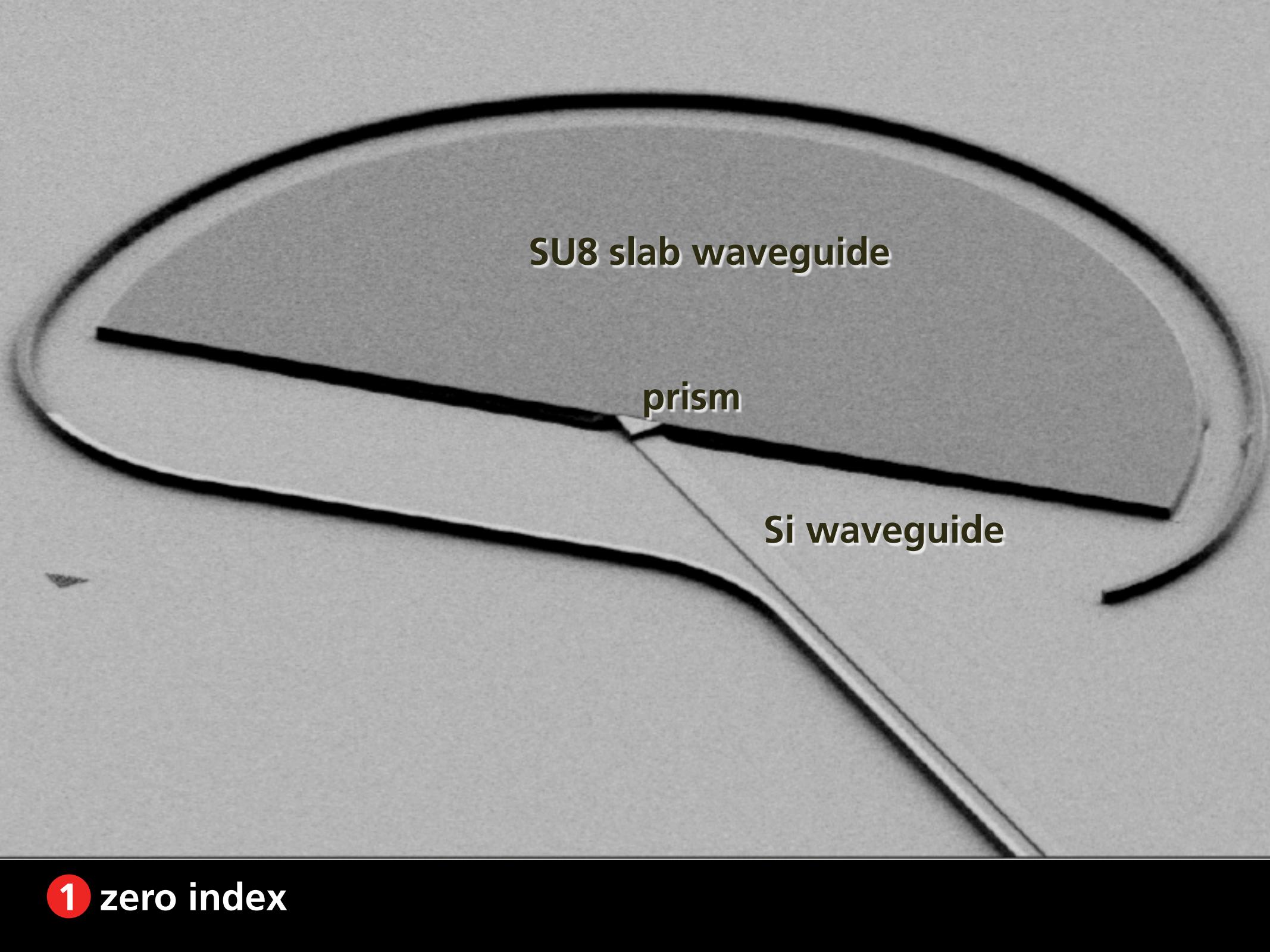
1 zero index



1 zero index



1 zero index

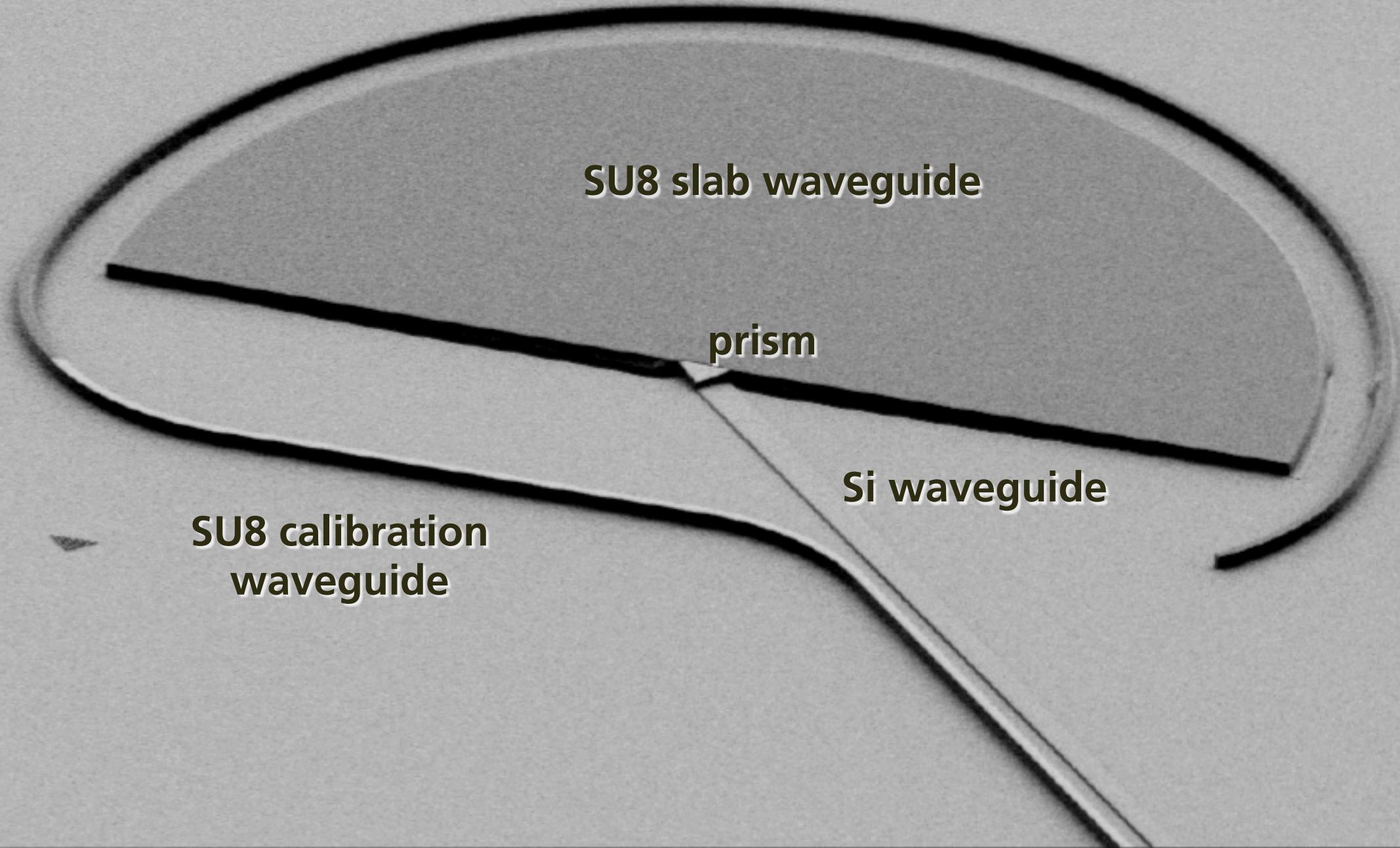


SU8 slab waveguide

prism

Si waveguide

1 zero index



SU8 slab waveguide

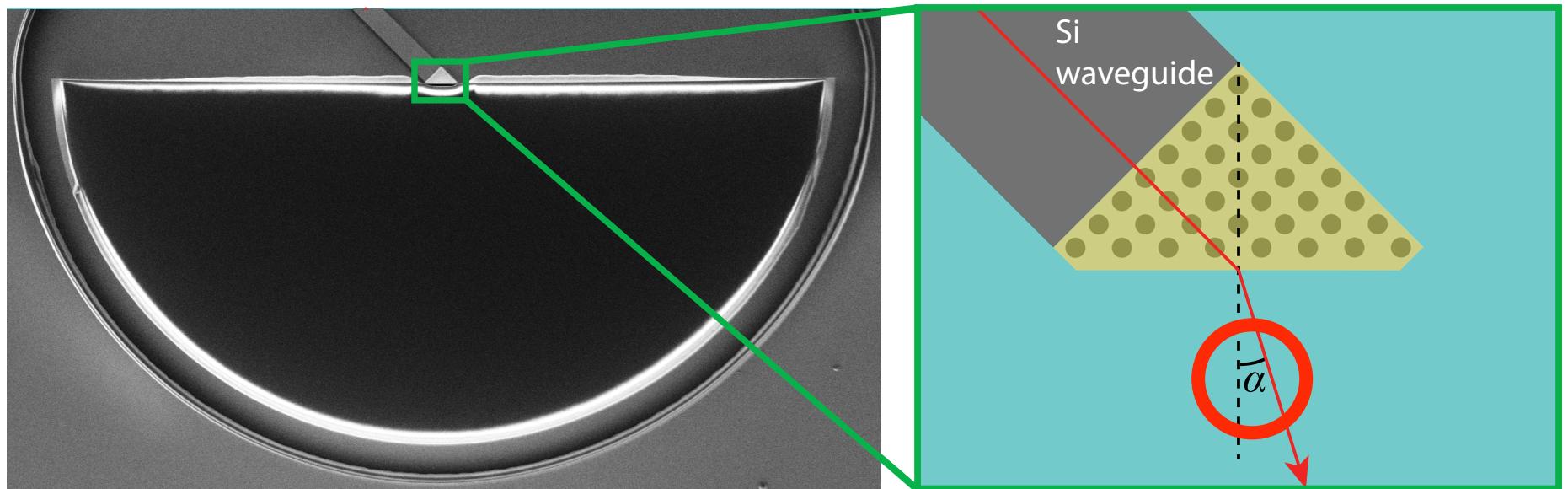
prism

**SU8 calibration
waveguide**

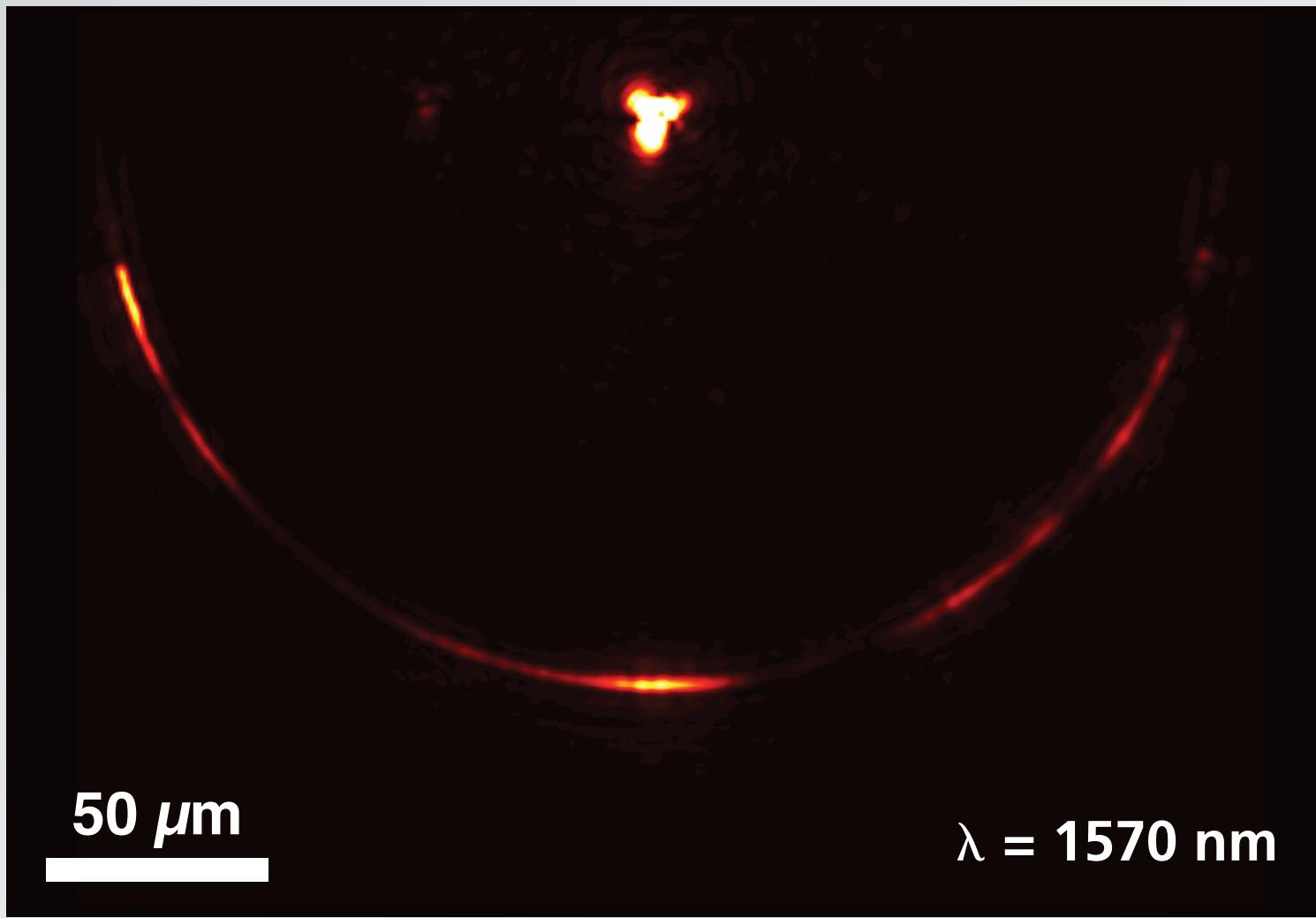
Si waveguide

1 zero index

On-chip zero-index prism



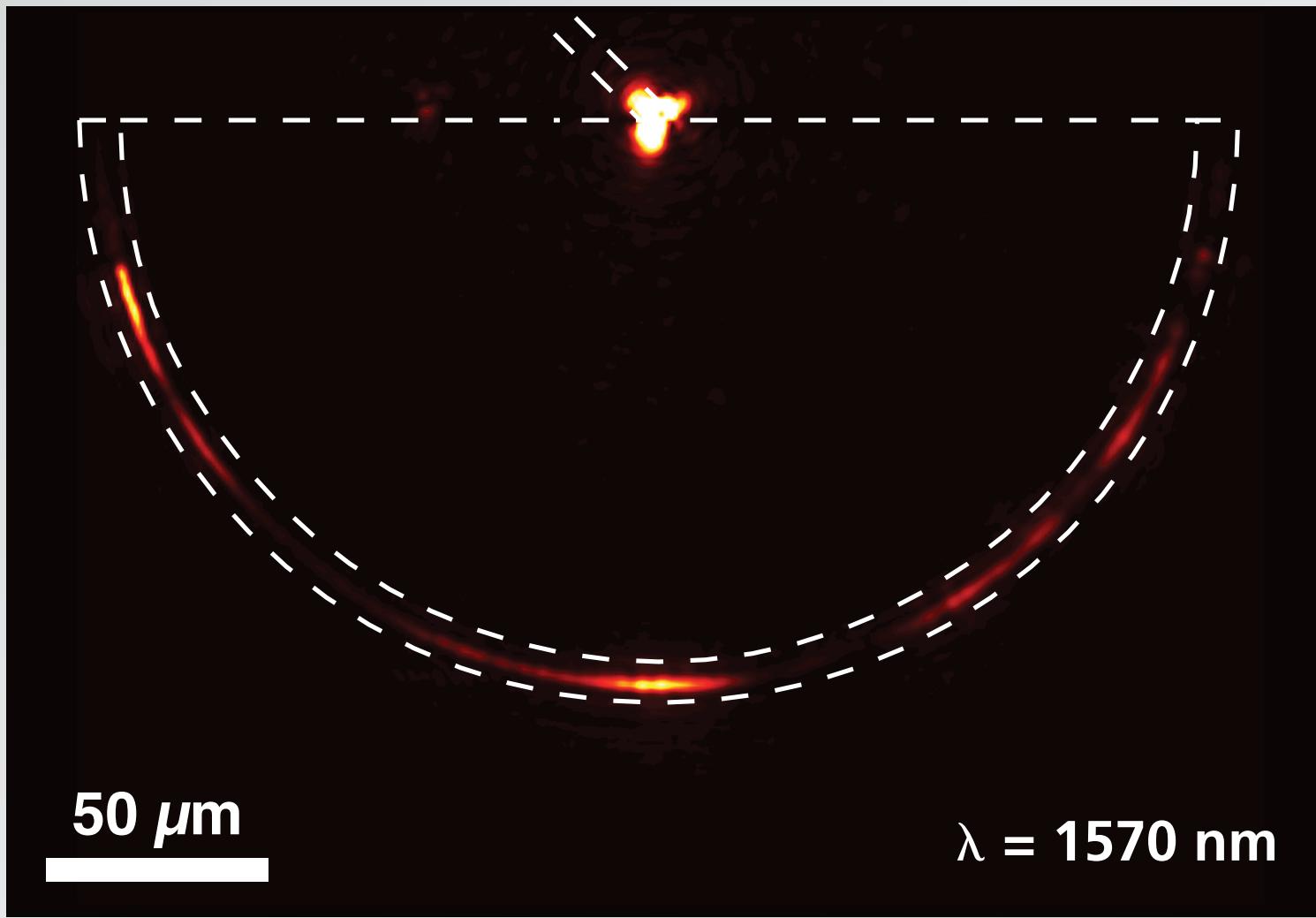
1 zero index



50 μm

$\lambda = 1570 \text{ nm}$

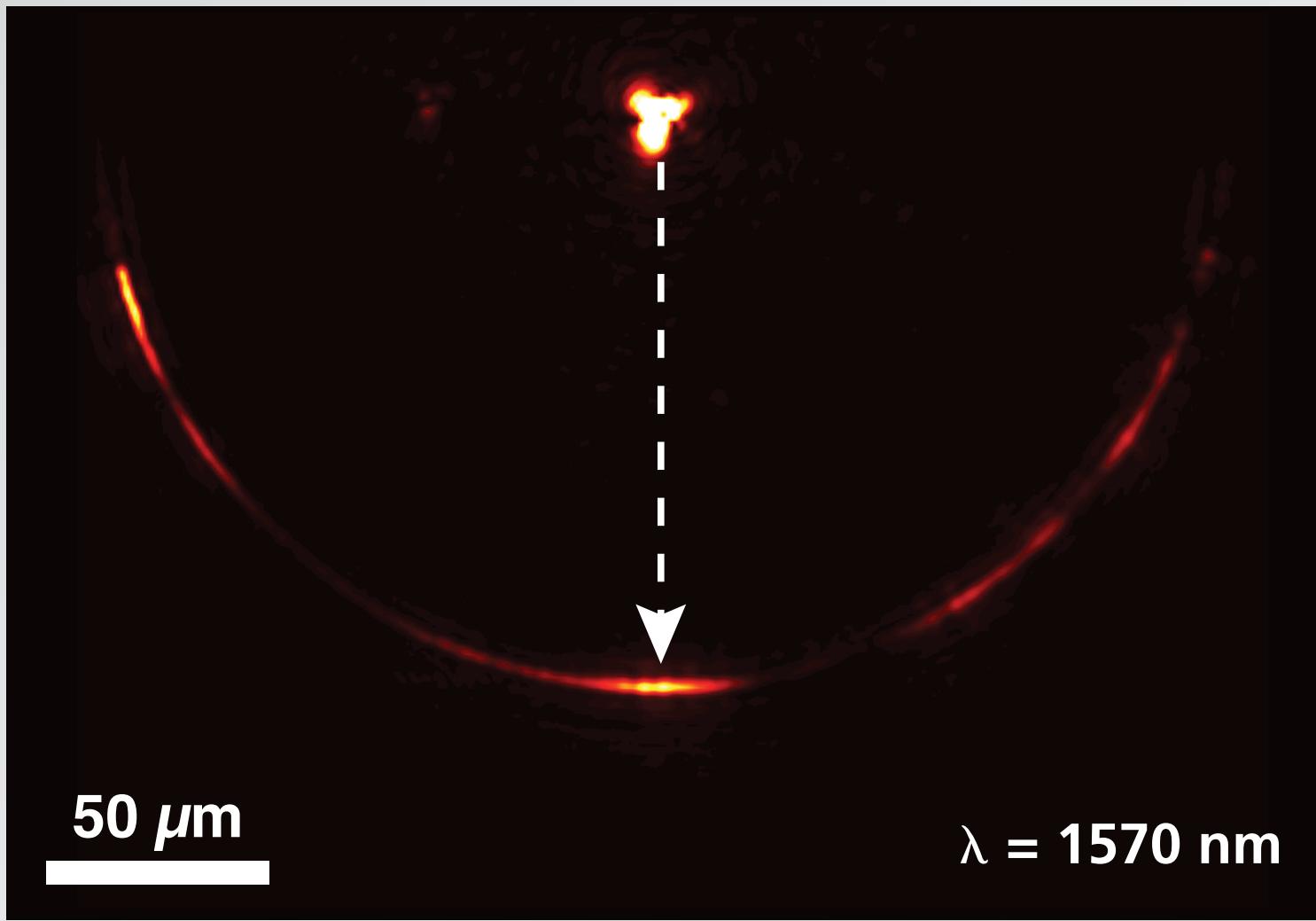
1 zero index



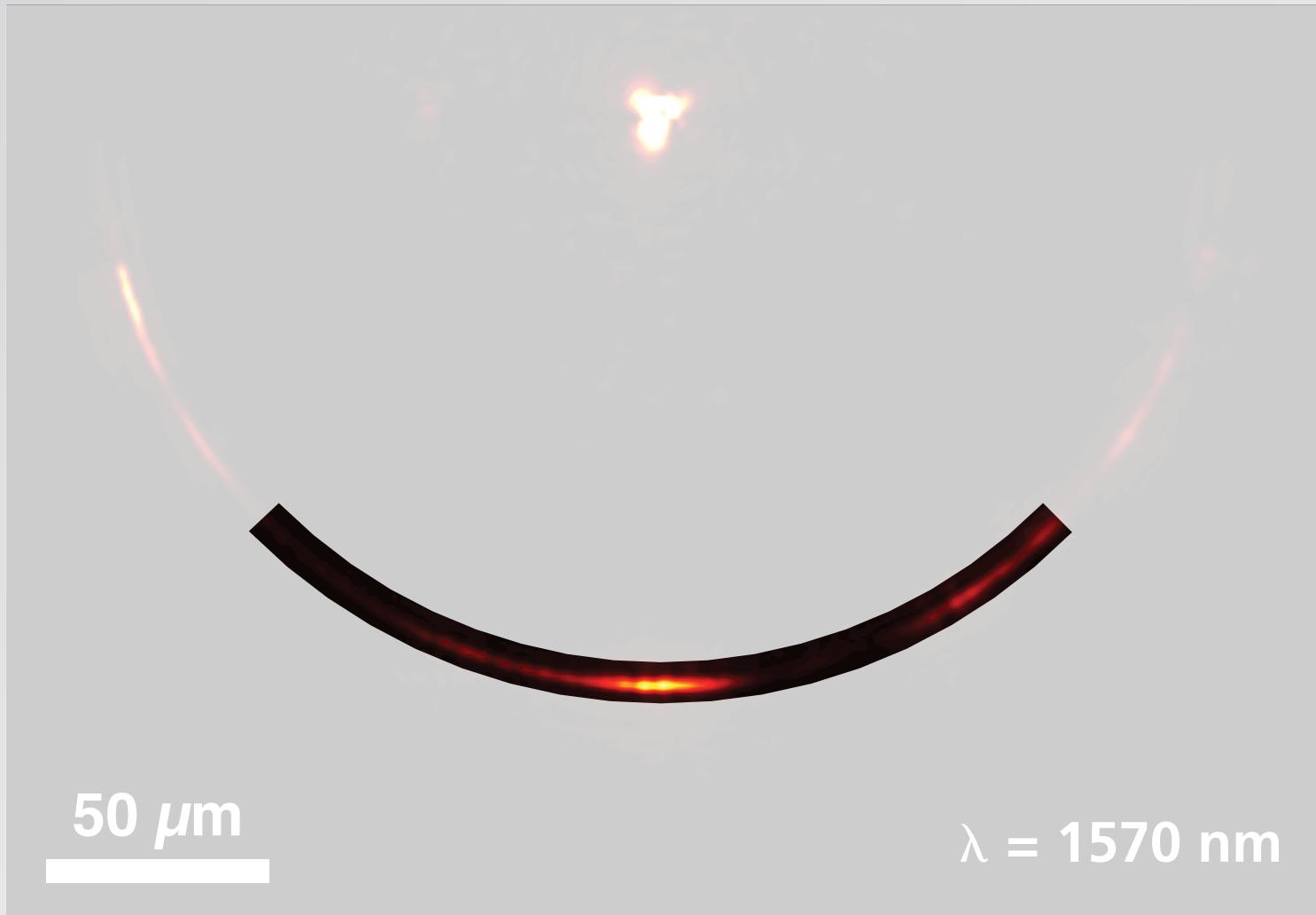
50 μm

$\lambda = 1570 \text{ nm}$

1 zero index

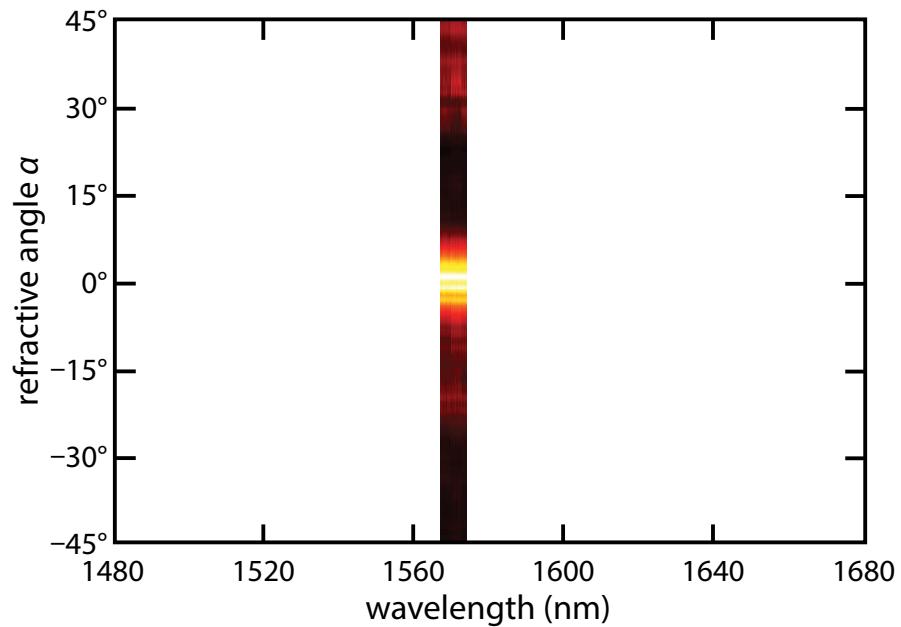


1 zero index



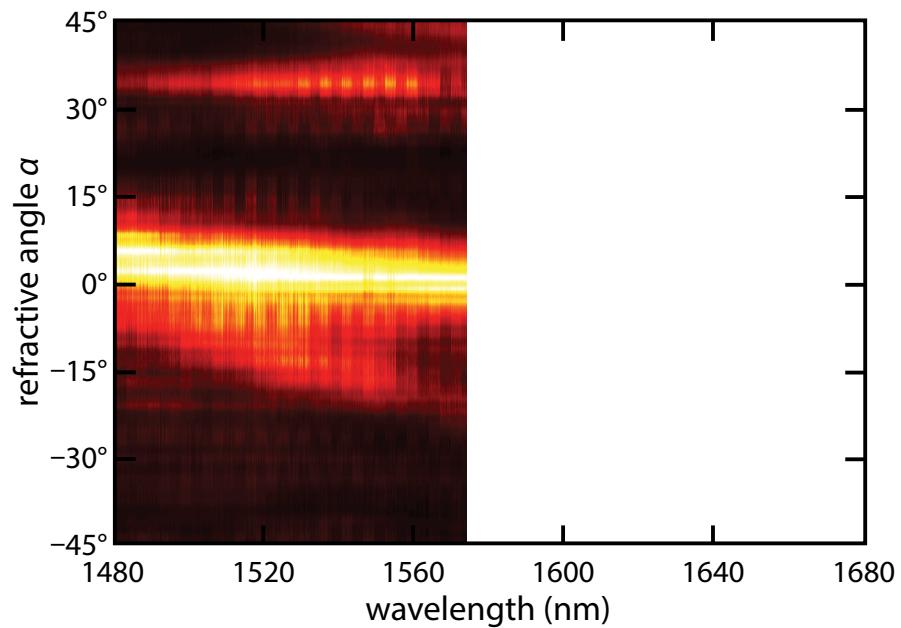
1 zero index

Wavelength dependence of refraction angle



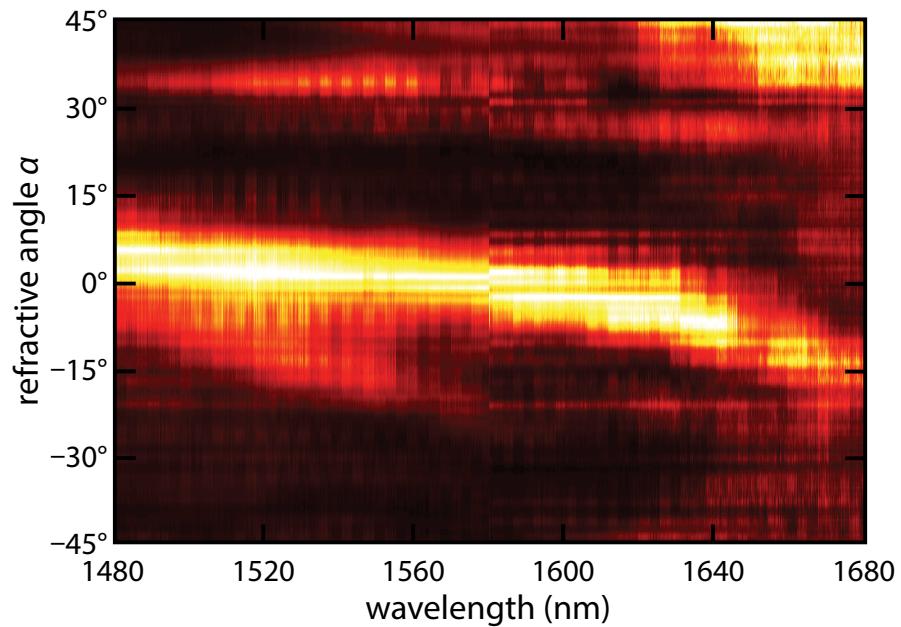
1 zero index

Wavelength dependence of refraction angle



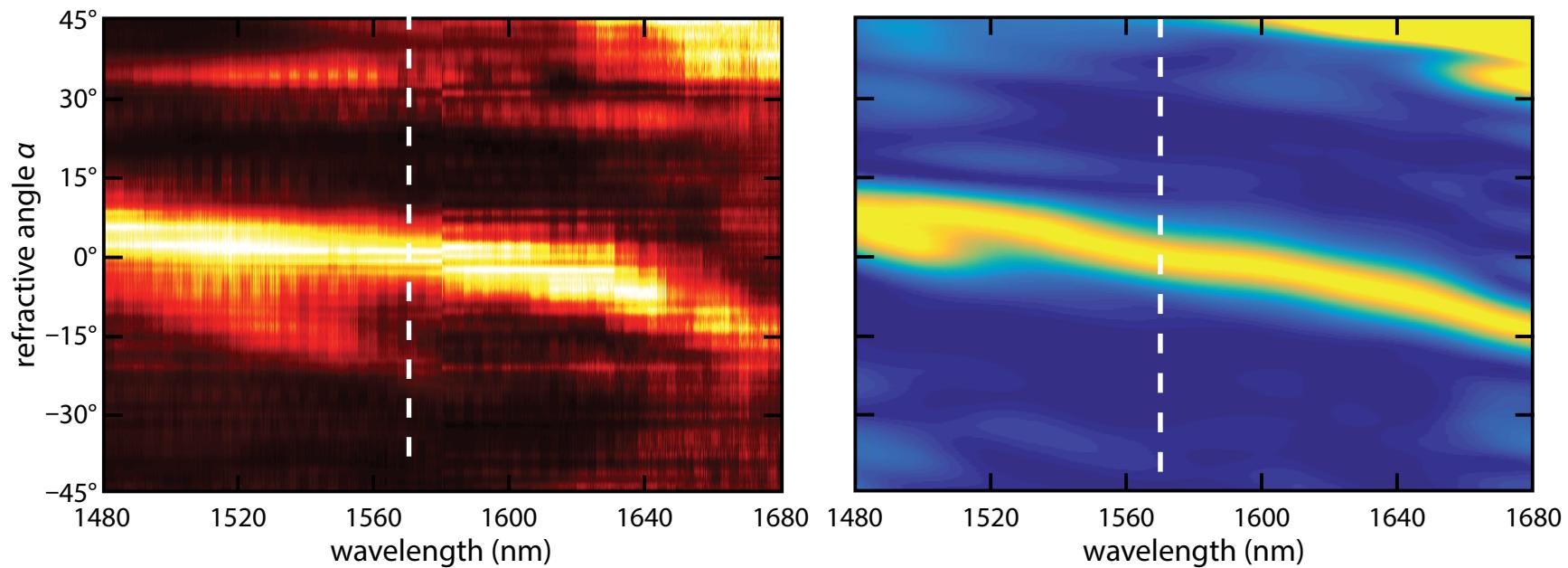
1 zero index

Wavelength dependence of refraction angle



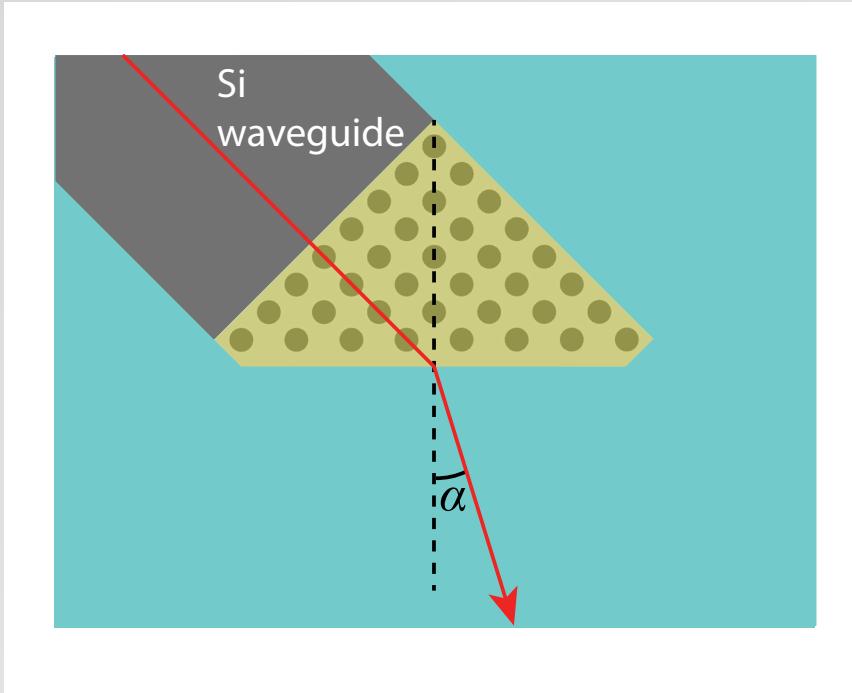
1 zero index

Wavelength dependence of refraction angle



1 zero index

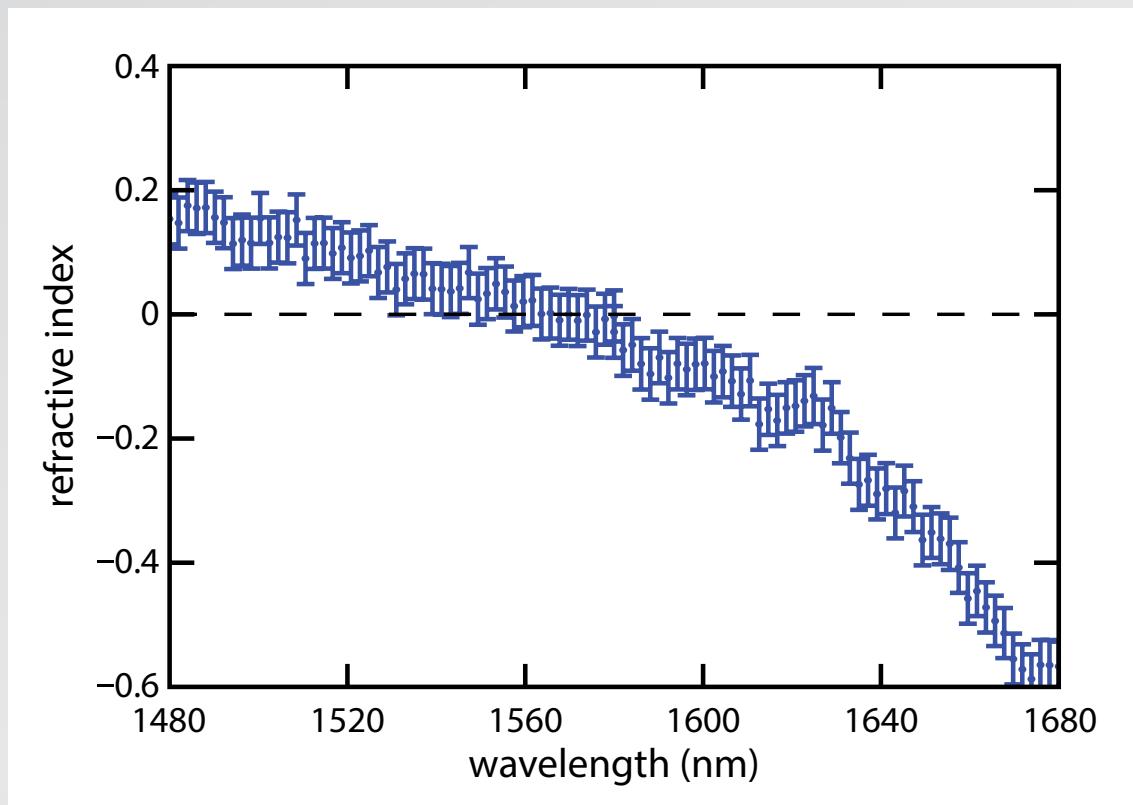
Wavelength dependence of index



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

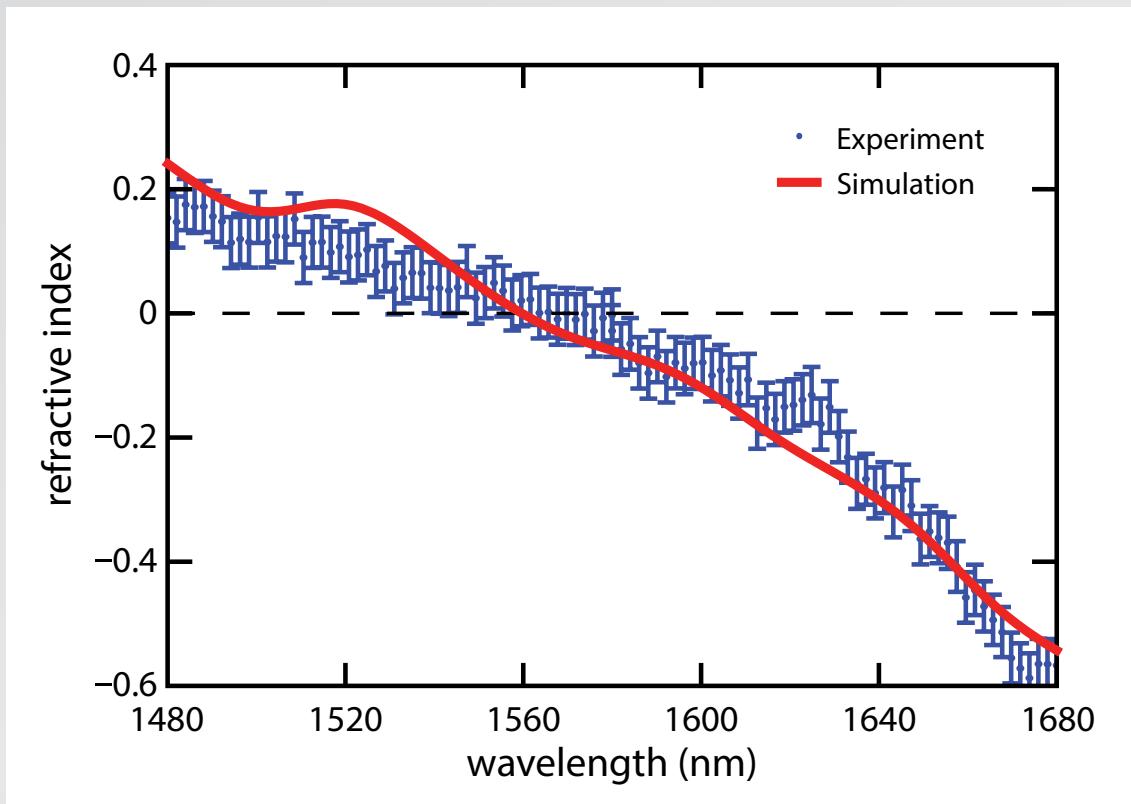
1 zero index

Wavelength dependence of index



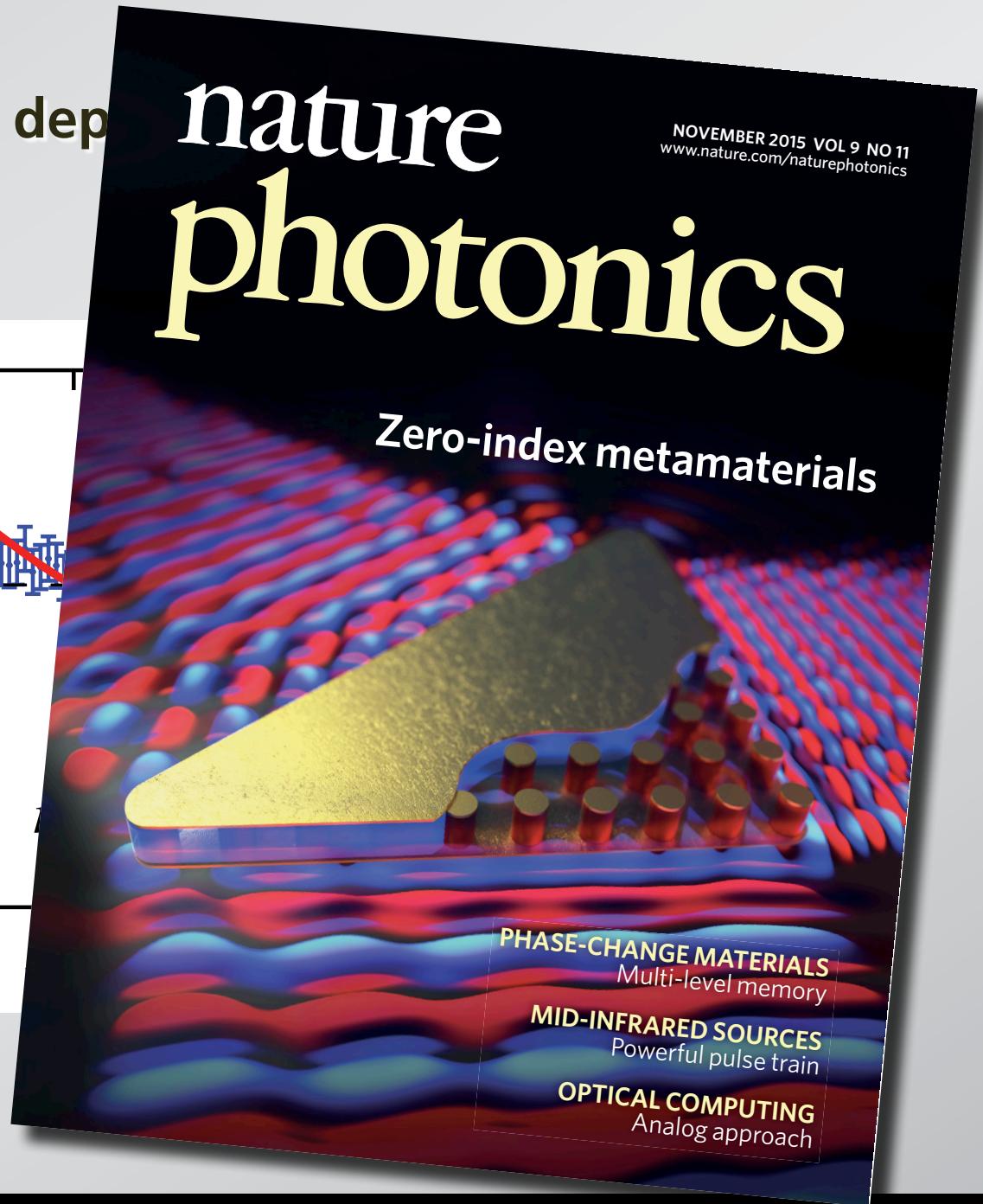
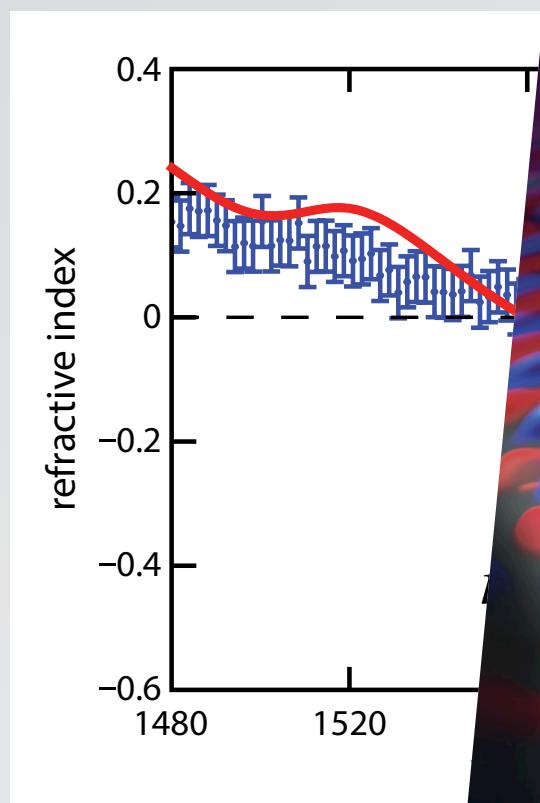
1 zero index

Wavelength dependence of index



1 zero index

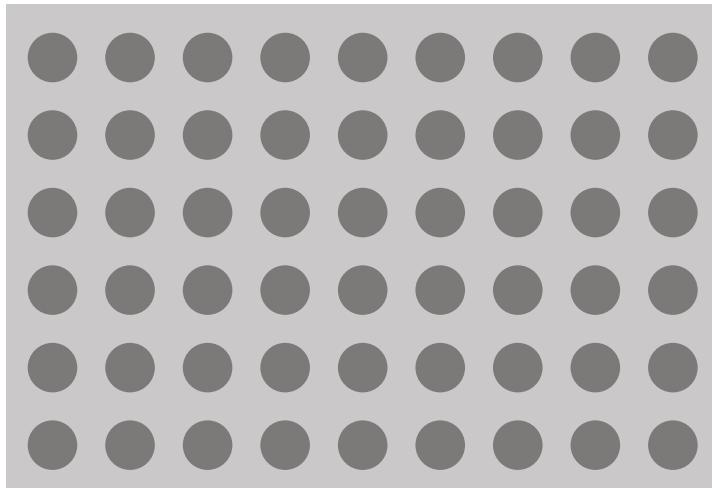
Wavelength dep



1 zero index

simplify fabrication

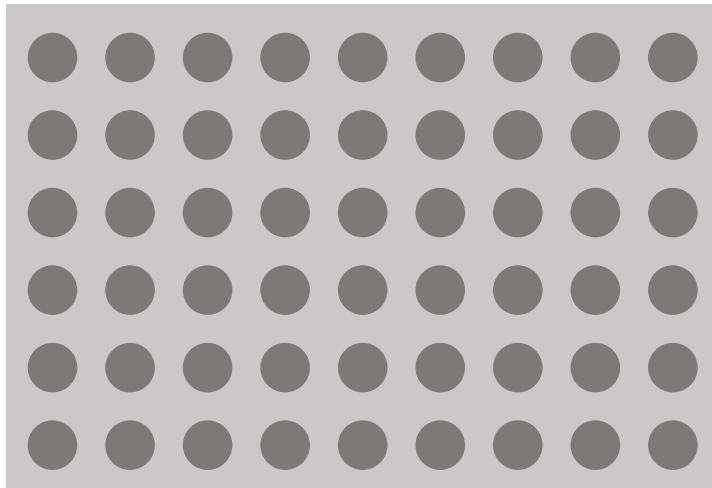
pillar array



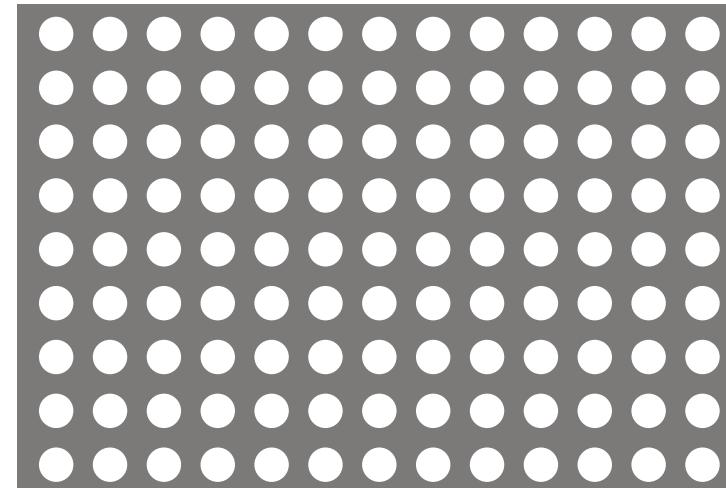
1 zero index

simplify fabrication

pillar array

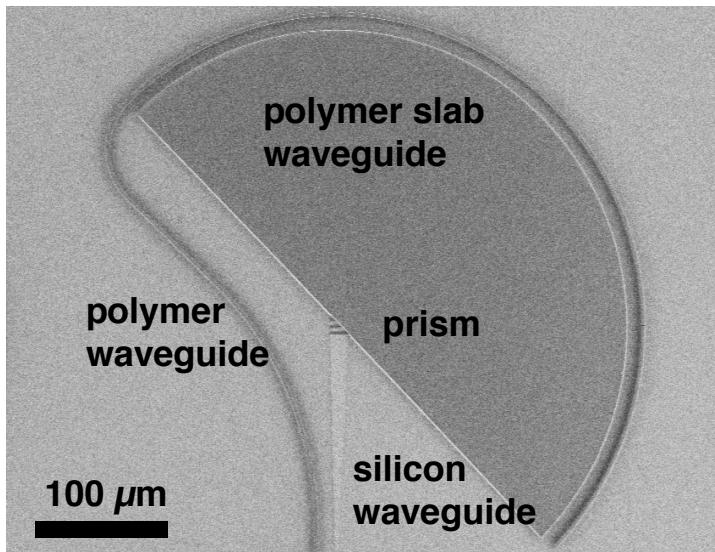


airhole array



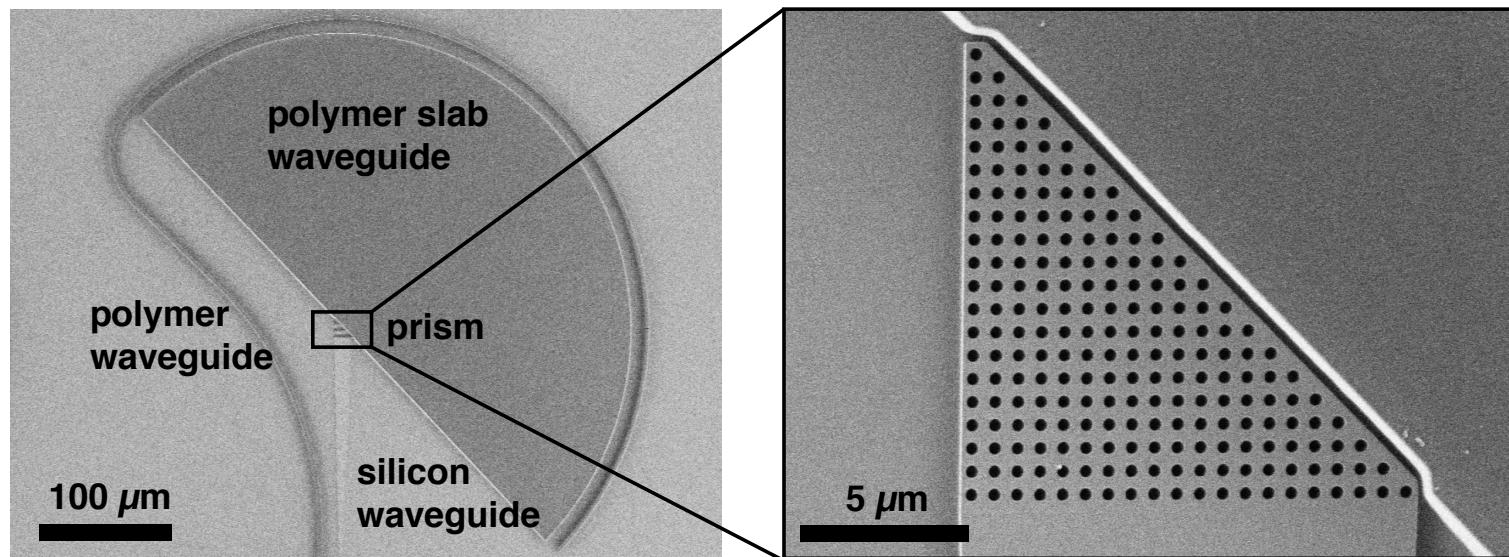
1 zero index

simplify fabrication



1 zero index

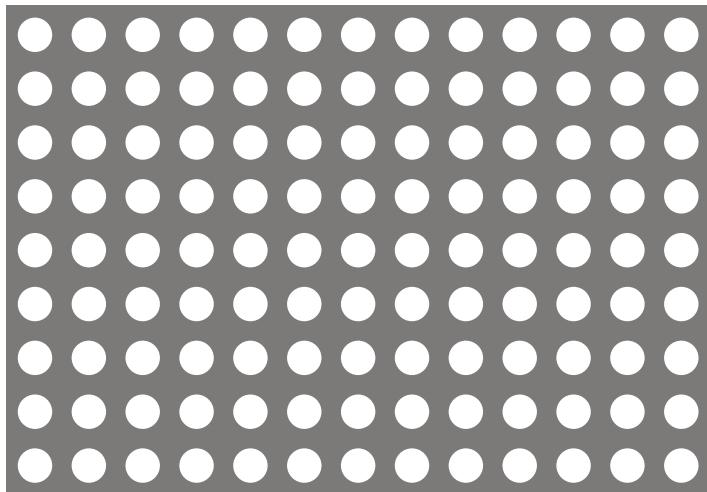
simplify fabrication



1 zero index

simplify further!

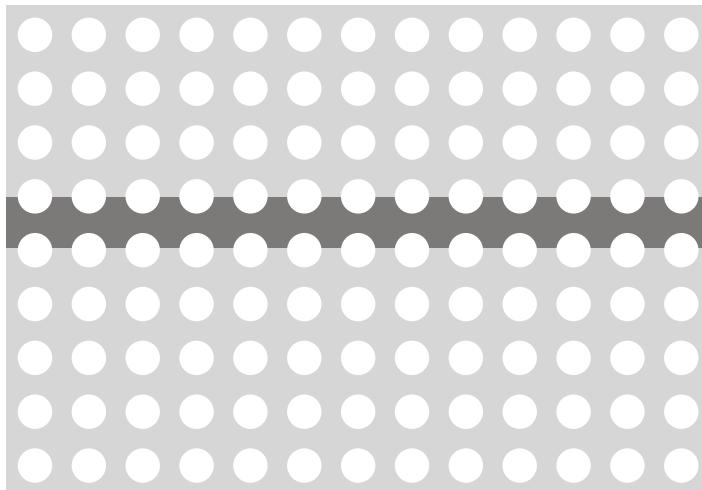
airhole array



1 zero index

simplify further!

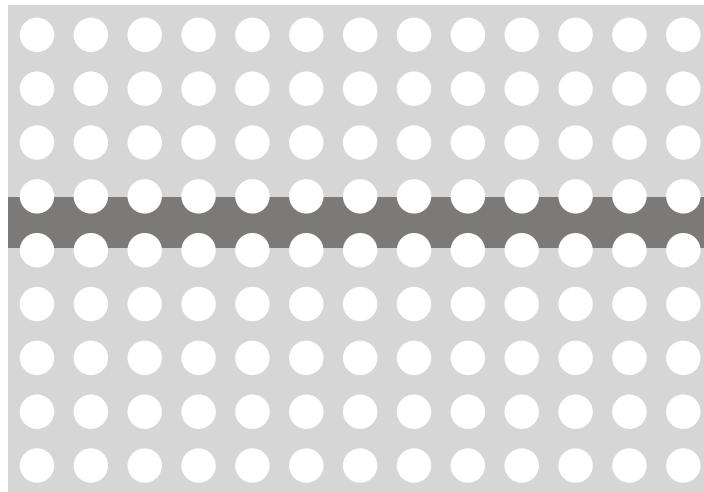
airhole array



1 zero index

simplify further!

airhole array



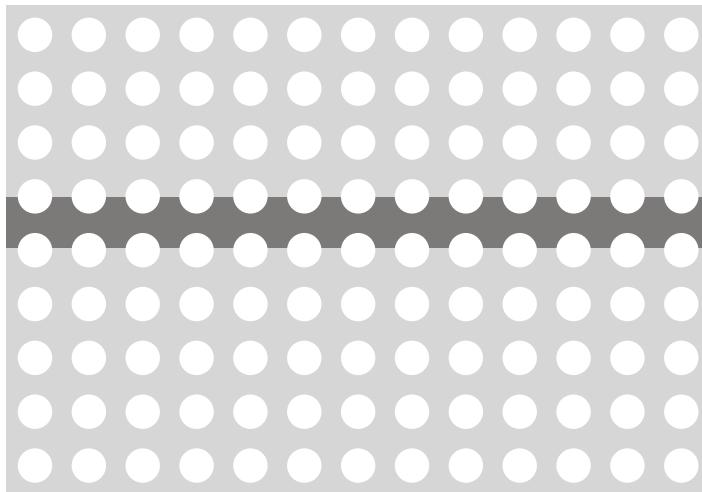
1D ZIM waveguide



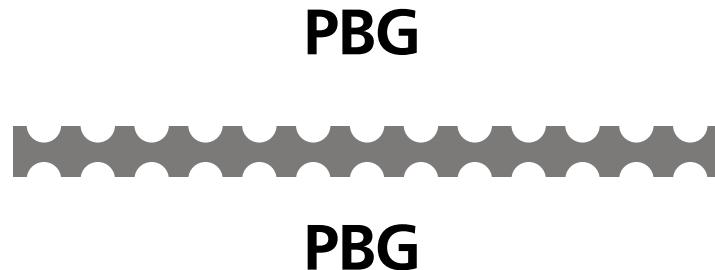
1 zero index

simplify further!

airhole array

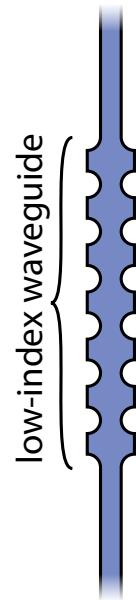


1D ZIM waveguide



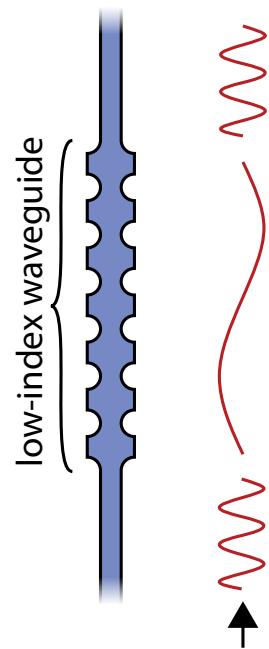
1 zero index

waveguiding



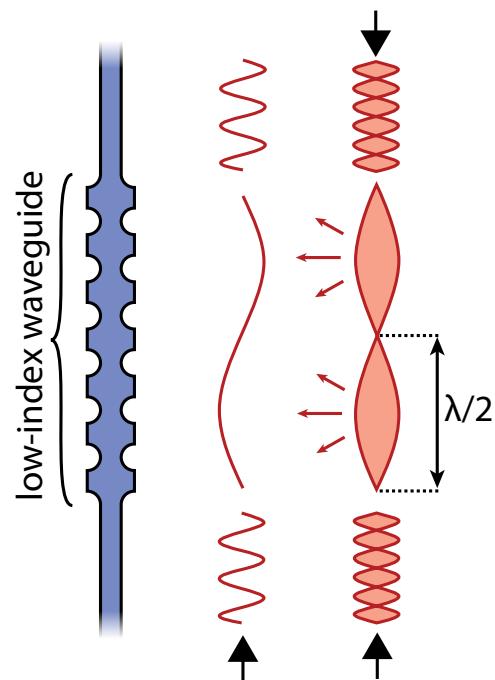
1 zero index

waveguiding



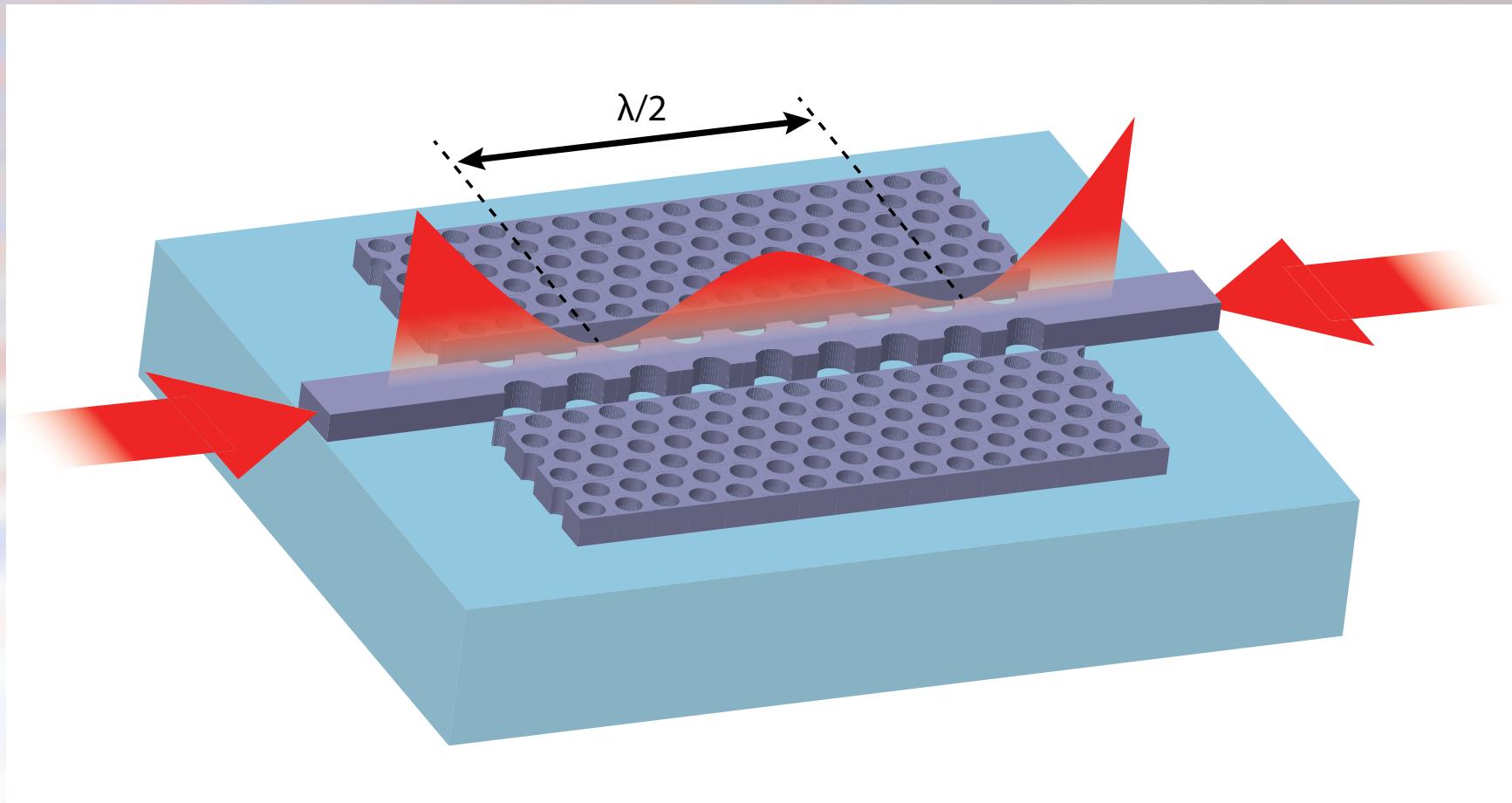
1 zero index

waveguiding



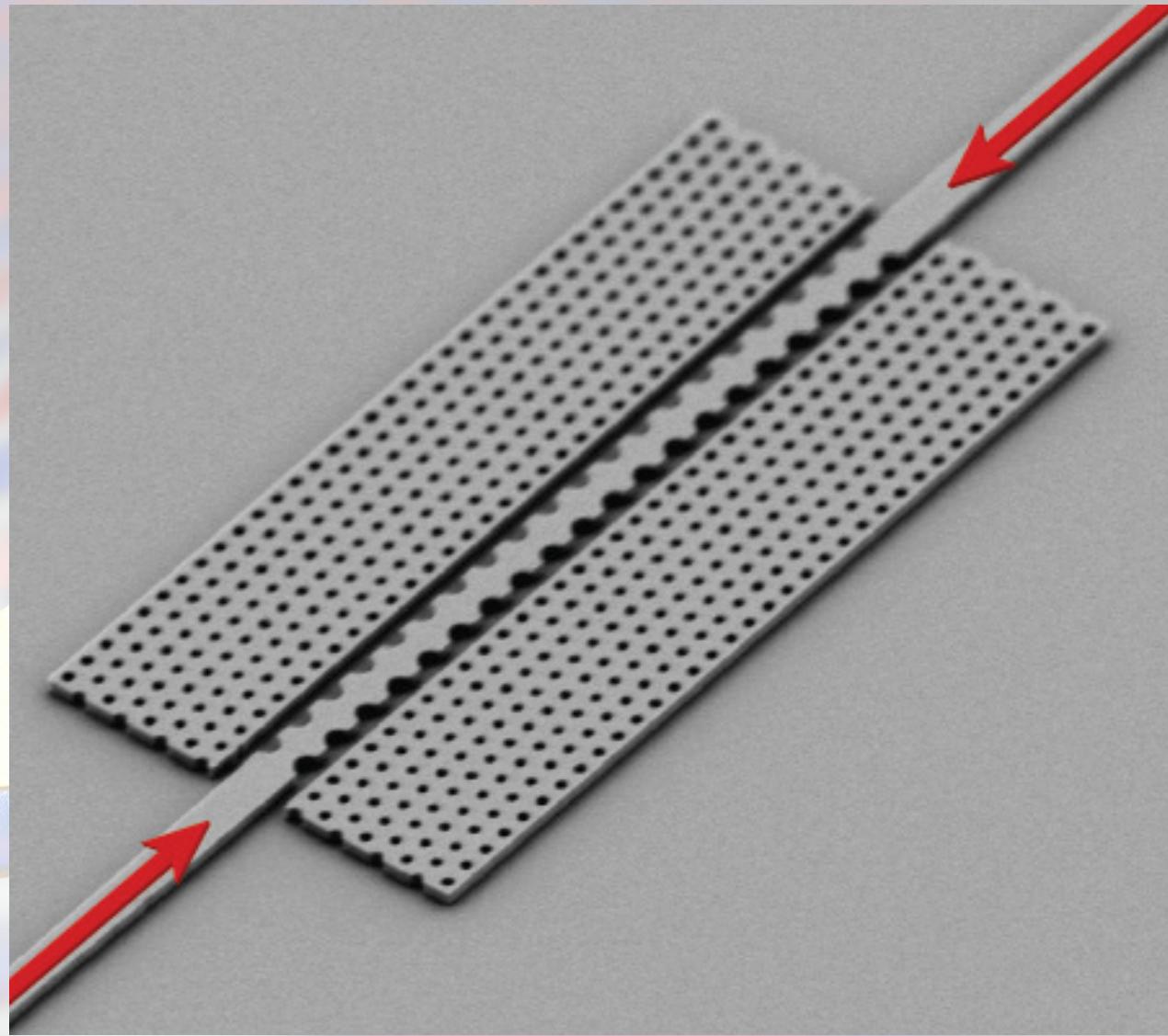
1 zero index

look at standing waves



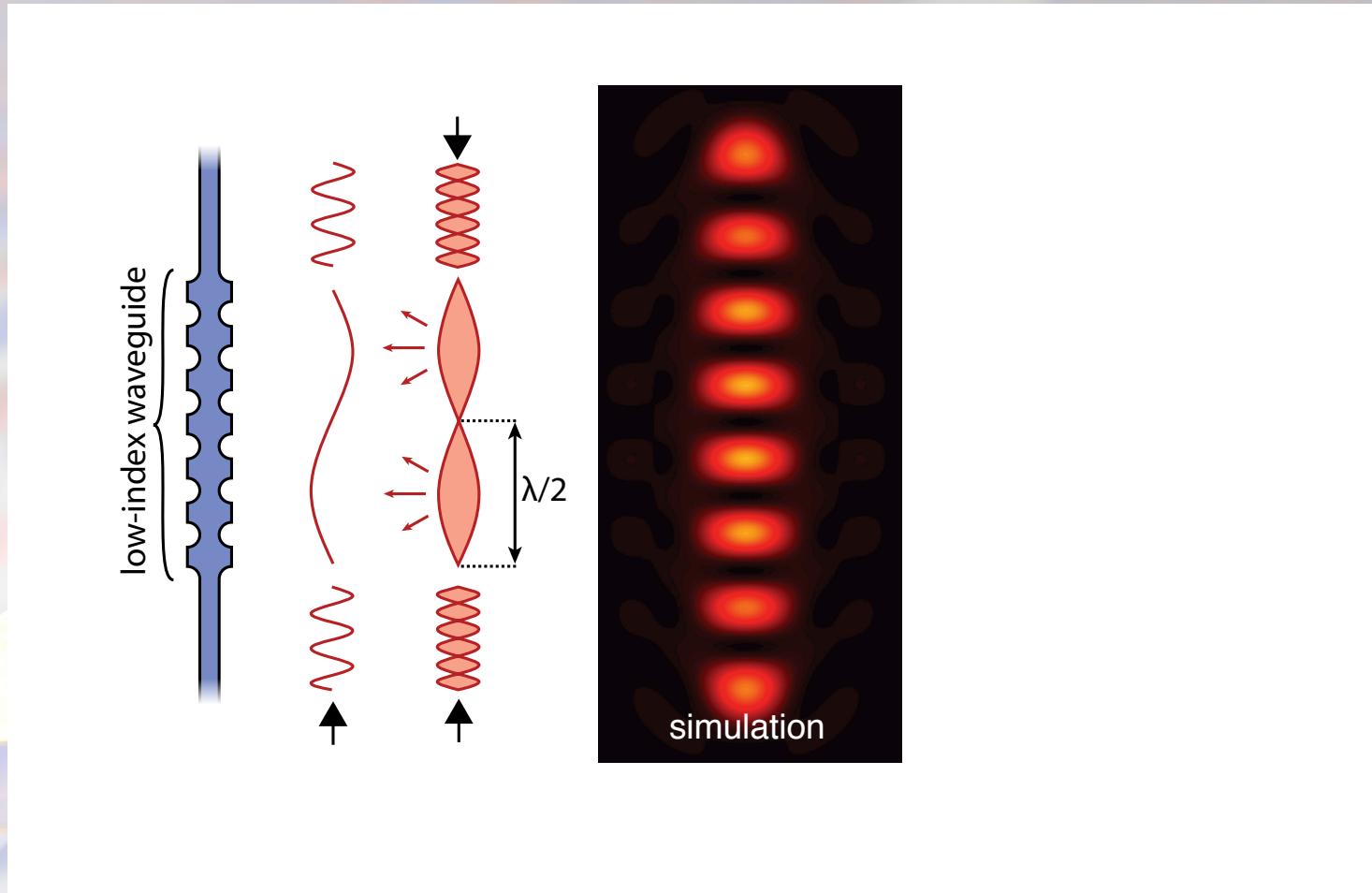
1 zero index

look at standing waves



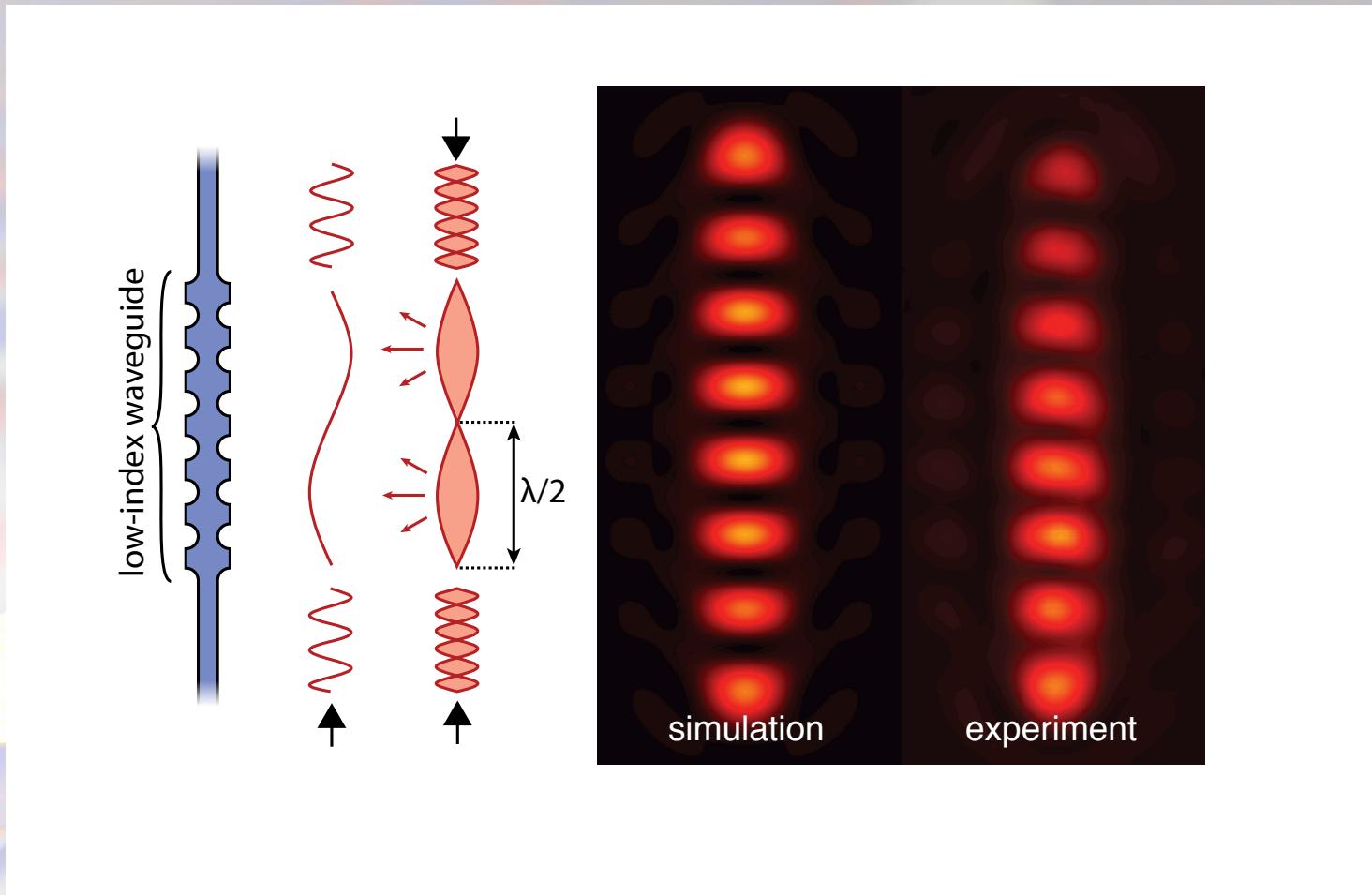
1 zero index

look at standing waves



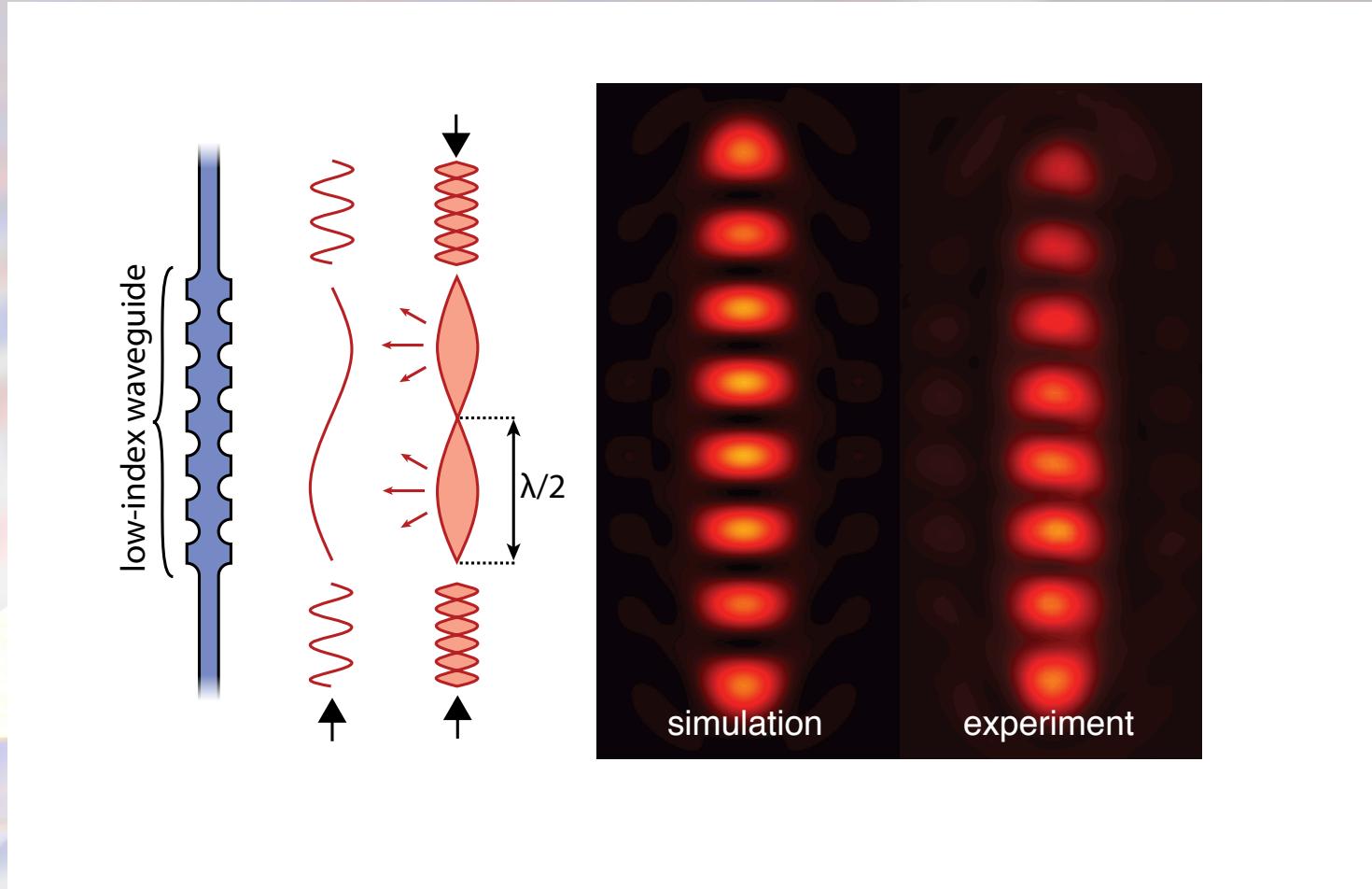
1 zero index

look at standing waves



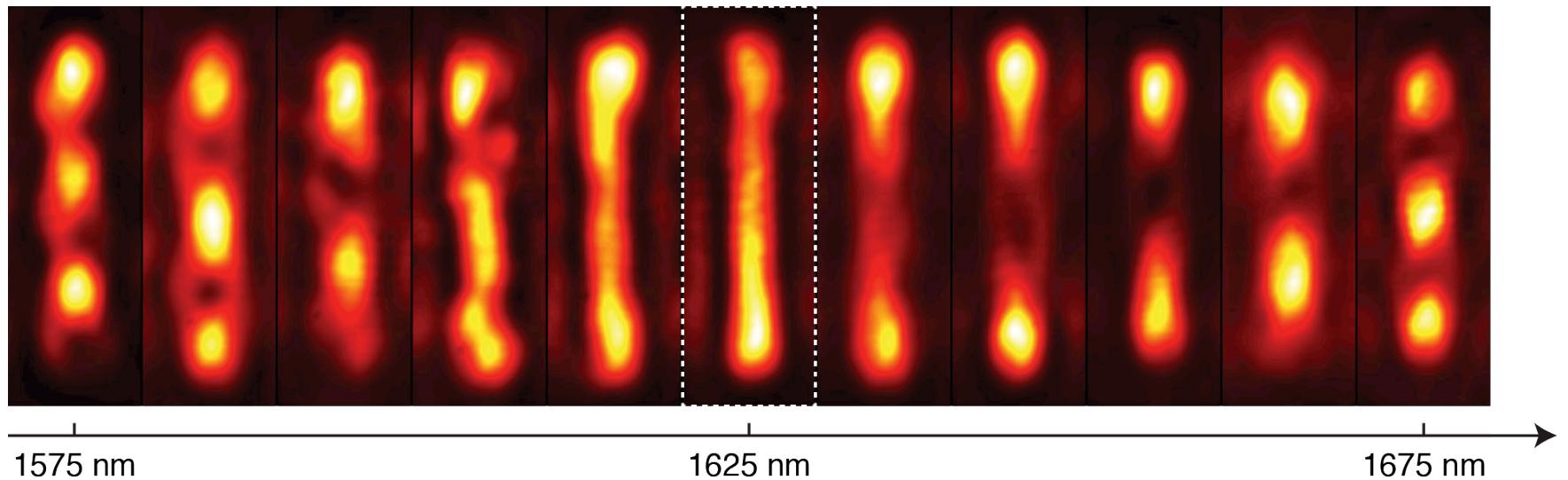
1 zero index

direct observation of effective wavelength!!



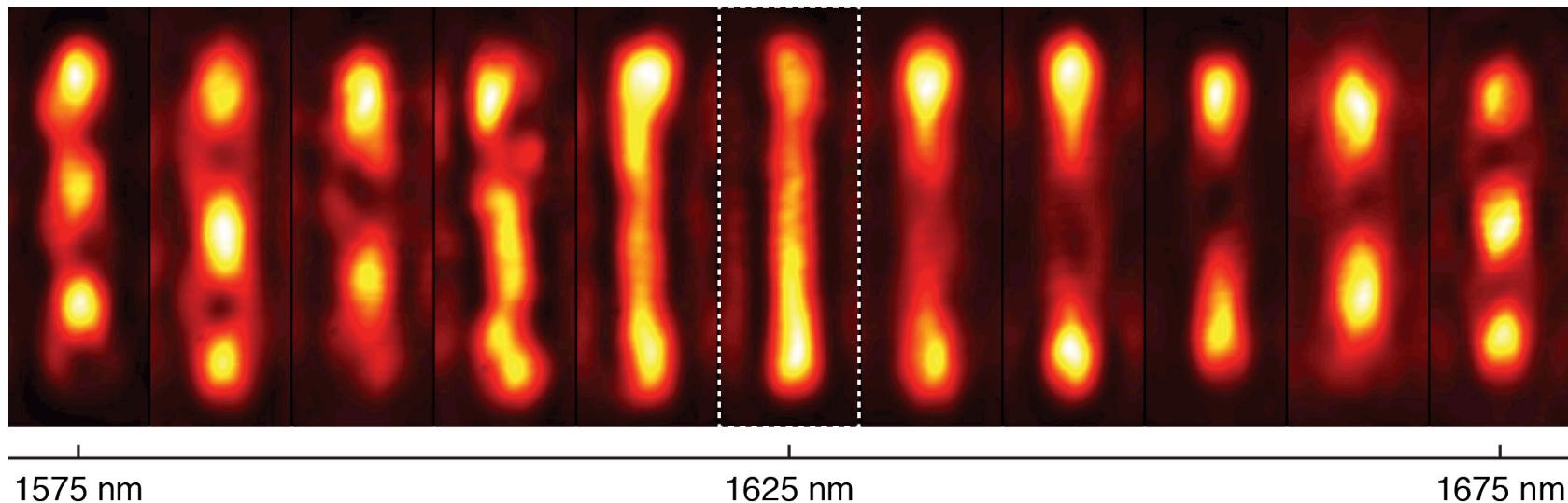
1 zero index

look at standing waves



1 zero index

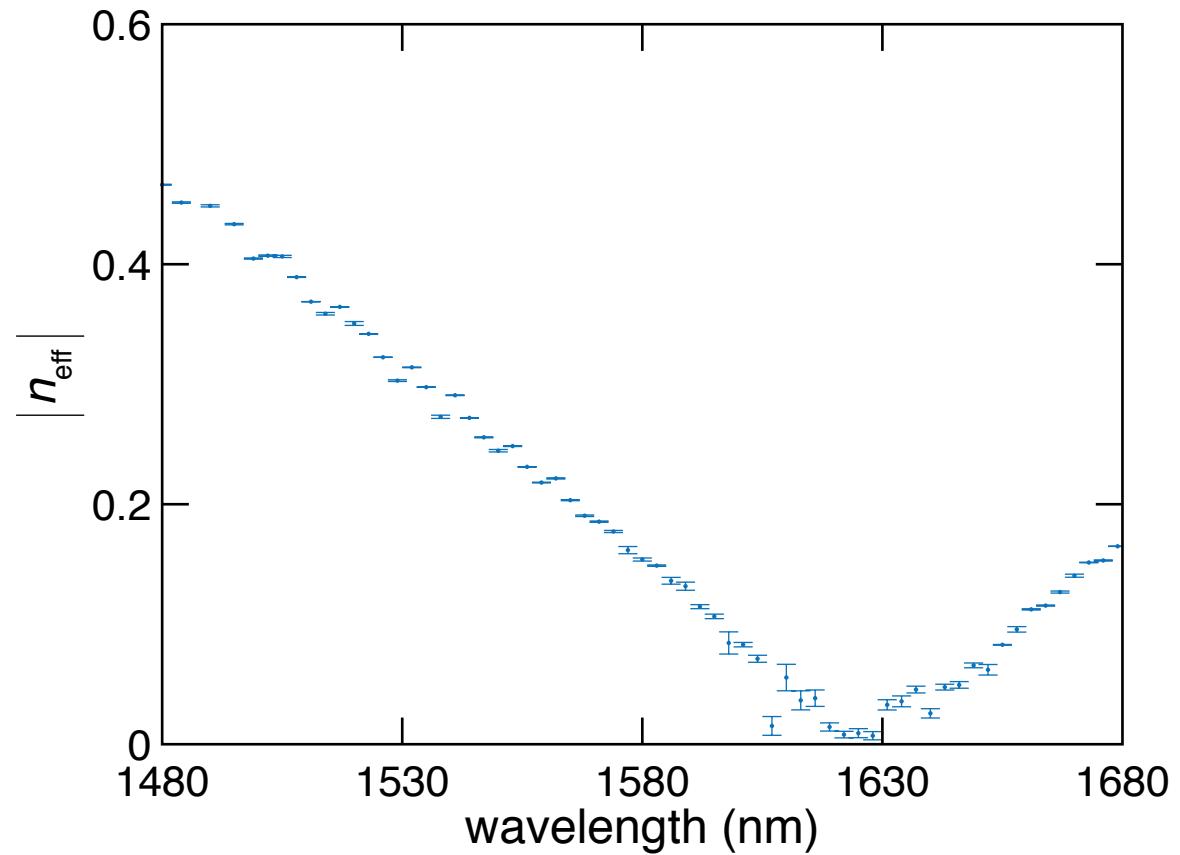
look at standing waves



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

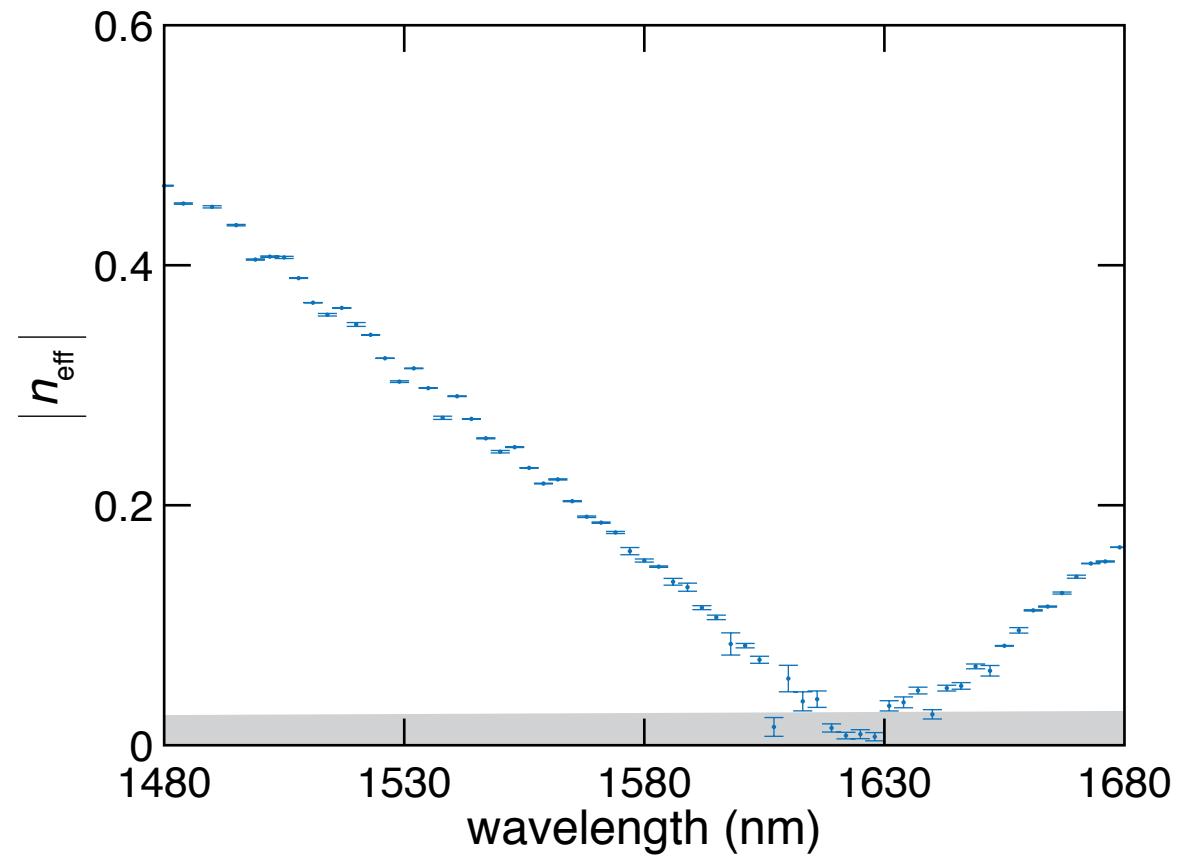
1 zero index

comparison of experiment and simulation



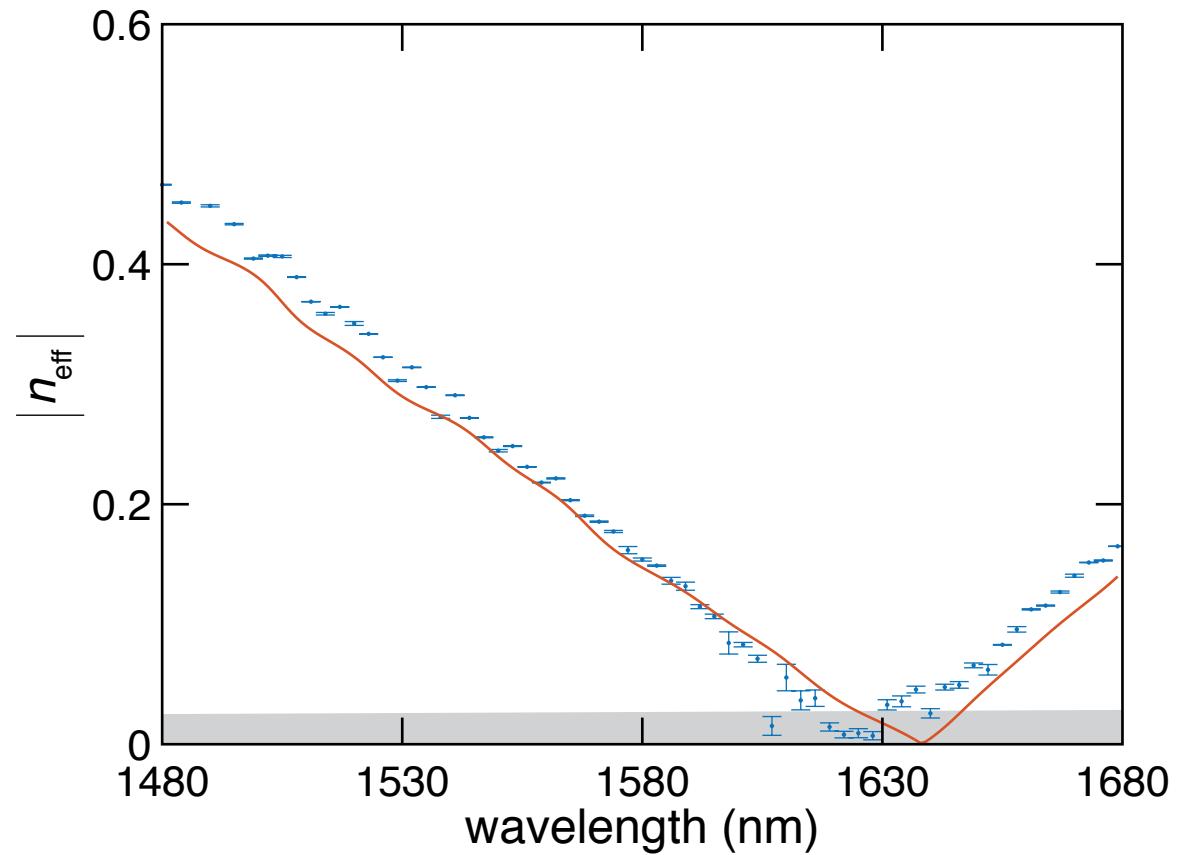
1 zero index

comparison of experiment and simulation



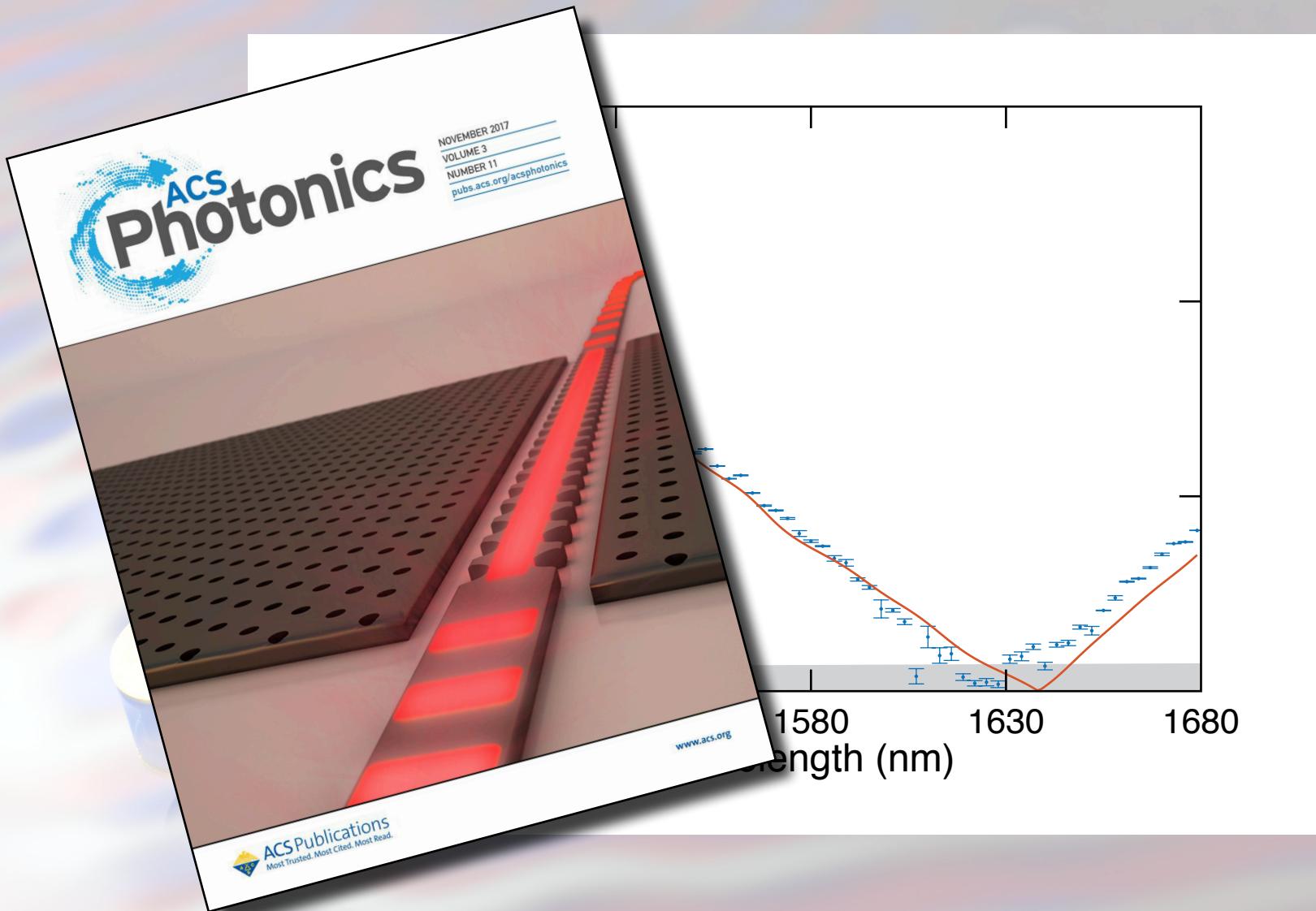
1 zero index

comparison of experiment and simulation

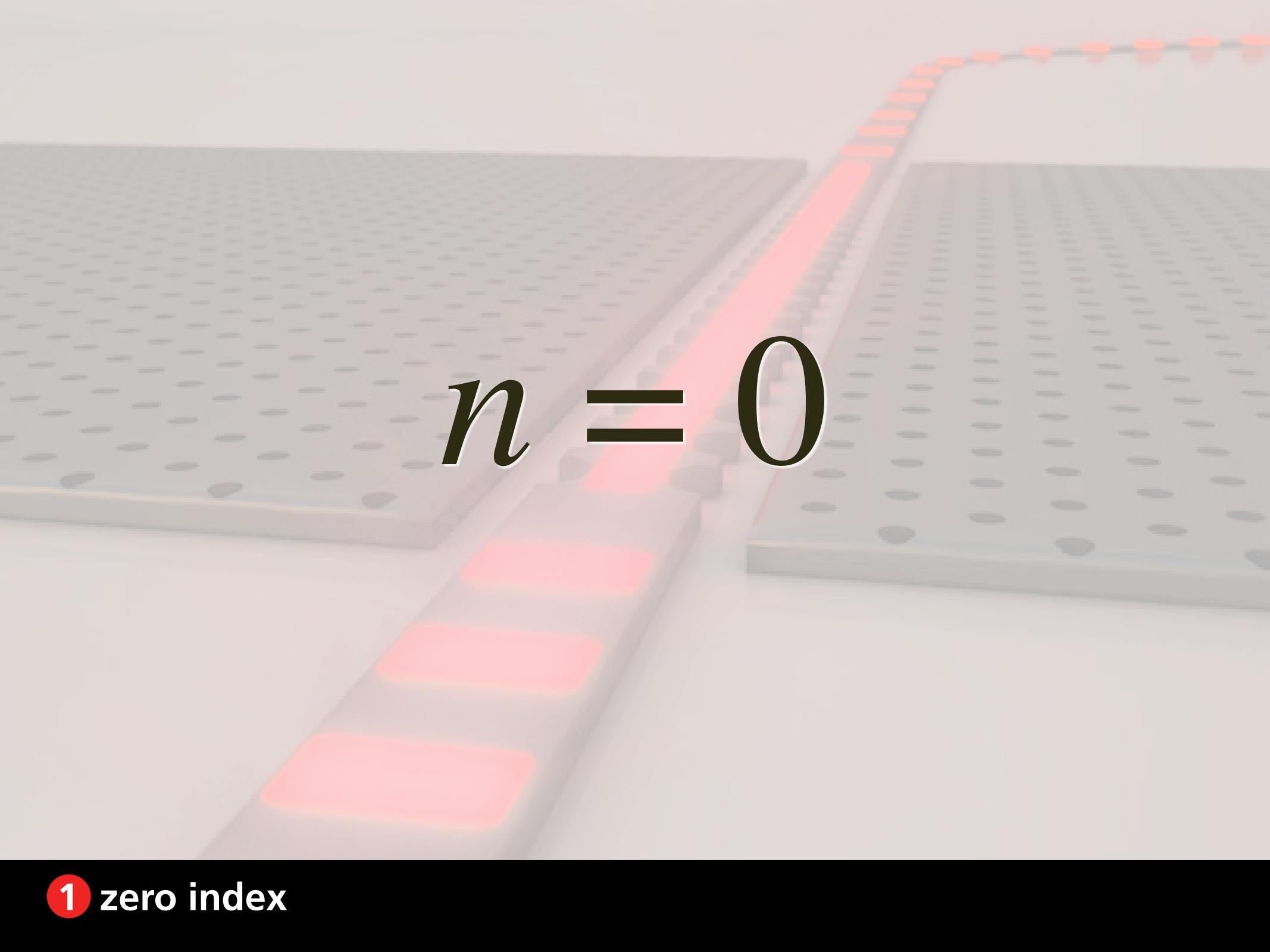


1 zero index

comparison of experiment and simulation



1 zero index

 $n = 0$

1 zero index

(extreme) opportunities

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

(extreme) opportunities

$$A_{21}(\omega) \rightarrow 0 \quad \text{and} \quad B_{21}(\omega) \rightarrow \infty$$

1 zero index

$$v_g = \frac{d\omega}{dk}$$

1 zero index

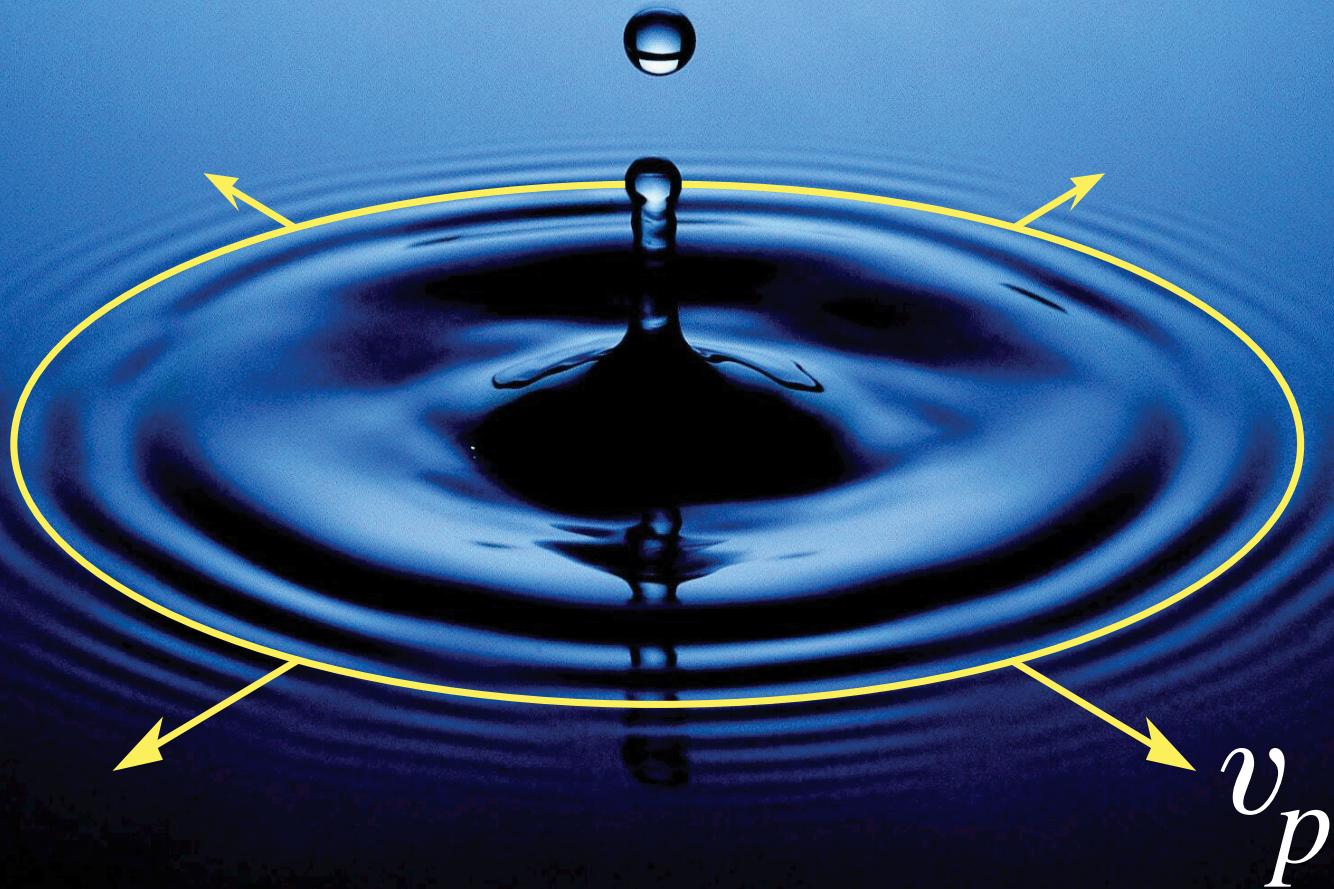
2 zero group velocity



1 zero index

2 zero group velocity

phase velocity



1 zero index

2 zero group velocity

group velocity



1 zero index

2 zero group velocity

$$v_g = \frac{1}{2} v_p$$



1 zero index

2 zero group velocity

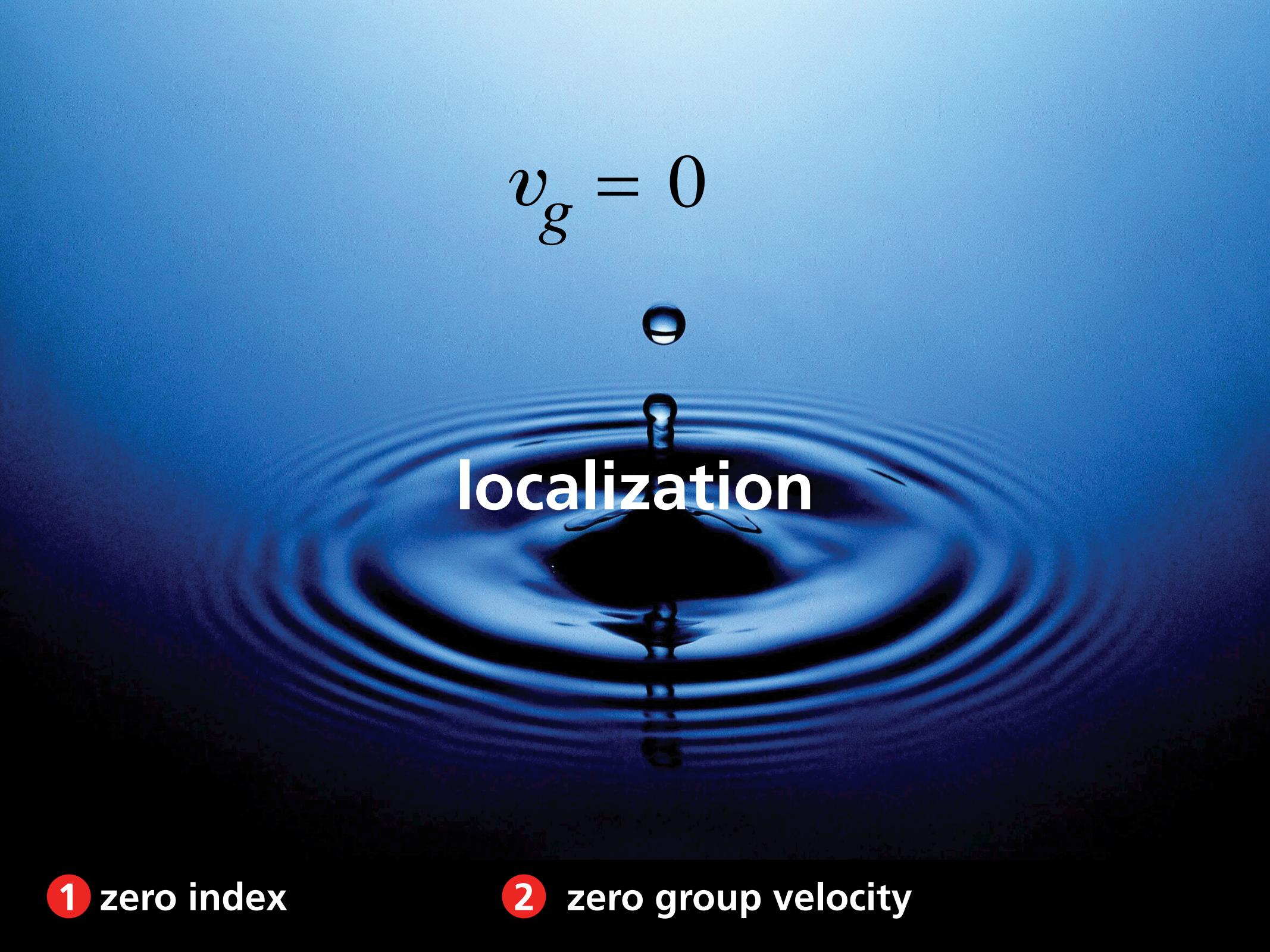
$$v_g = 0$$



1 zero index

2 zero group velocity

$$v_g = 0$$

A close-up photograph of a single water droplet hitting a dark blue surface. The impact has created a series of concentric, glowing blue ripples that radiate outwards from the center. The droplet itself is suspended in mid-air above the impact point.

localization

1 zero index

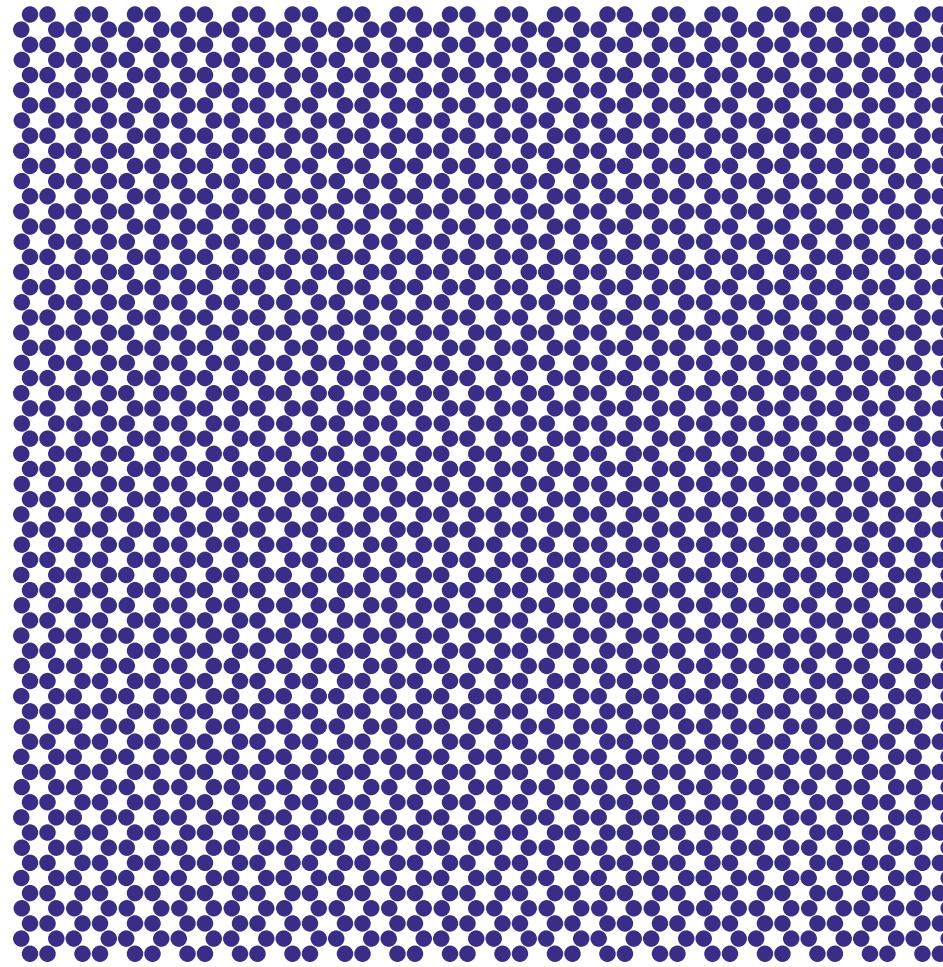
2 zero group velocity



how can we localize light?

1 zero index

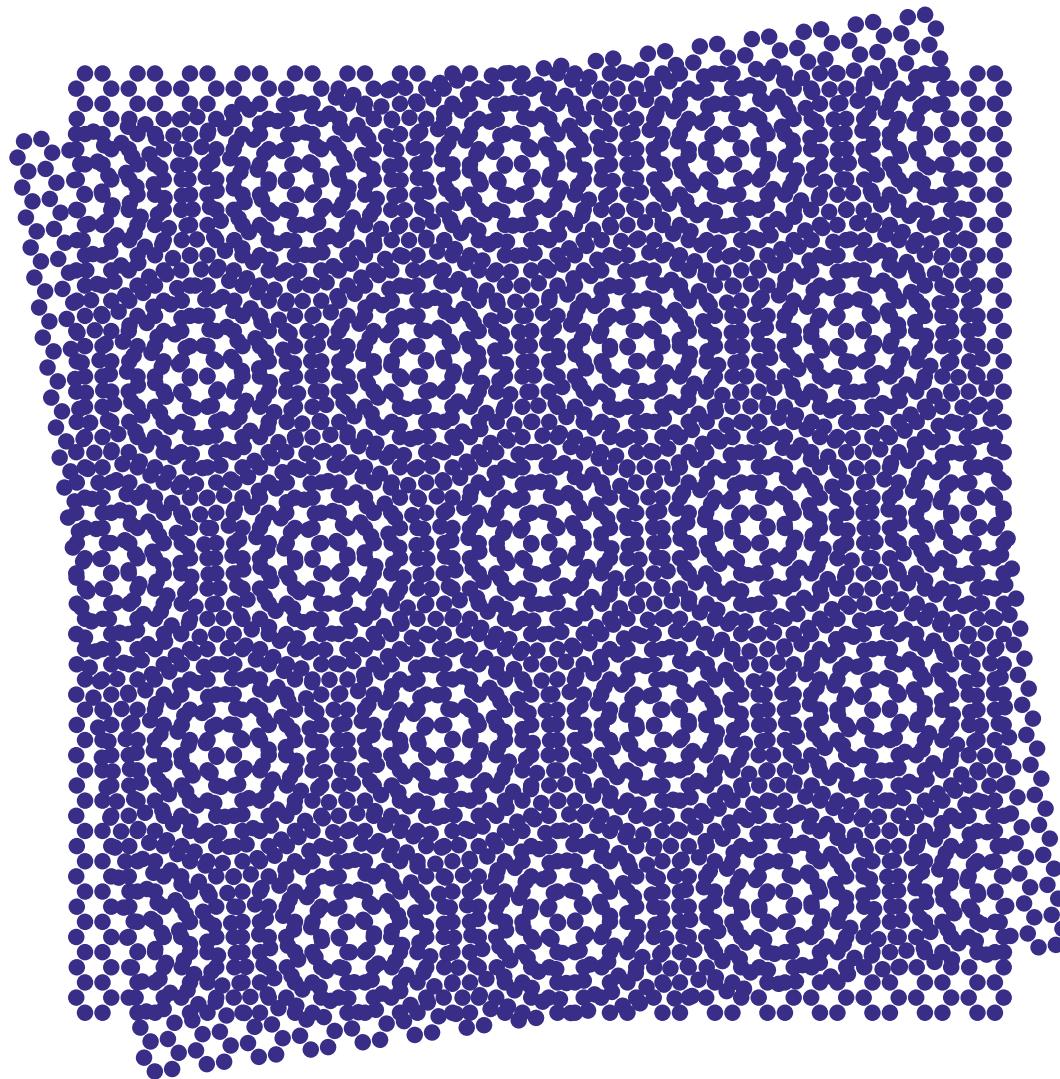
2 zero group velocity



1 zero index

2 zero group velocity

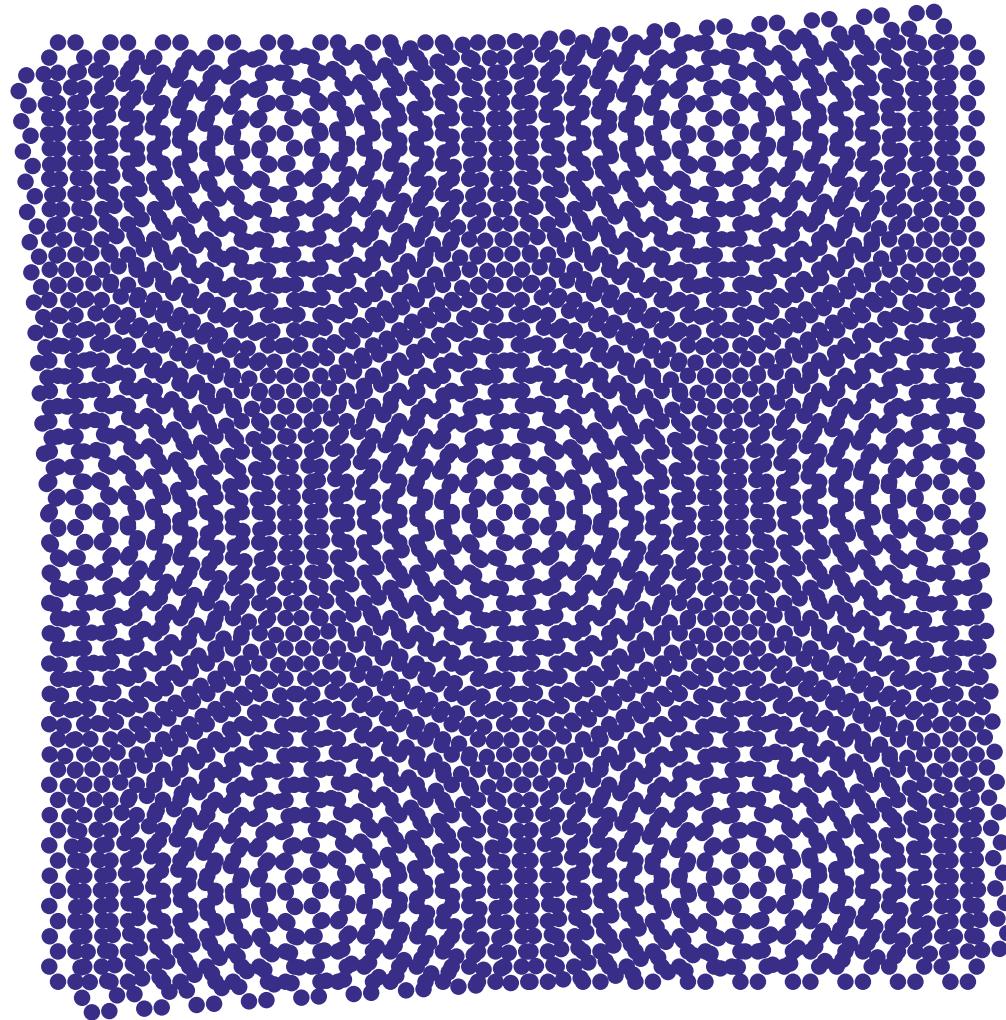
8°



1 zero index

2 zero group velocity

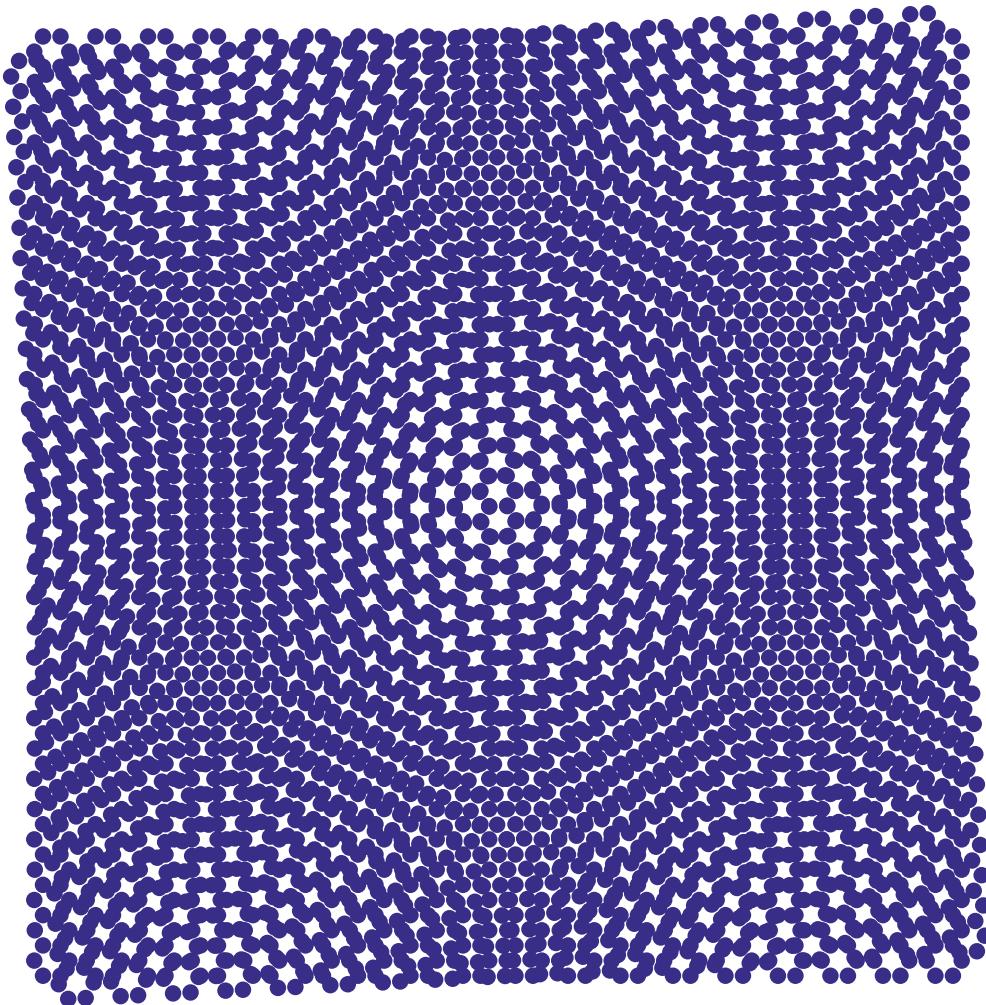
4°



1 zero index

2 zero group velocity

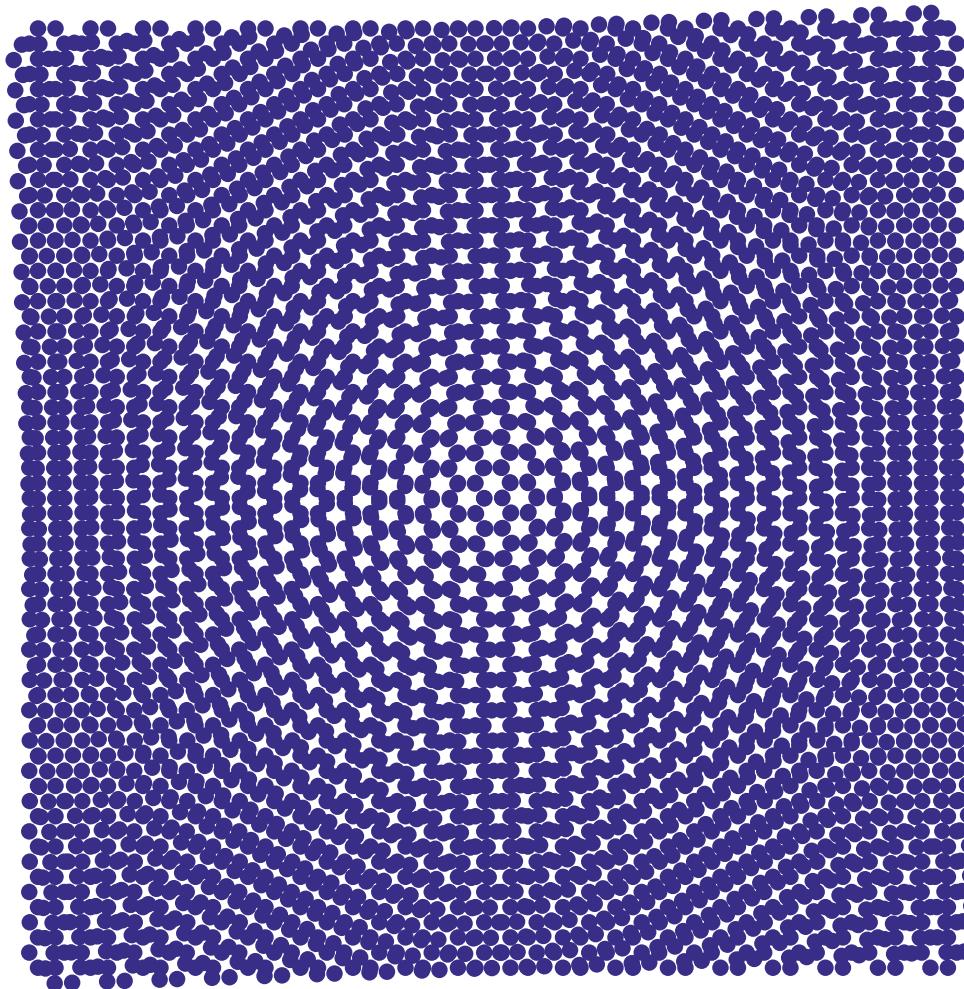
3°



1 zero index

2 zero group velocity

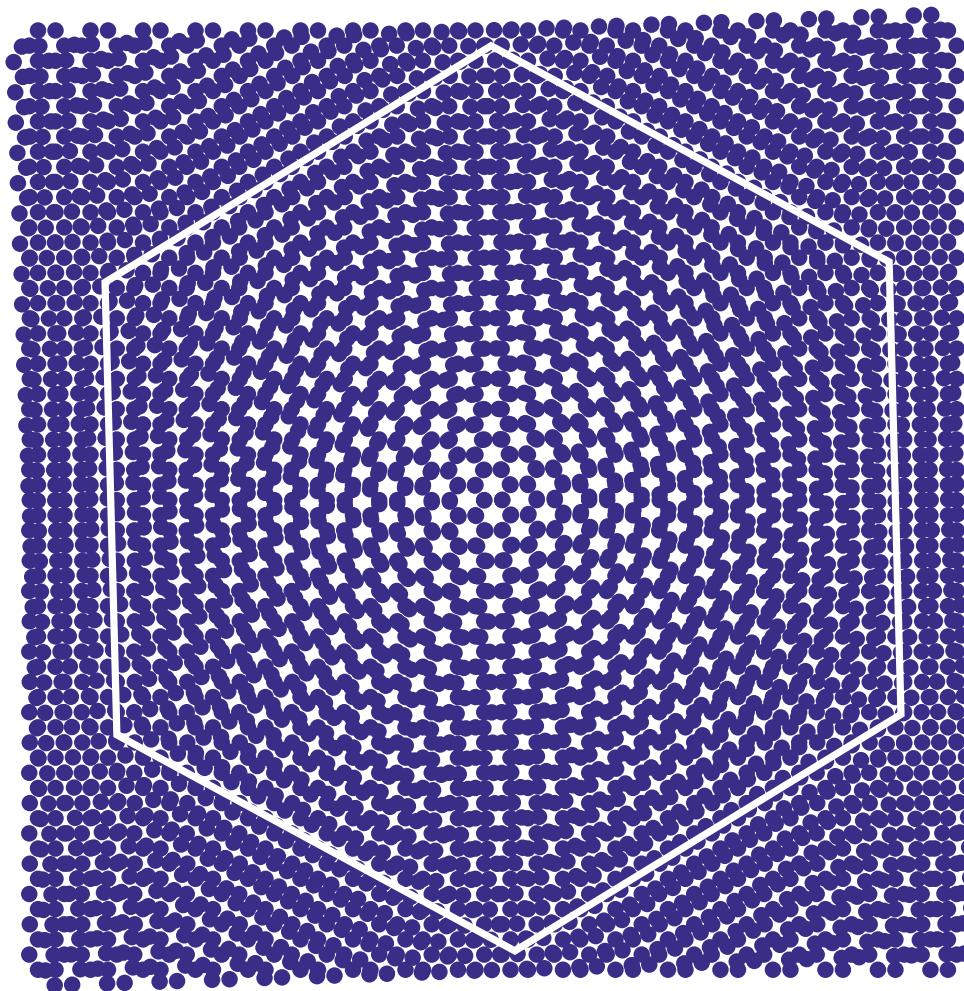
2°



1 zero index

2 zero group velocity

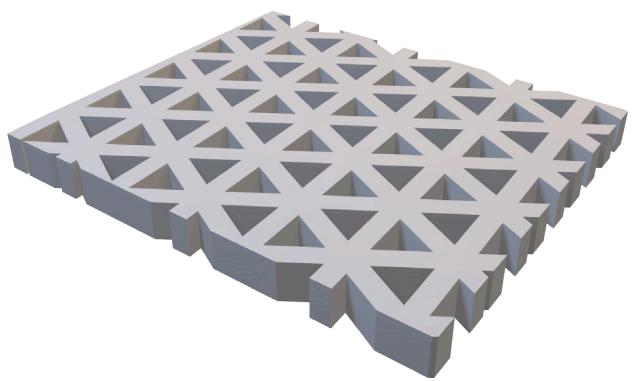
2°



1 zero index

2 zero group velocity

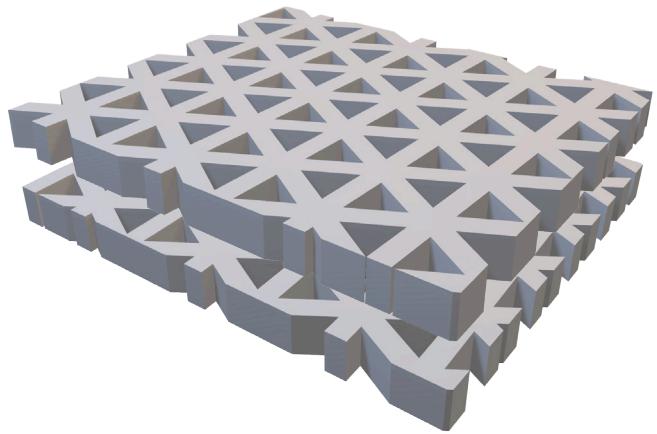
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

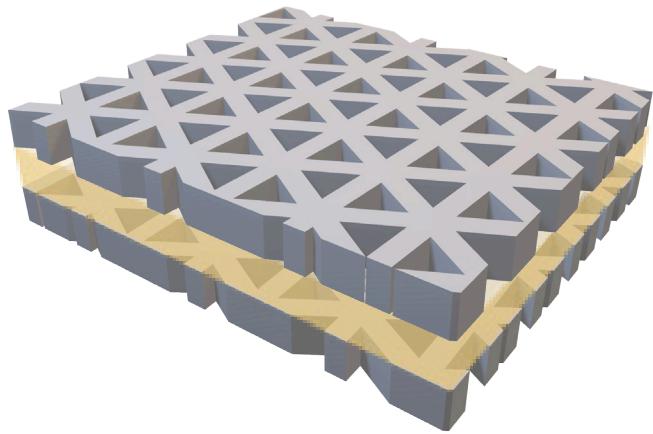
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

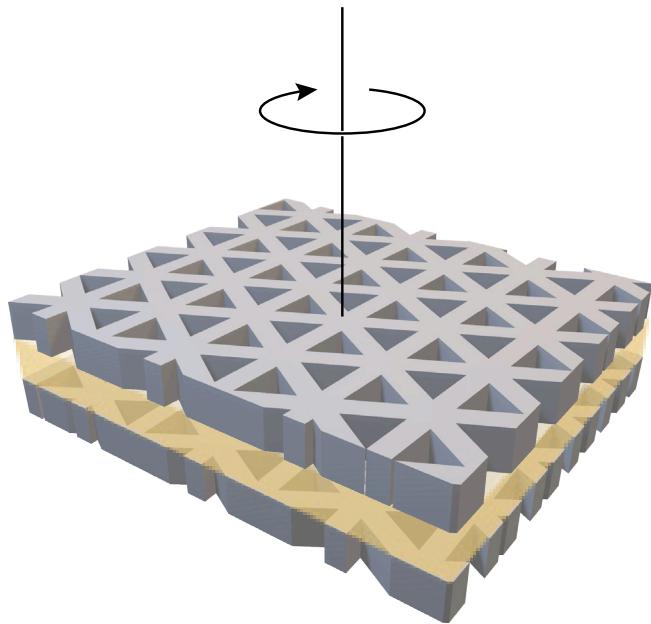
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

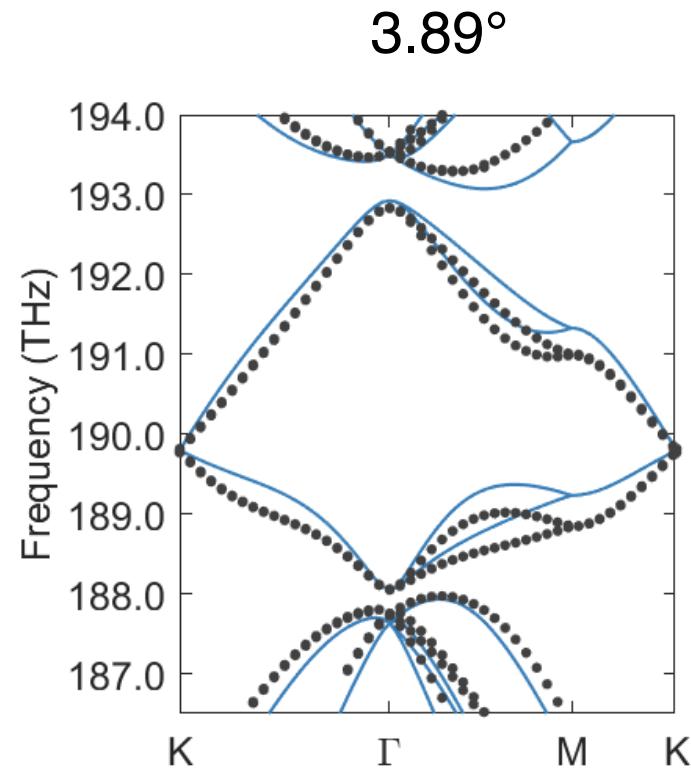
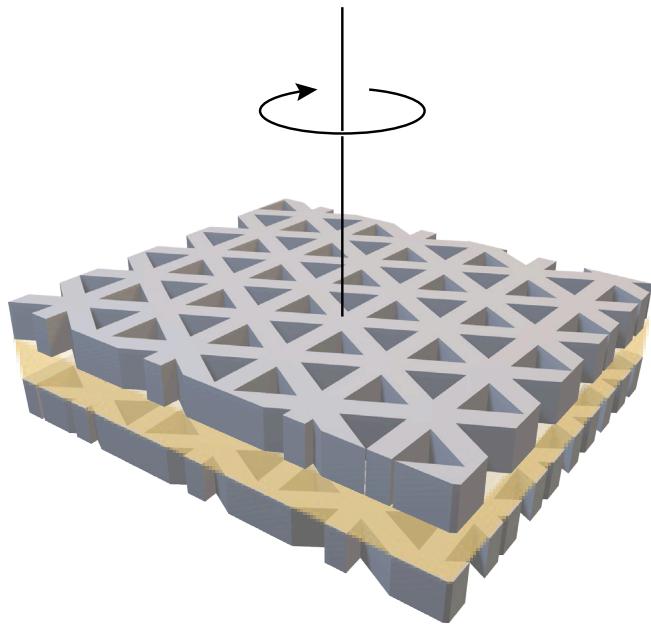
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

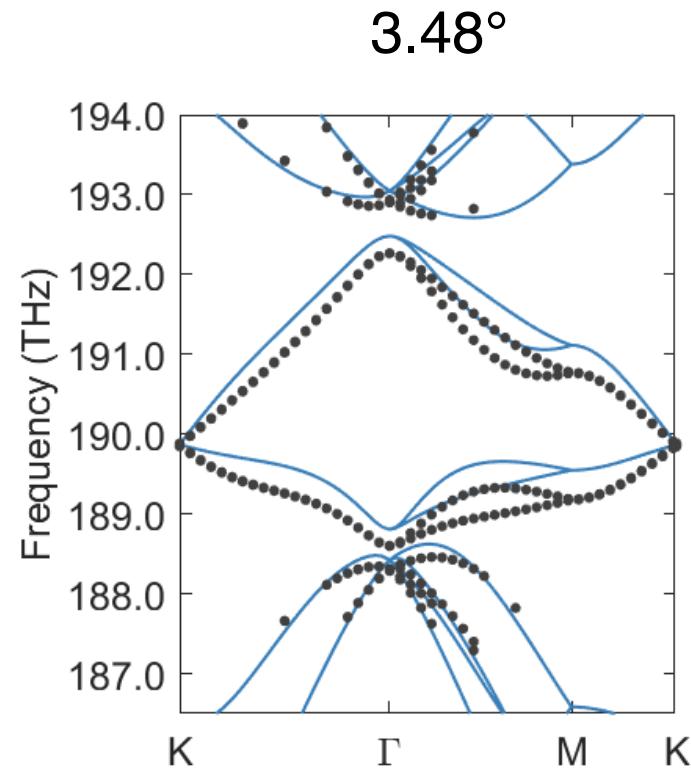
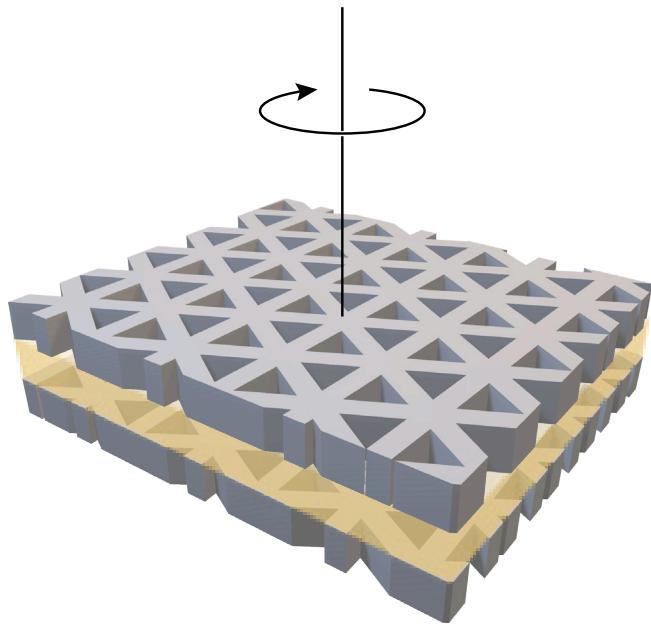
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

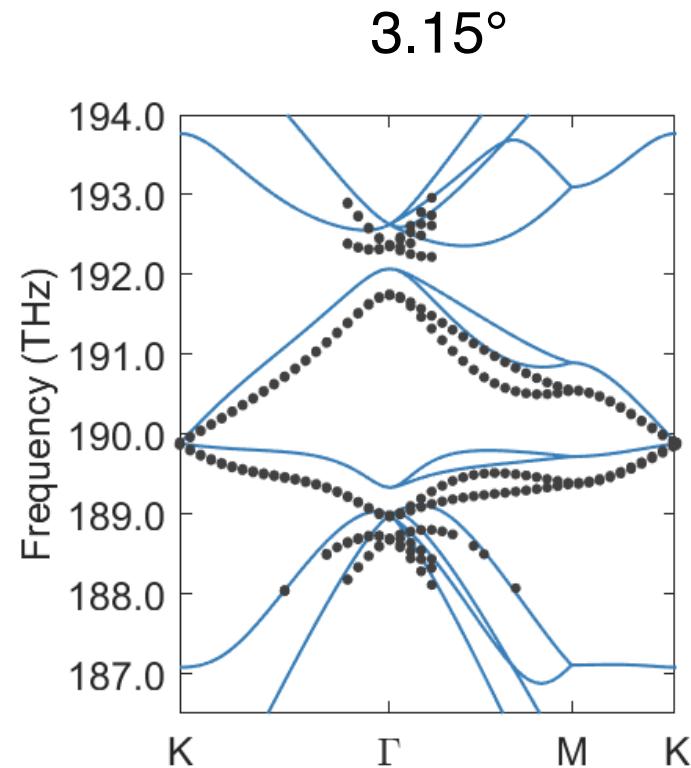
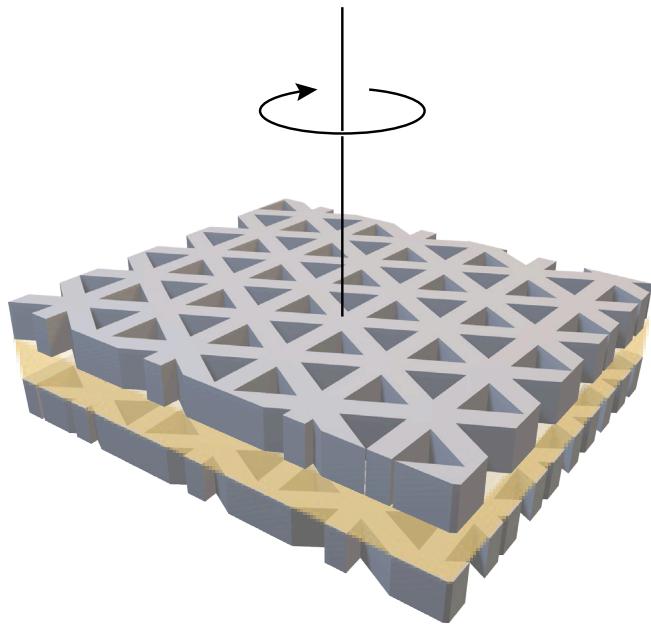
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

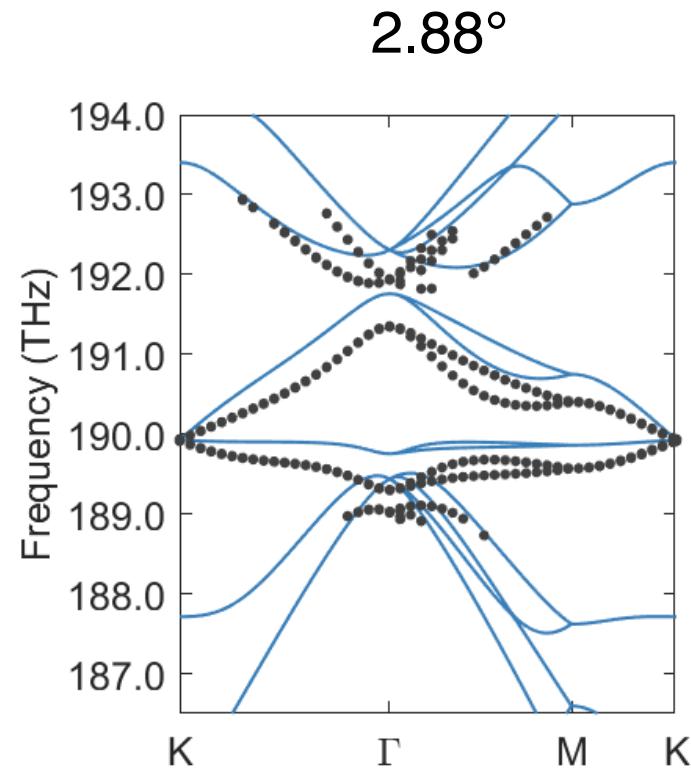
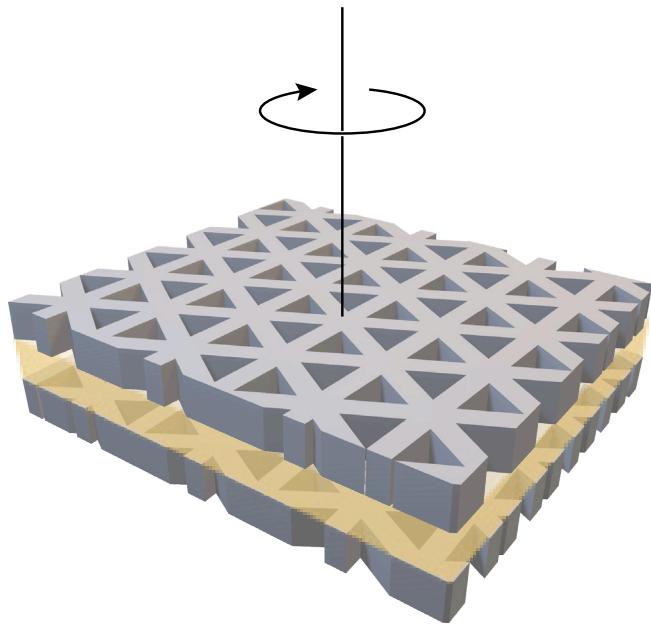
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

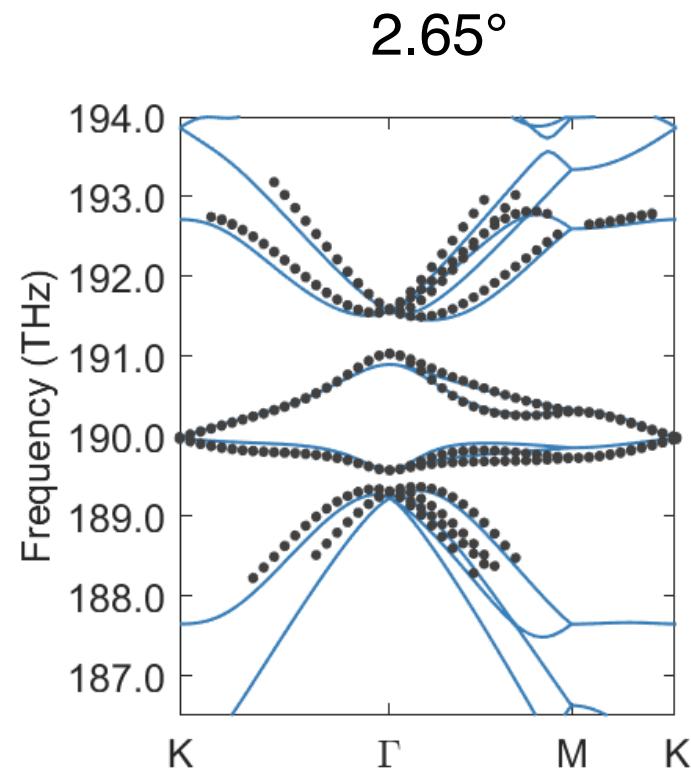
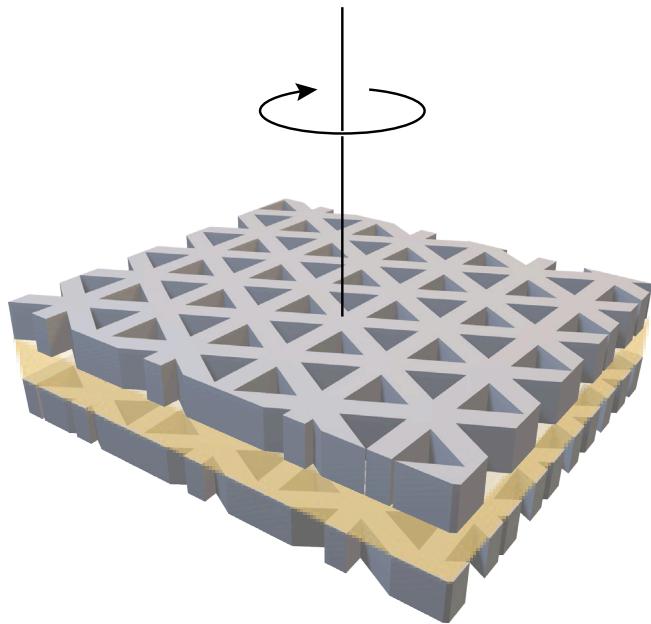
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

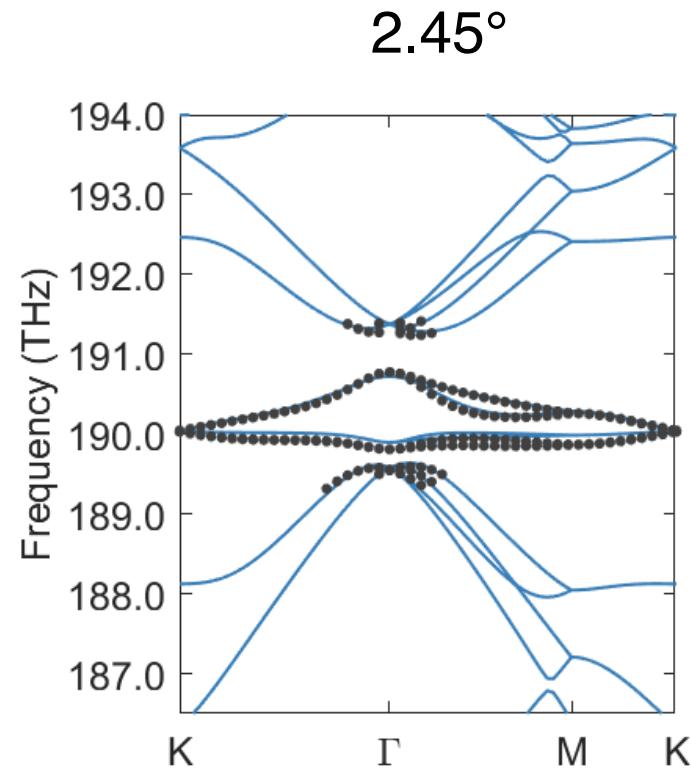
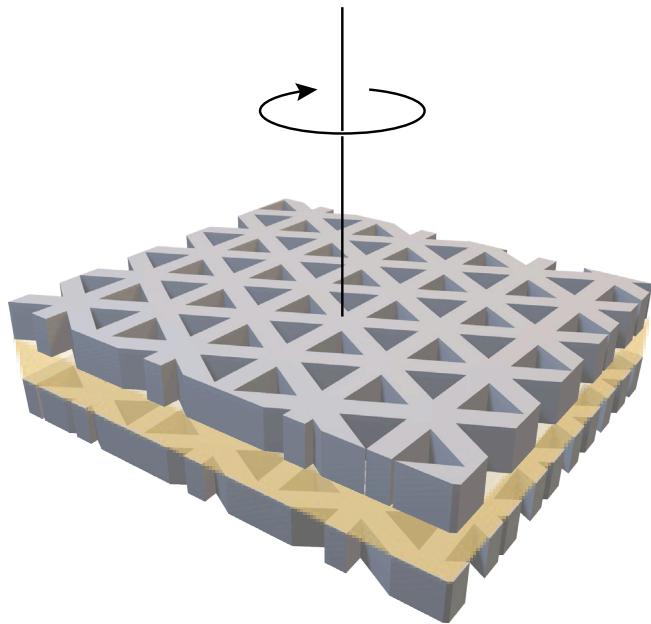
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

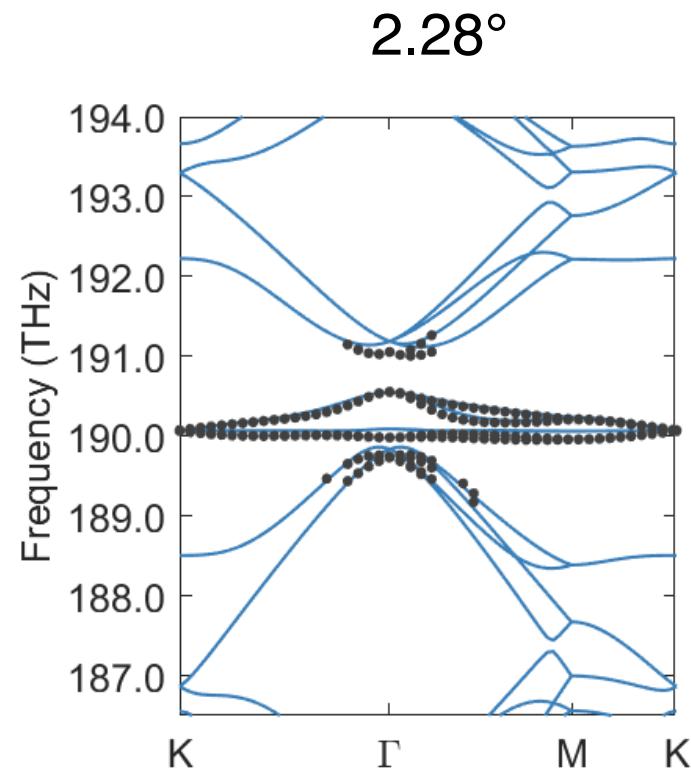
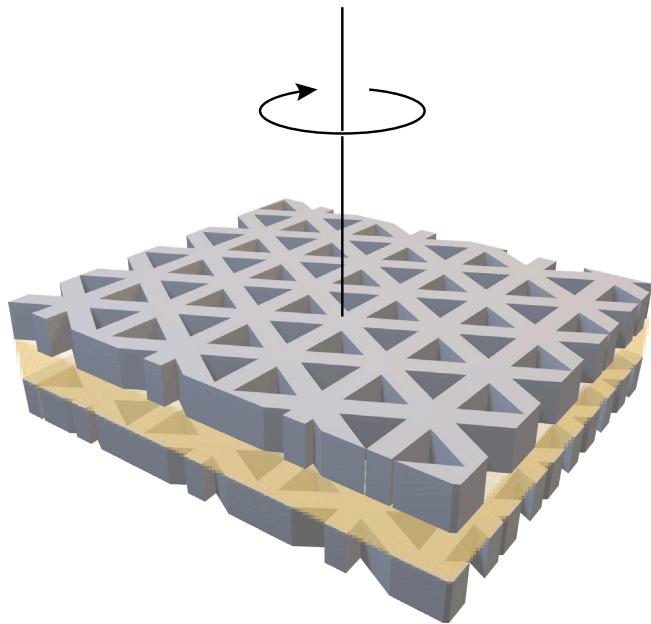
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

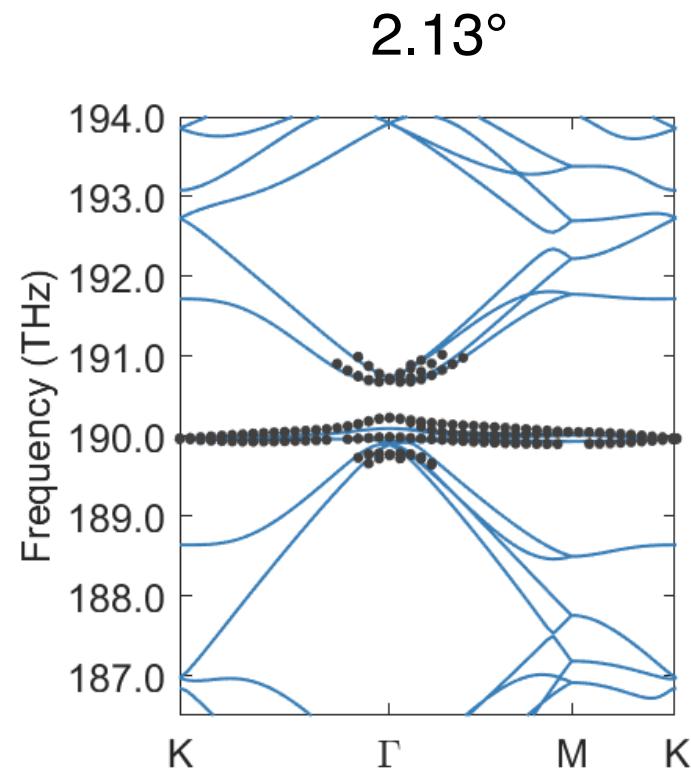
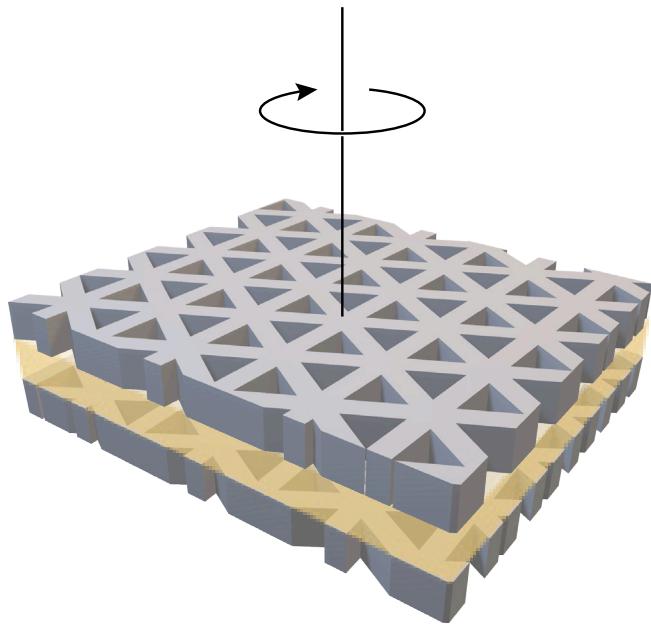
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

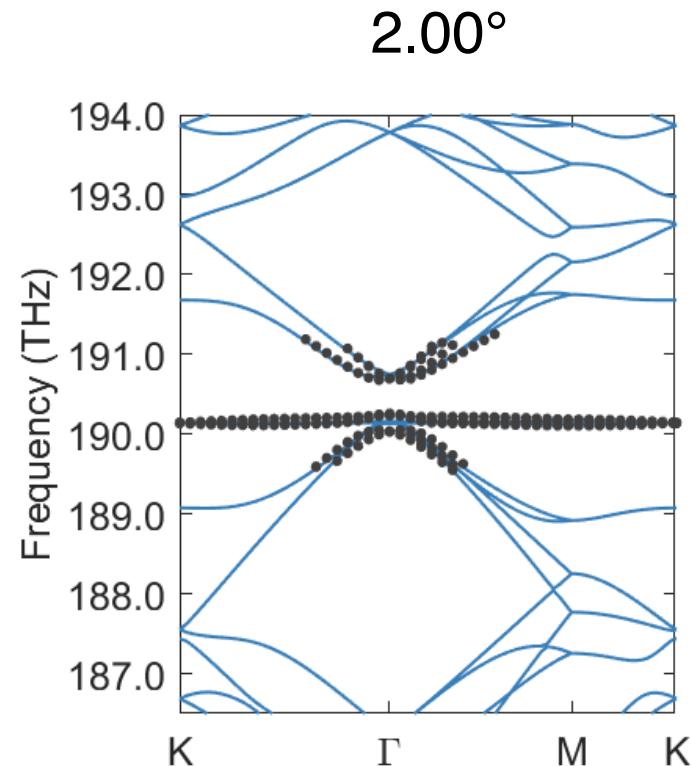
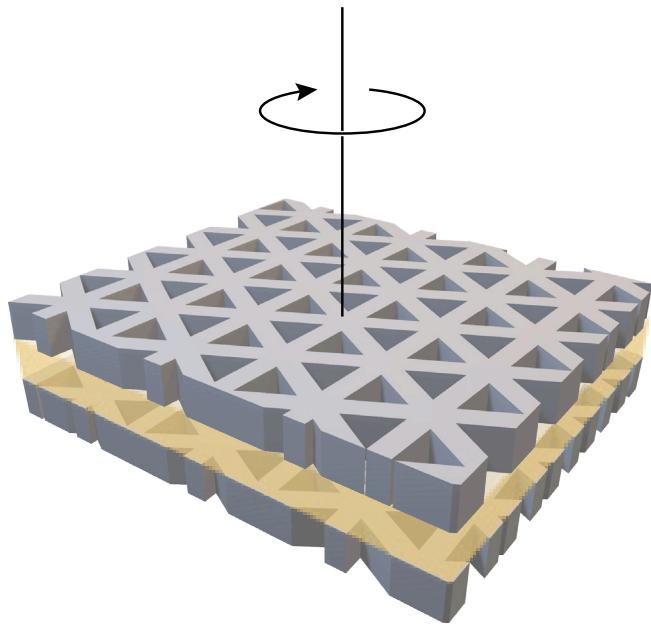
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

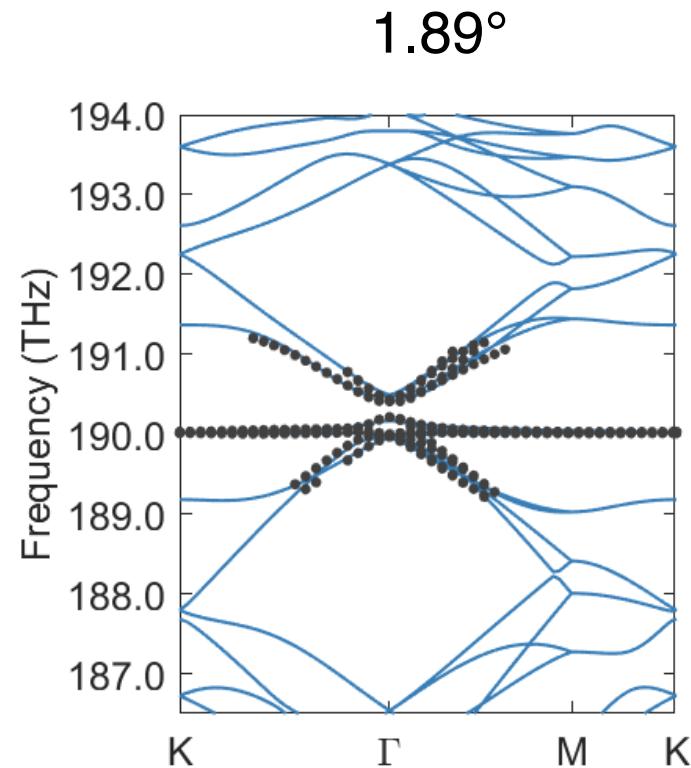
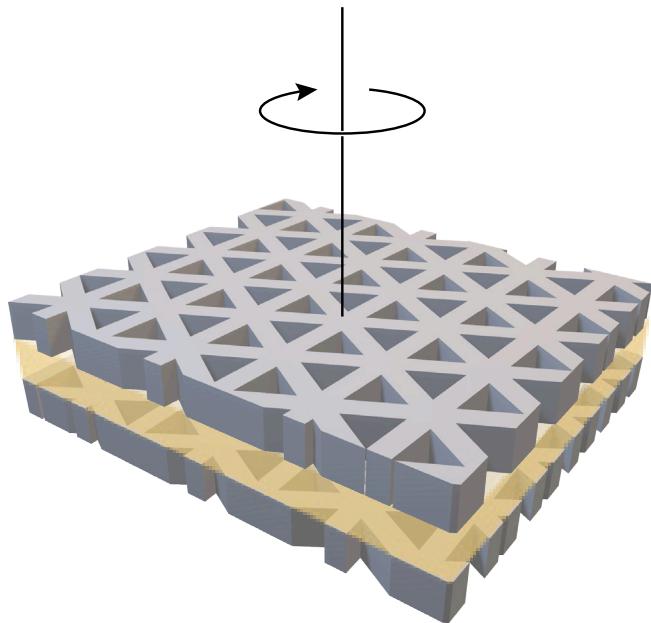
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

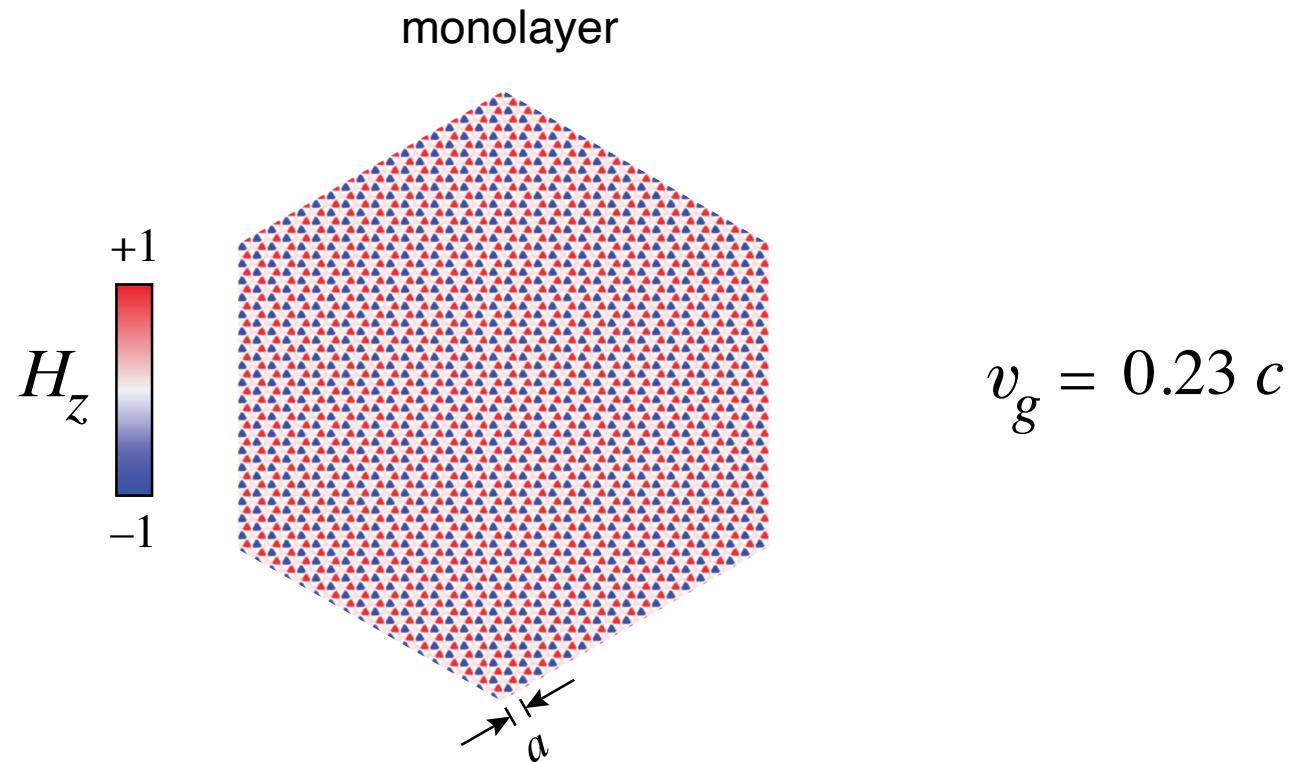
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

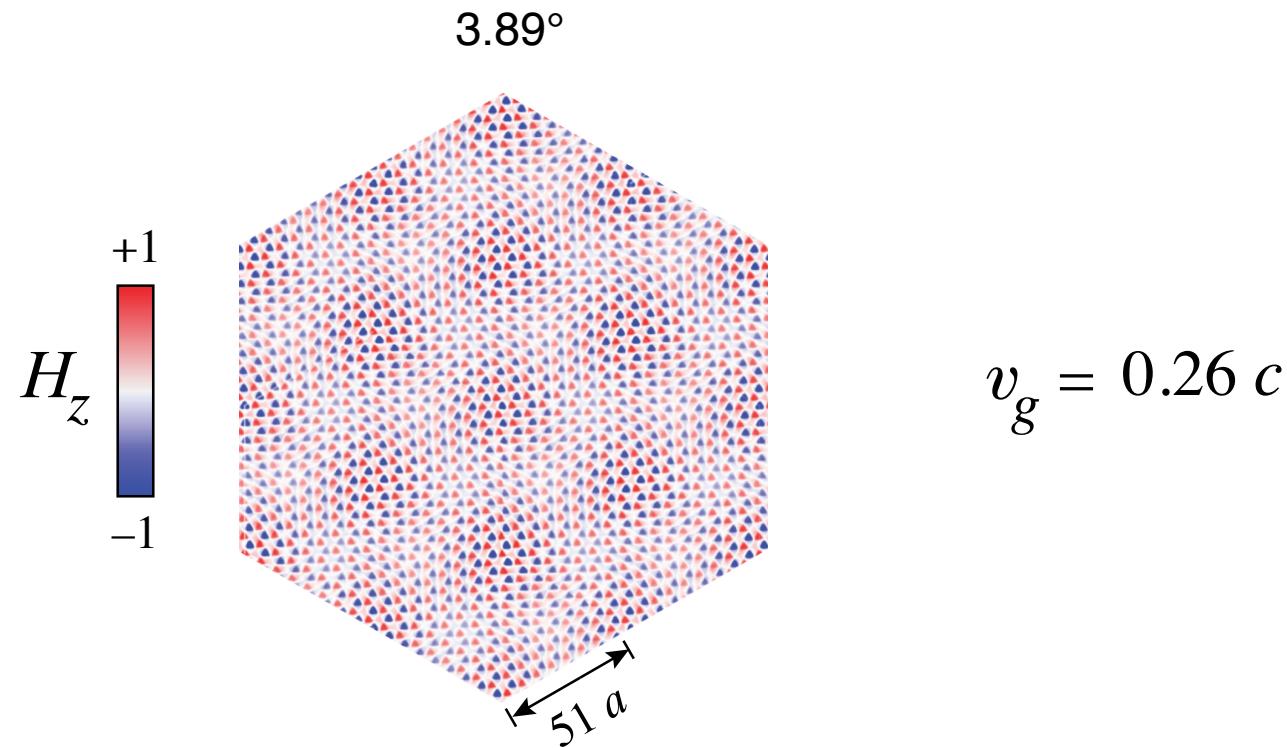
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

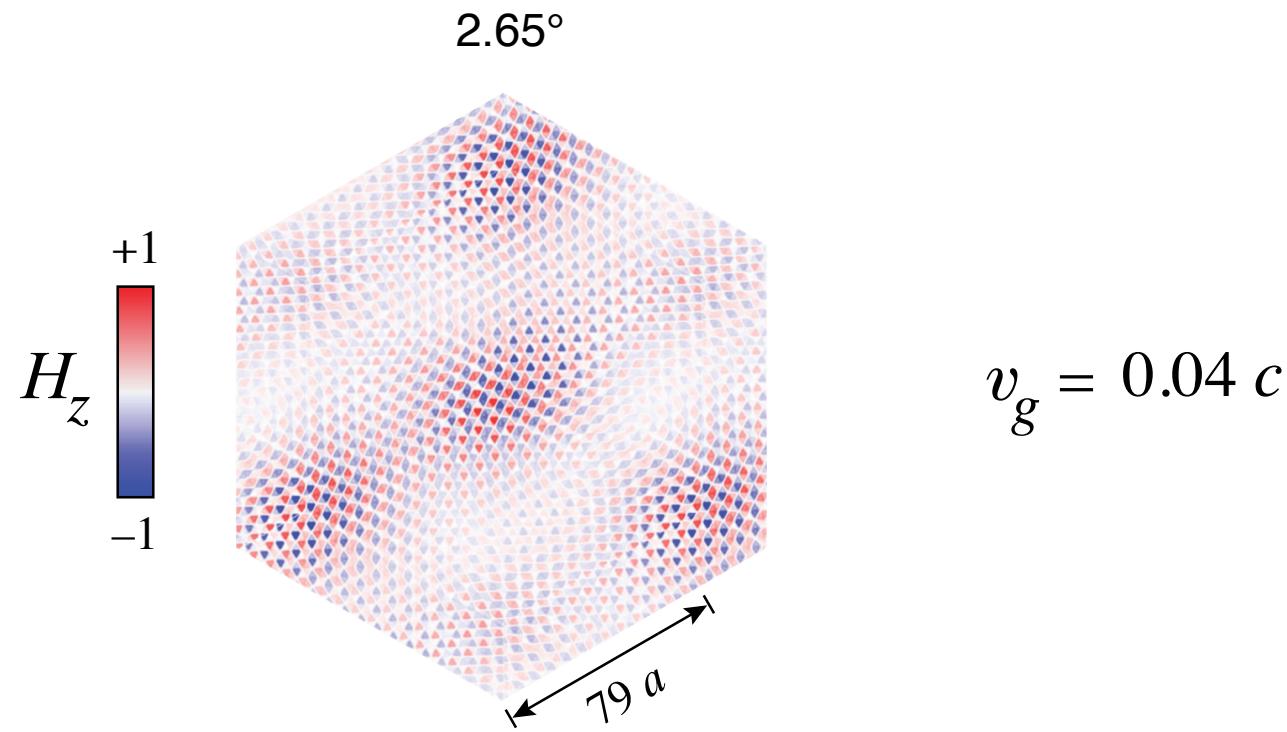
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

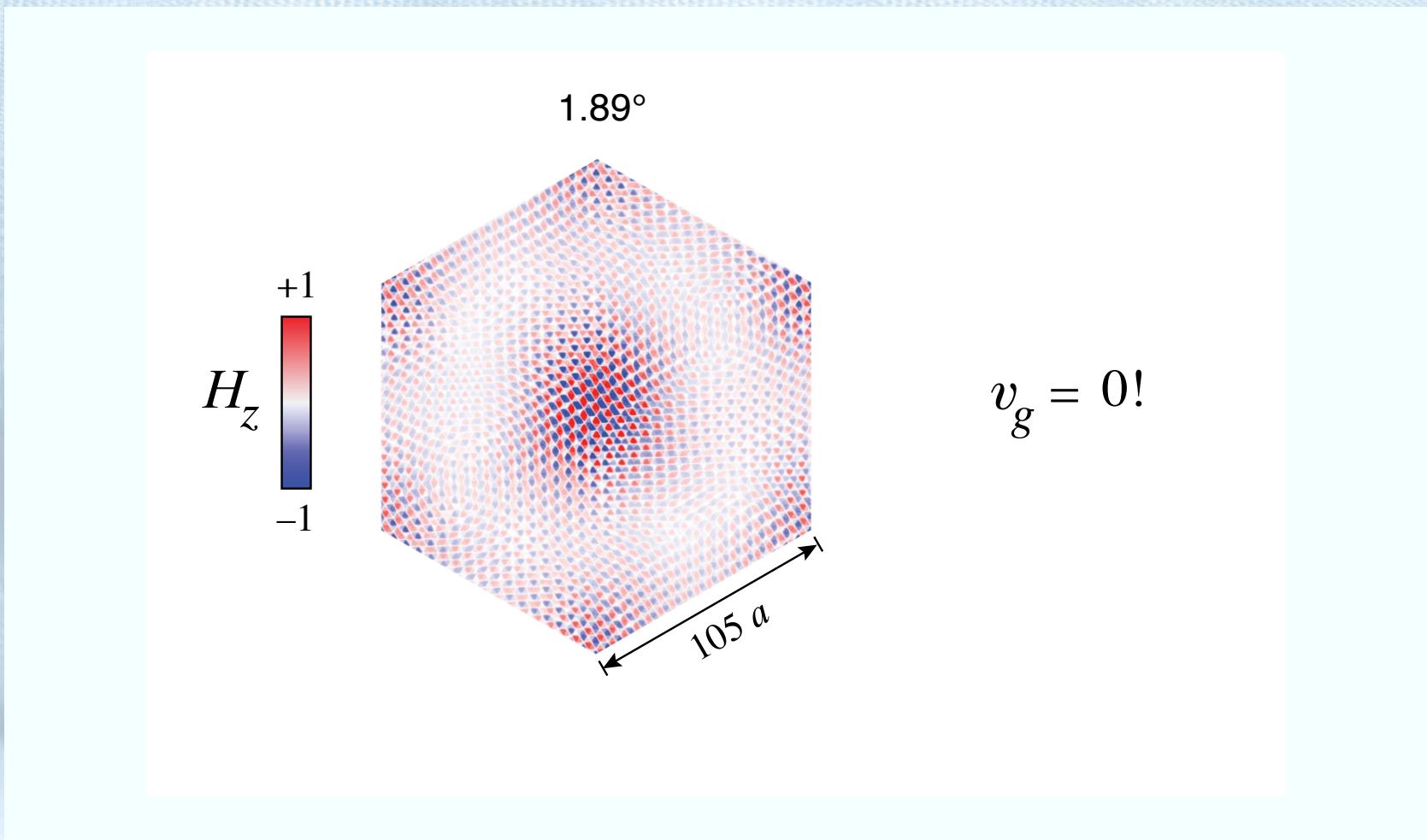
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

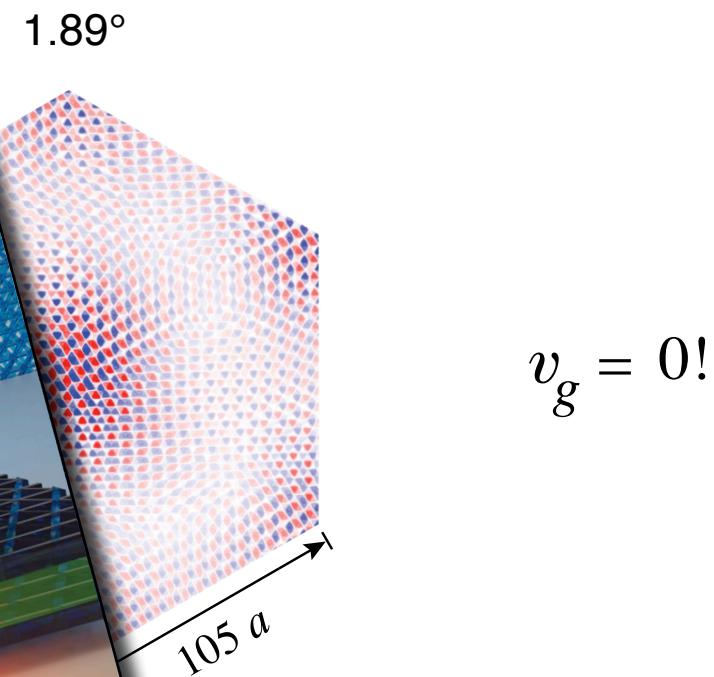
twisted bilayer photonic crystals



1 zero index

2 zero group velocity

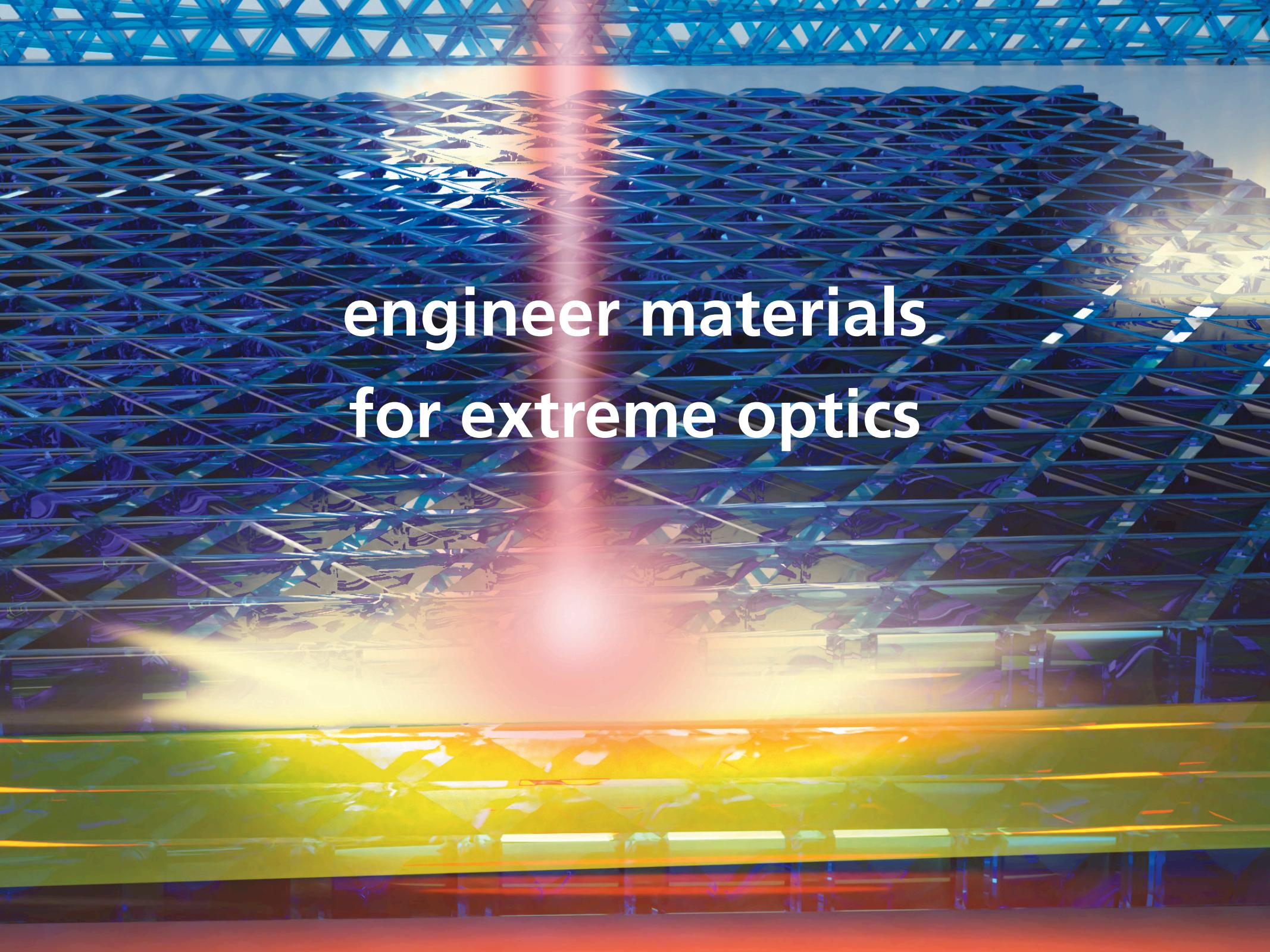
twisted bilayer photonic crystals



$$v_g = 0!$$

1 zero index

2 zero group velocity



engineer materials
for extreme optics



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Daryl Vulis, Mei Yin, Lysander Christakis, Zin Lin, Cleaven Chia,
Olivia Mello, Haoning Tang, Justin Gagnon, Marko Ločcar**

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