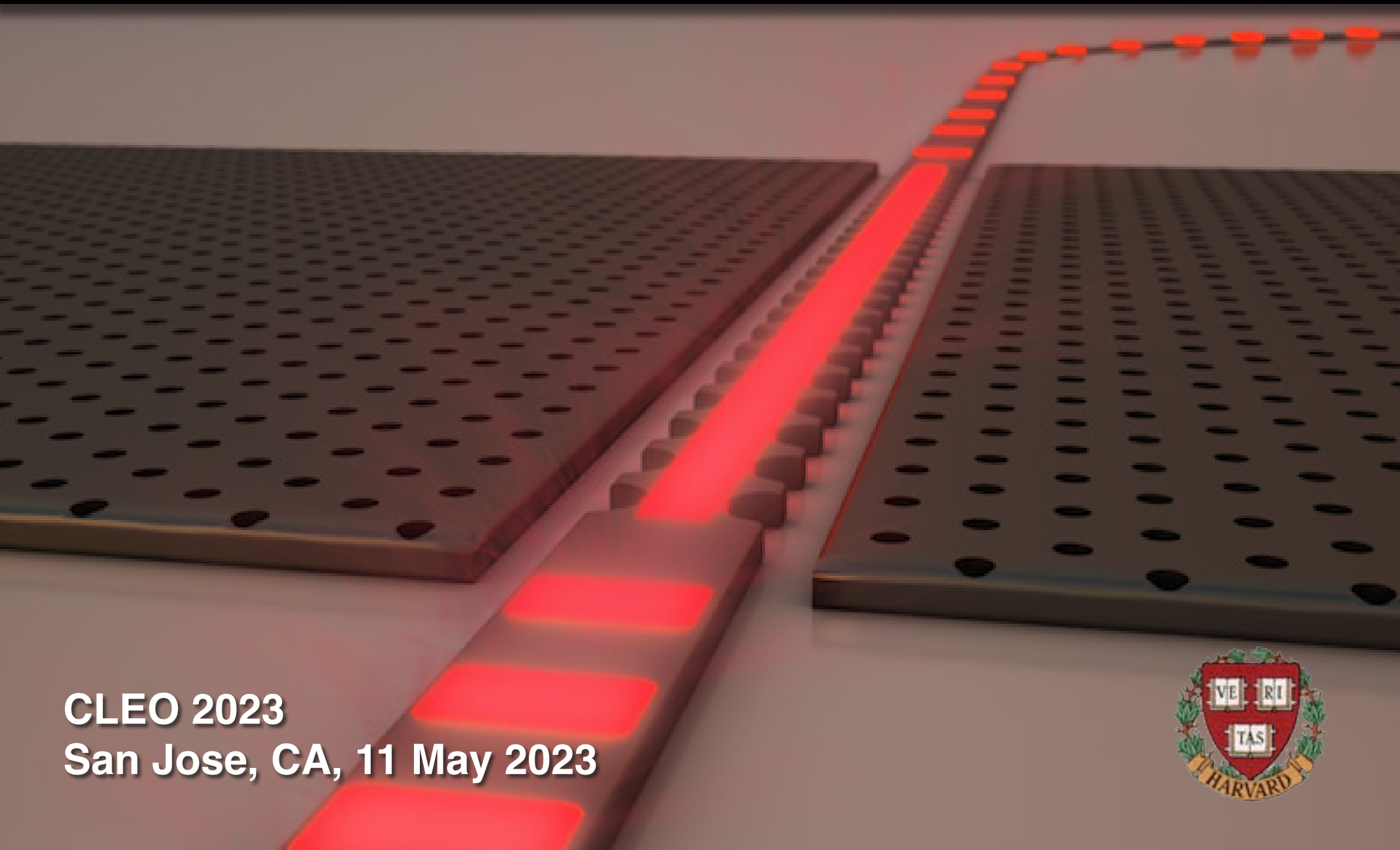
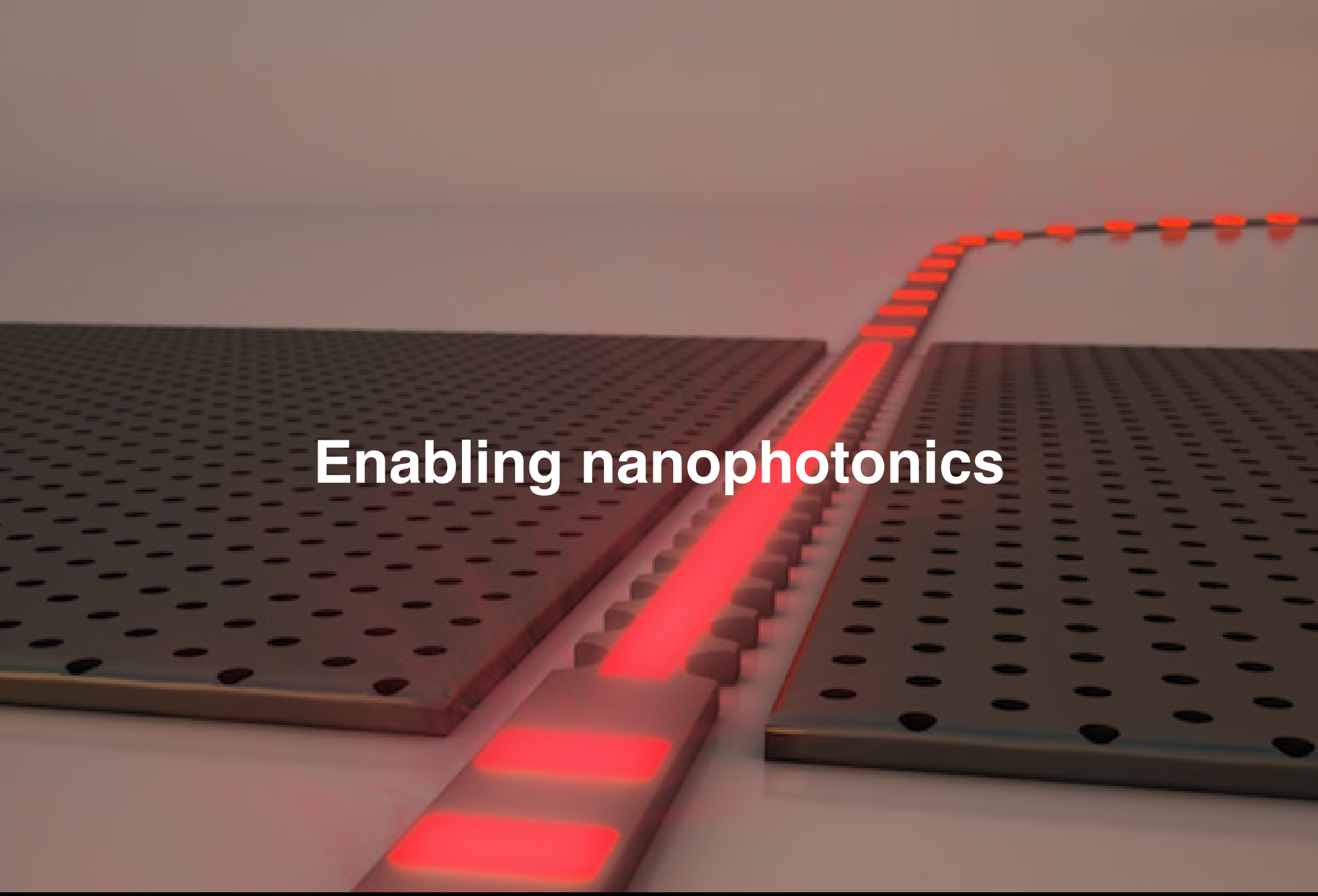
Zero-index metamaterials for extreme optics

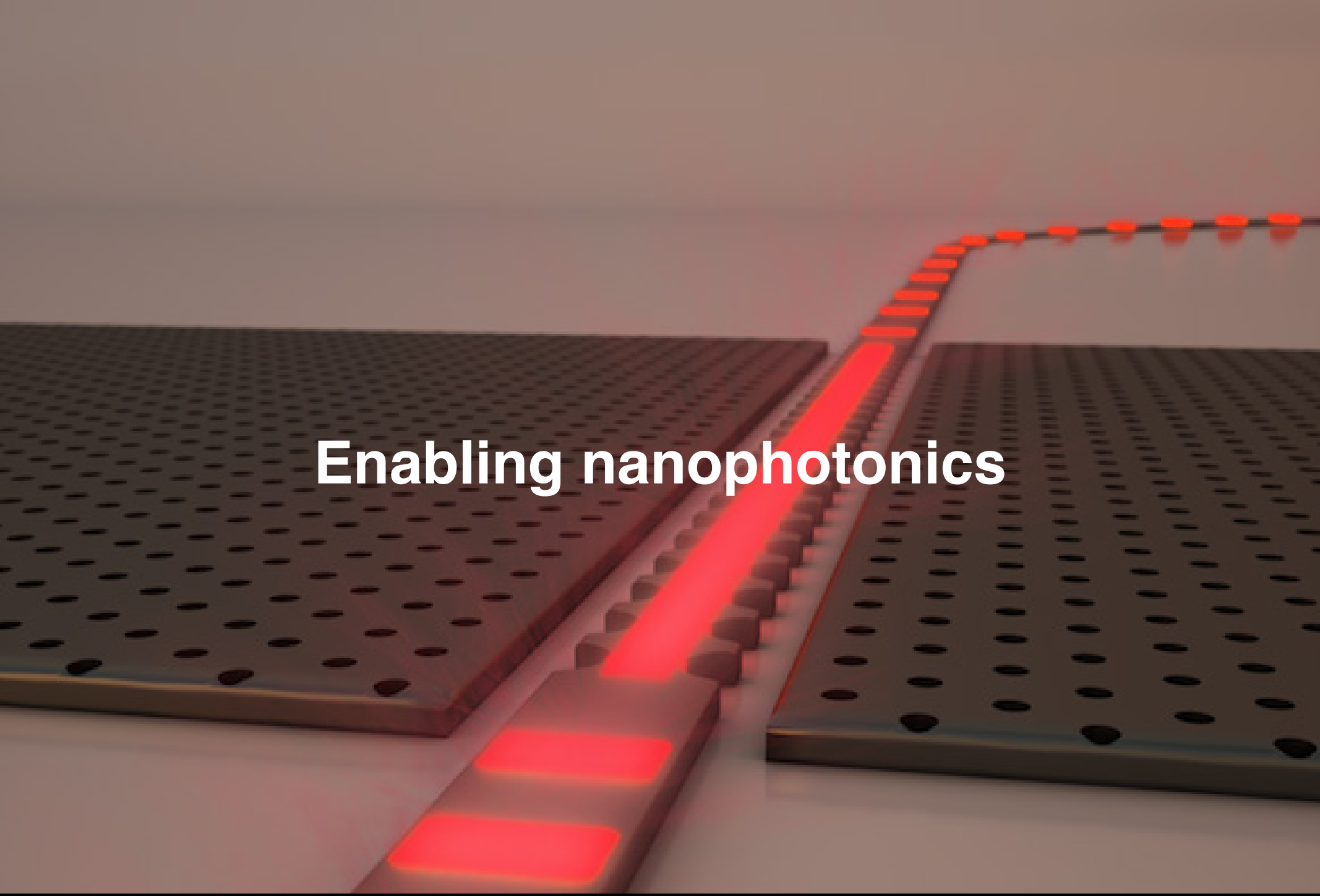


CLEO 2023
San Jose, CA, 11 May 2023

Zero-index metamaterials for extreme optics

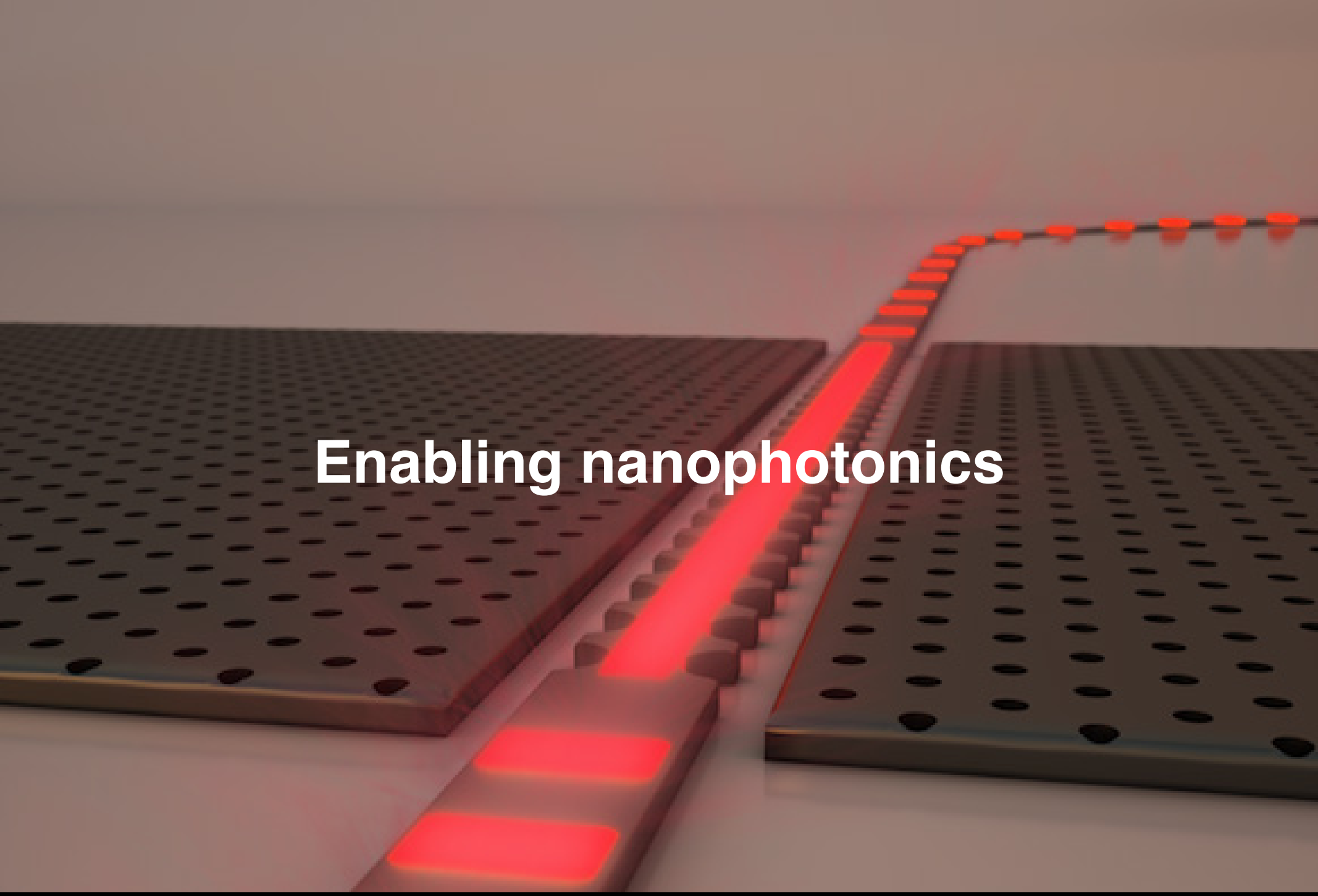
CLEO 2023
San Jose, CA, 11 May 2023


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

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

1 zero index

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

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

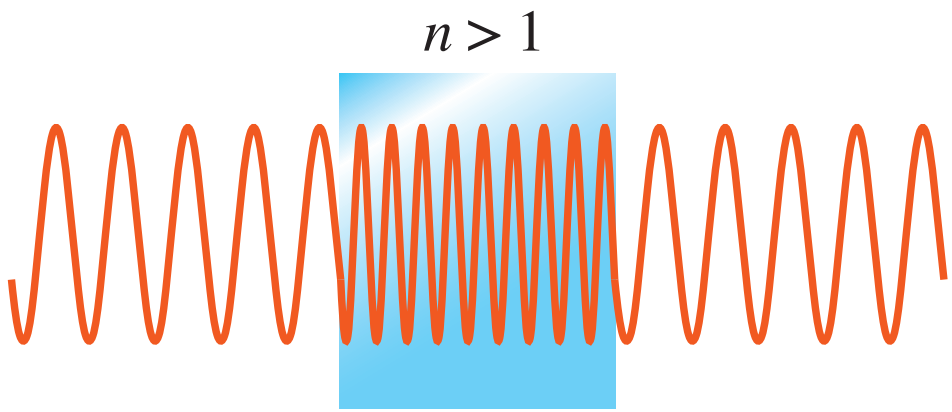
solution

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

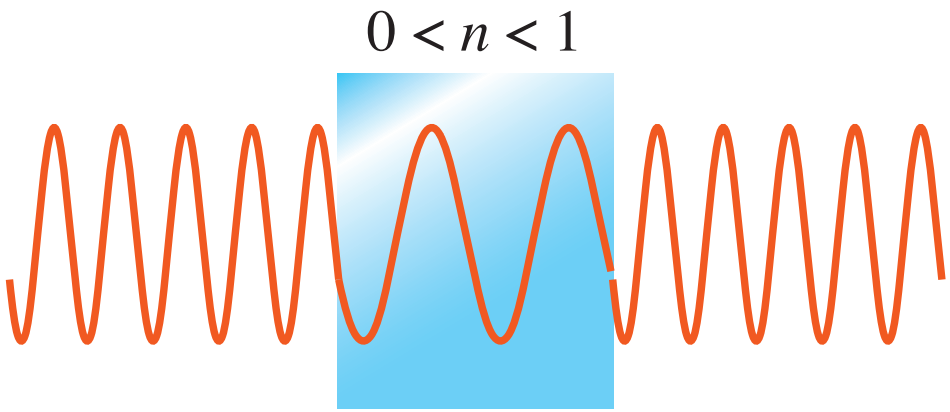
where

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

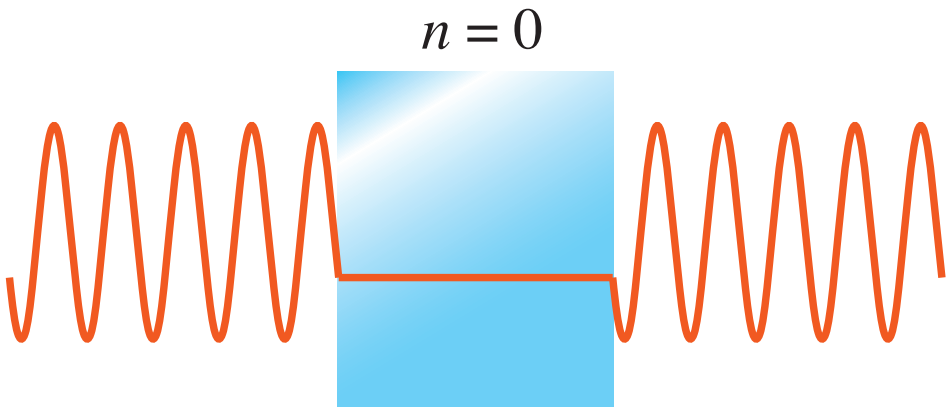
1 zero index



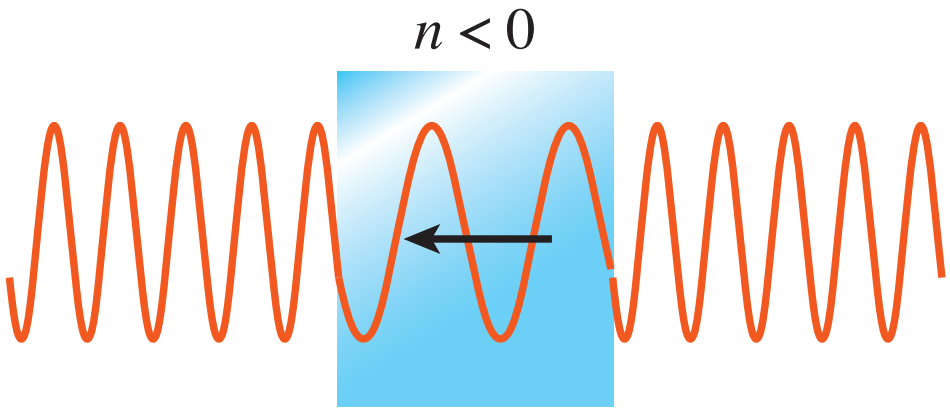
1 zero index



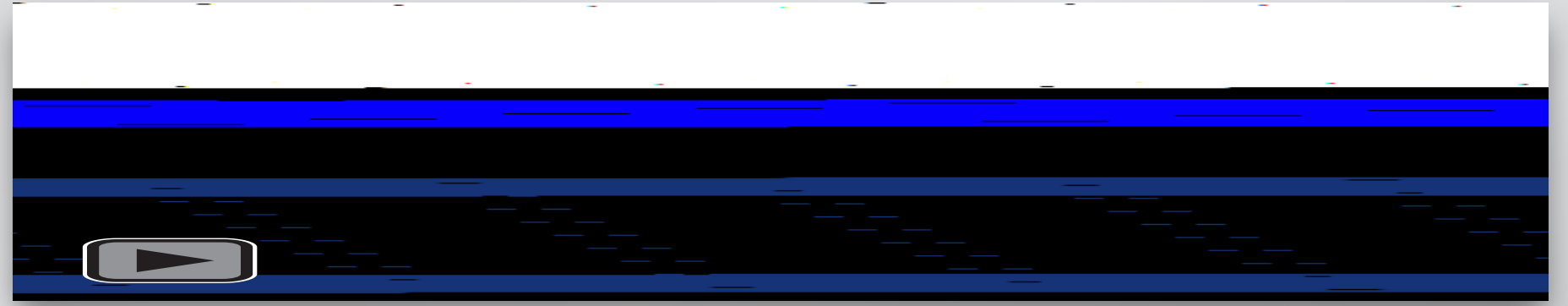
1 zero index



1 zero index



1 zero index

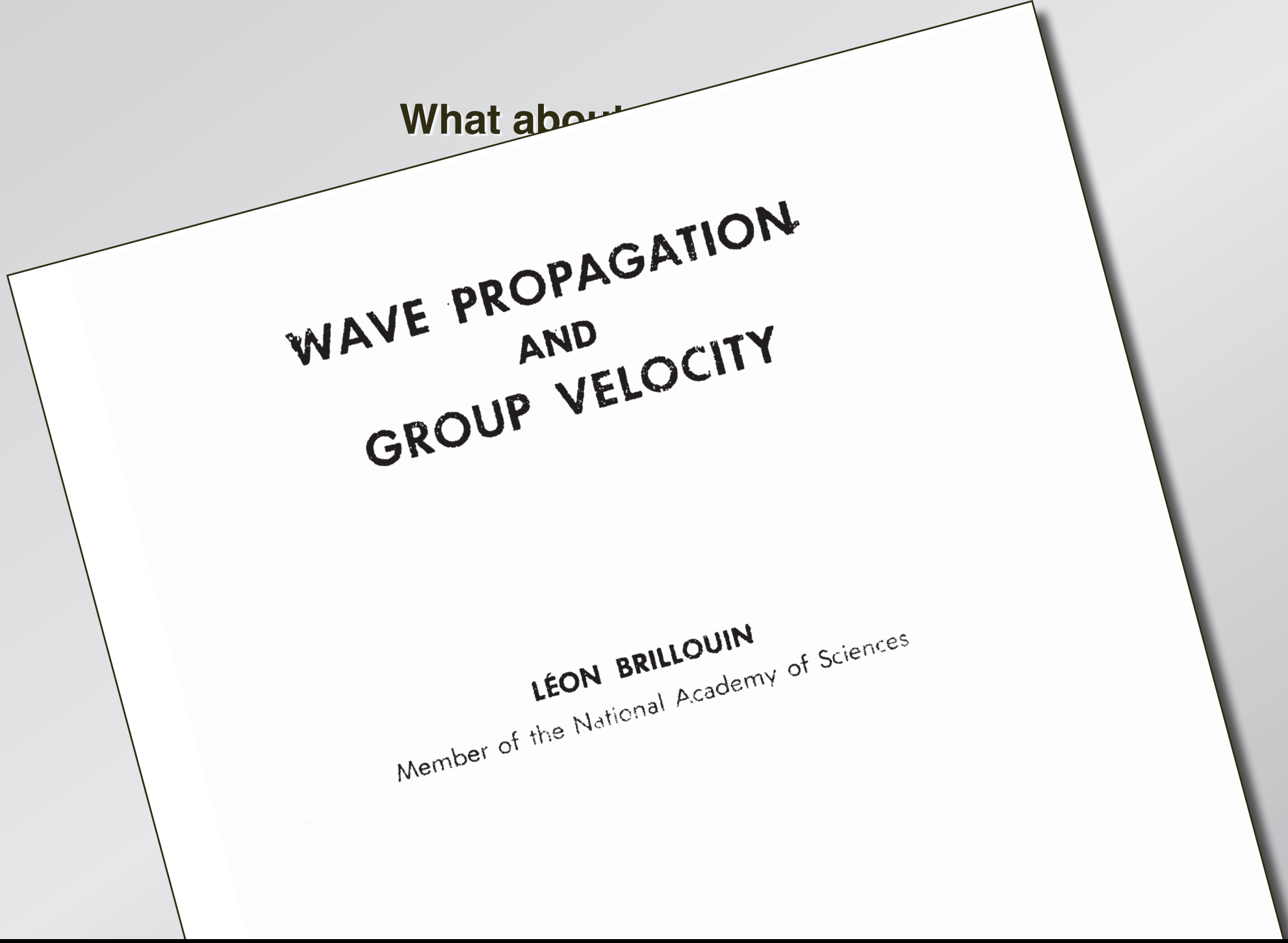


1 zero index

“Superluminal”?!

What about causality?

What abou



WAVE PROPAGATION
AND
GROUP VELOCITY

LÉON BRILLOUIN
Member of the National Academy of Sciences

1 zero index

What abou

was used in Chapters II and III but its mathematical complications will not be introduced here.

What happens to the signal after it traverses a distance x? Each wave ω propagates with its phase velocity $W(\omega)$ and the integral (34) becomes

$$f(x,t) = \frac{1}{2\pi}\,\mathrm{Re}\int_{-\infty}^{+\infty}\left\{e^{i\omega\left(t-T-\frac{x}{W}\right)} - e^{i\omega\left(t-\frac{x}{W}\right)}\right\}\frac{d\omega}{\omega-\omega_0} \tag{36}$$

This integral must be evaluated. A complete discussion of the process was given in Chapter III; it requires recourse to integrations in the complex plane. The discussion will now be limited to the case of *propagation without absorption*, i.e., to the case of W remaining always real.[2]

The waves with frequencies near ω_0 always have a much greater amplitude than all the others. For these waves the second exponent in Eq. (36) may be expanded:

$$\omega\left(t-\frac{x}{W}\right) = \omega_0\left(t-\frac{x}{W_0}\right) + \left(t-\frac{x}{U_0}\right)(\omega-\omega_0)$$

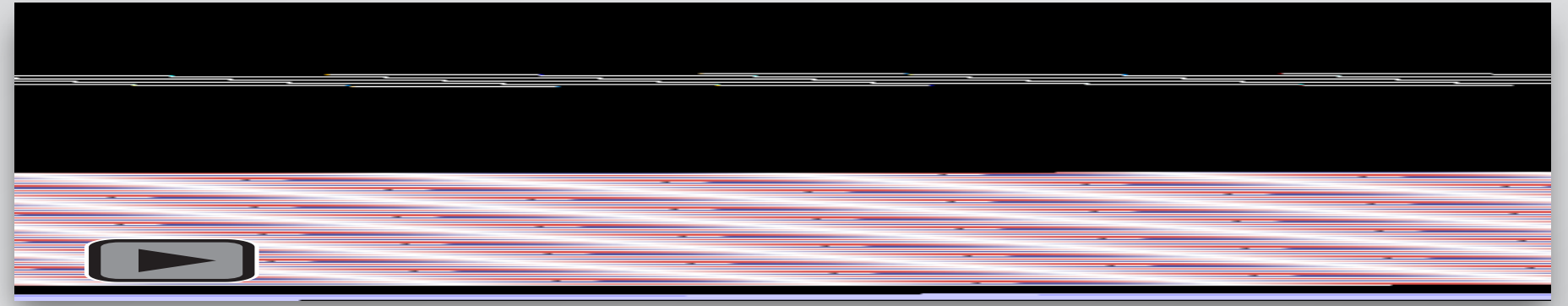
$$\frac{1}{\ldots} = \partial(\omega/W)/\partial\omega$$

...ilarly. This contributes

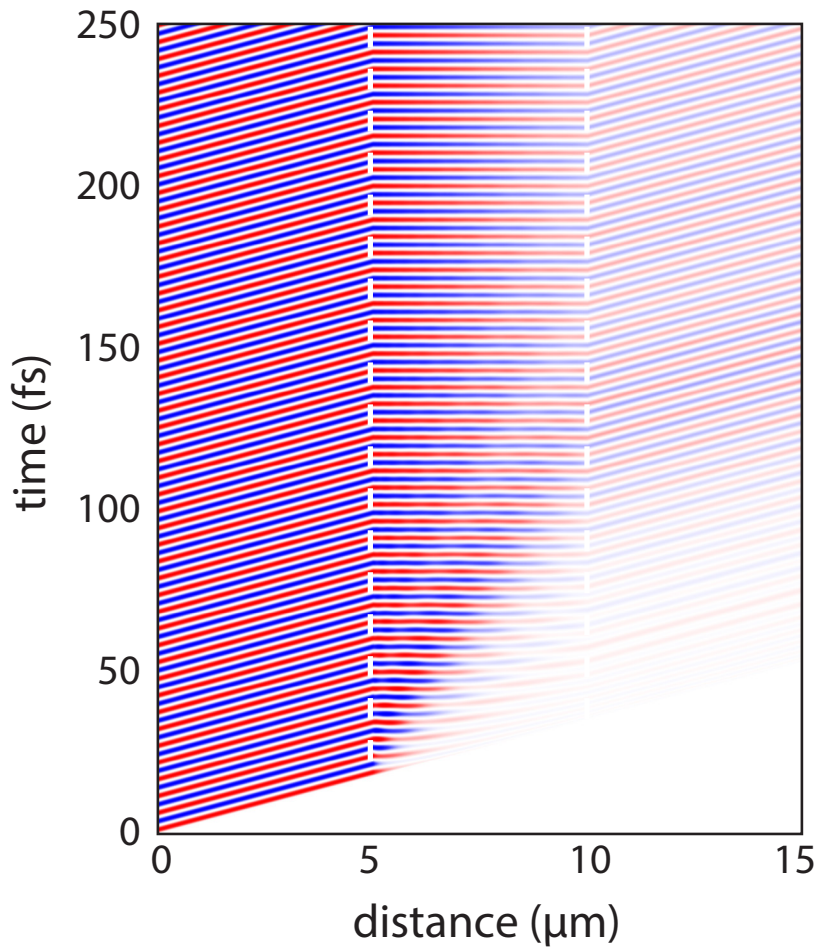
...$d\omega$

1 zero index

What about causality?



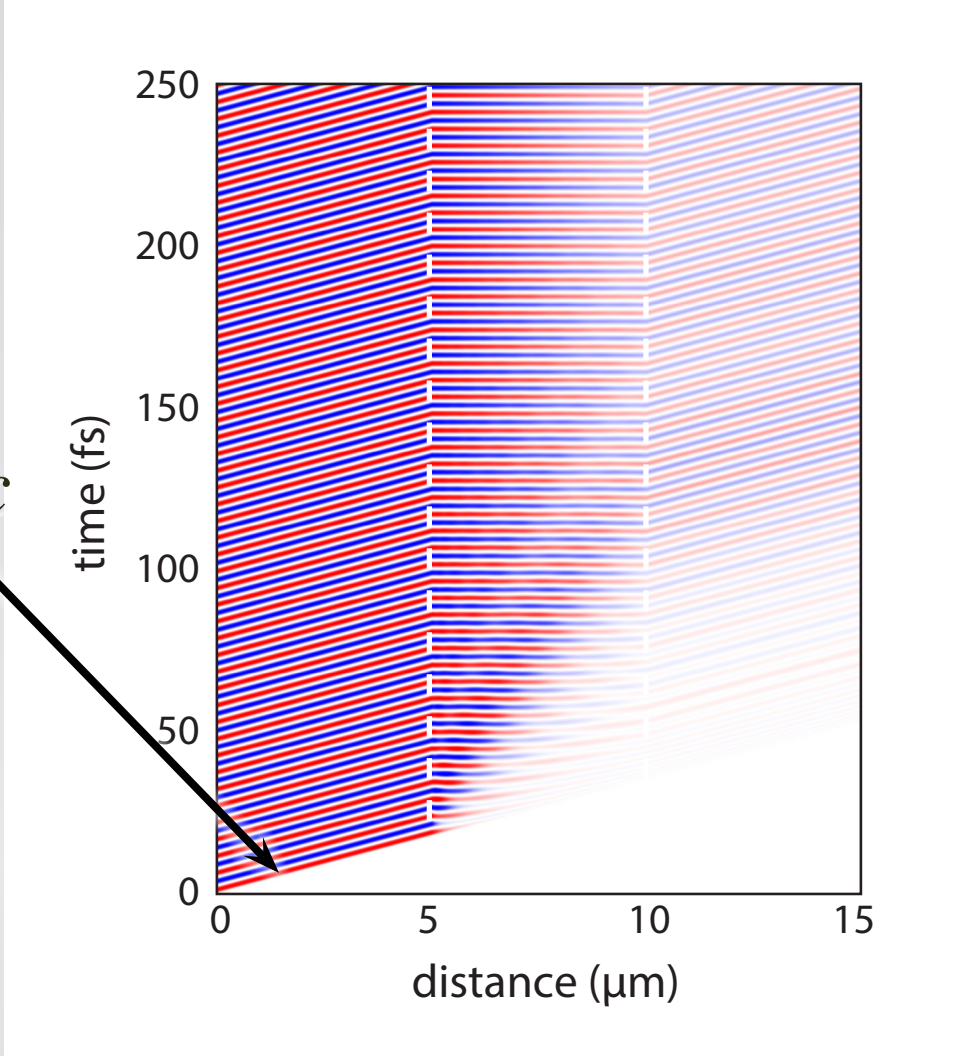
What about causality?



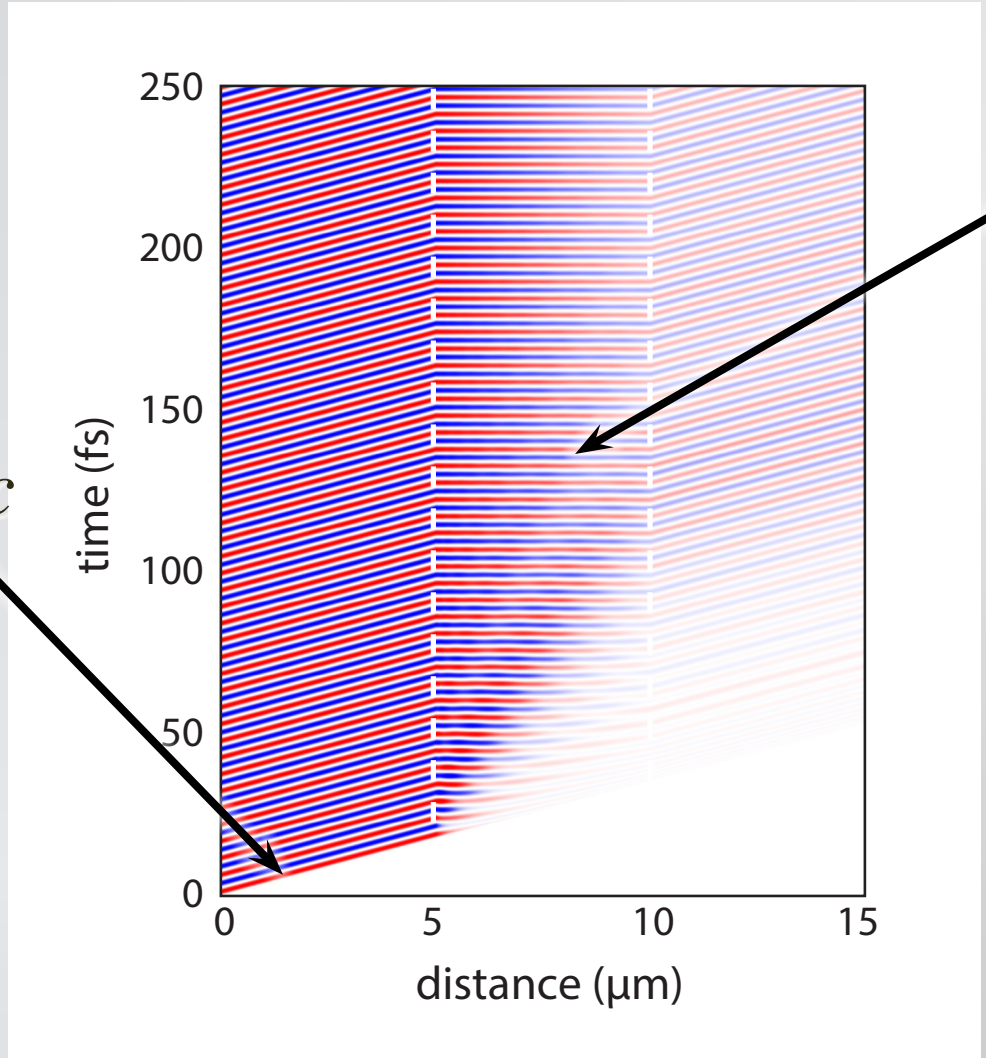
1 zero index

What about causality?

speed of light c



What about causality?



constant phase

speed of light c

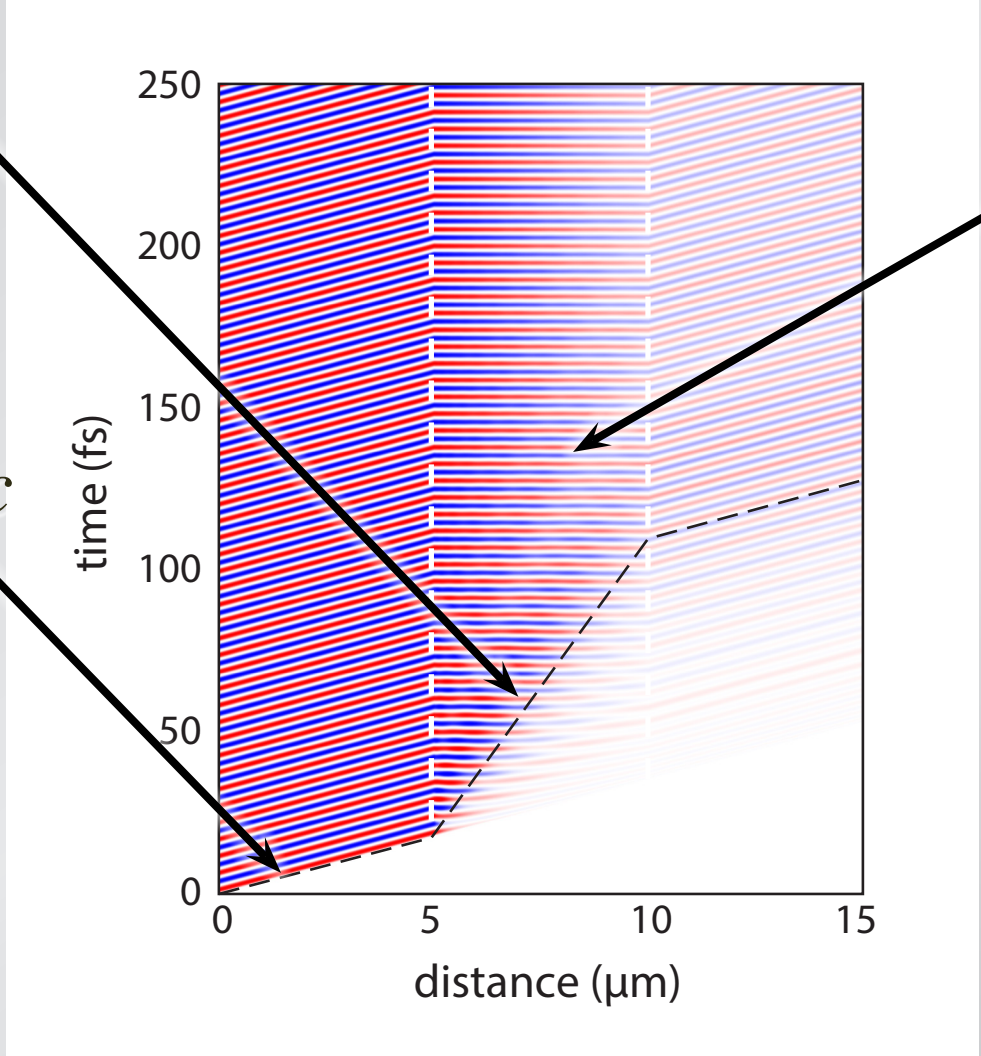
1 zero index

What about causality?

group velocity

$v_g < c$

speed of light c



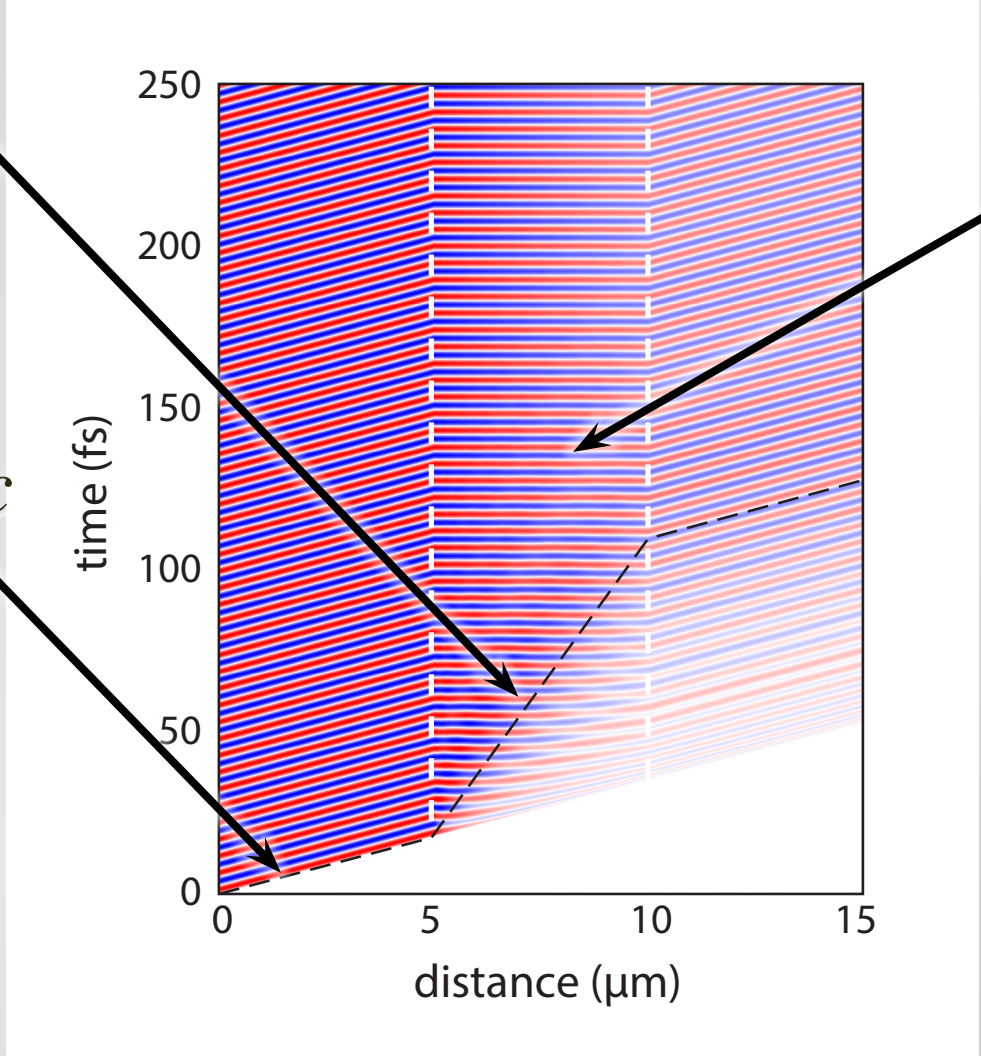
constant phase

What about causality?

group velocity

$v_g < c$

speed of light c



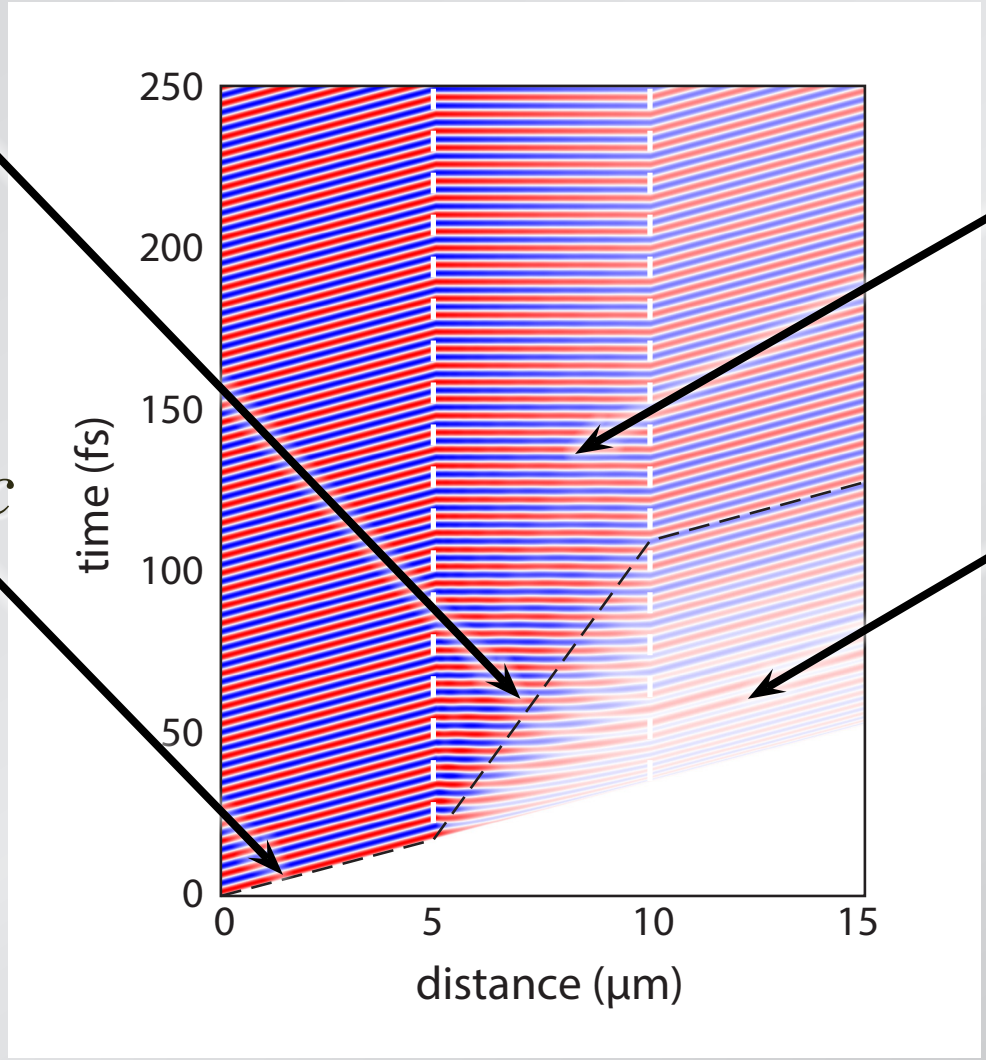
constant phase

What about causality?

group velocity

$v_g < c$

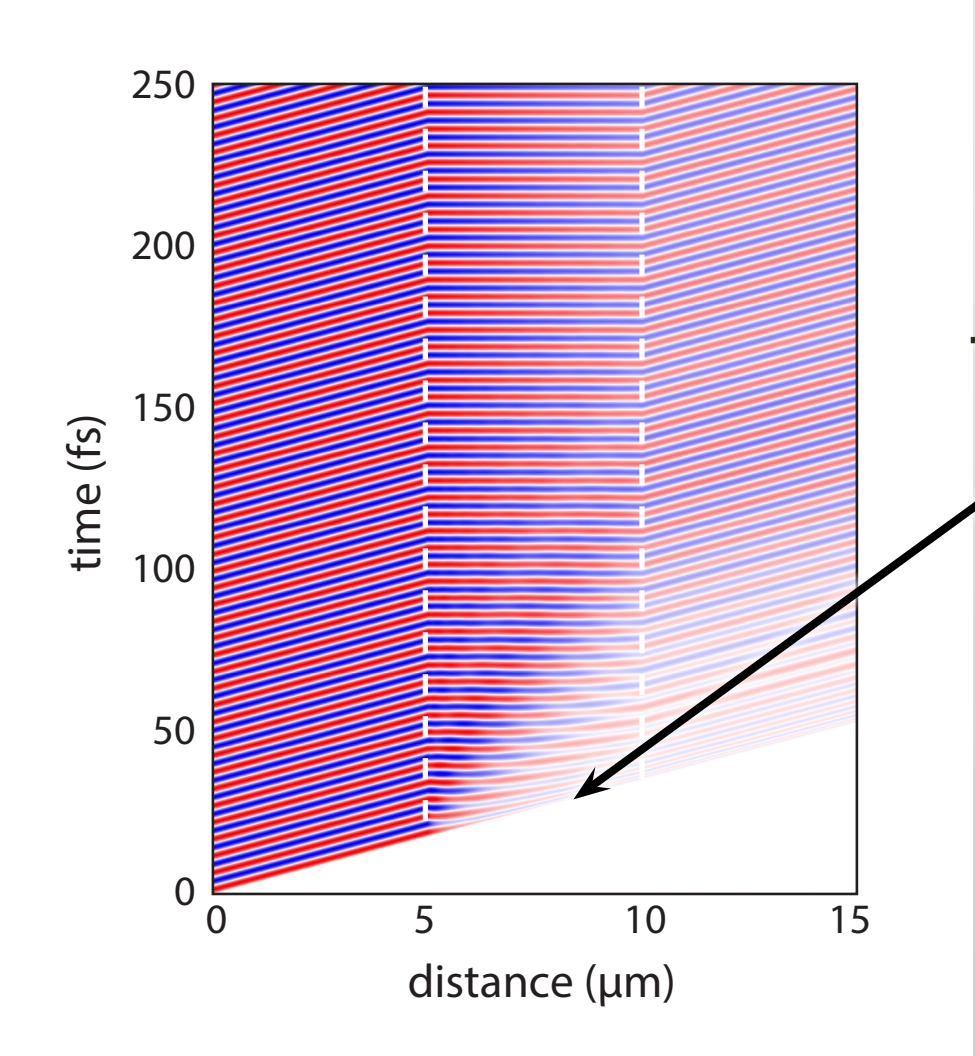
speed of light c



constant phase

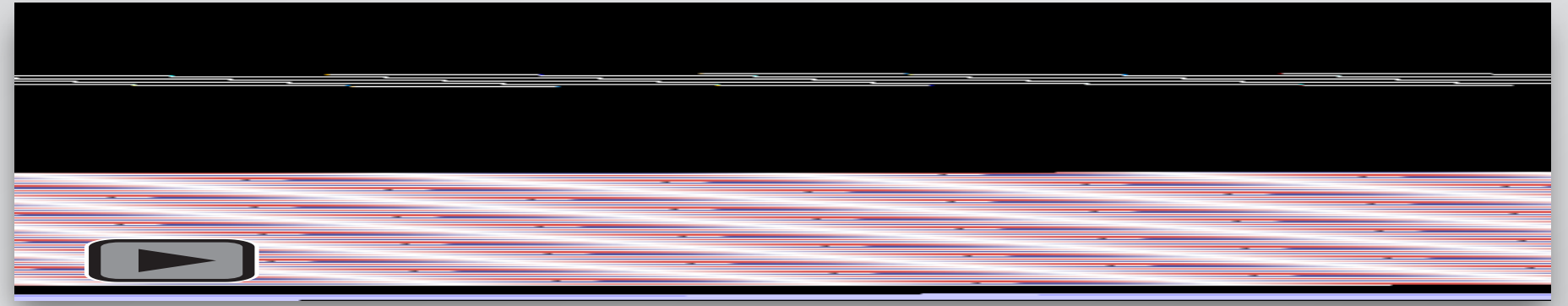
high-frequency precursors

What about causality?



signal *always* travels at speed c!

What about causality?



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

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

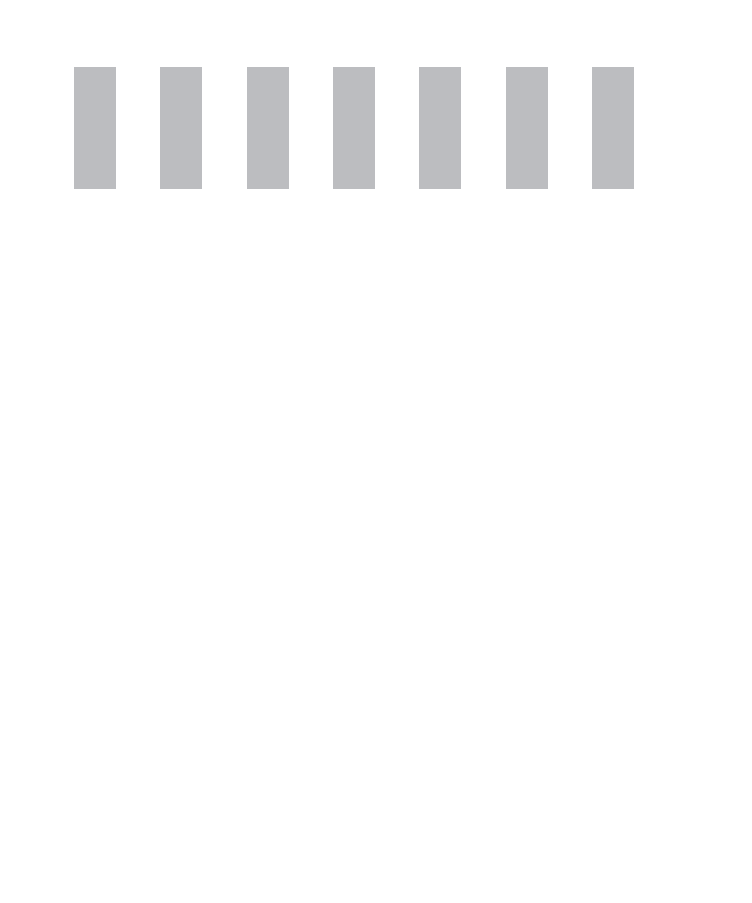
finite!

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

Engineering a magnetic response

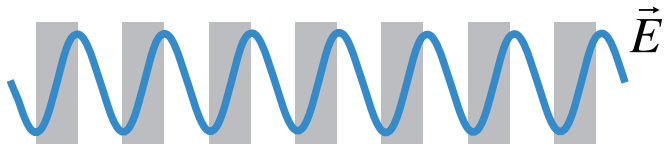
Engineering a magnetic response

use array of dielectric rods



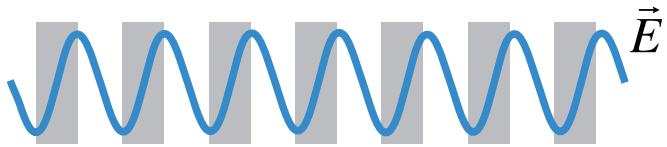
Engineering a magnetic response

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



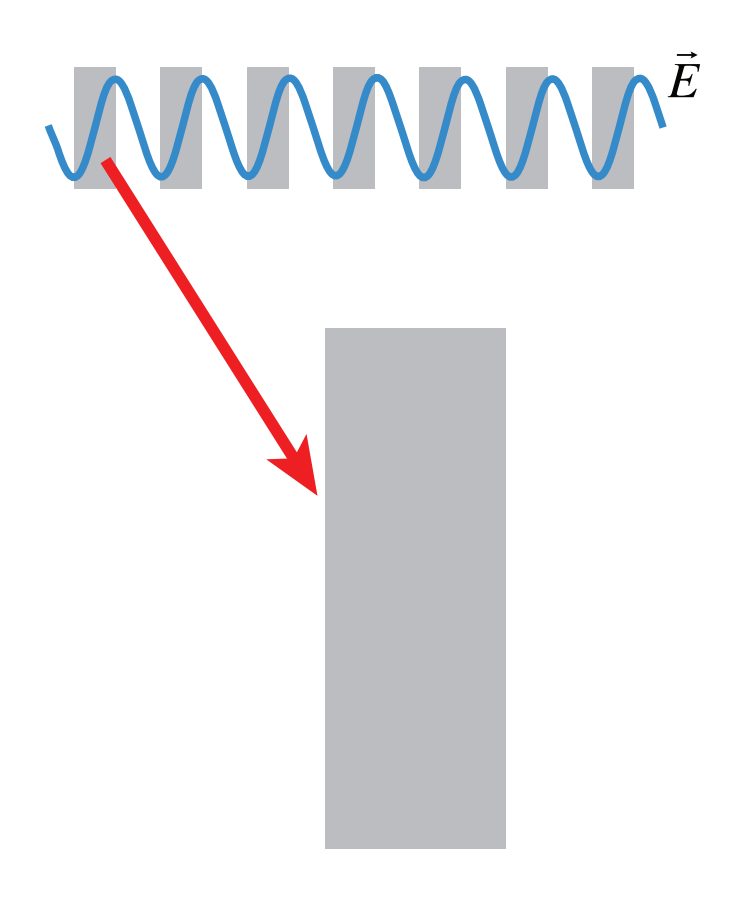
Engineering a magnetic response

produces an electric response…



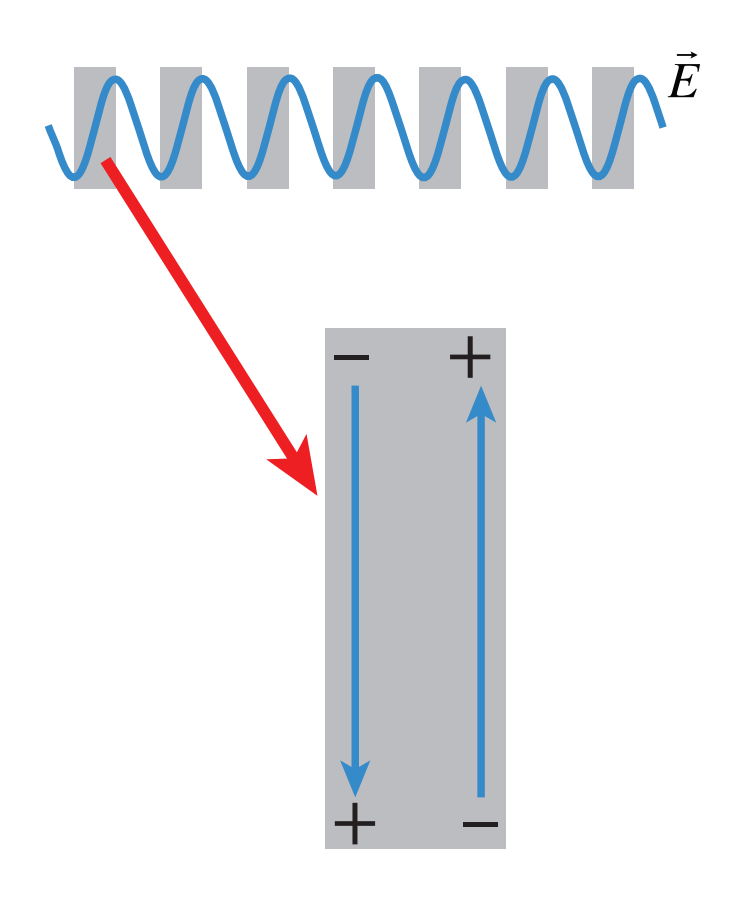
Engineering a magnetic response

… but different electric fields front and back…



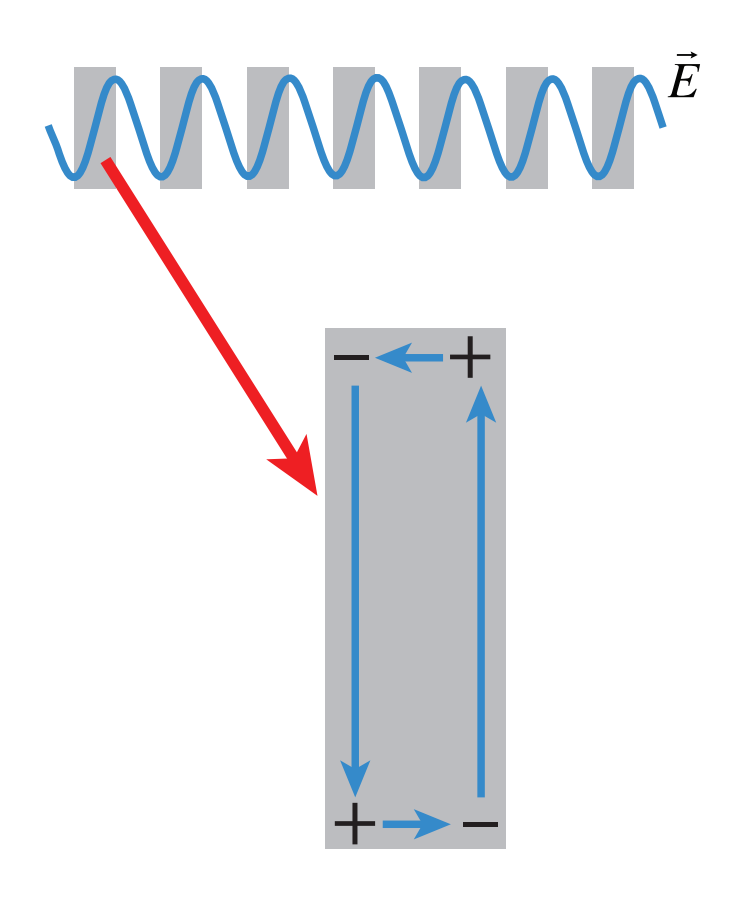
Engineering a magnetic response

…induce different polarizations on opposite sides…



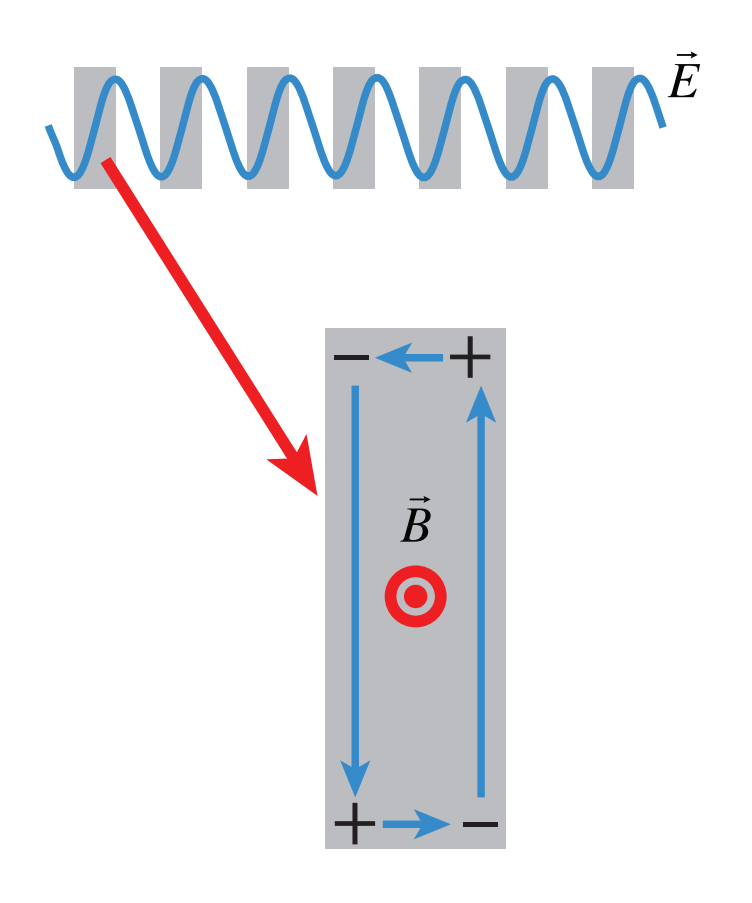
Engineering a magnetic response

…causing a current loop…



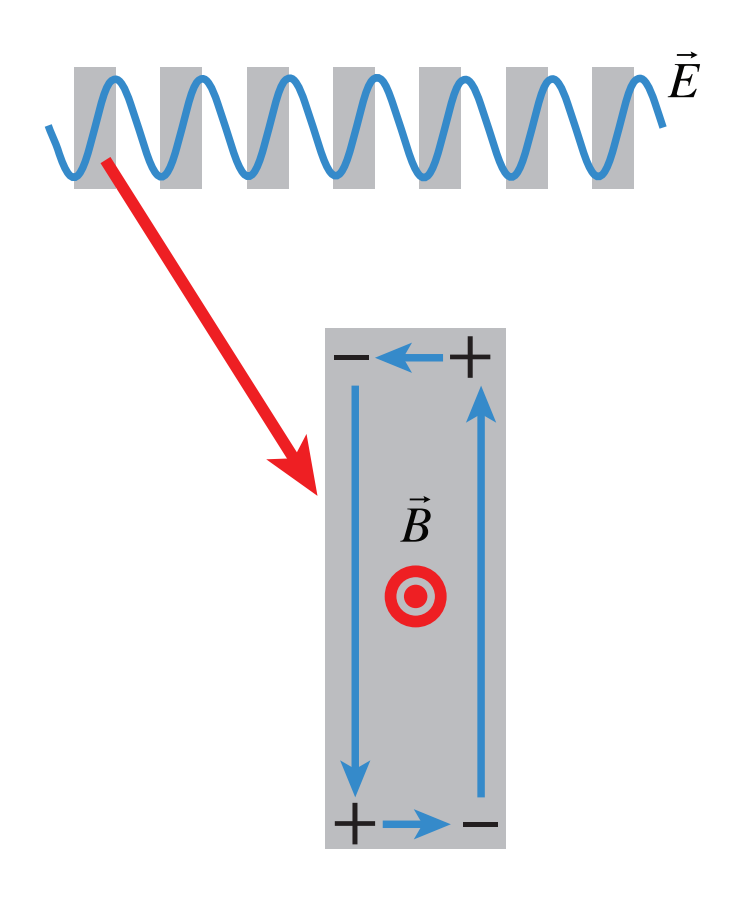
Engineering a magnetic response

…which, in turn, produces an induced magnetic field



Engineering a magnetic response

adjust design so ε and μ cross zero at the same time



Engineering a magnetic response

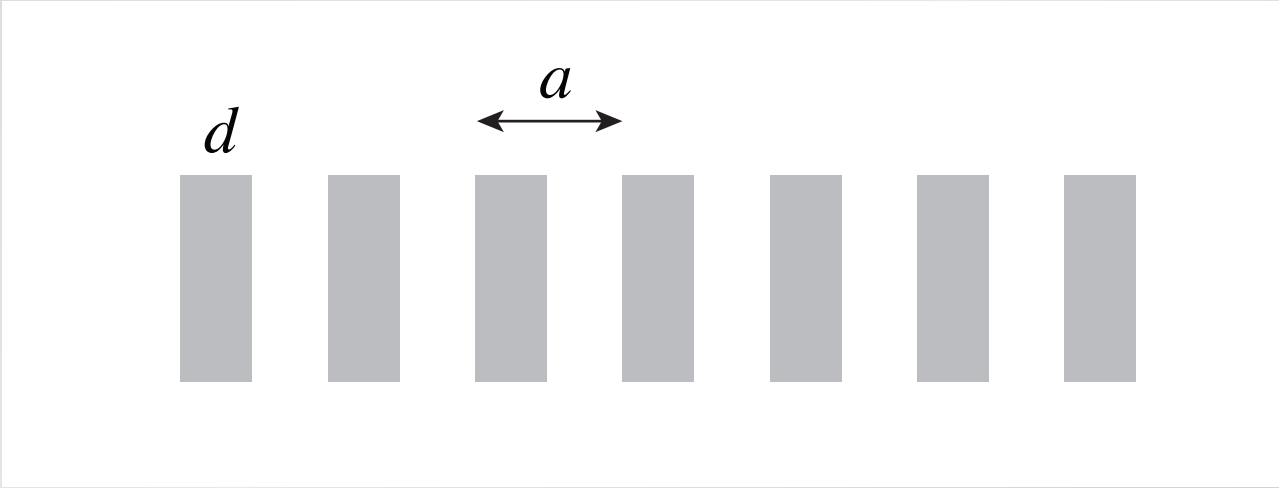
adjustable parameters

Engineering a magnetic response

adjustable parameters

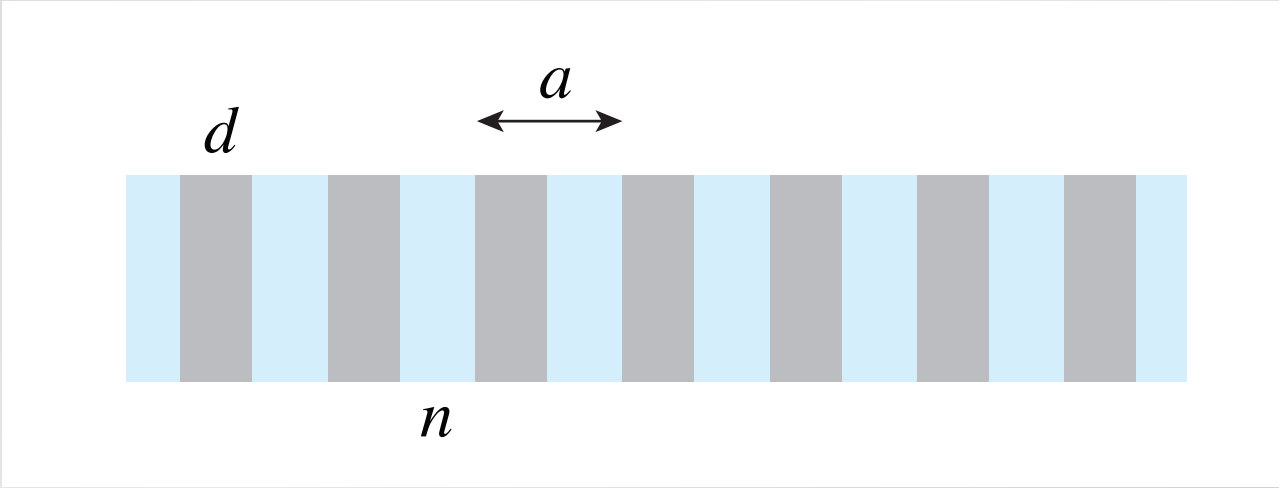
Engineering a magnetic response

adjustable parameters



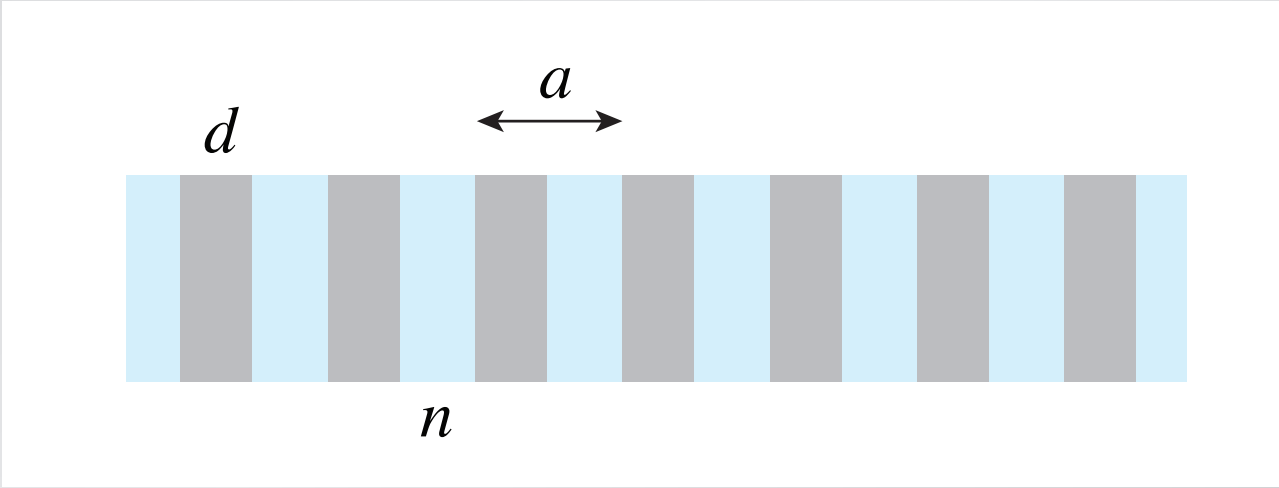
Engineering a magnetic response

adjustable parameters



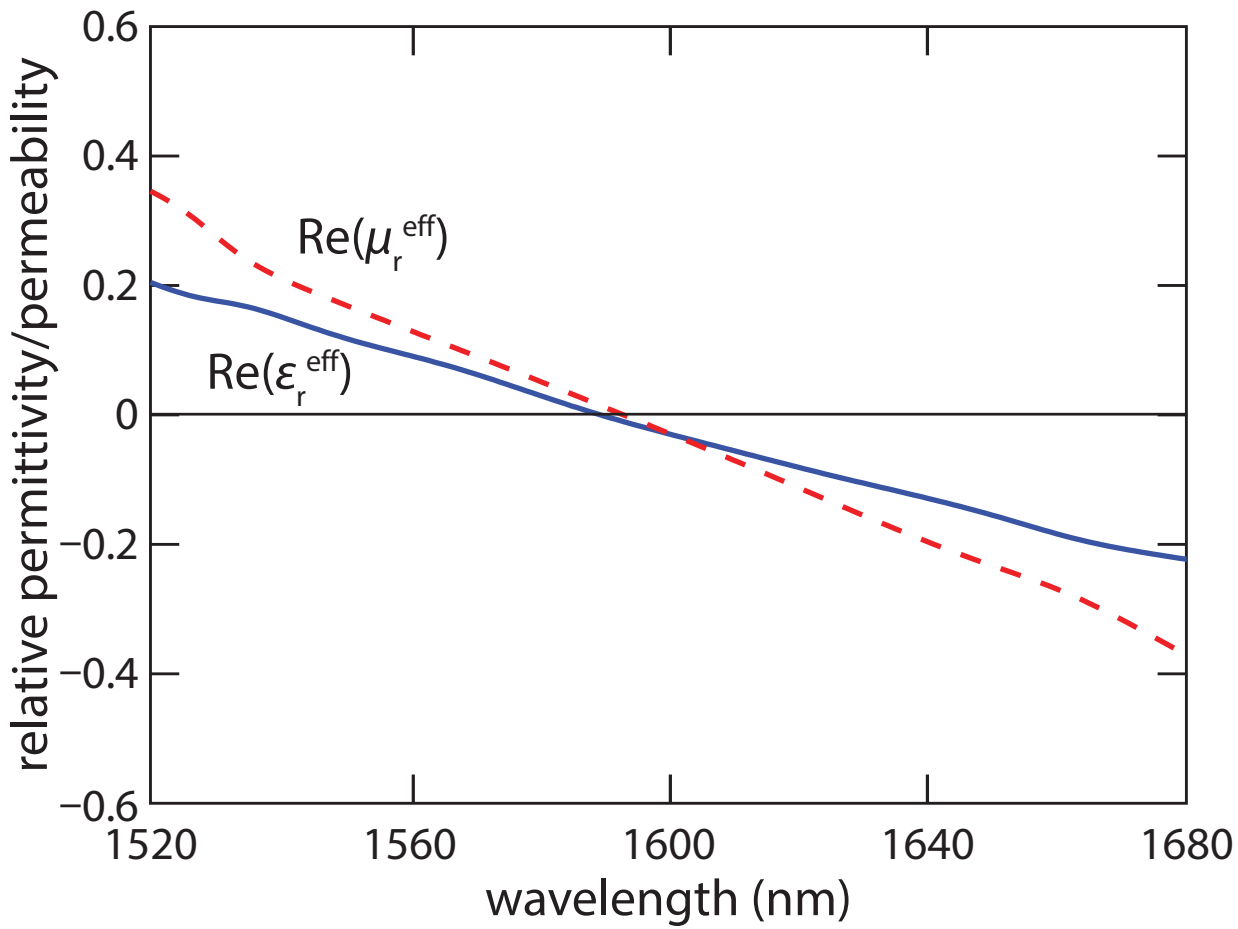
Engineering a magnetic response

adjustable parameters

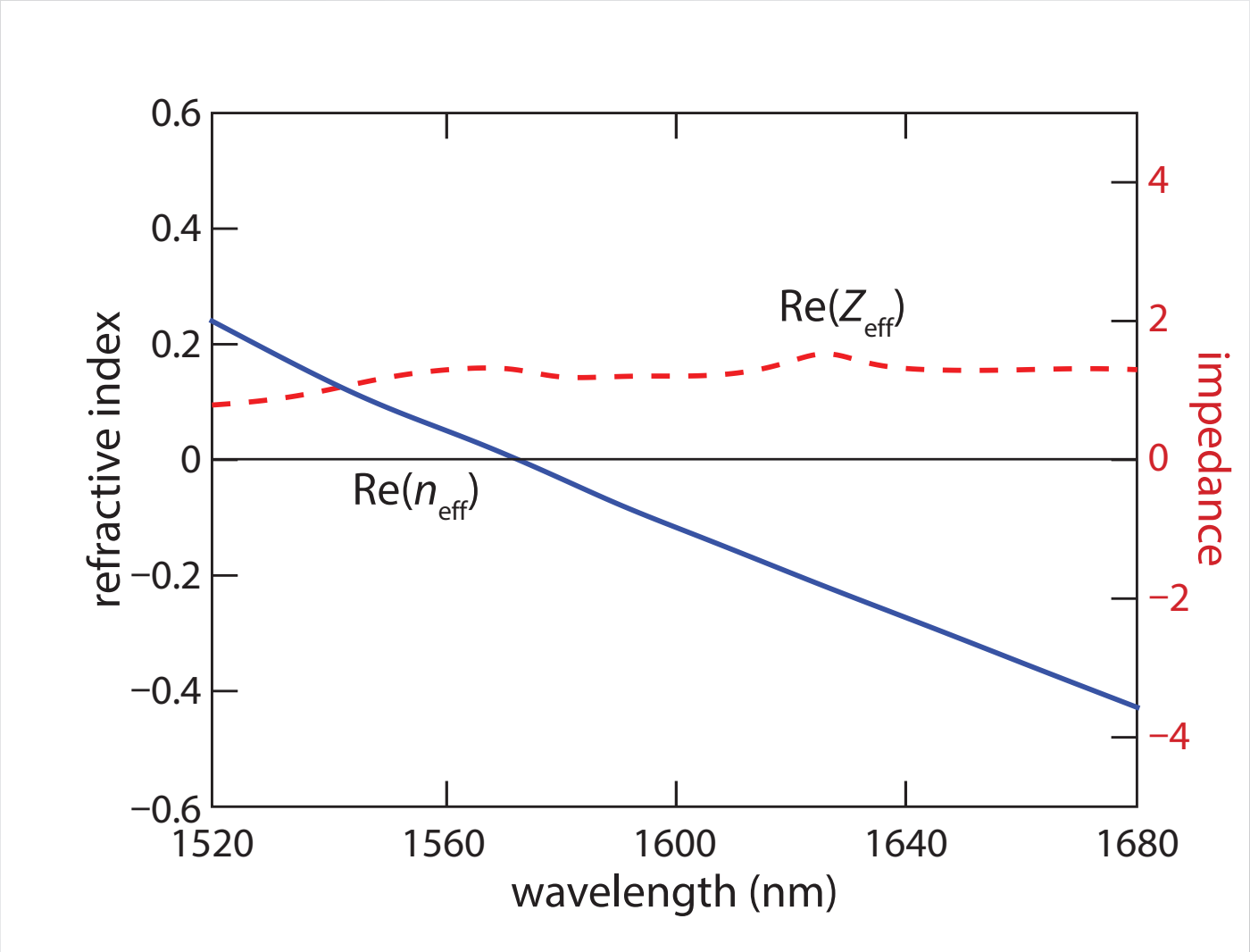


d = 422 nm, a = 690 nm, n = 1.57 (SU8)

1 zero index

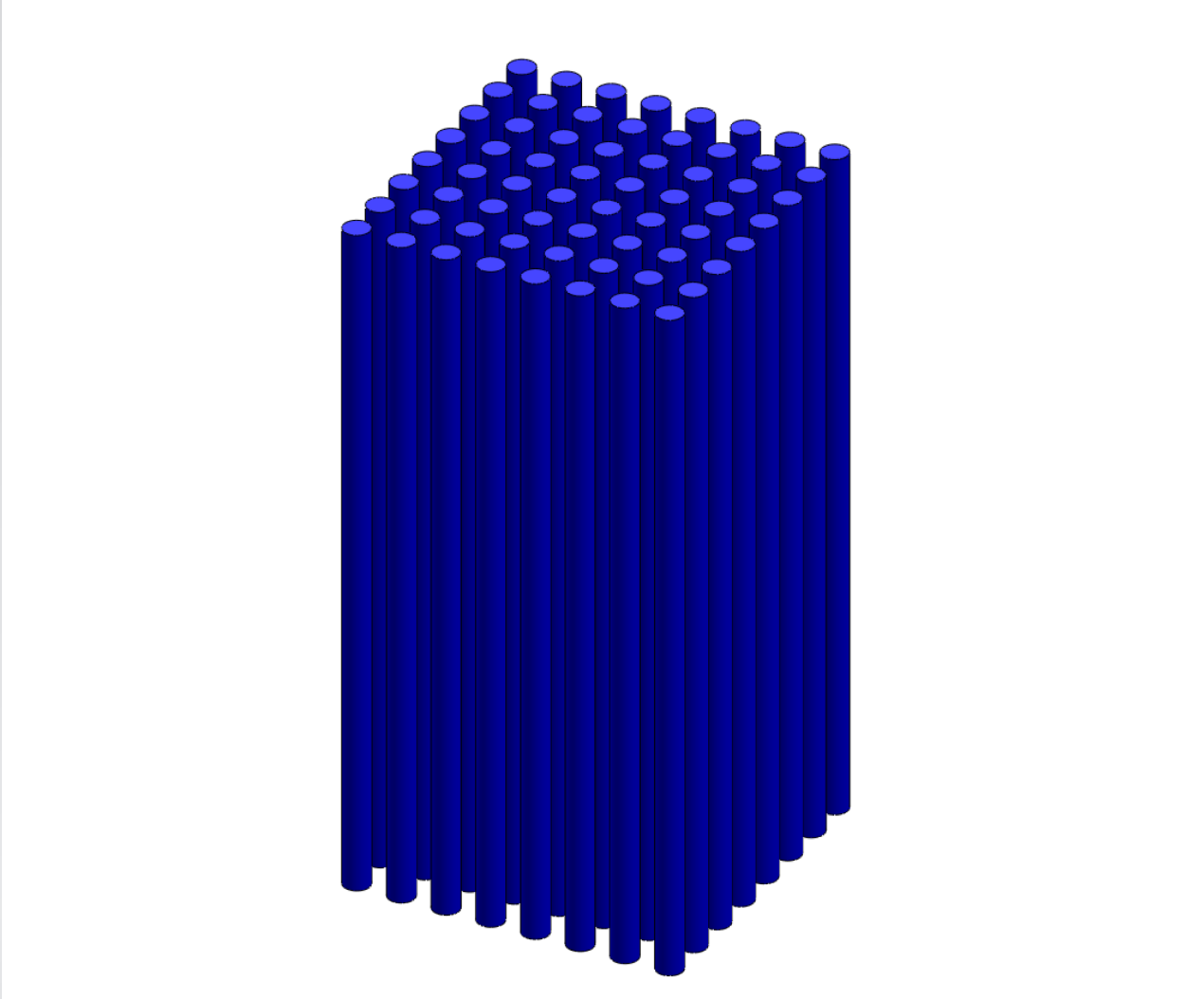

0.6
0.4
0.2
0
−0.2
−0.4
−0.6
relative permittivity/permeability
Re(μ_r^{eff})
Re(ε_r^{eff})
1520
1560
1600
1640
1680
wavelength (nm)

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)

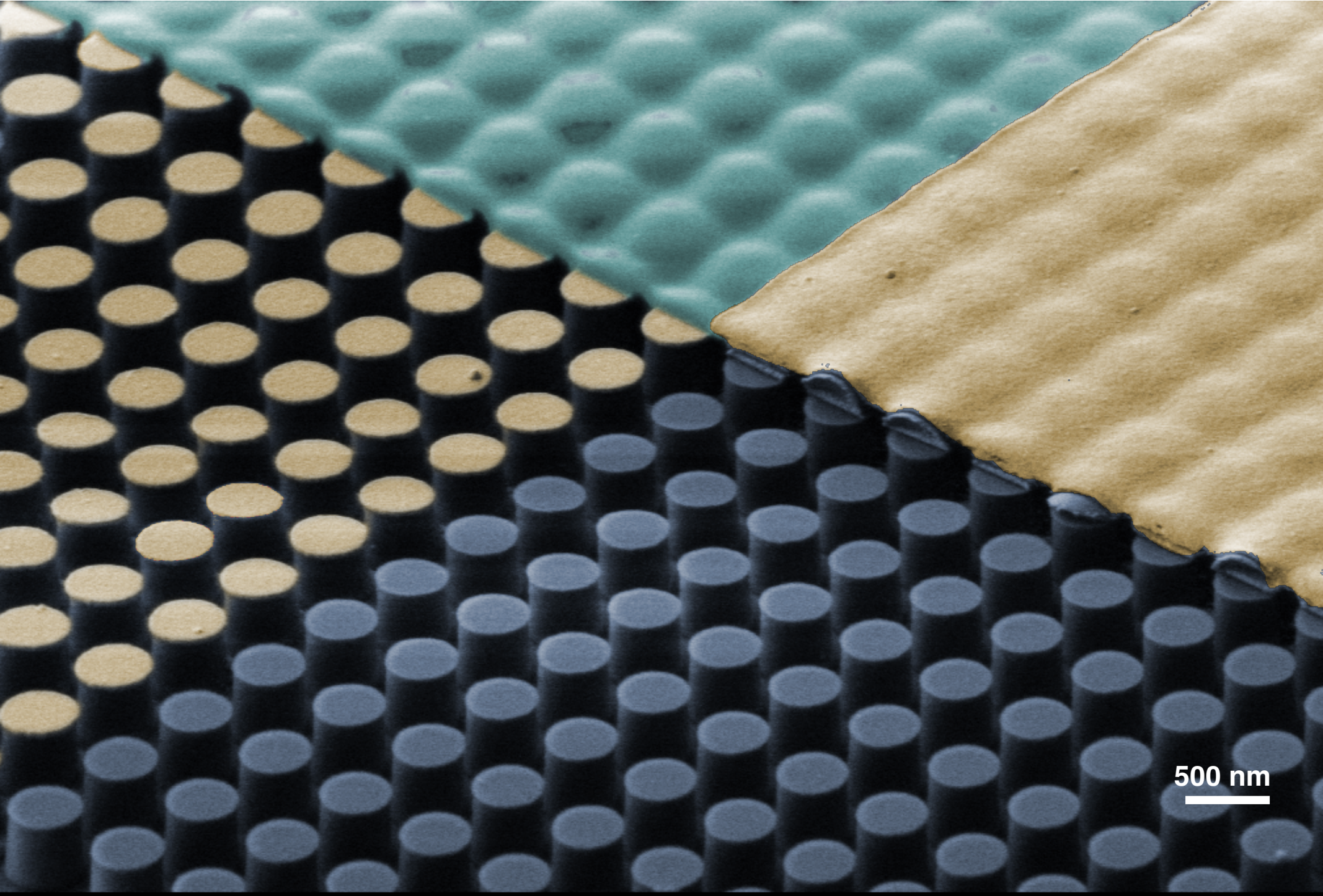
1 zero index

How to fabricate?



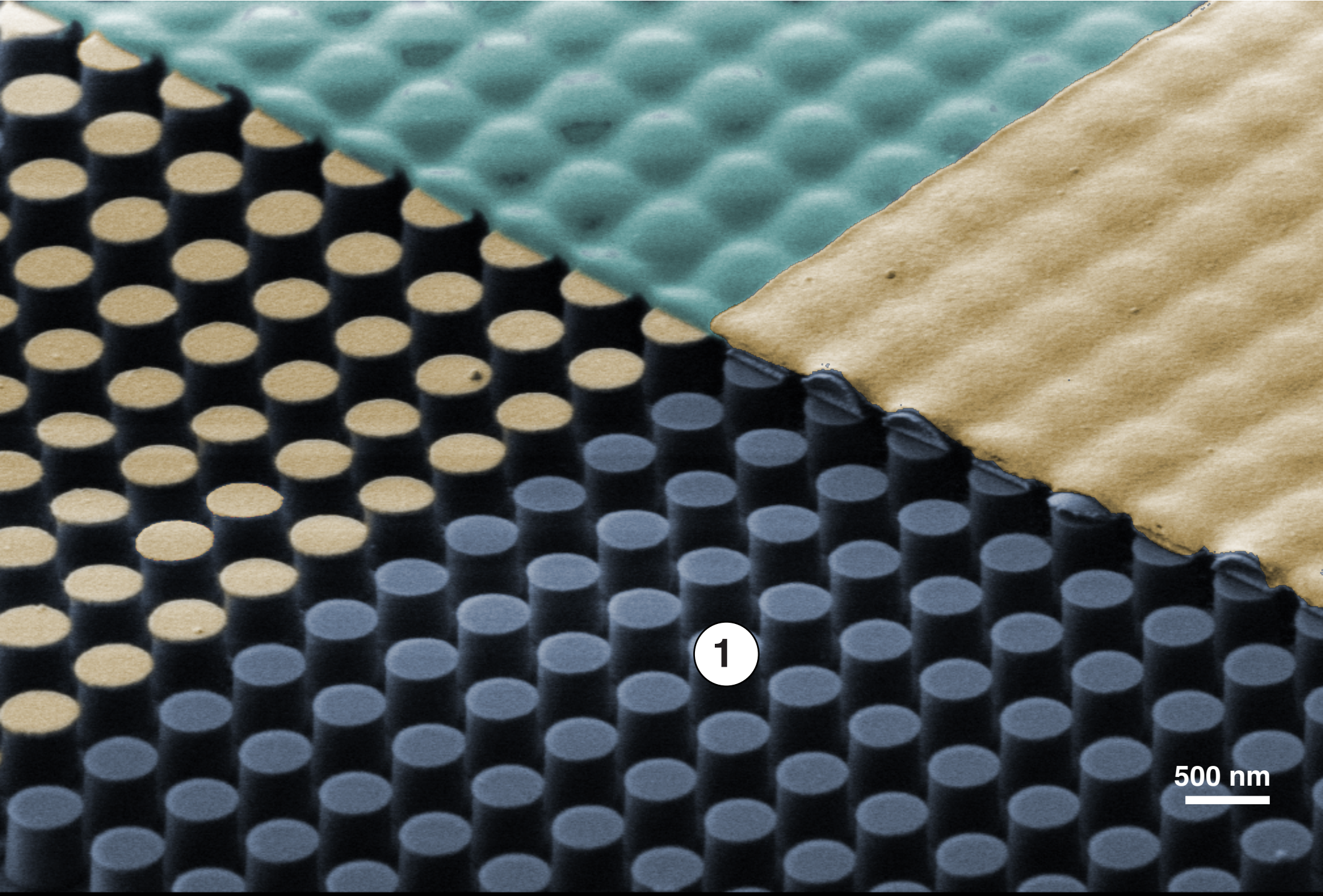
1 zero index

2 fabrication



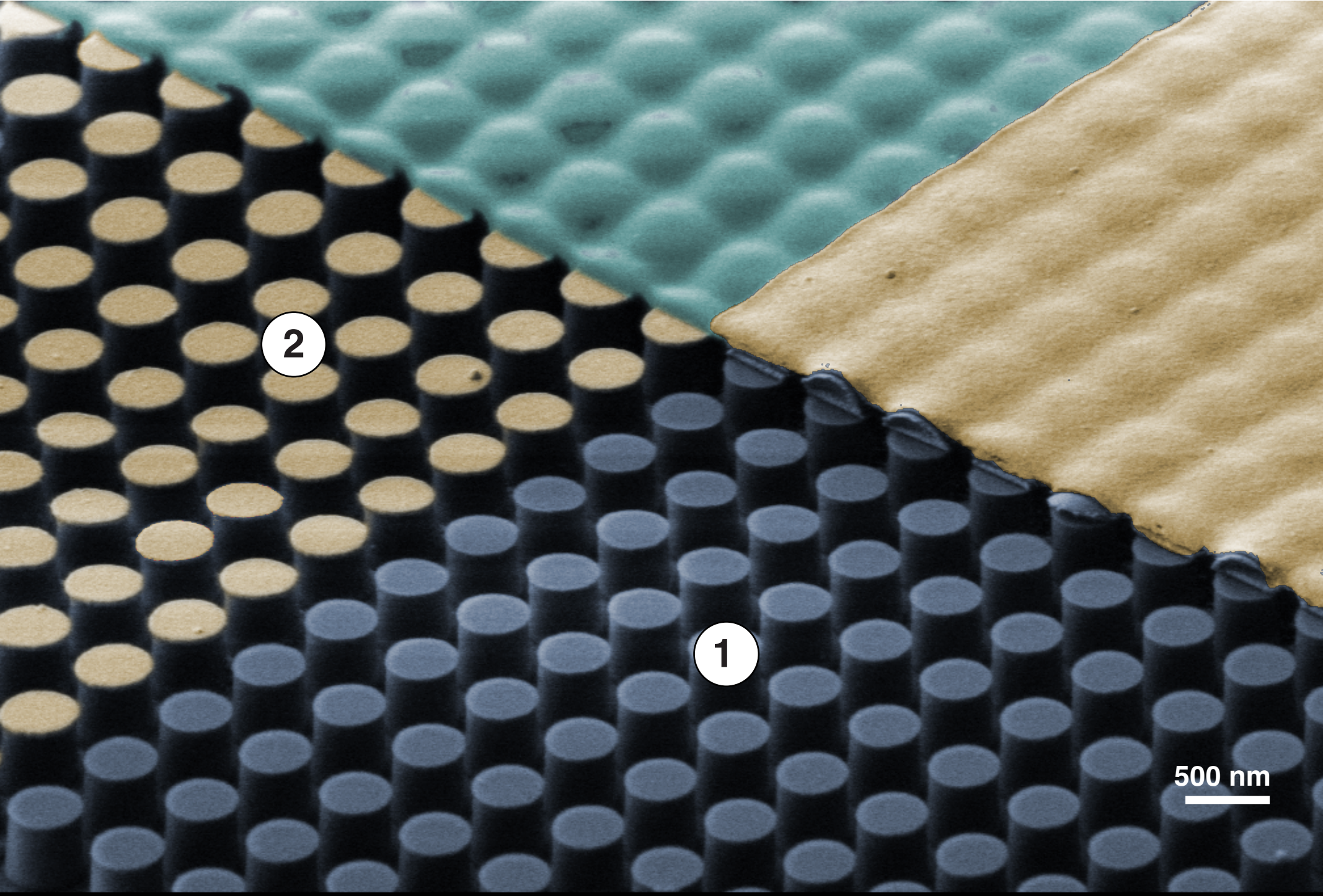
1 zero index

2 fabrication



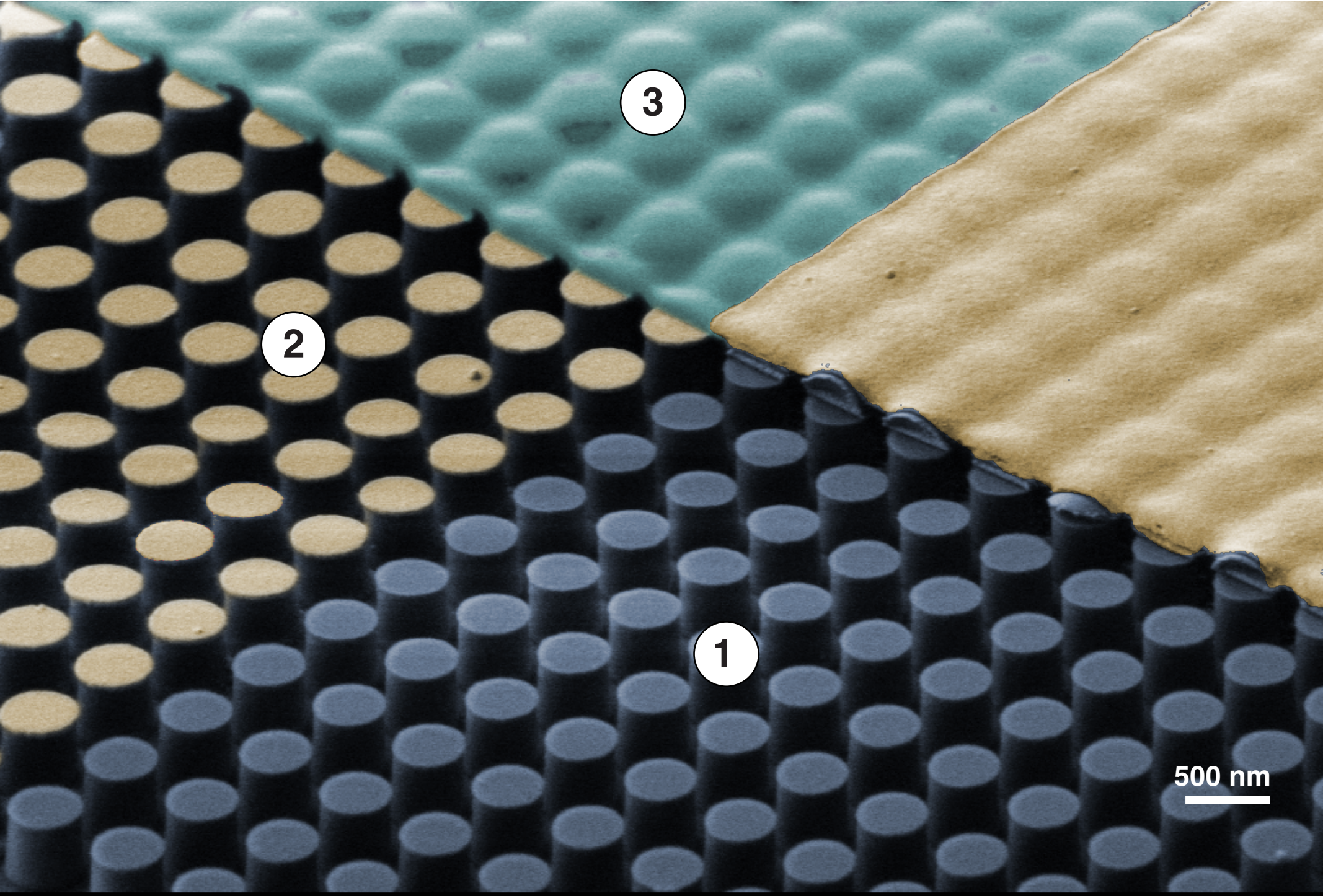
1 zero index

2 fabrication



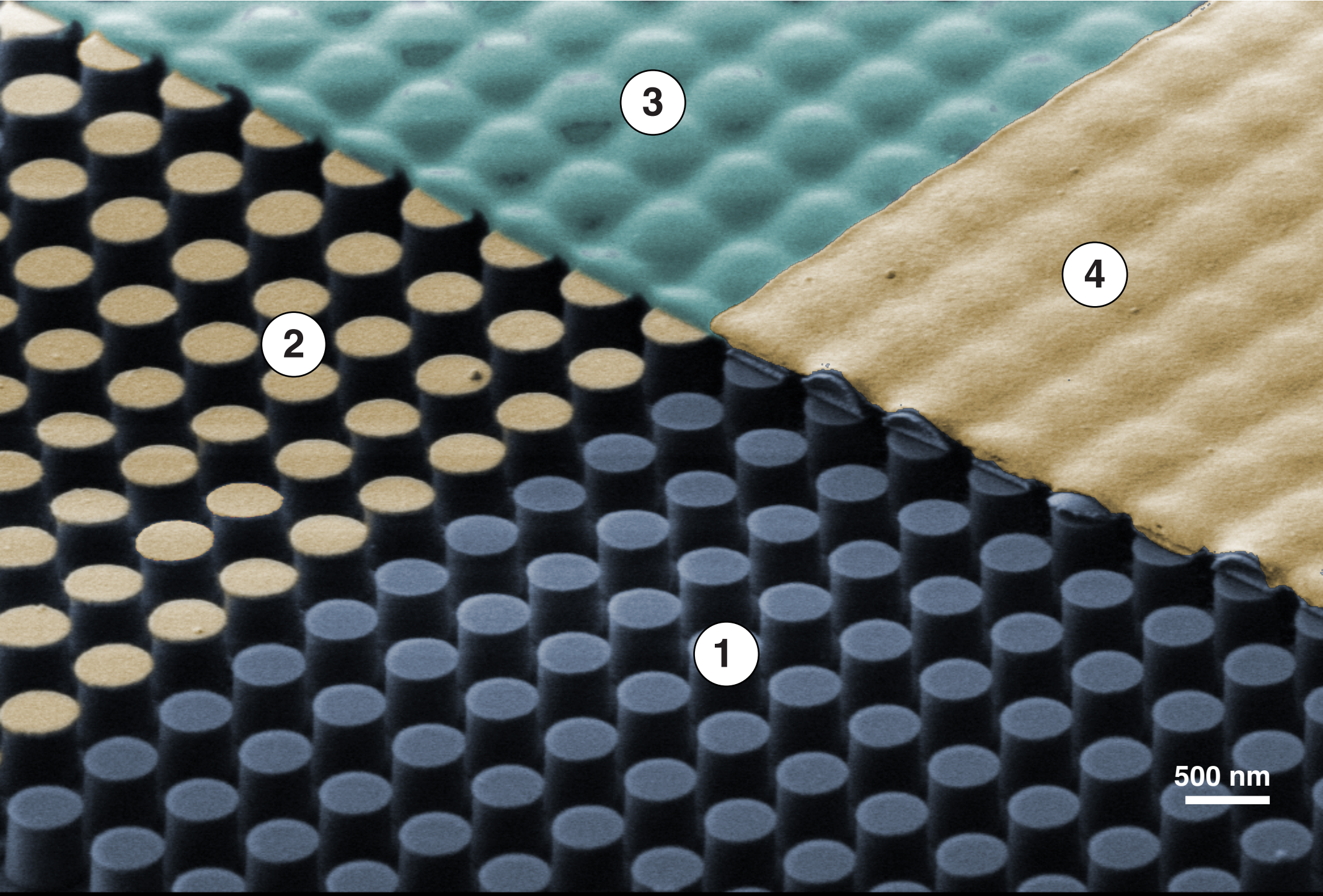
1 zero index

2 fabrication



1 zero index

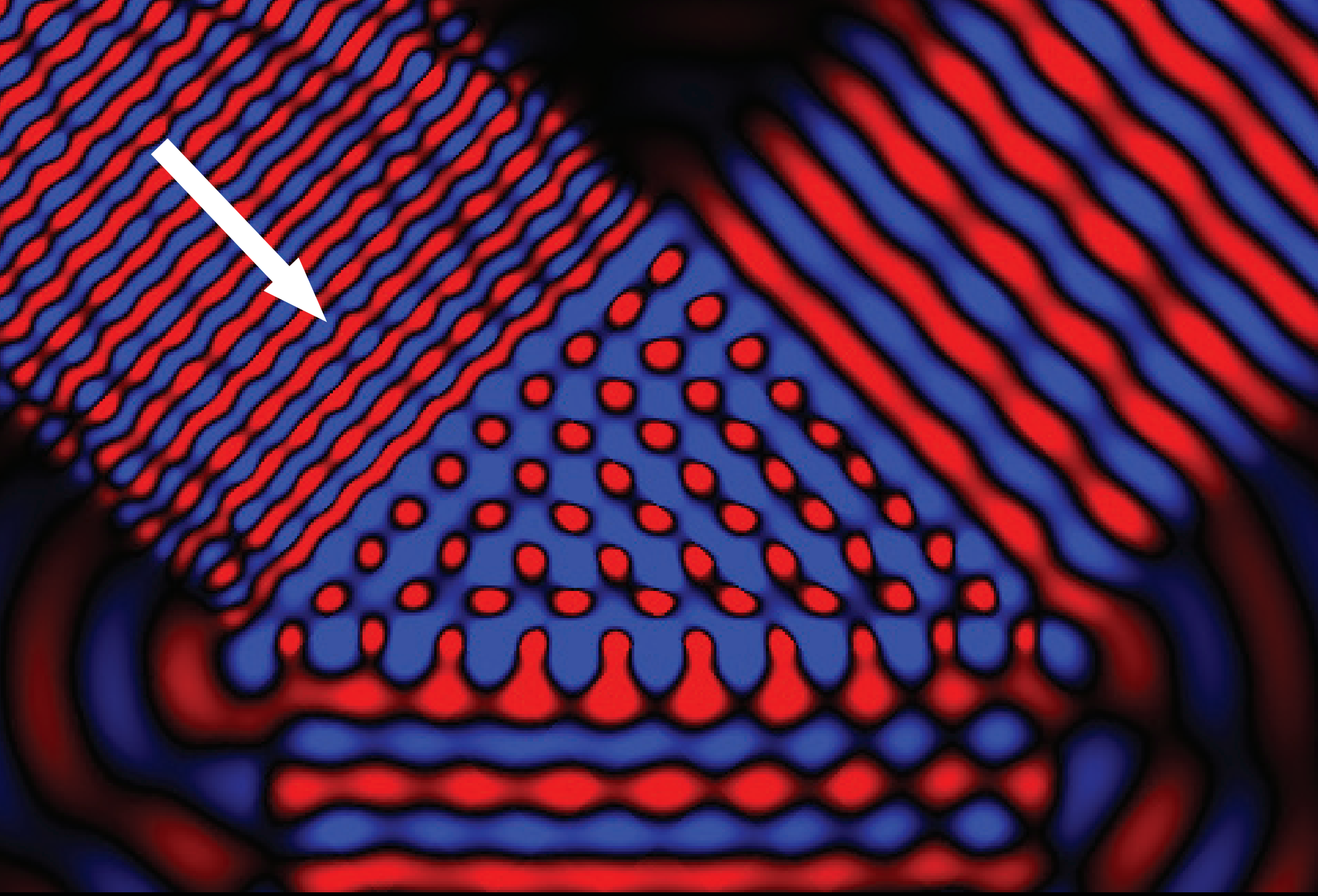
2 fabrication



1 zero index

2 fabrication

Can make this on chip and in any shape!



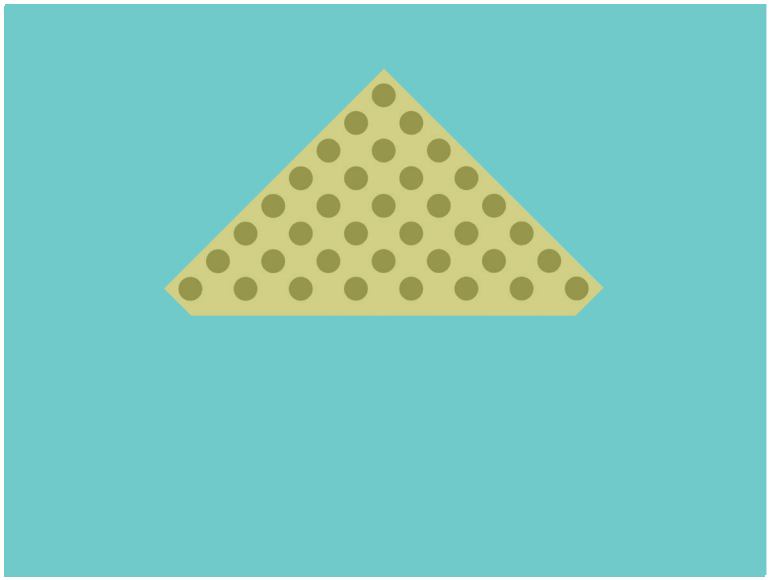
1 zero index

2 fabrication

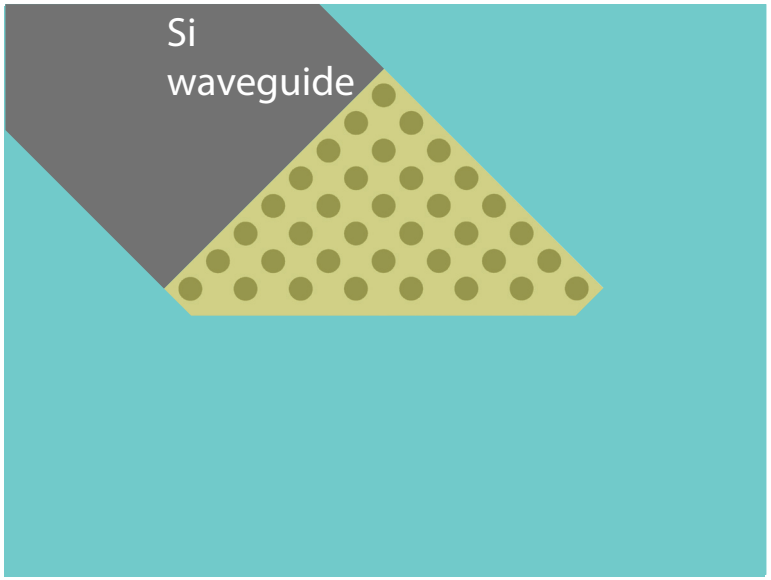
3 results

On-chip zero-index prism

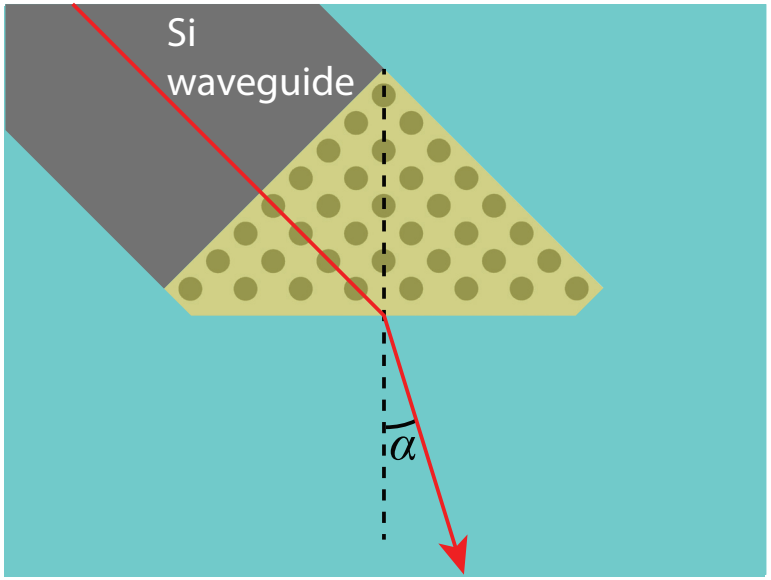
On-chip zero-index prism



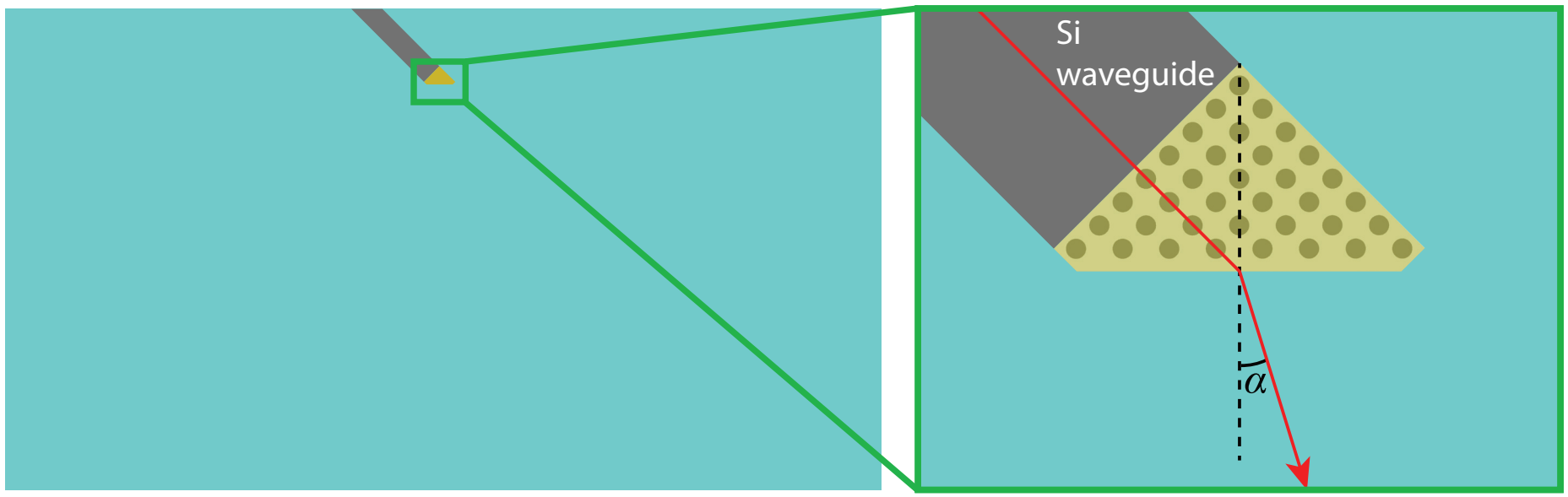
On-chip zero-index prism



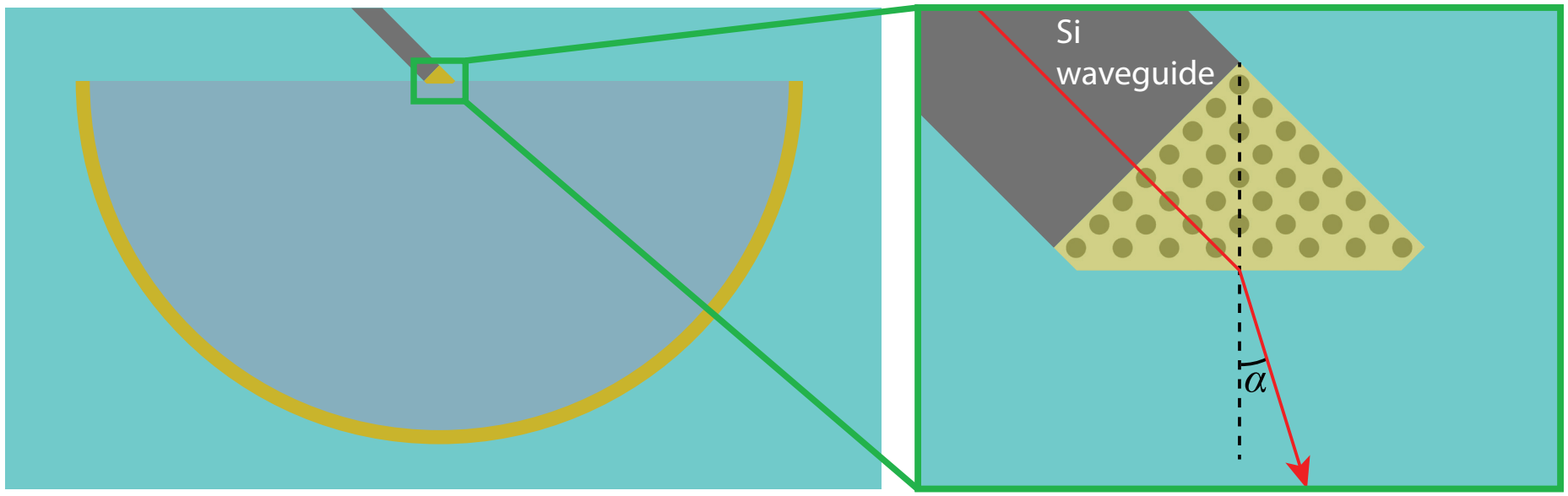
On-chip zero-index prism



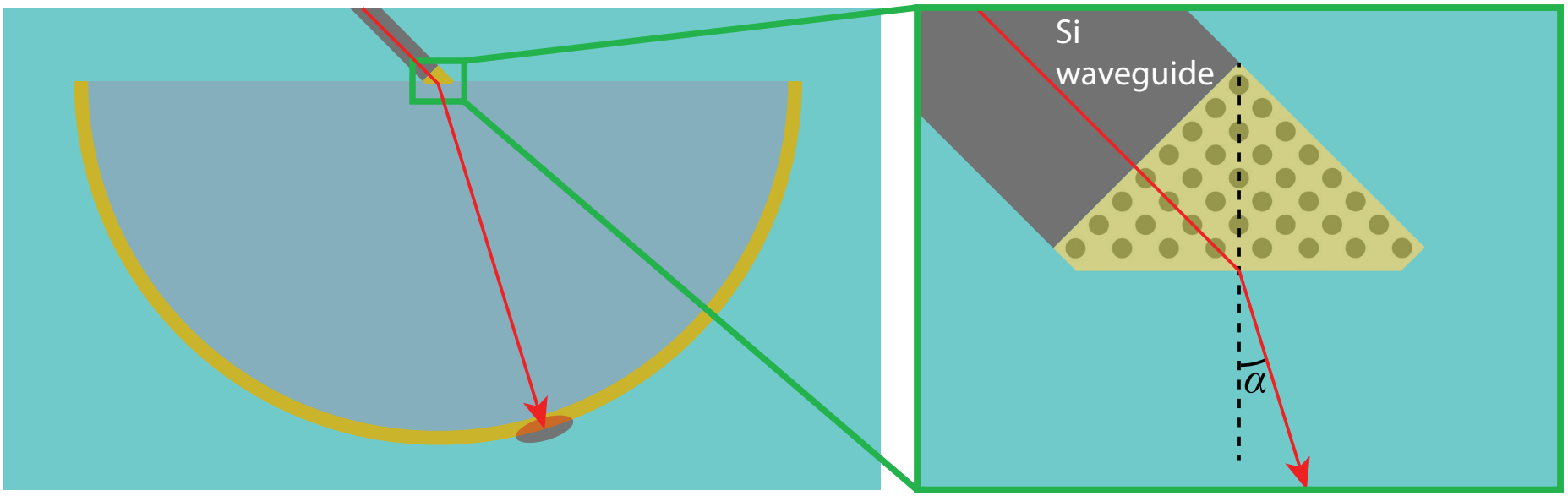
On-chip zero-index prism



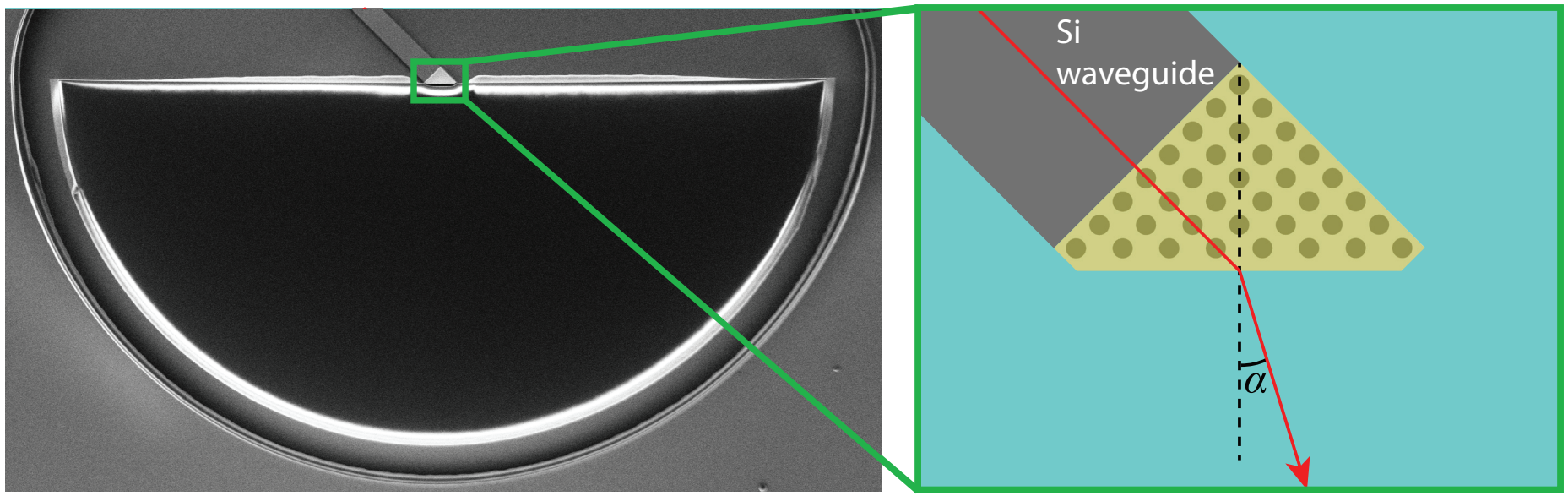
On-chip zero-index prism



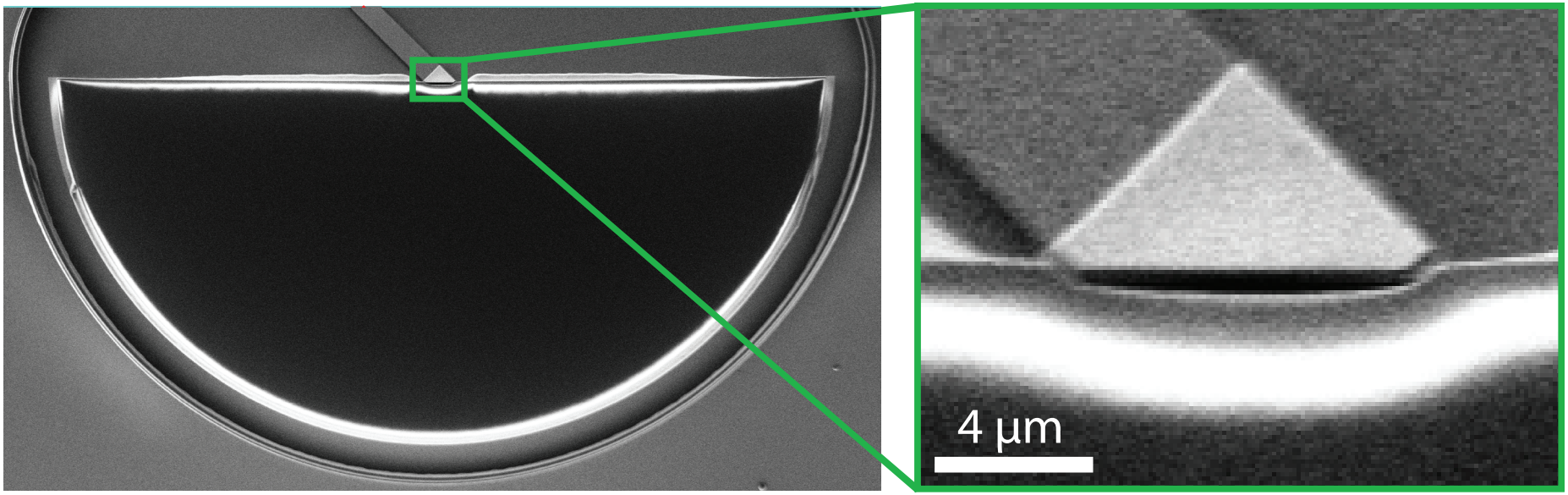
On-chip zero-index prism

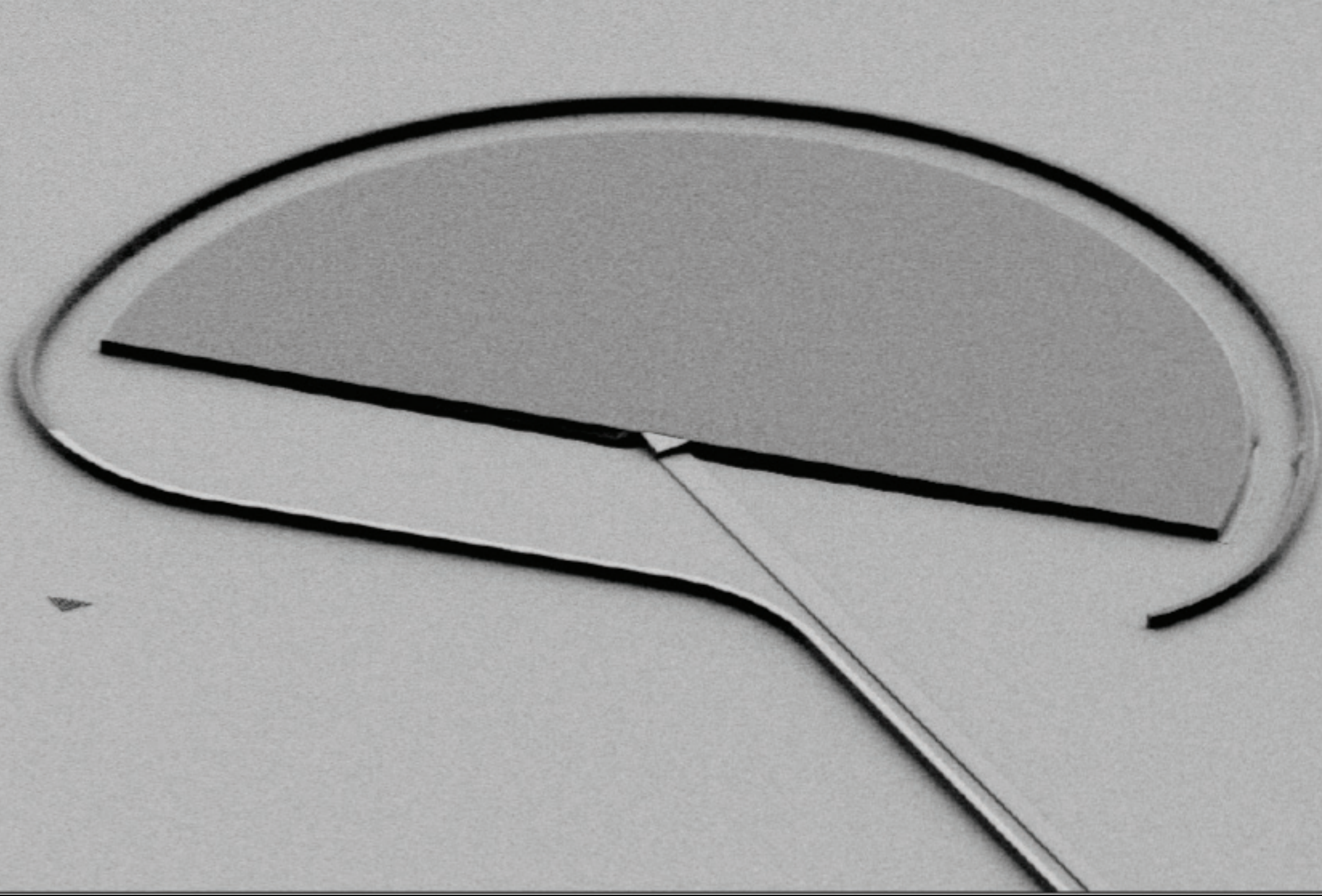


On-chip zero-index prism

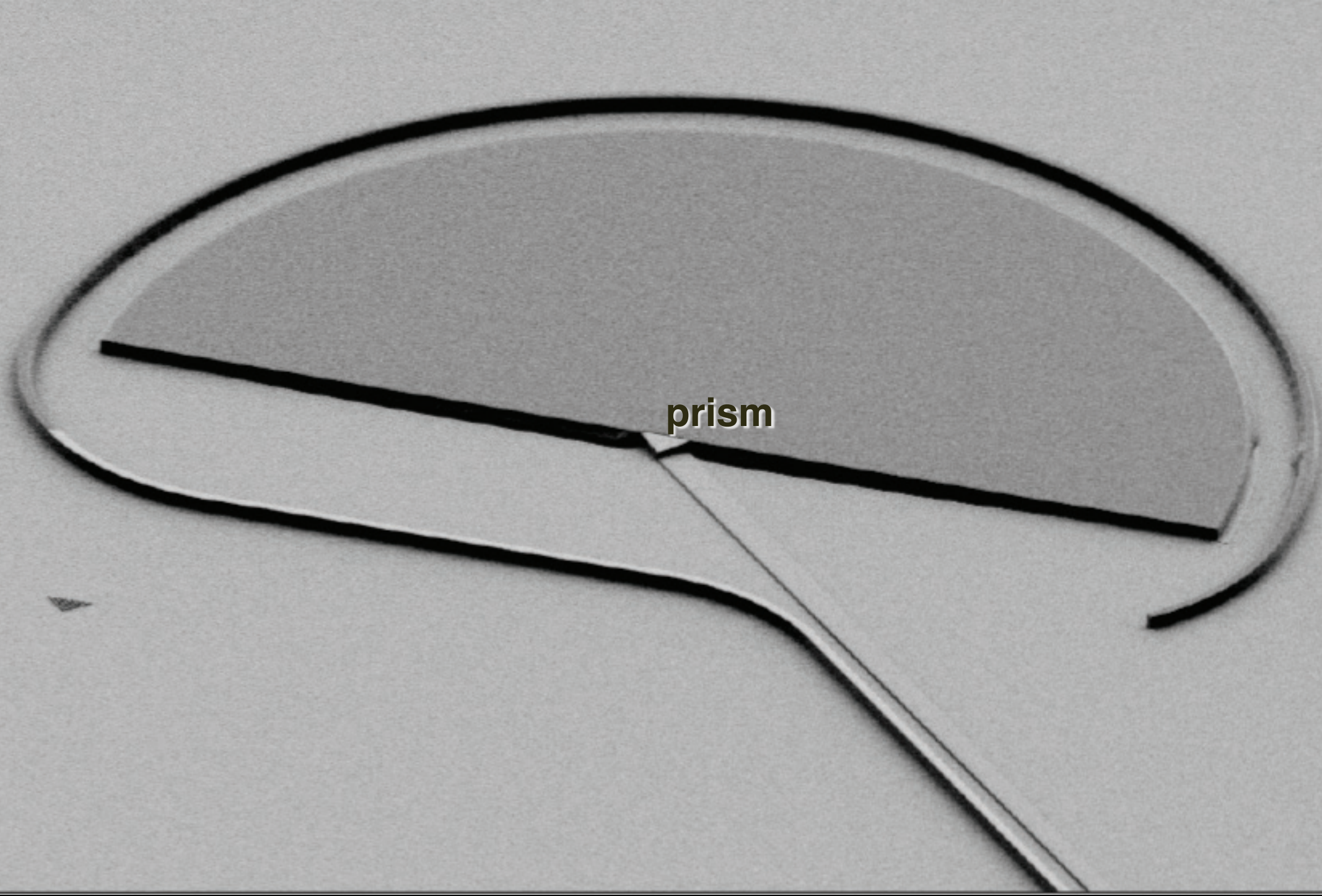


On-chip zero-index prism

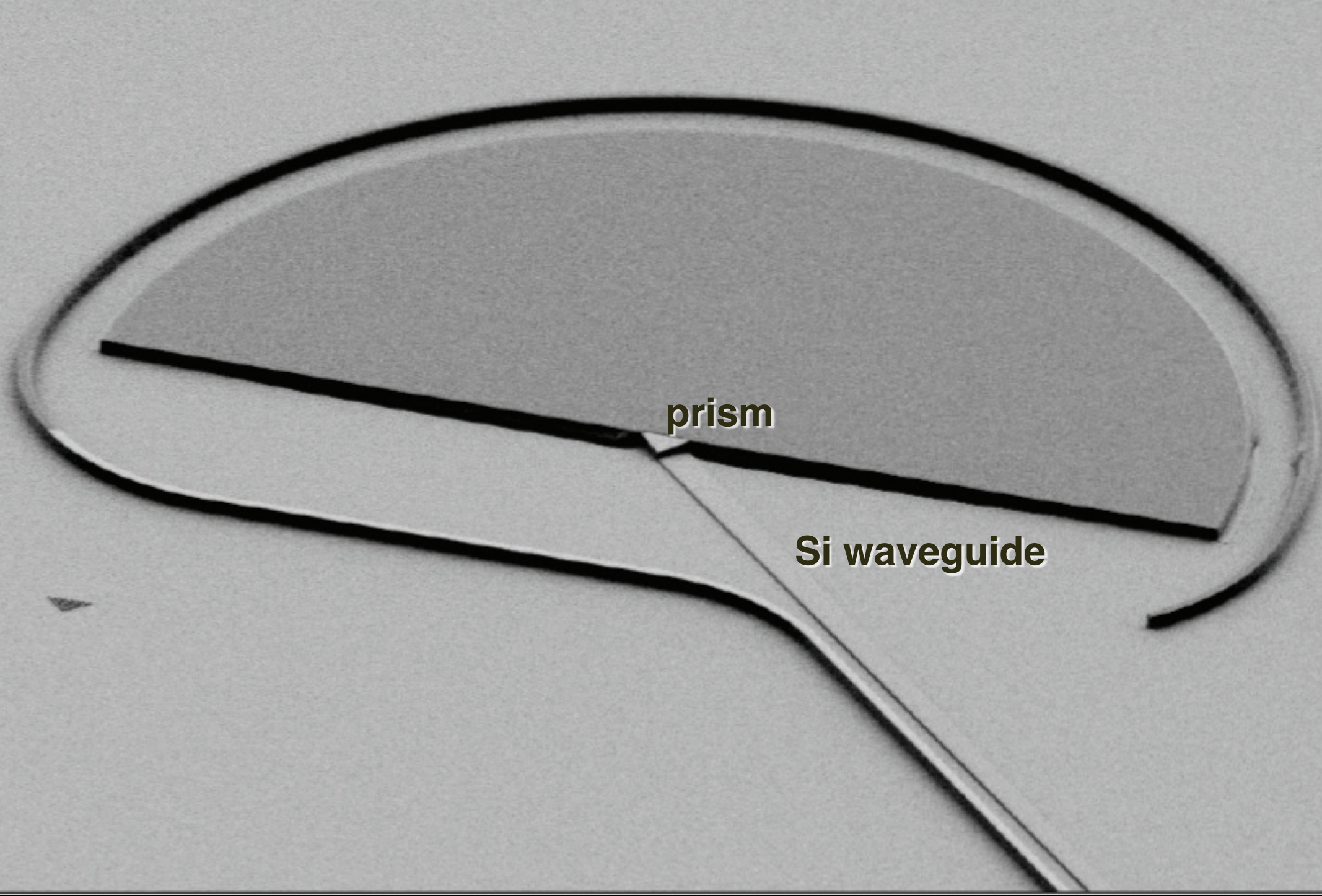


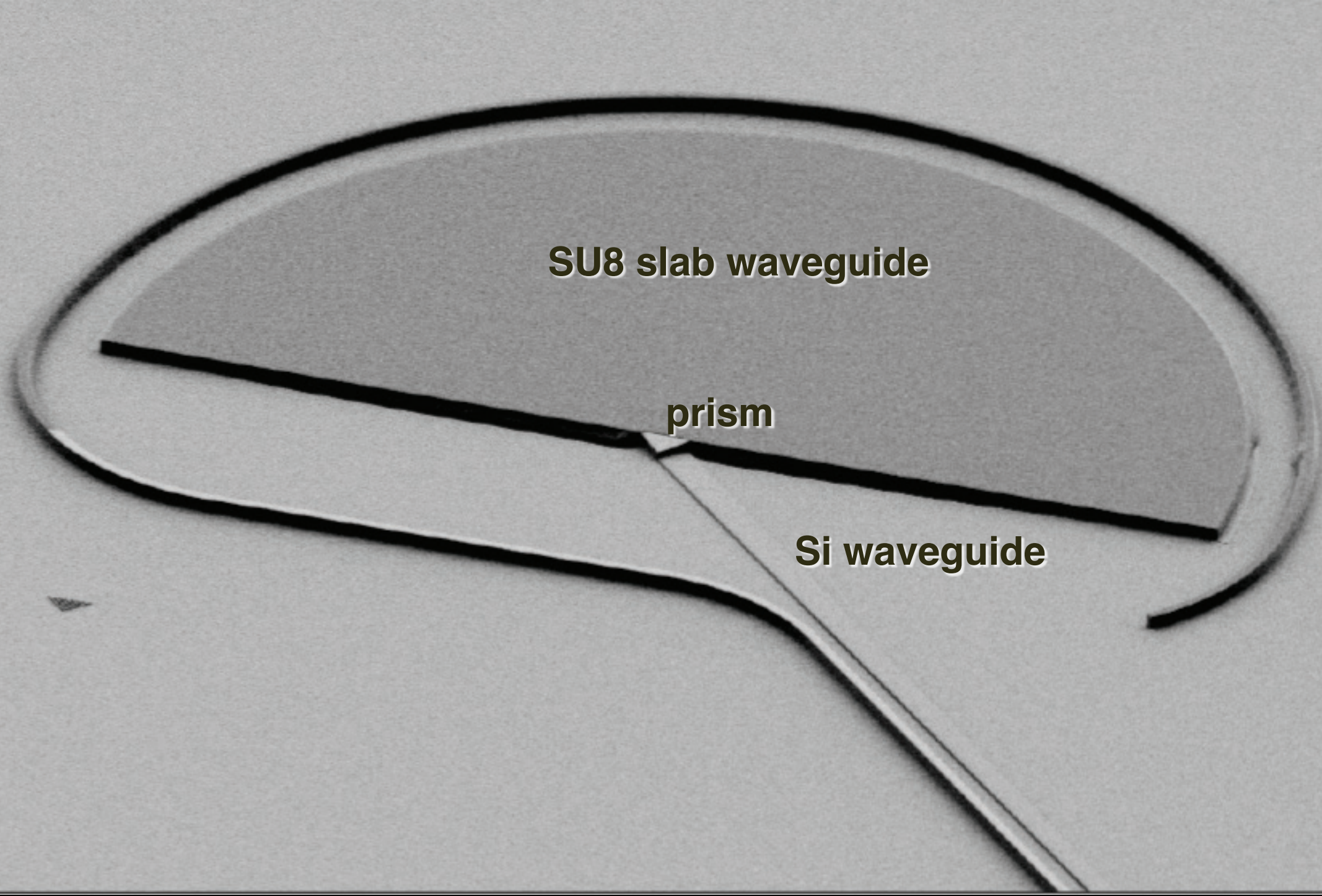


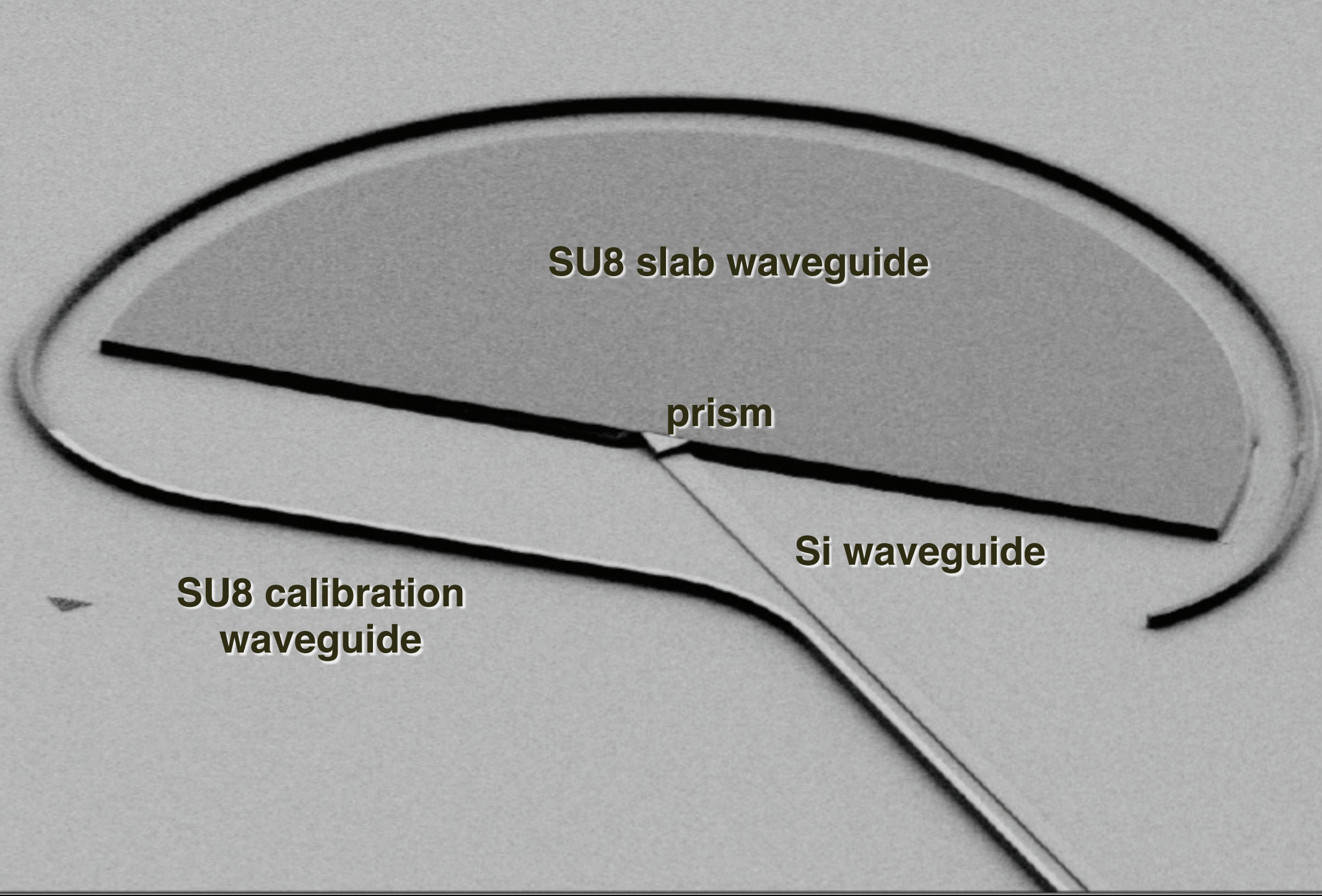
1 zero index 2 fabrication 3 results

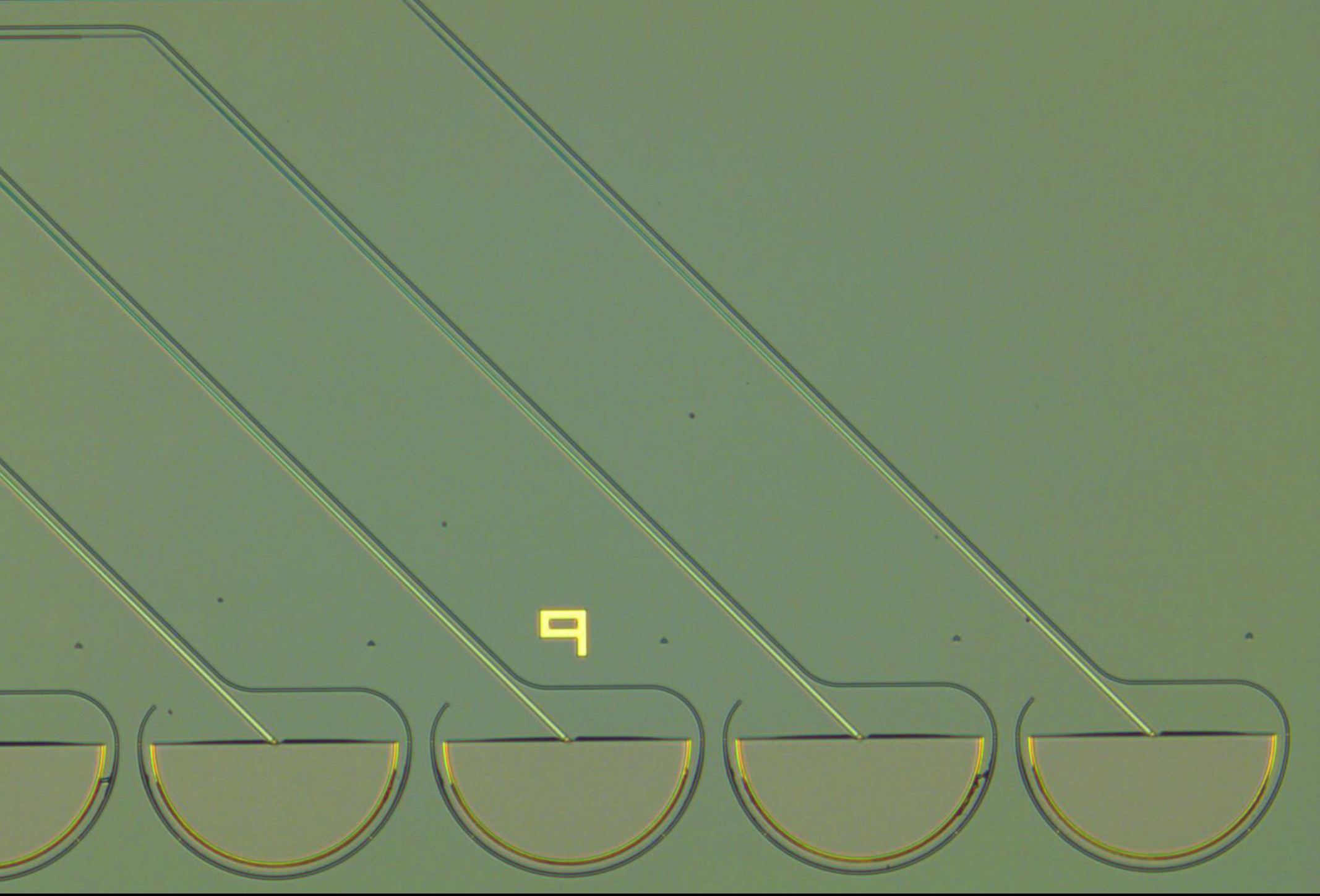


1 zero index 2 fabrication 3 results


prism
Si waveguide


SU8 slab waveguide
prism
Si waveguide


SU8 slab waveguide
prism
Si waveguide
SU8 calibration
waveguide

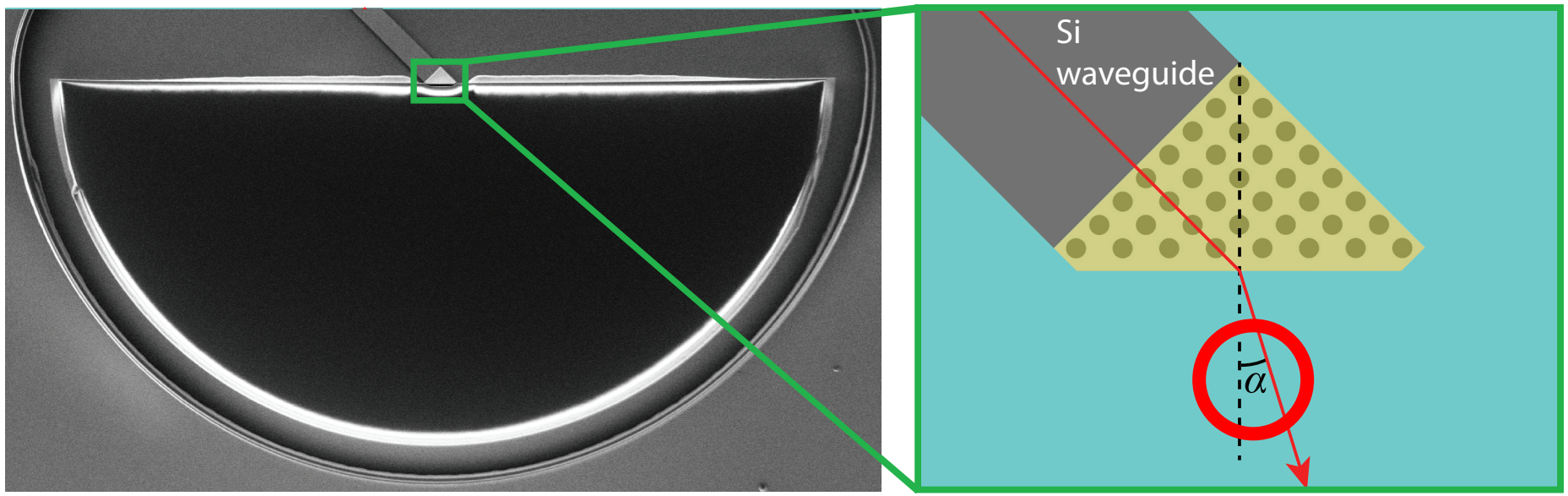


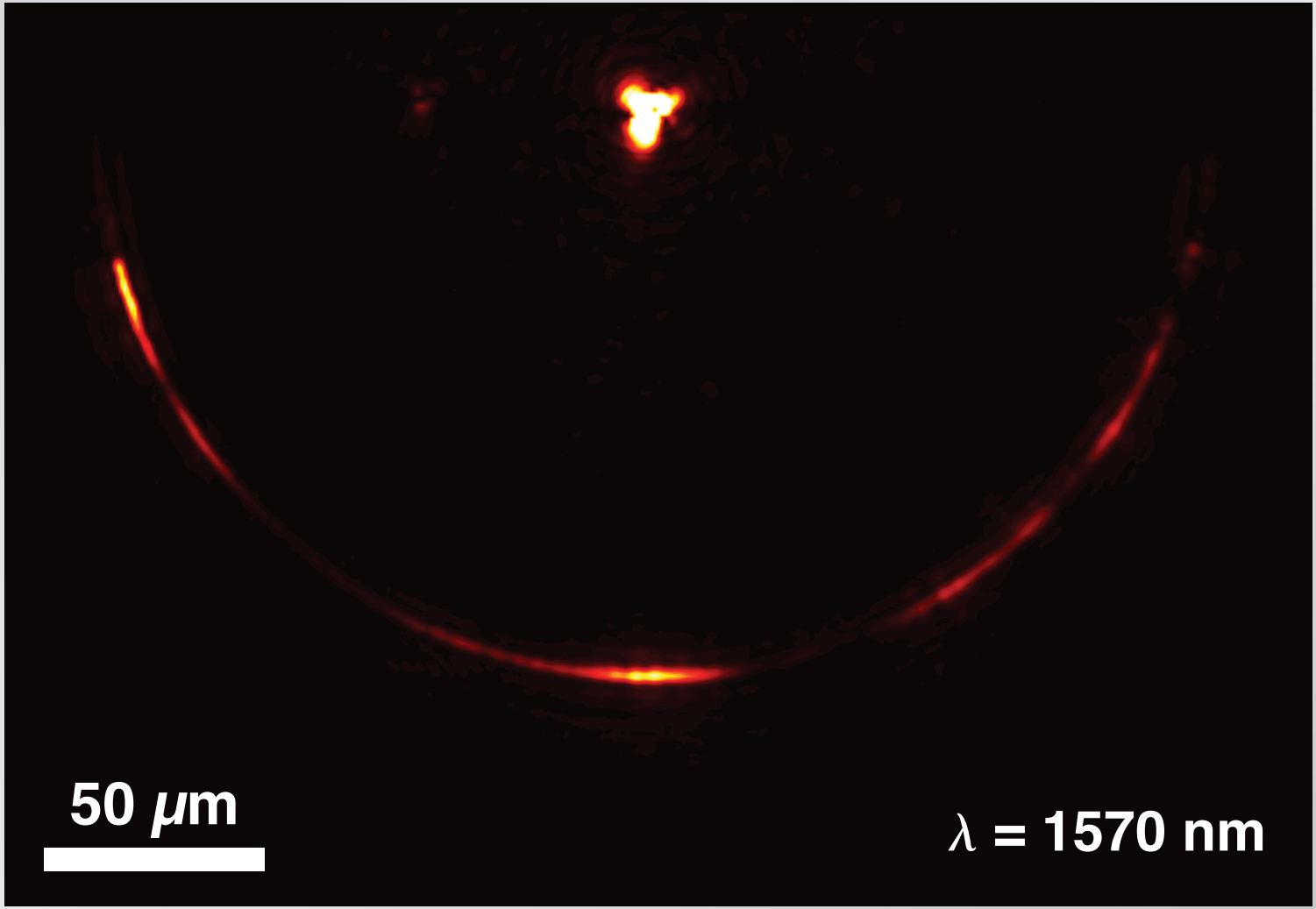
1 zero index

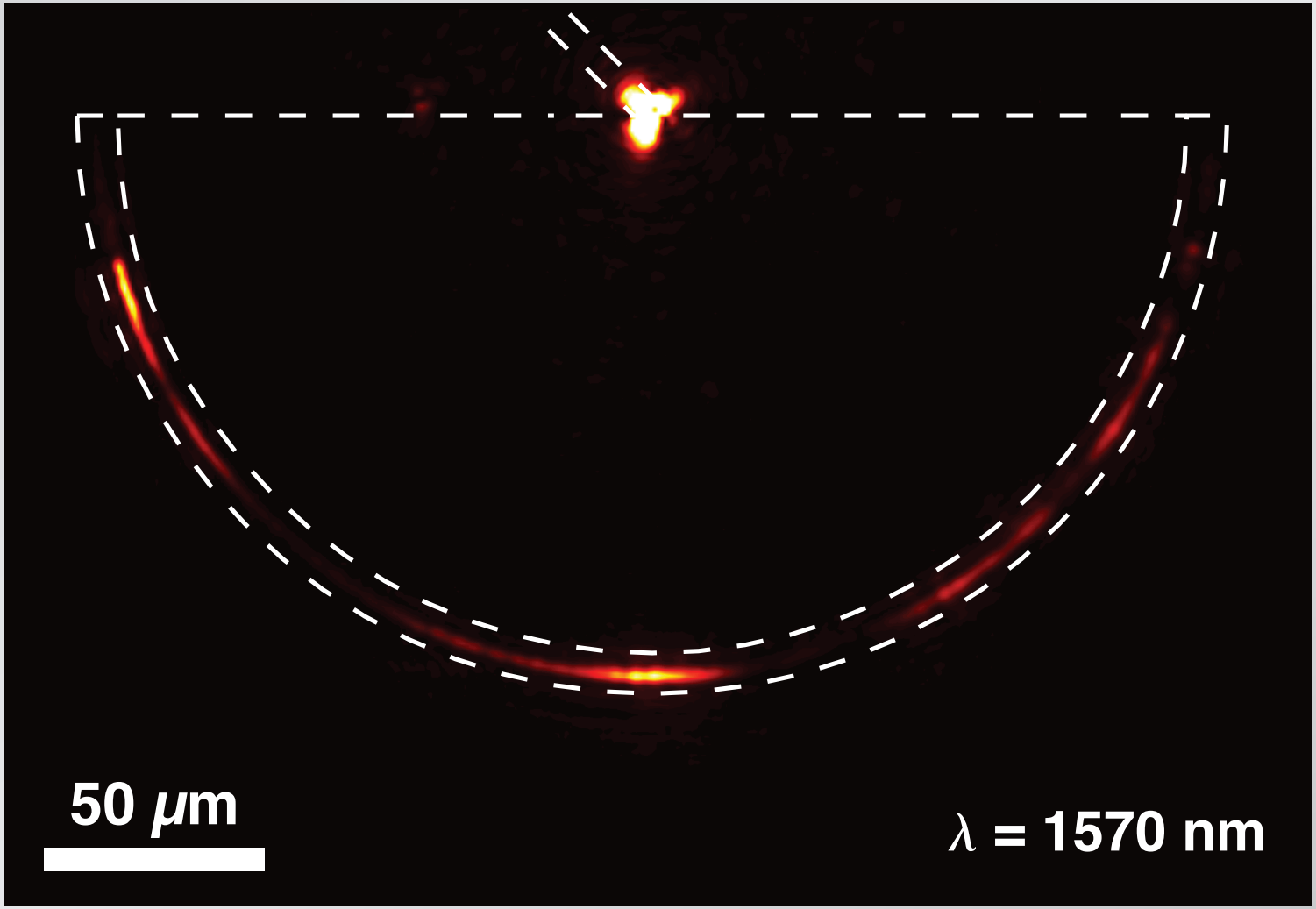
2 fabrication

3 results

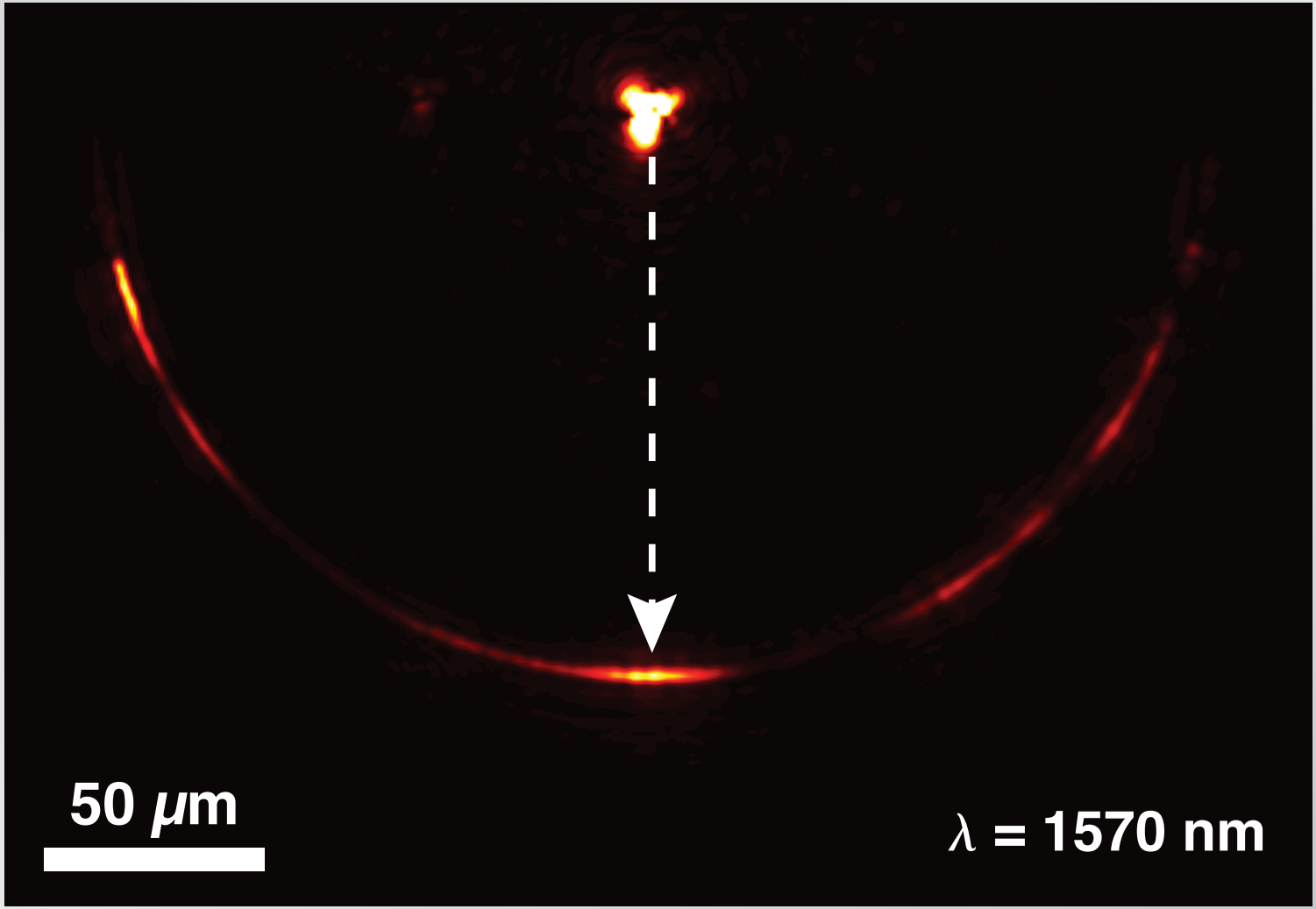
On-chip zero-index prism

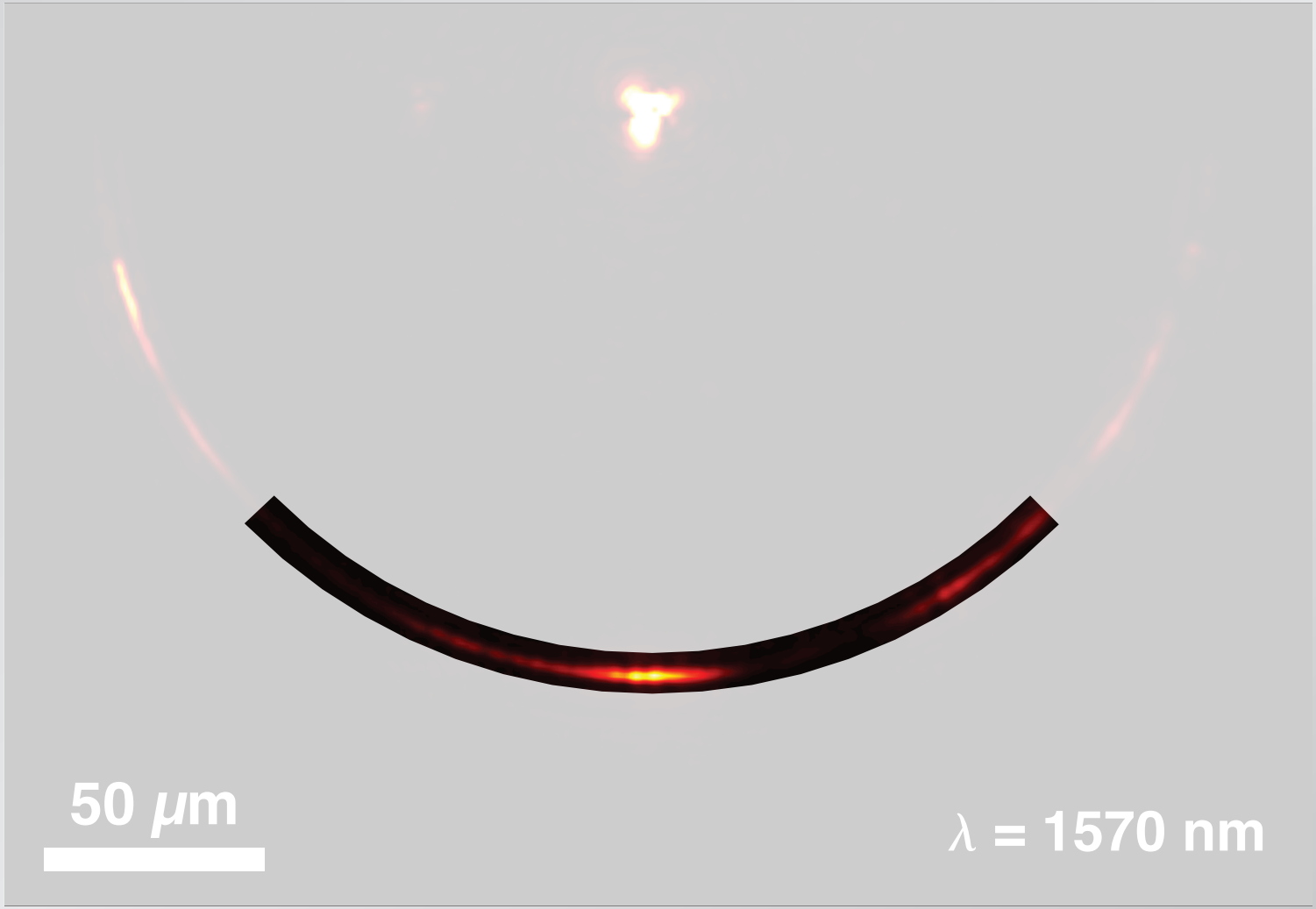



50 μm
λ = 1570 nm

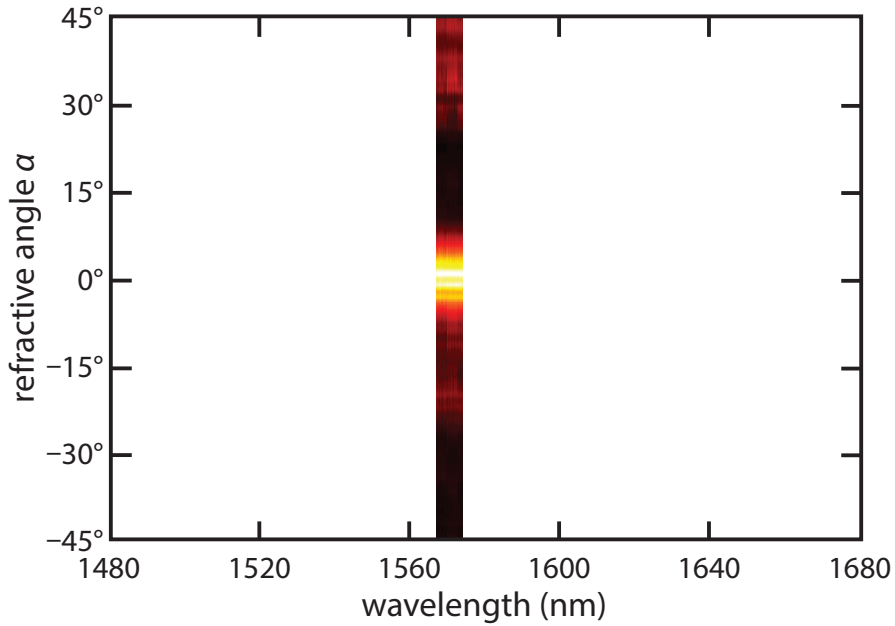


1 zero index 2 fabrication 3 results

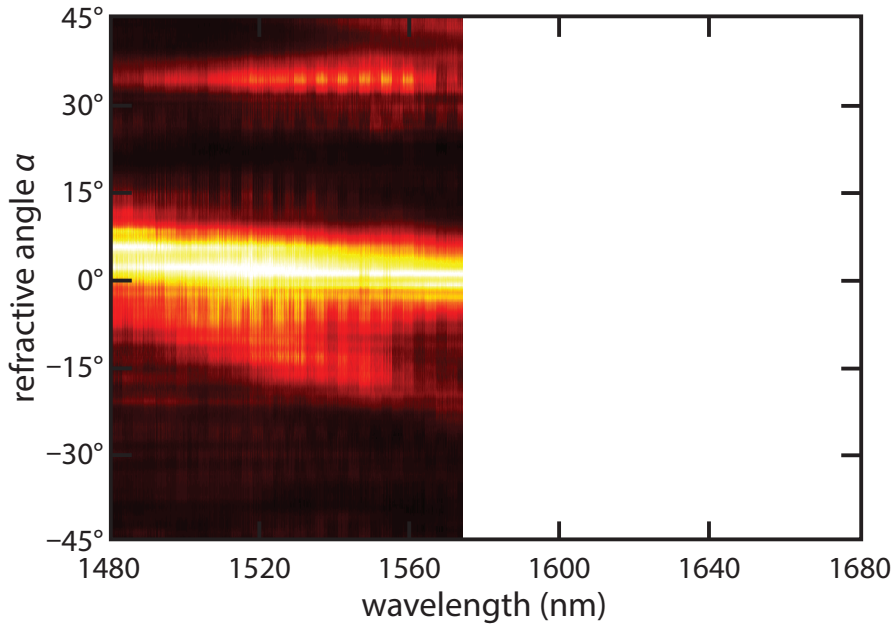

50 μm
λ = 1570 nm


50 μm
λ = 1570 nm

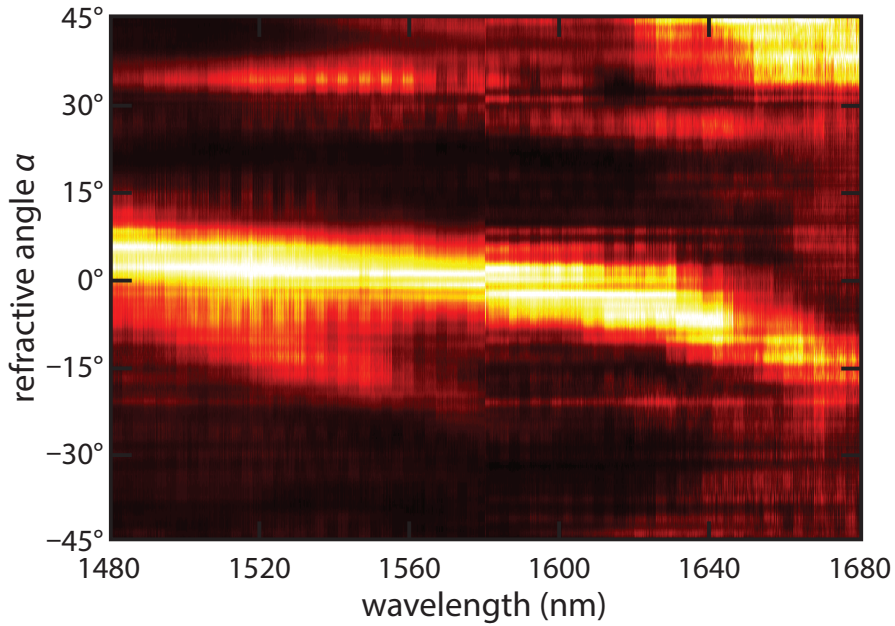
Wavelength dependence of refraction angle



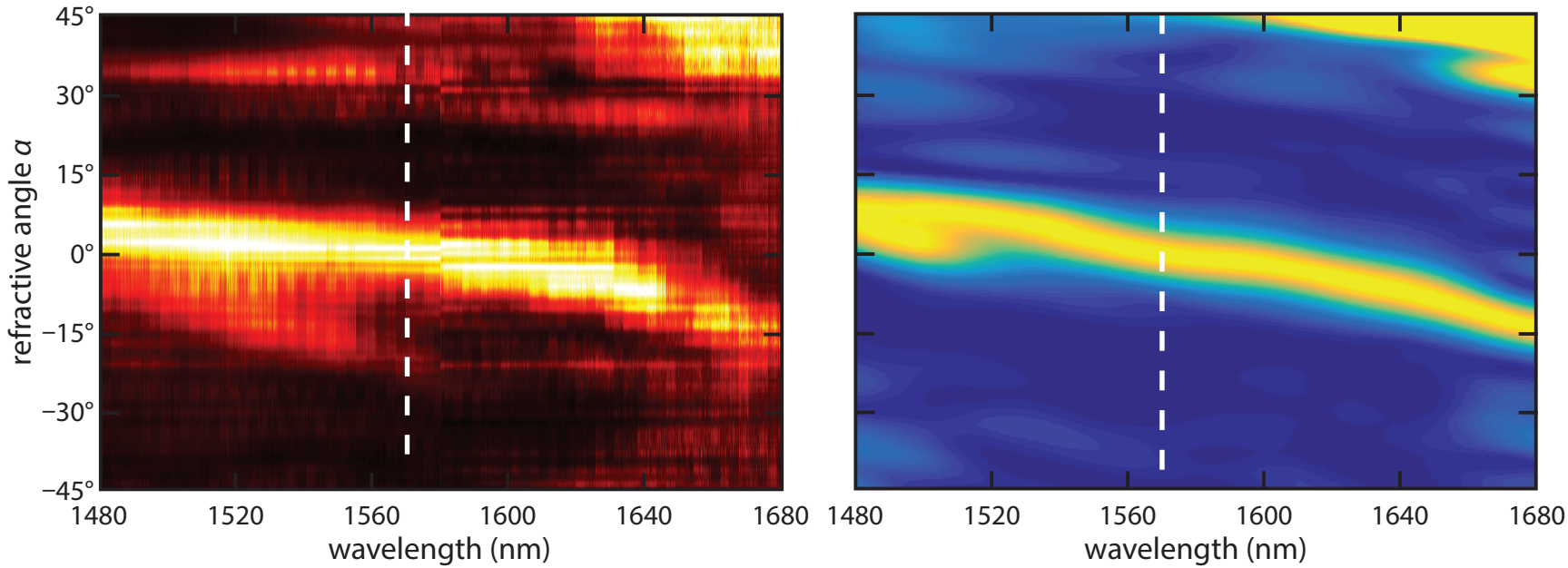
Wavelength dependence of refraction angle



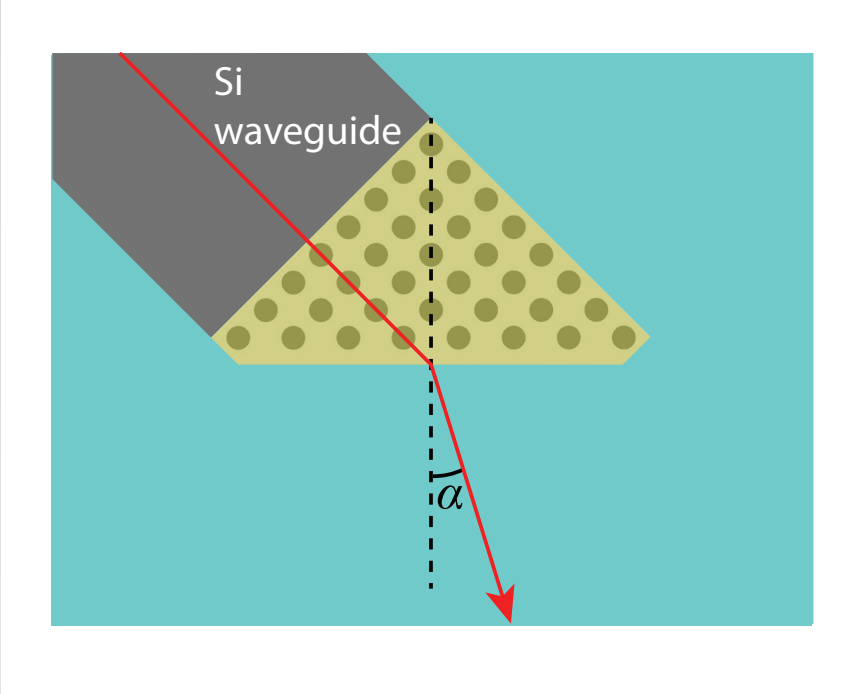
Wavelength dependence of refraction angle



Wavelength dependence of refraction angle

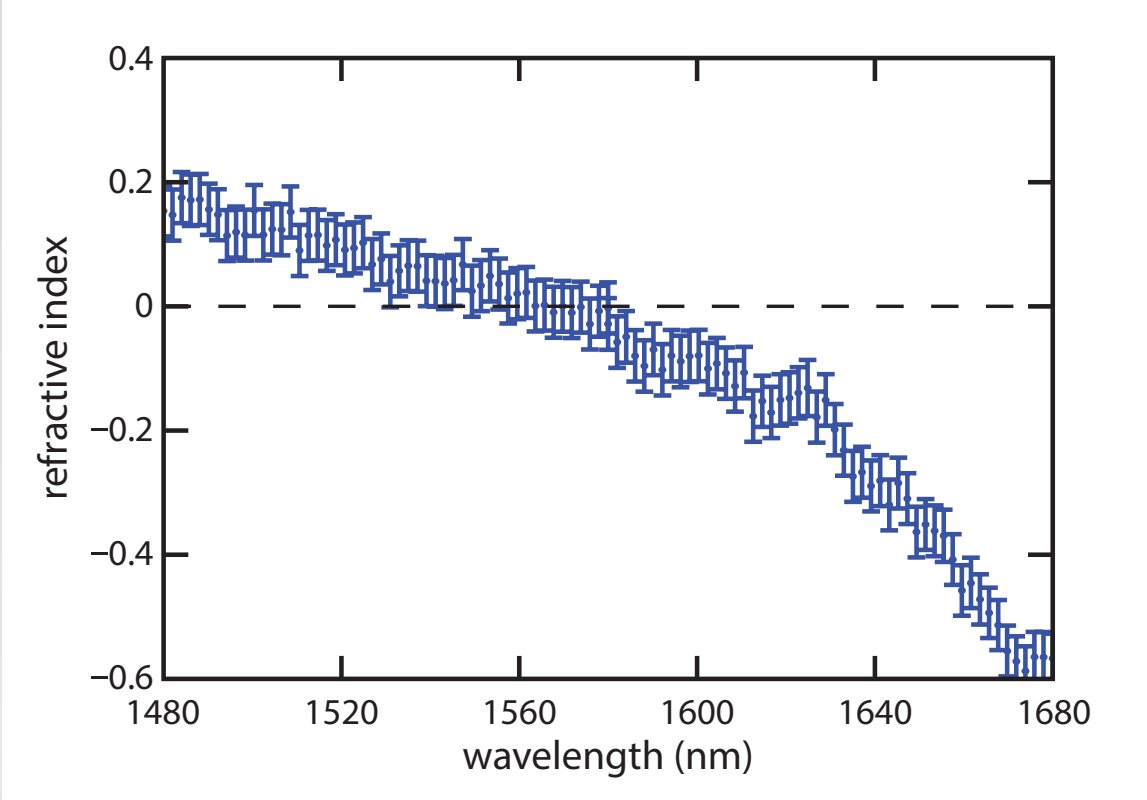


Wavelength dependence of index

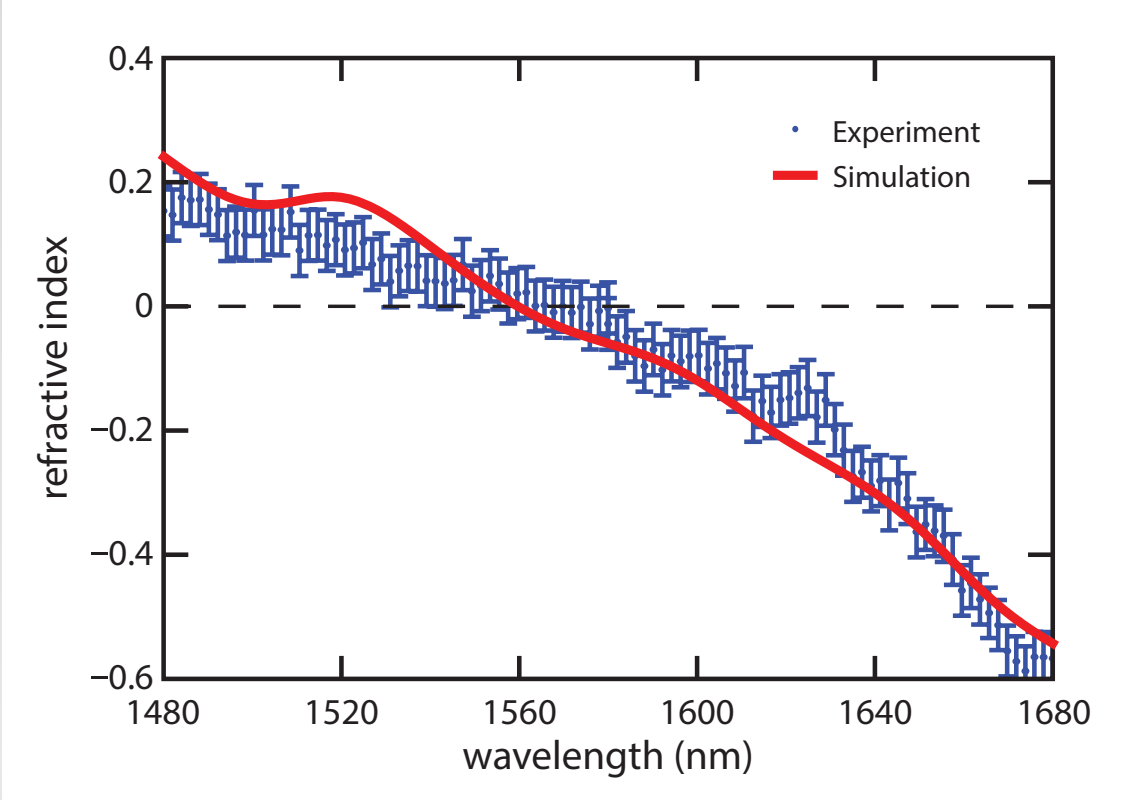


$$n_{\text{prism}} = n_{\text{slab}} \frac{\sin\alpha}{\sin 45^\circ}$$

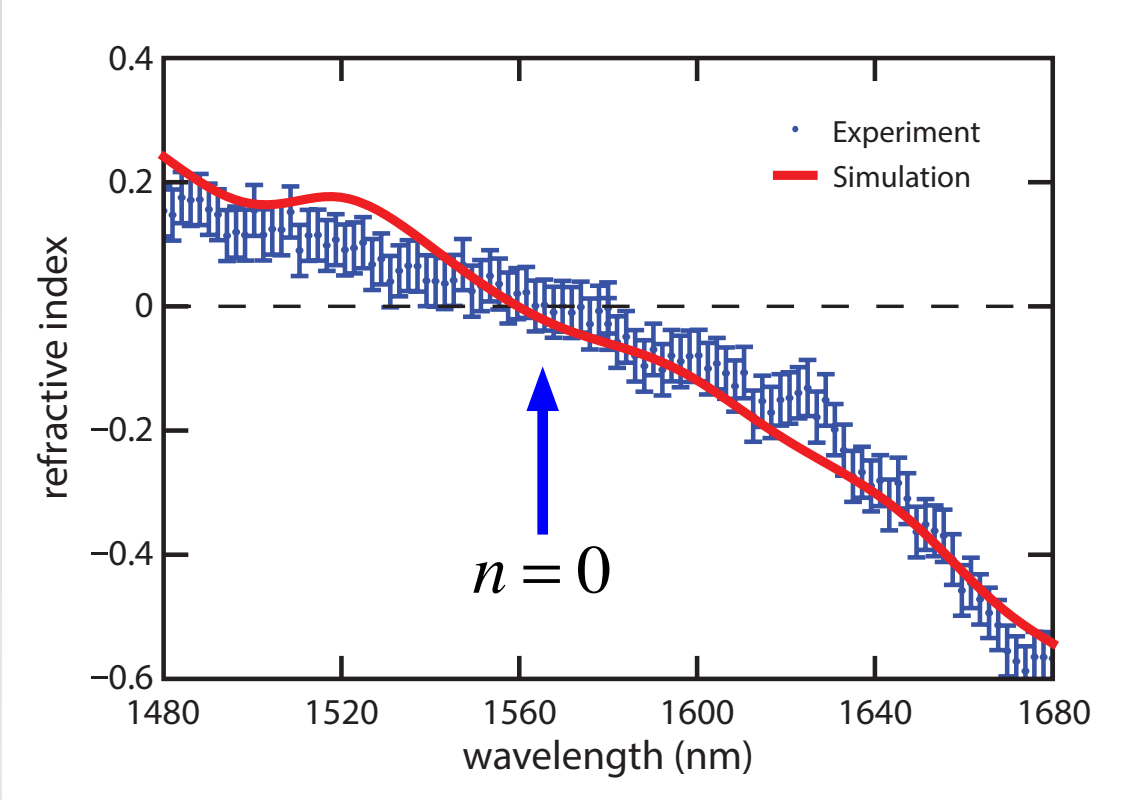
Wavelength dependence of index



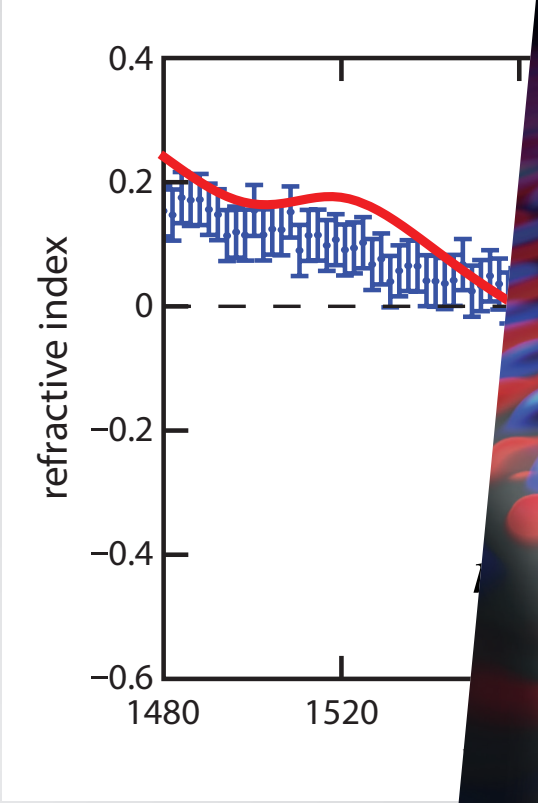
Wavelength dependence of index

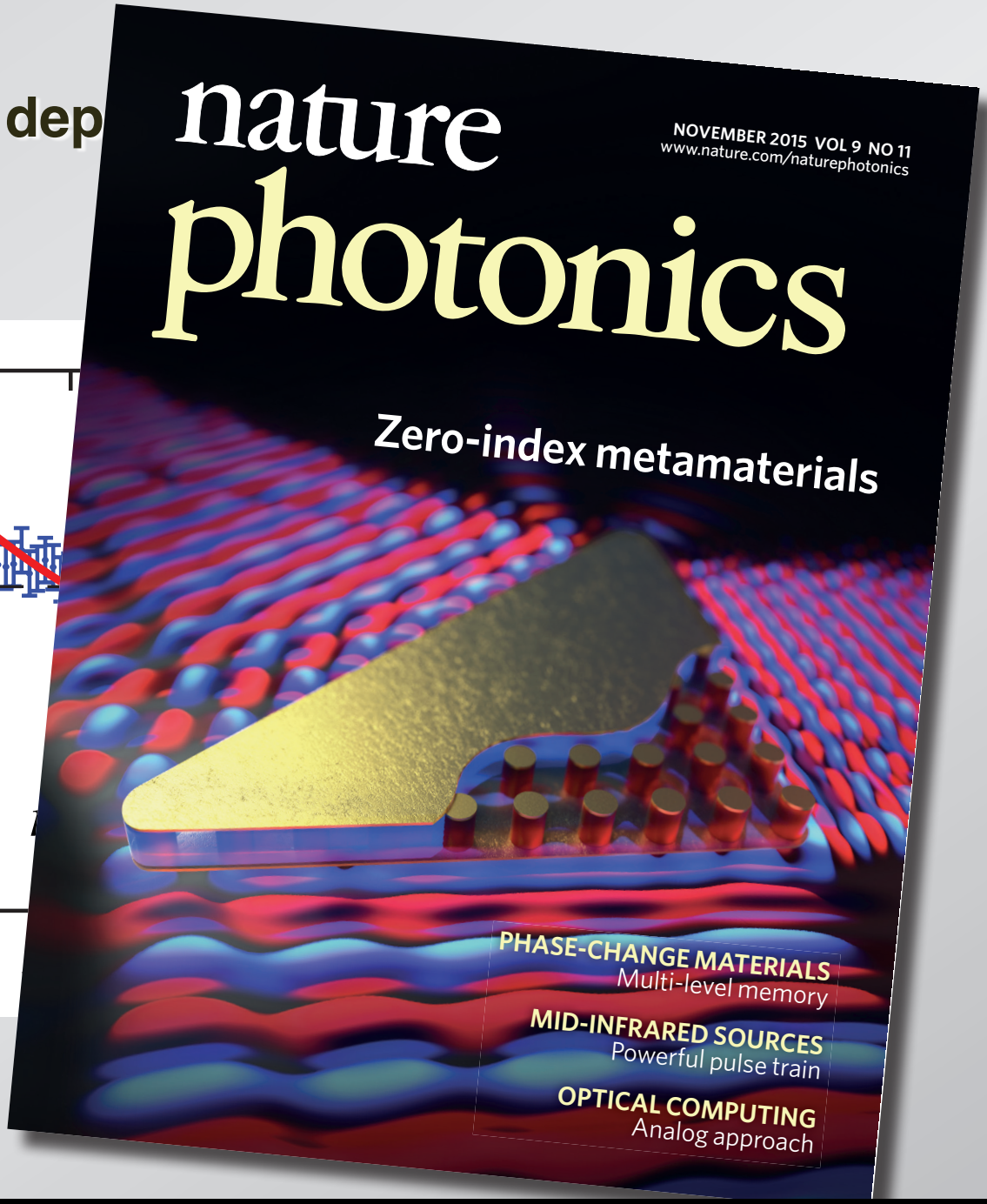


Wavelength dependence of index



Wavelength dep

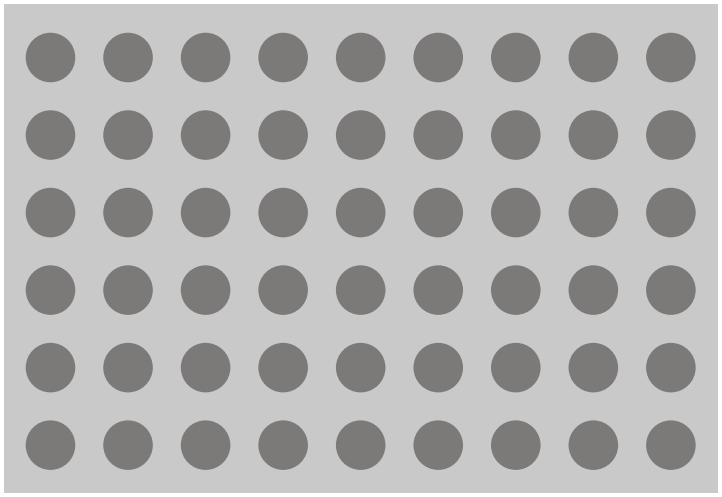




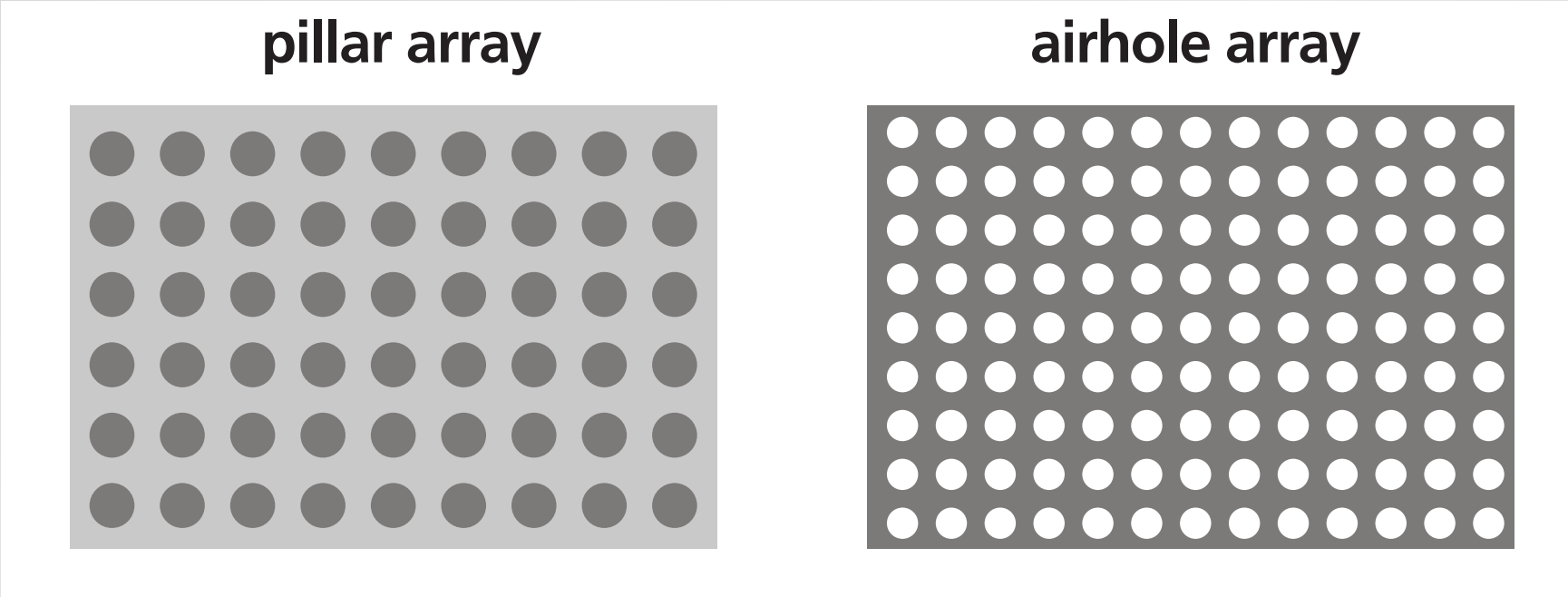
1 zero index 2 fabrication 3 results

simplify fabrication

pillar array

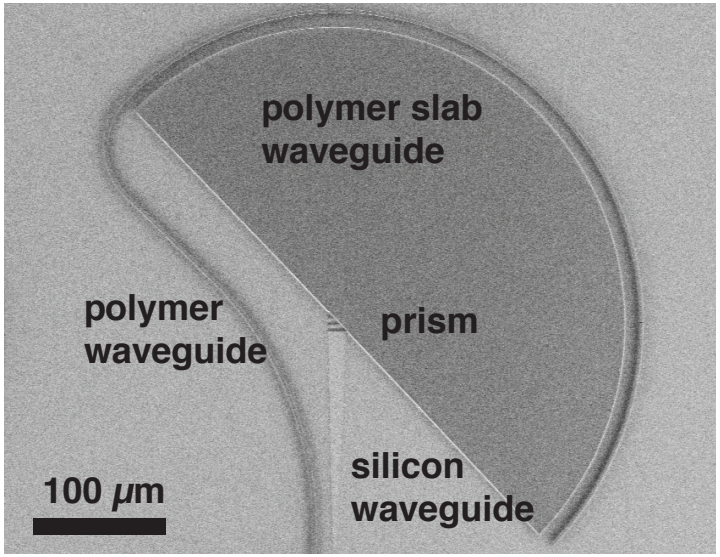


simplify fabrication

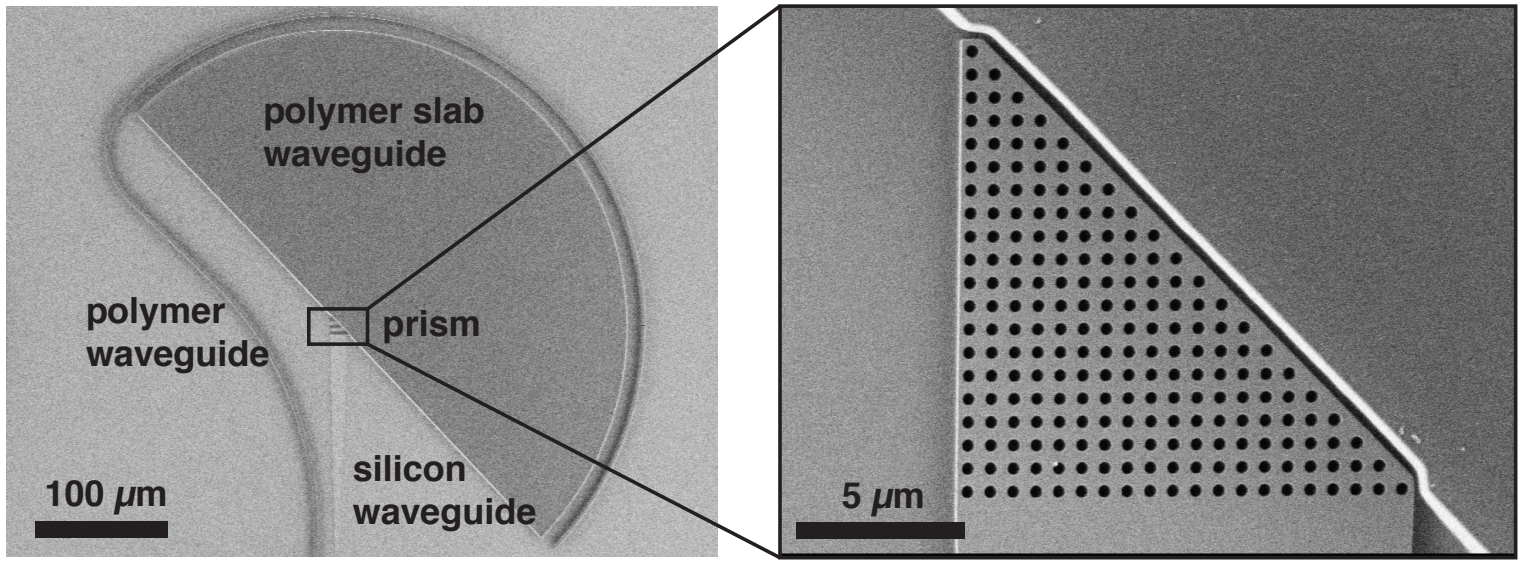


1 zero index 2 fabrication 3 results

simplify fabrication

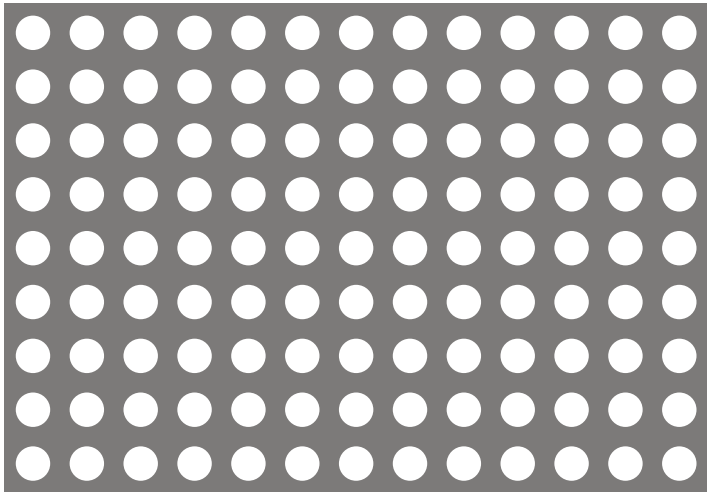


simplify fabrication



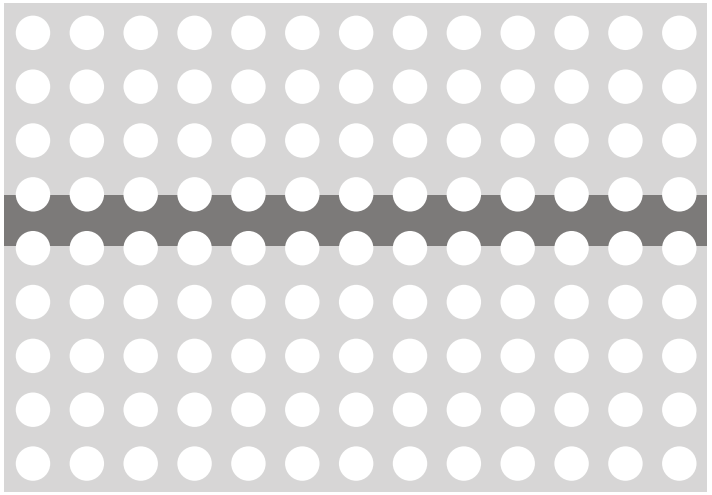
simplify further!

airhole array



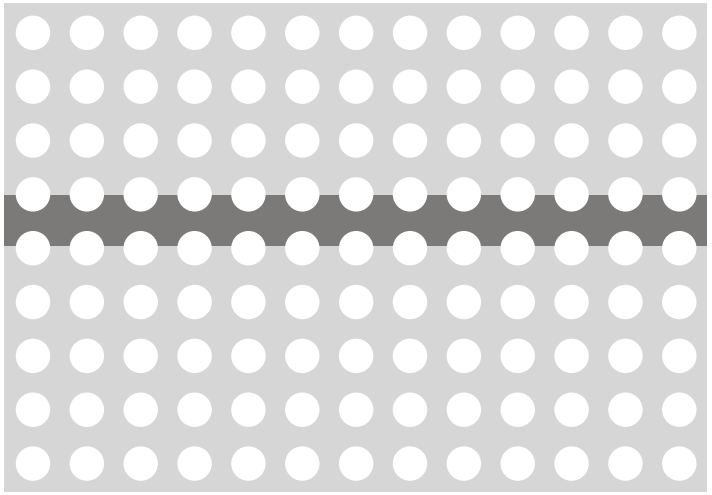
simplify further!

airhole array



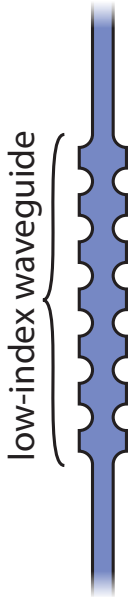
simplify further!

airhole array

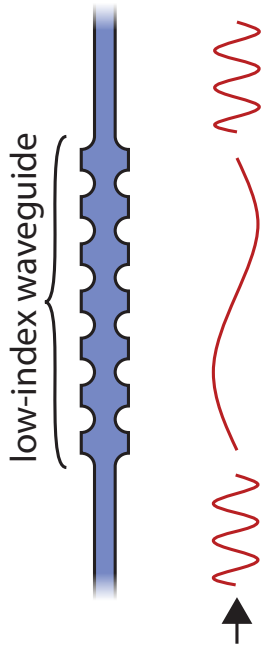


1D ZIM waveguide

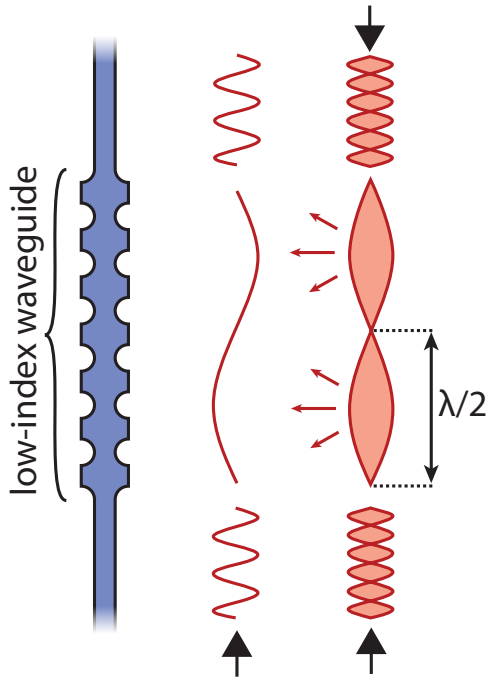
waveguiding



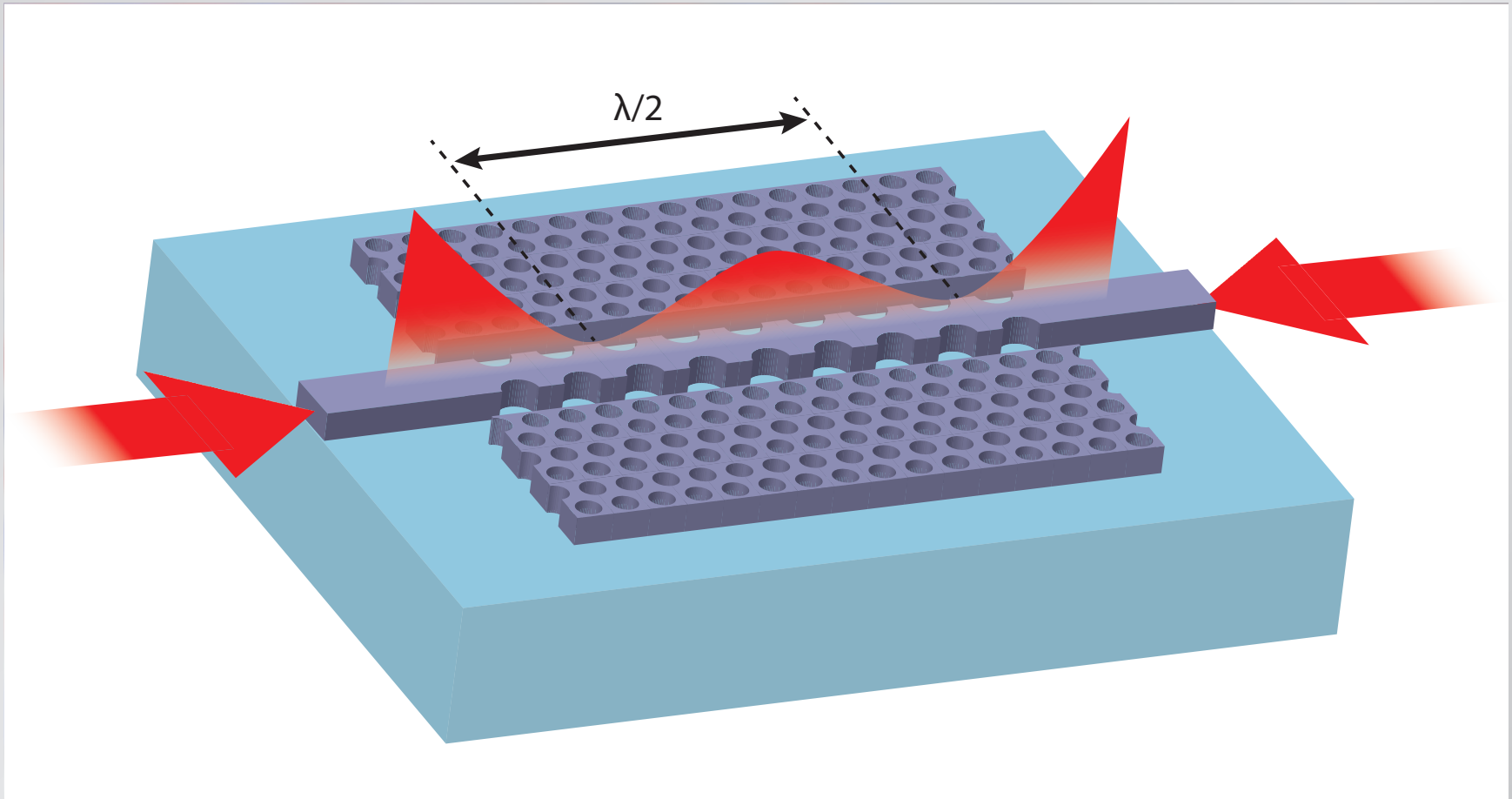
waveguiding



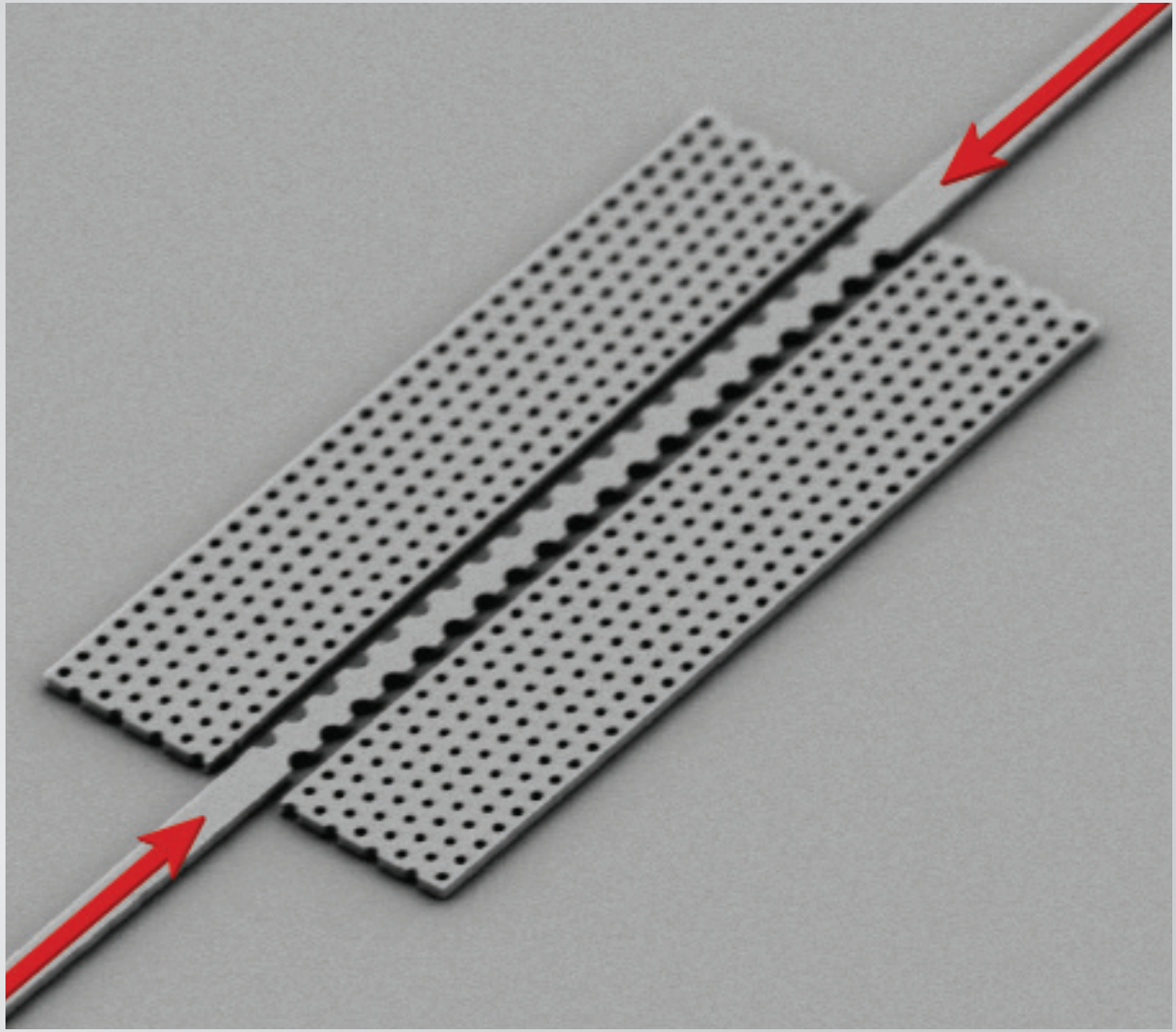
waveguiding



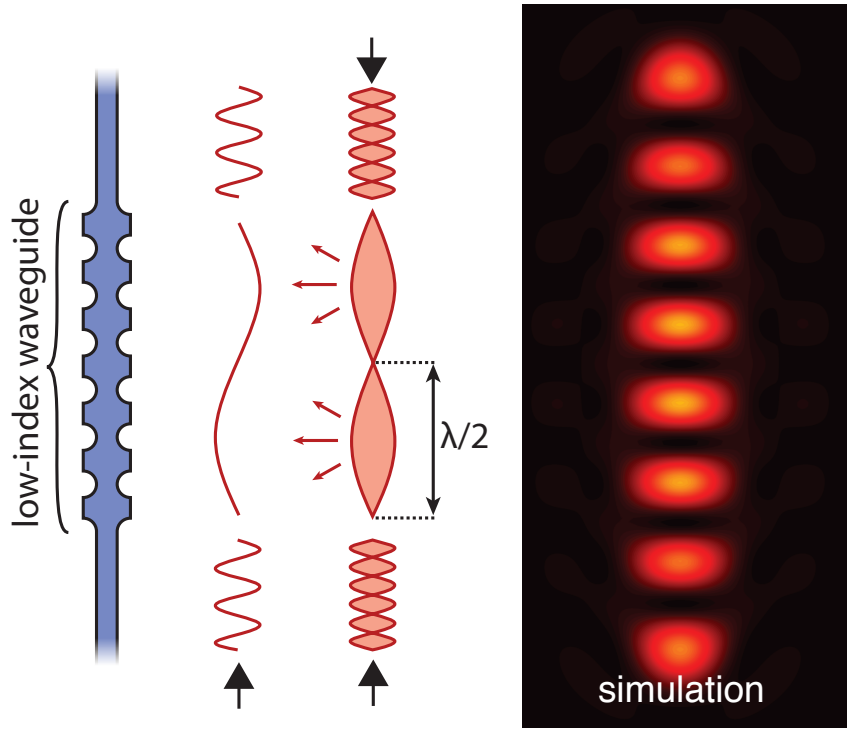
look at standing waves



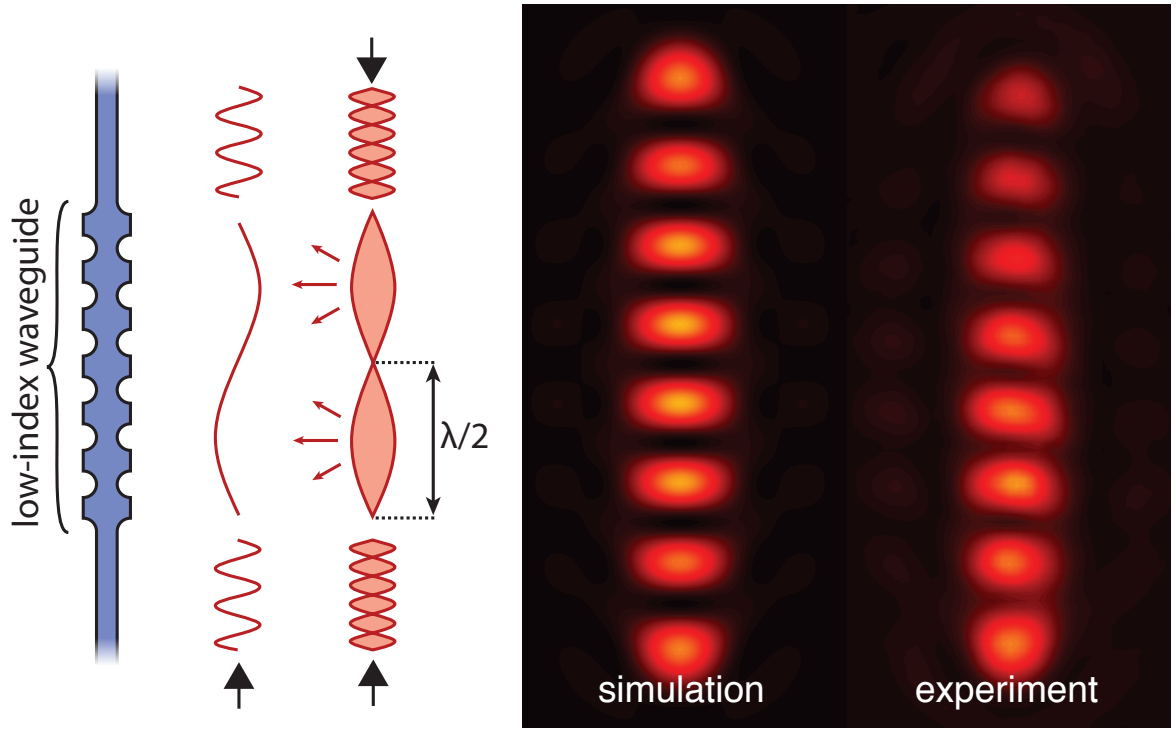
look at standing waves



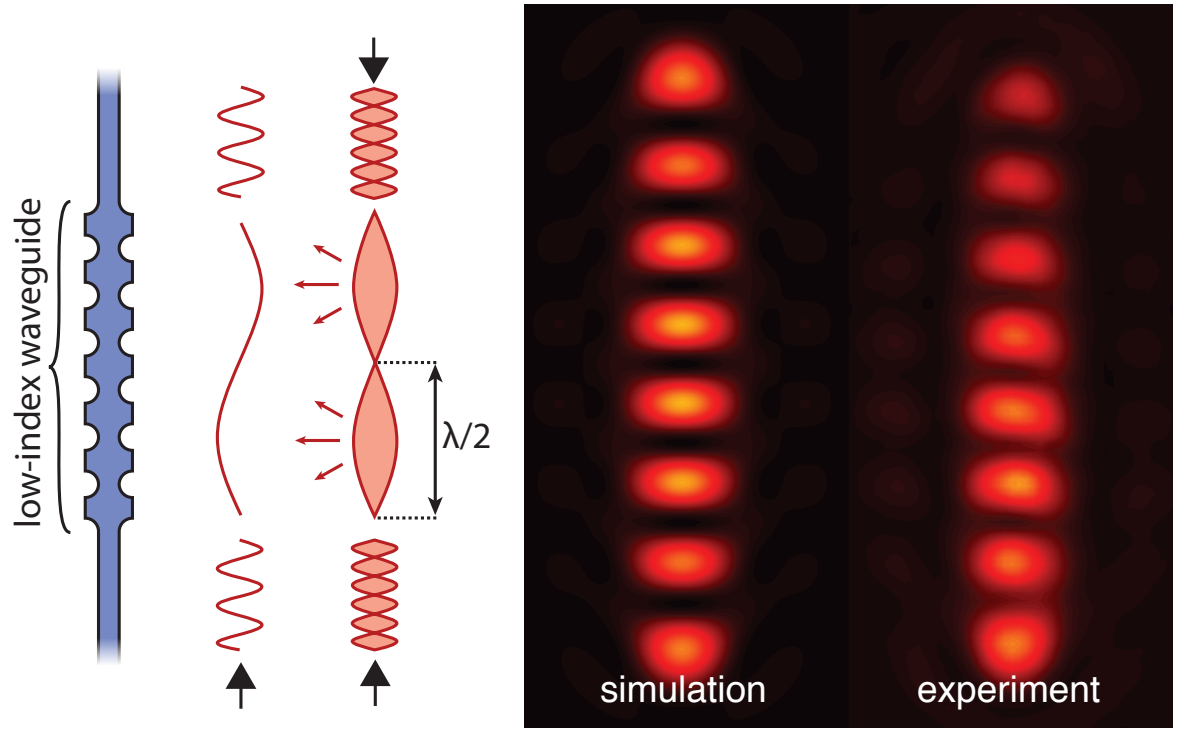
look at standing waves



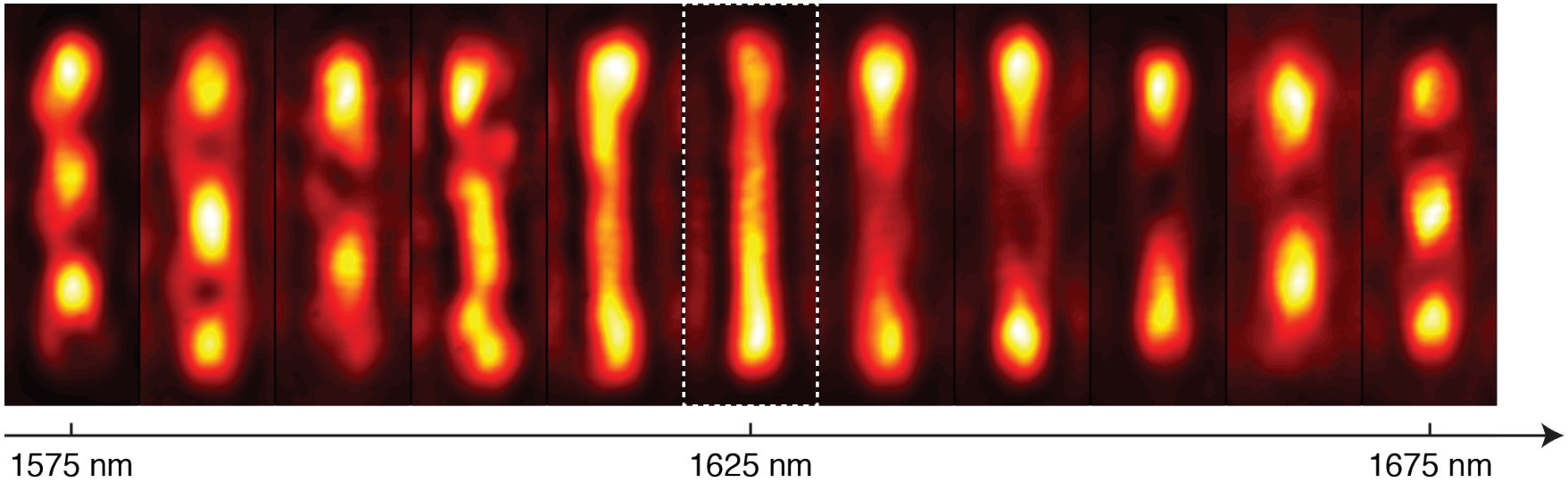
look at standing waves



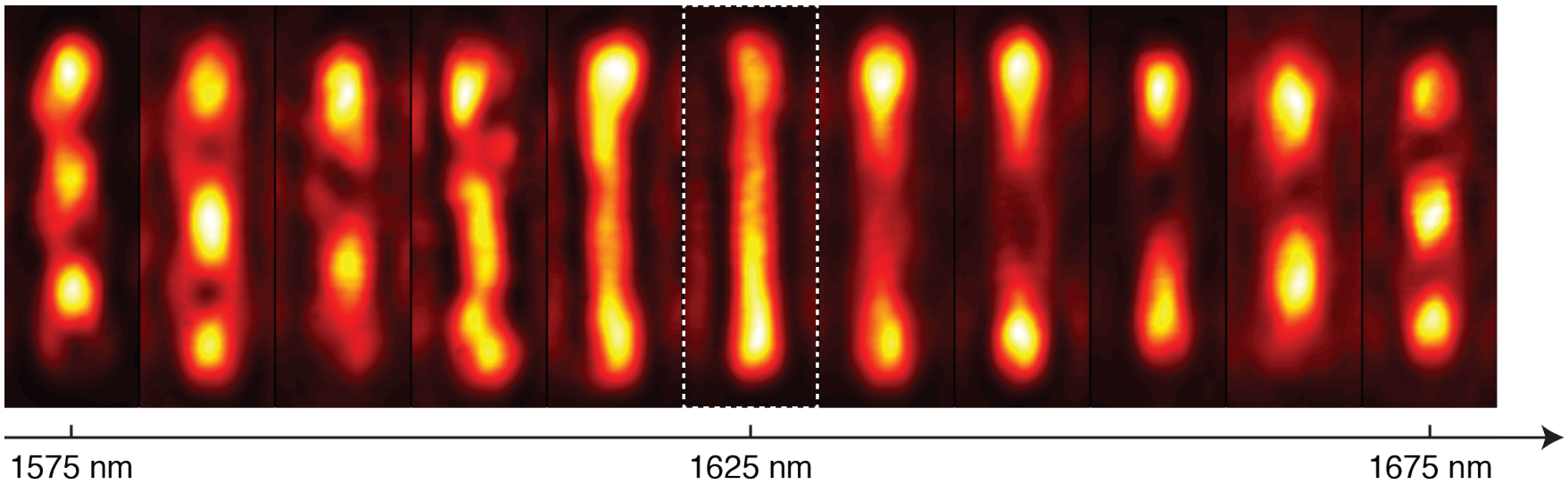
direct observation of effective wavelength!!



look at standing waves

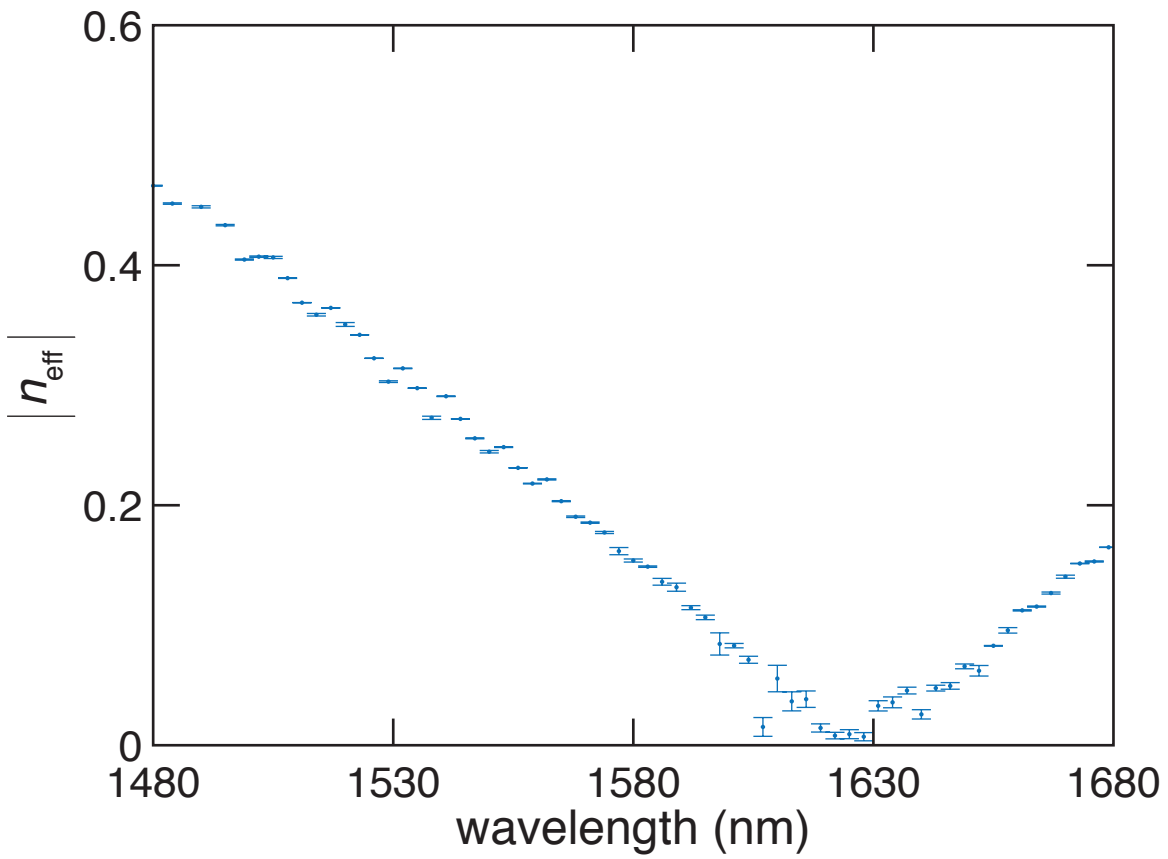


look at standing waves

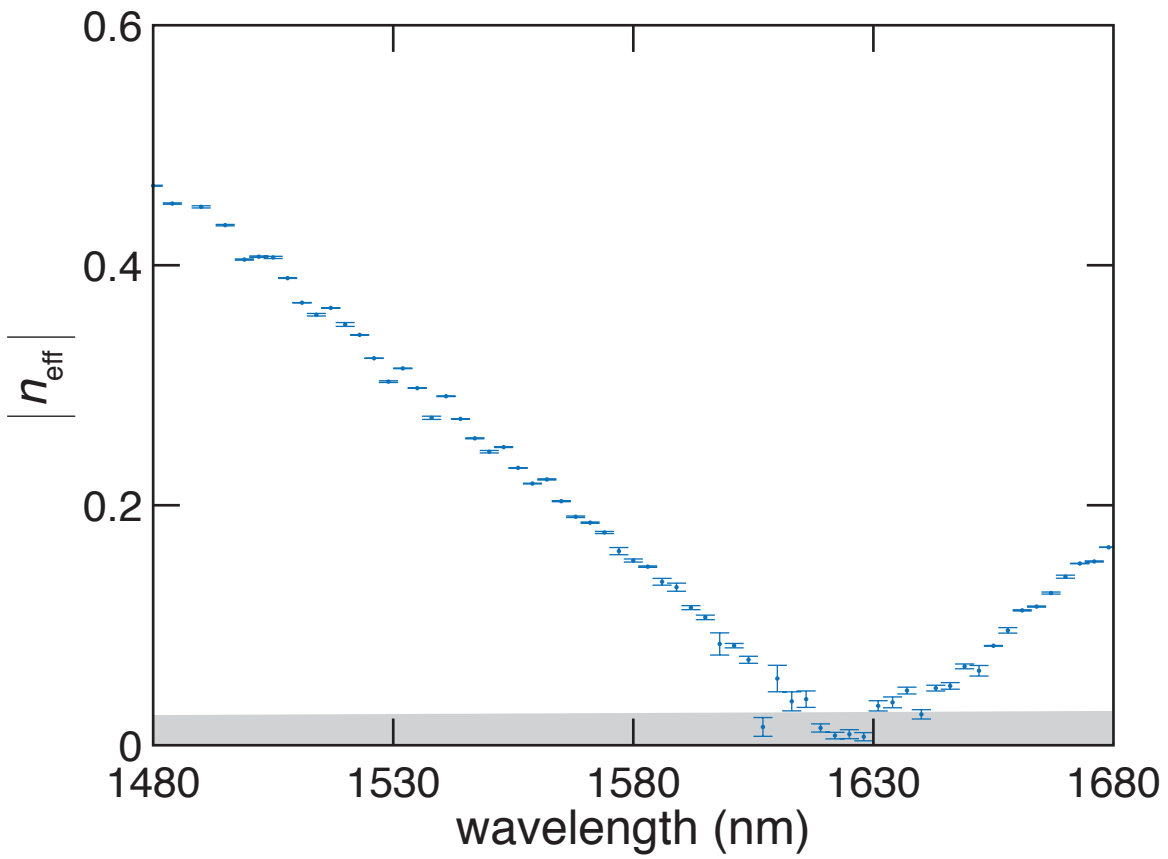


$$|n_{\text{eff}}| = \frac{\lambda_0}{\lambda_{\text{eff}}}$$

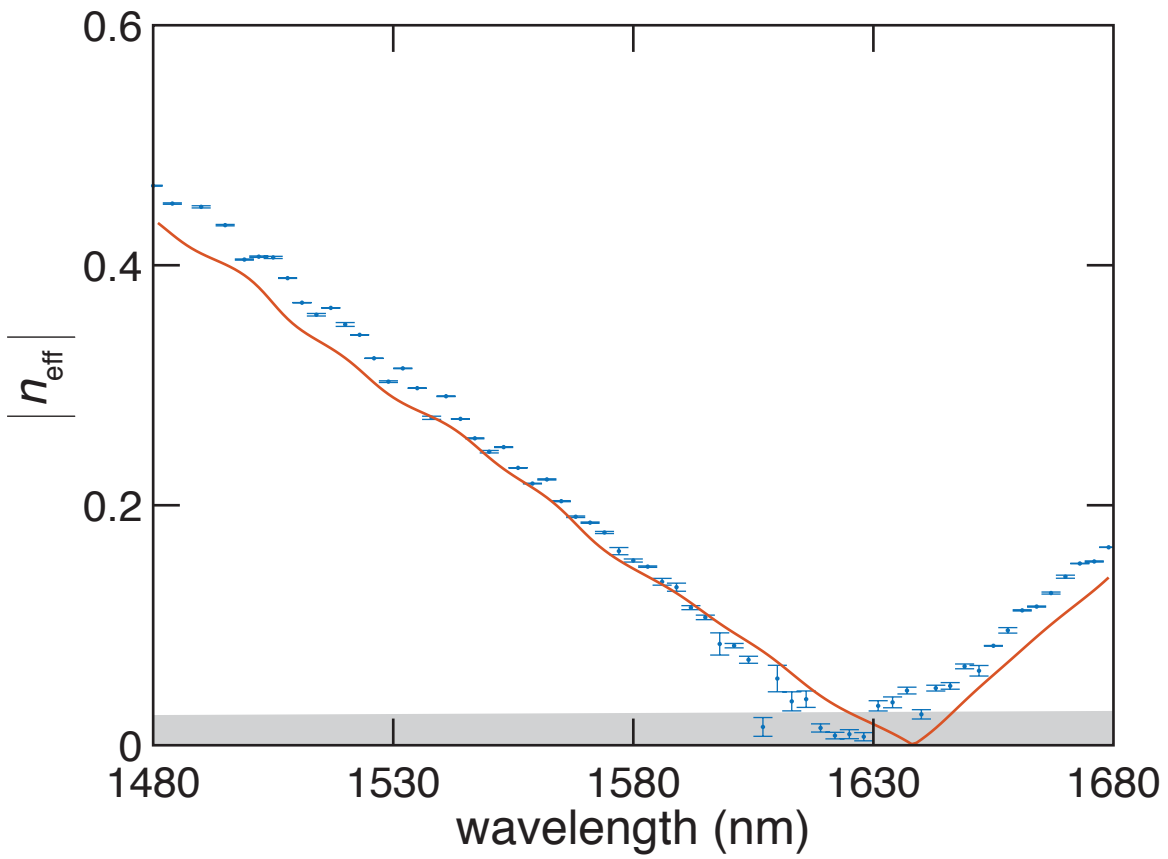
comparison of experiment and simulation



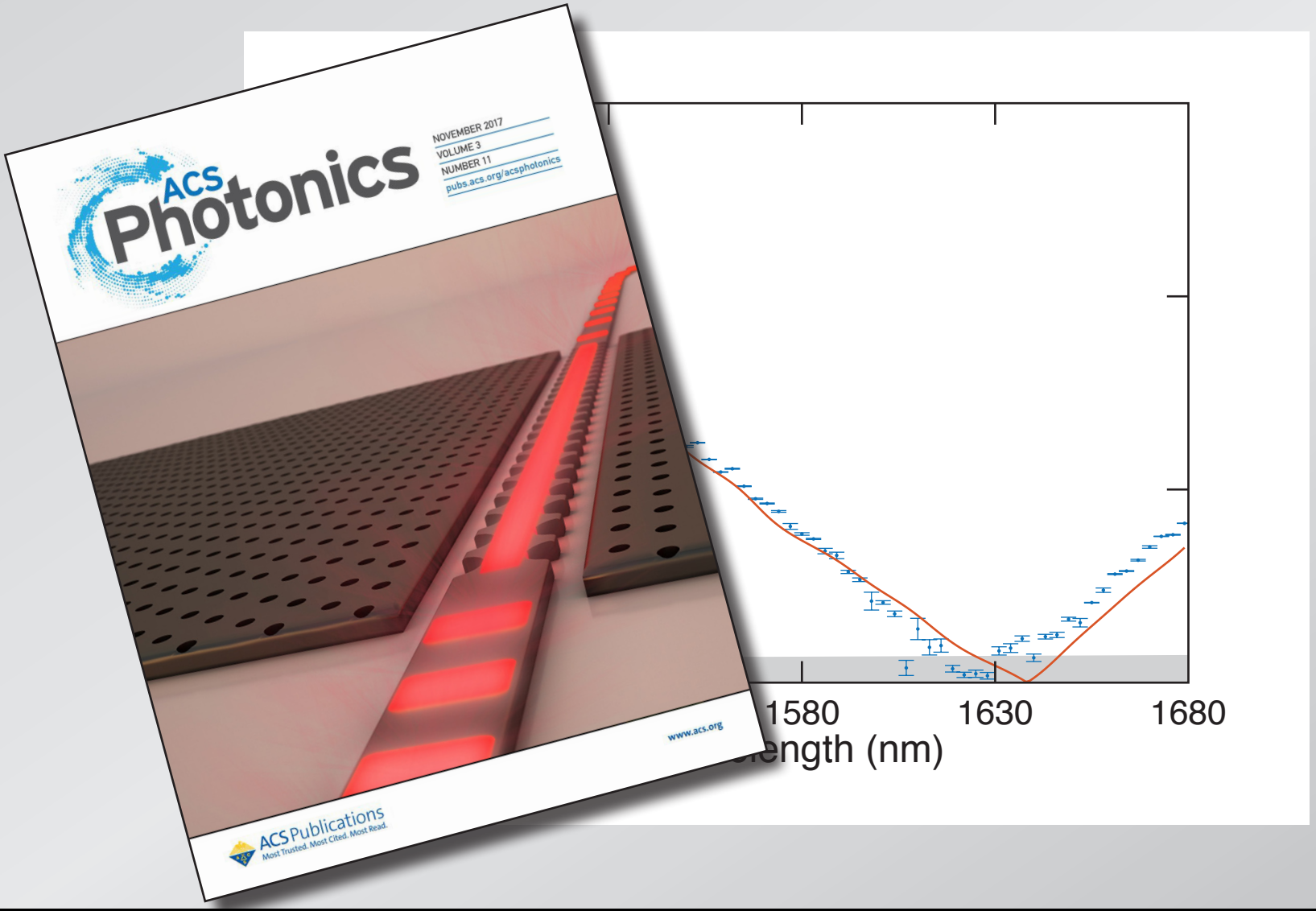
comparison of experiment and simulation



comparison of experiment and simulation



comparison of experiment and simulation



1 zero index

2 fabrication

3 results

where do we go from here?

$$n = 0$$

1 zero index

2 fabrication

3 results

where do we go from here?

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

where do we go from here?

A_{21}

1 zero index

Applied Physics Letters ARTICLE scitation.org/journal/apl

Extended many-body superradiance in diamond epsilon near-zero metamaterials

Cite as: Appl. Phys. Lett. **120**, 061105 (2022); doi: 10.1063/5.0062869
Submitted: 9 July 2021 · Accepted: 22 January 2022 ·
Published Online: 8 February 2022

View Online Export Citation CrossMark

Olivia Mello,[1,a)] Yang Li,[1,2] Sarah Alejandra Camayd-Muñoz,[1] Clayton DeVault,[1] Michaël Lobet,[1,3] Haoning Tang,[1] Marko Lončar,[1] and Eric Mazur[1,a)]

AFFILIATIONS

[1]School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[2]State Key Laboratory of Precision Measurement Technology and Instrument, Department of Precision Instrument, Tsinghua University, Beijing 100084, China
[3]Laboratoire de Physique du Solide, Namur Institute of Structured Matter, University of Namur, Rue de Bruxelles 61, 5000 Namur, Belgium

Note: This paper is part of the APL Special Collection on Zero-index Metamaterials for Classical and Quantum Light.
[a)]**Authors to whom correspondence should be addressed:** oliviamello@g.harvard.edu and mazur@seas.harvard.edu

ABSTRACT

We theoretically and numerically demonstrate enhanced extended superradiance using a diamond epsilon near-zero metamaterial design. Due to the large spatial coherence in this metamaterial, we experience an ultra-high superradiant decay rate enhancement over distances greater than 13 times the free-space wavelength for both two emitters and many-body configurations of emitters. We observe a power enhancement three orders of magnitude higher than an incoherent array of emitters in bulk diamond, corresponding to an N^2 scaling with the number of emitters characteristic of superradiance.

As the field of quantum information has grown in the past decade, physicists have made countless efforts to enhance the spontaneous emission of quantum emitters. Enhancing spontaneous emissions is key to realizing quantum optics phenomena,[1,2] including quantum electrodynamics (QED),[3] nanoscale spectroscopy,[4] and optical quantum information [illegible] to enhance

Resonant nanophotonic structures, such as metamaterials,[10] cavities,[11] and photonic crystals,[12] are one such way of enhancing spontaneous emission and increasing the range of inter-emitter interactions. Several research groups have demonstrated a series of metamaterials with near-zero refractive index.[13–16] A near-zero refractive index (NZRI) occurs when either the effective permittivity (epsilon-near-zero, ENZ), permeability (mu-near-zero, MNZ), or both (epsilon-mu-near-zero, EMNZ) approach zero. Around the NZRI frequency, light [illegible] phase advance and has an effective infinite spa- [illegible] particular, offer additional optical [illegible] emission

where do we go from here?

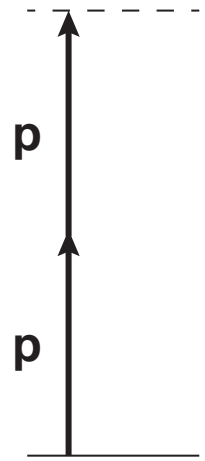
$$k = 0$$

1 zero index 2 fabrication 3 results

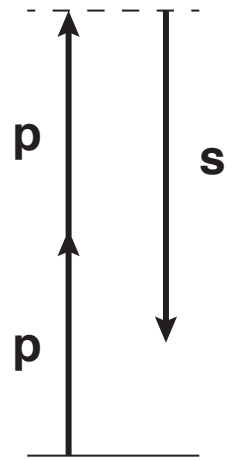

ISSN 2047-7538 (online)
Volume 11, 2022
Light | Science & Applications
nature.com/lsa
Light momentum in near-zero refractive index media
doi: 10.1038/s41377-022-00790-z
SPRINGER NATURE

1 zero index

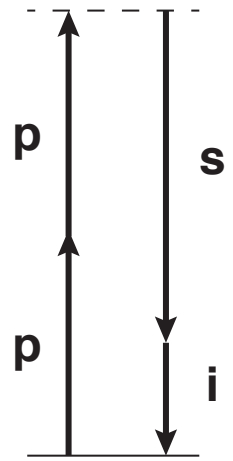
four-wave mixing



four-wave mixing



four-wave mixing



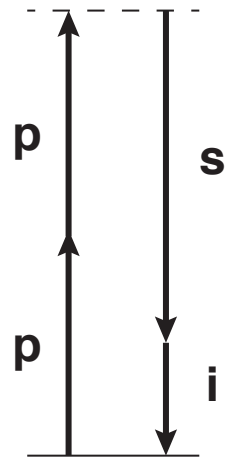
four-wave mixing

energy conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$

momentum conservation

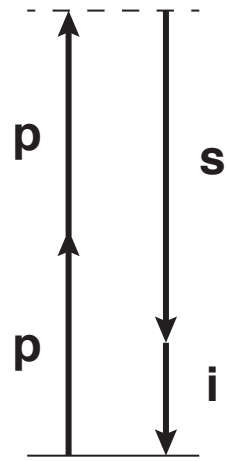
$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$



four-wave mixing

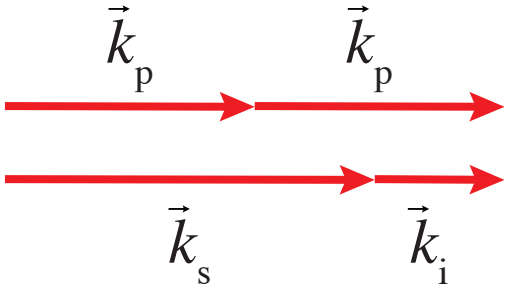
energy conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$



momentum conservation

$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$

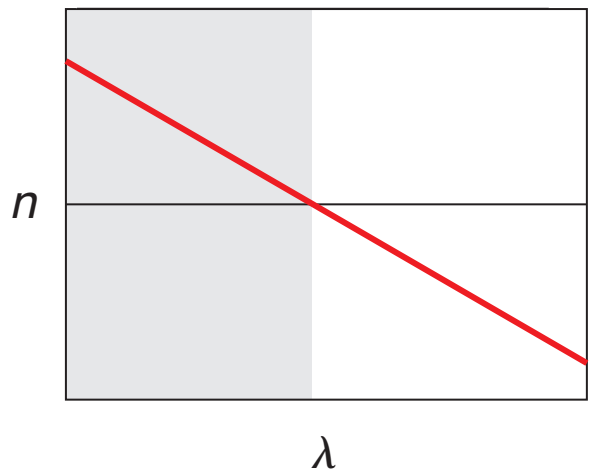


phase matching

four-wave mixing

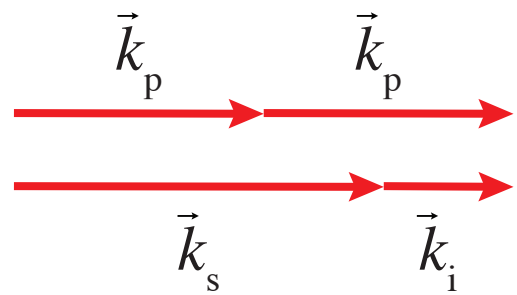
energy conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$



momentum conservation

$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$

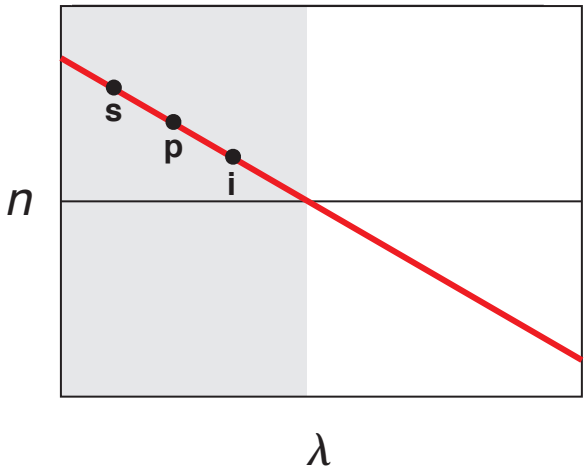


phase matching

four-wave mixing

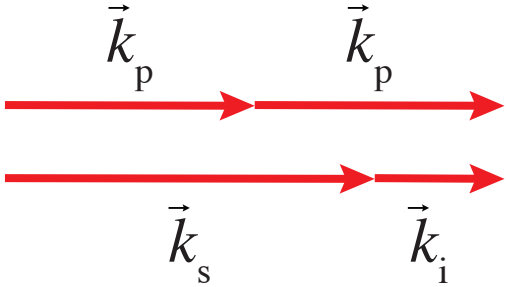
energy conservation

$$\Delta\omega = 2\omega_p - \omega_s - \omega_i = 0$$



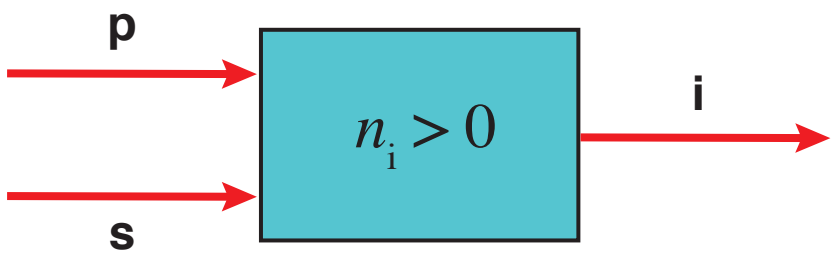
momentum conservation

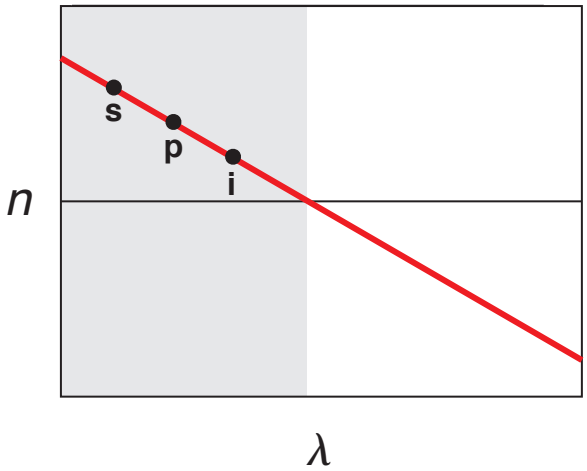
$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$

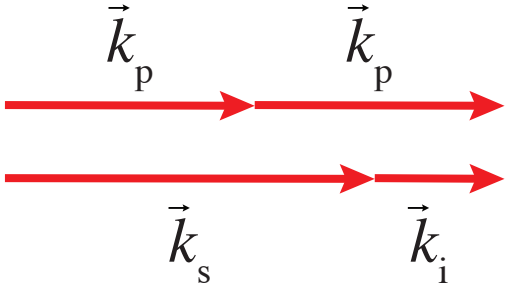


phase matching

four-wave mixing

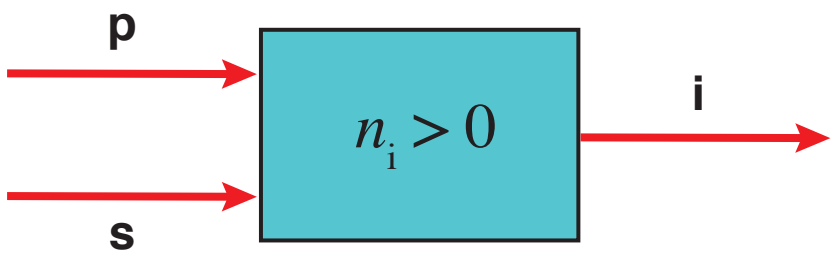


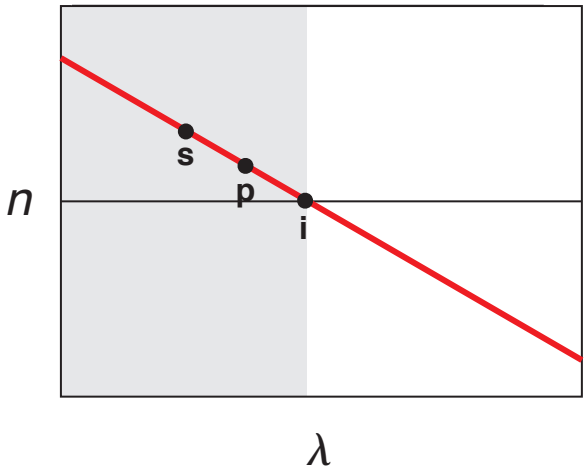


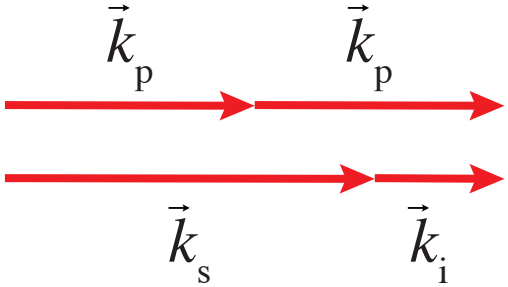


phase matching

four-wave mixing

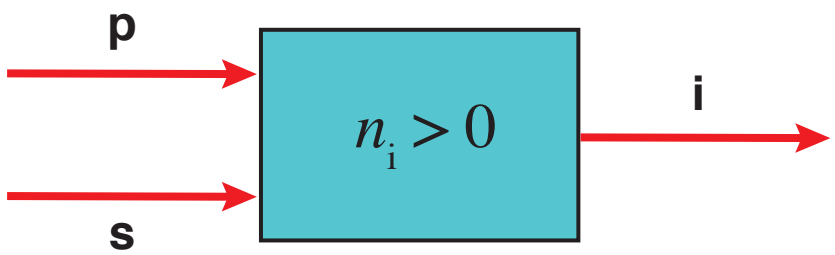


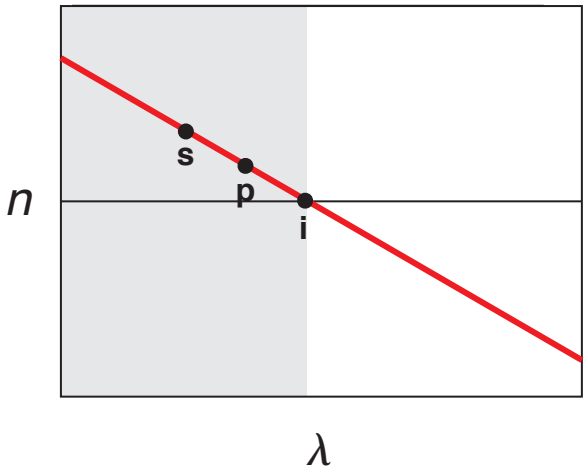


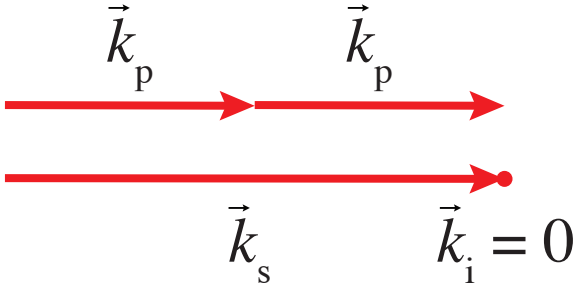


phase matching

four-wave mixing

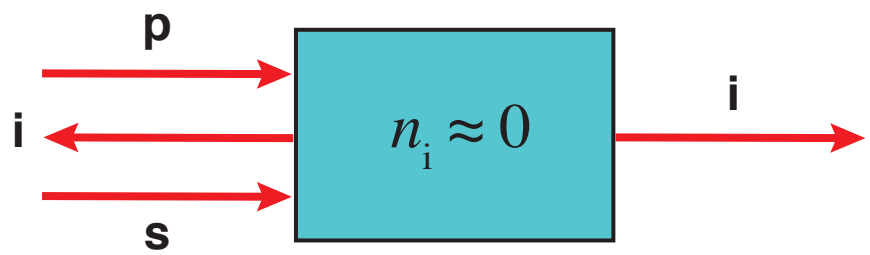




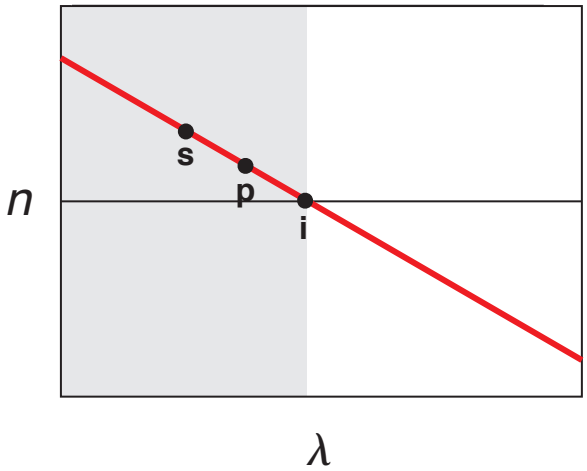


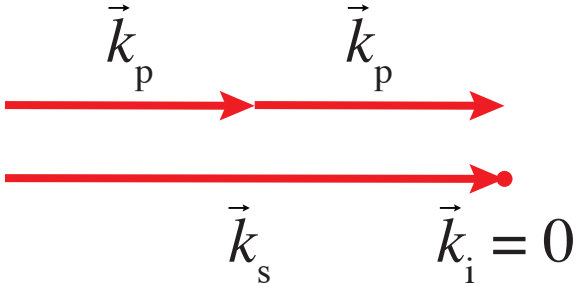
phase matching

four-wave mixing



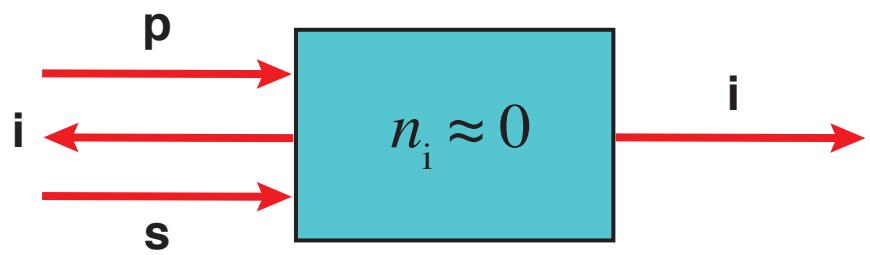
forward and backward



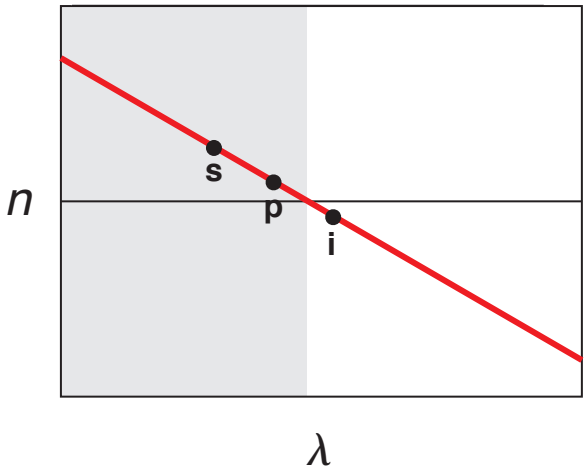


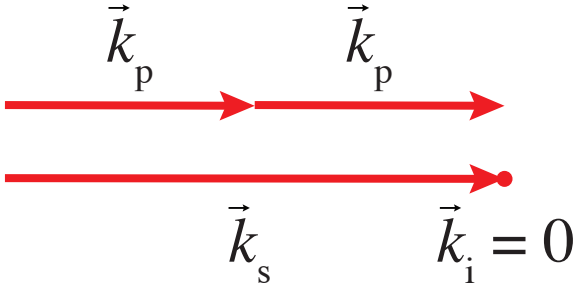
phase matching

four-wave mixing



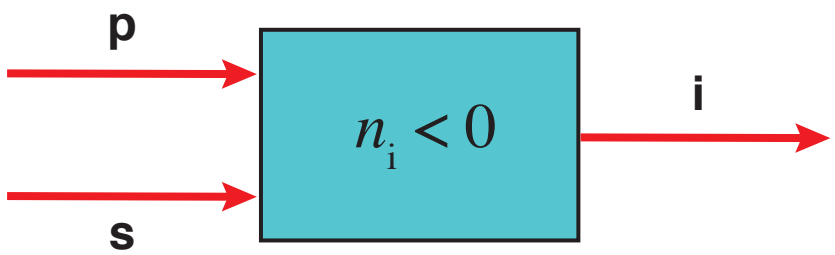
forward and backward

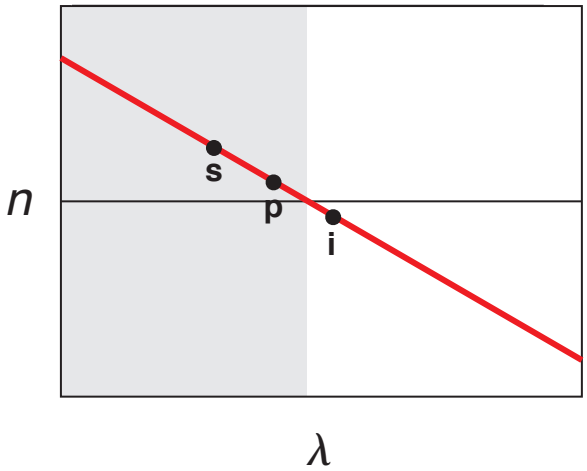


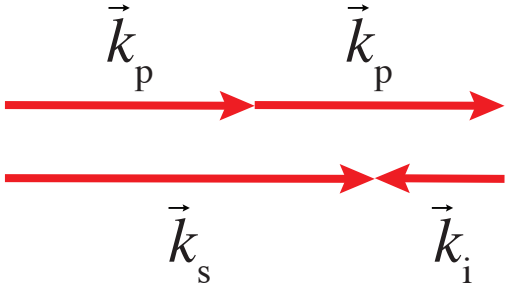


phase matching

four-wave mixing

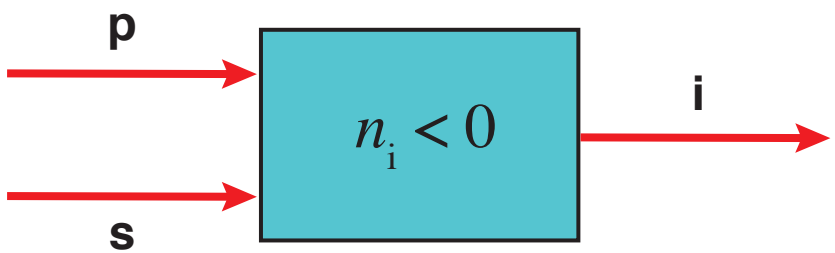




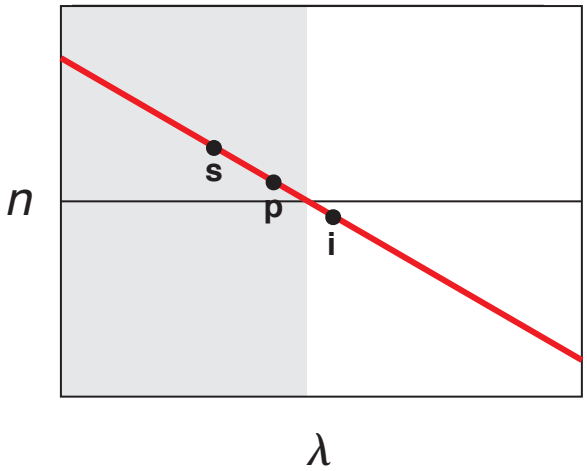


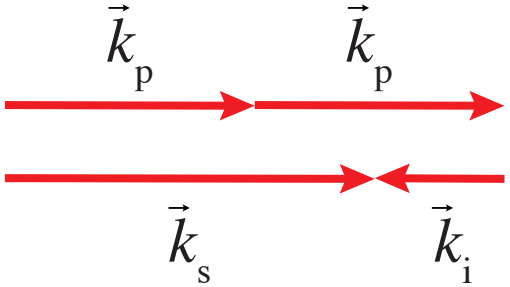
phase matching

four-wave mixing



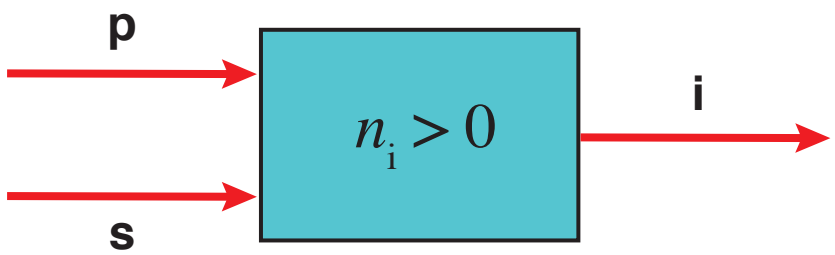
forward only

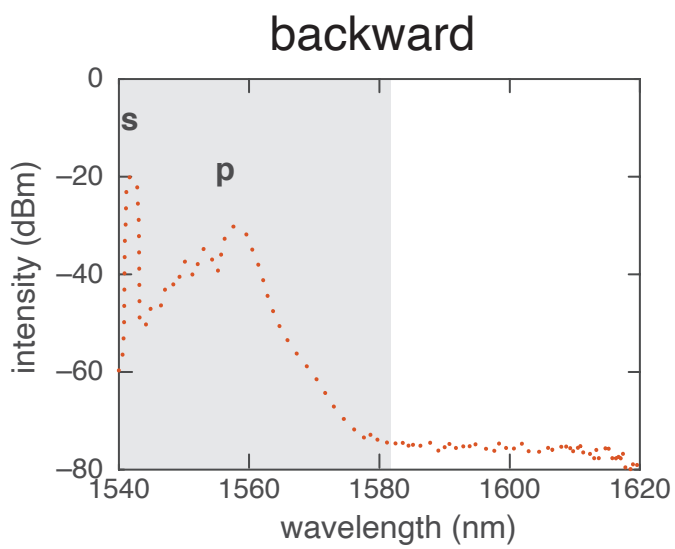


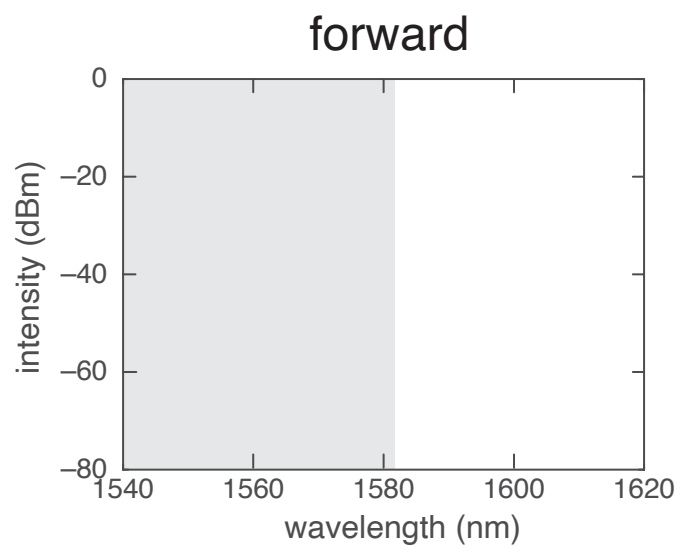


phase matching

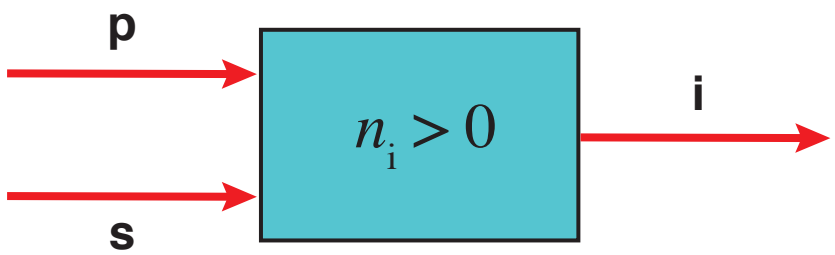
four-wave mixing

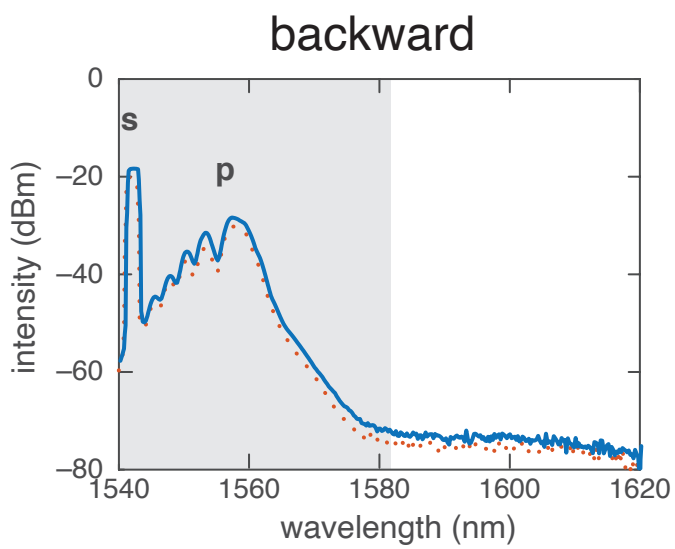


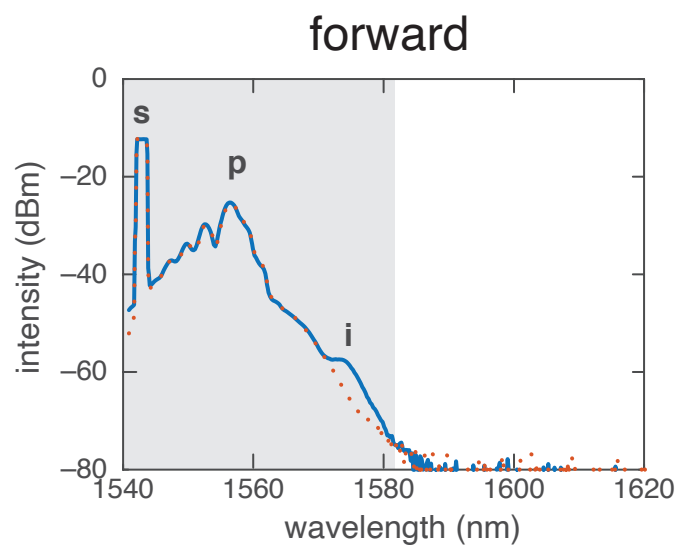




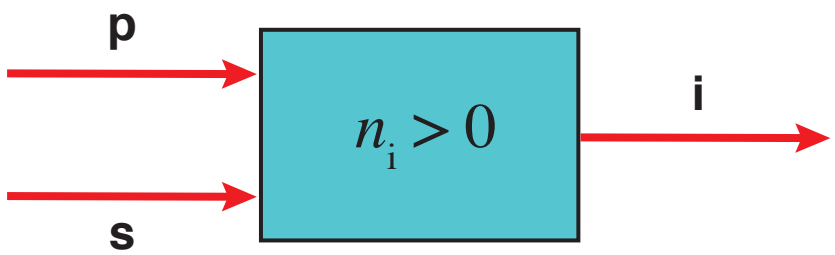
four-wave mixing

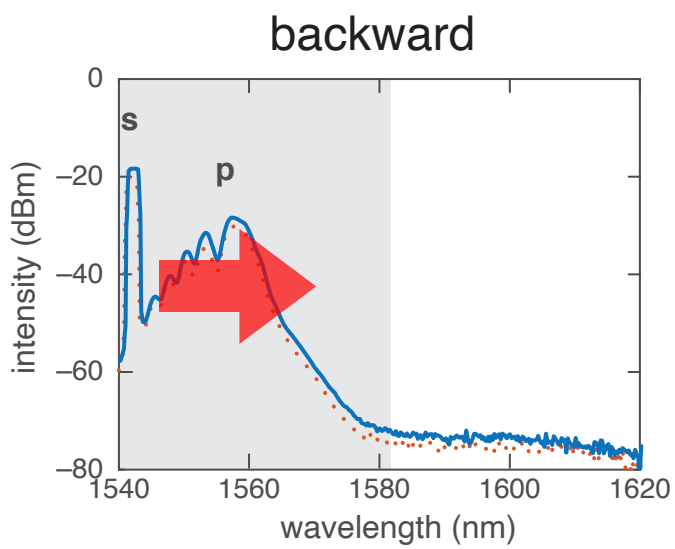


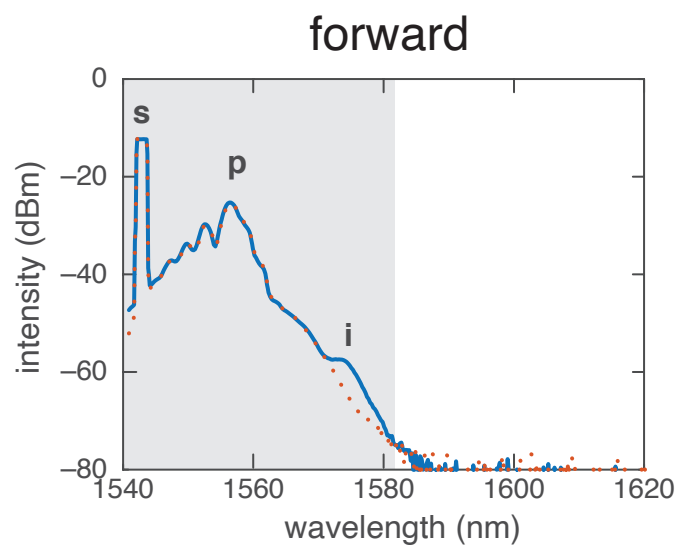




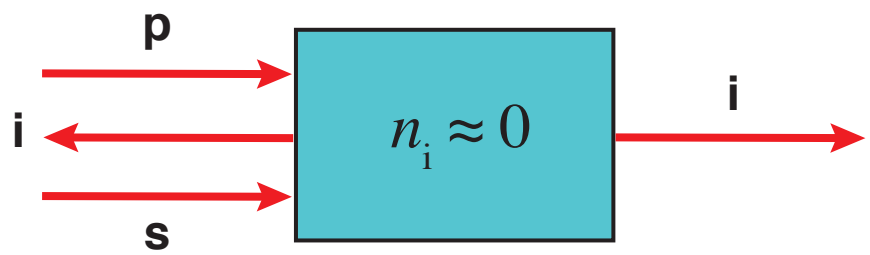
four-wave mixing



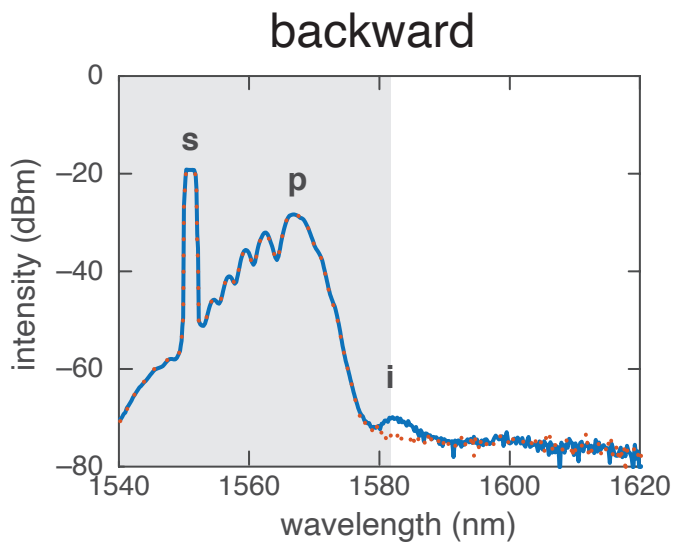


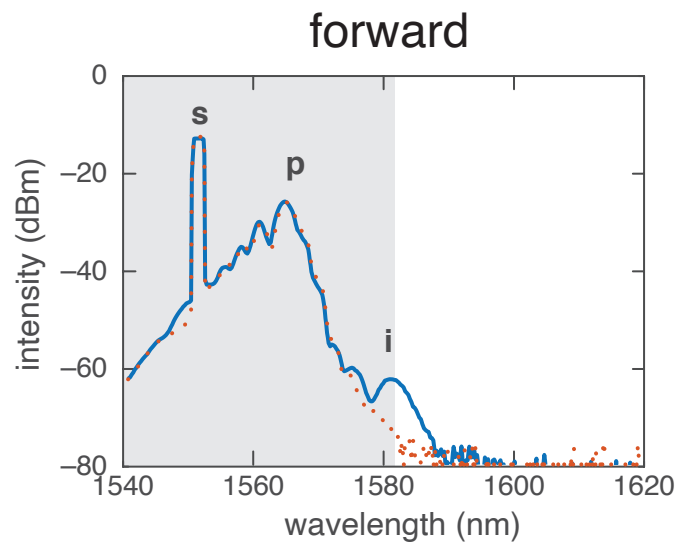


four-wave mixing

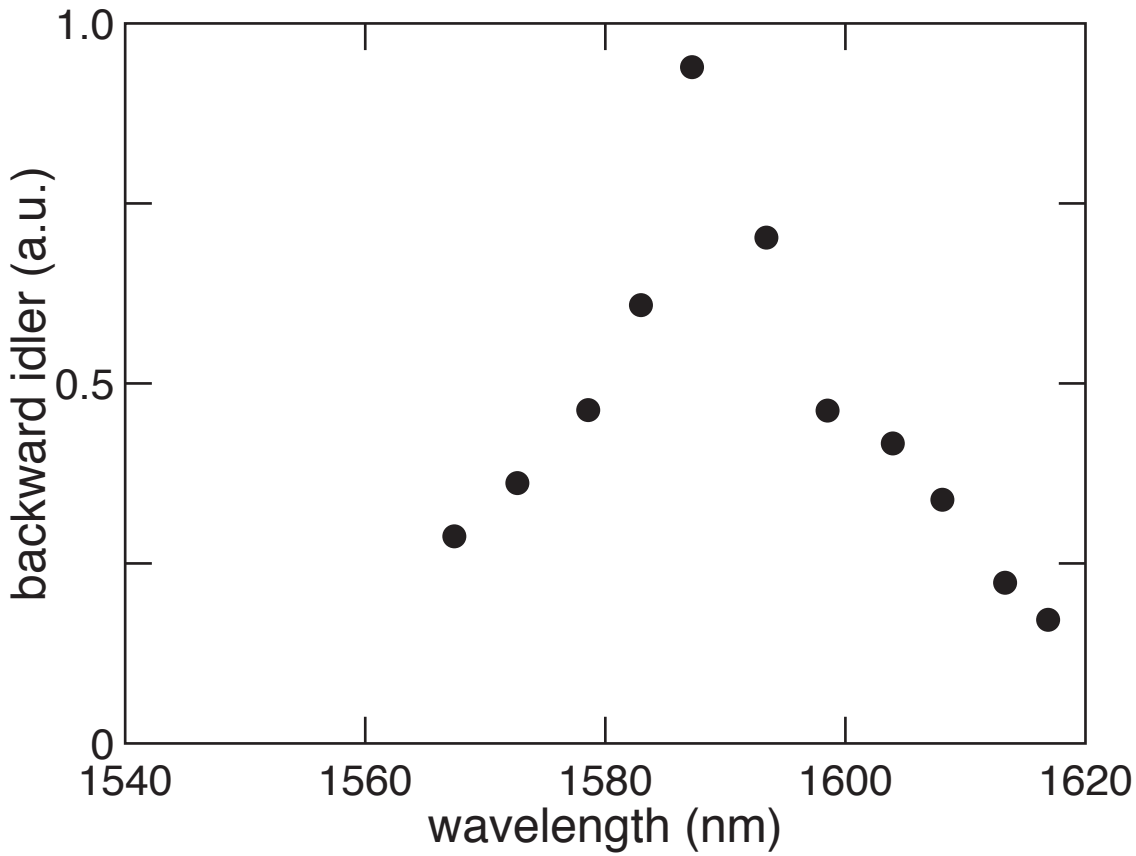


forward and backward





backward idler intensity



backward idler

PHYSICAL REVIEW LETTERS **128,** 203902 (2022)

Editors' Suggestion

Relaxed Phase-Matching Constraints in Zero-Index Waveguides

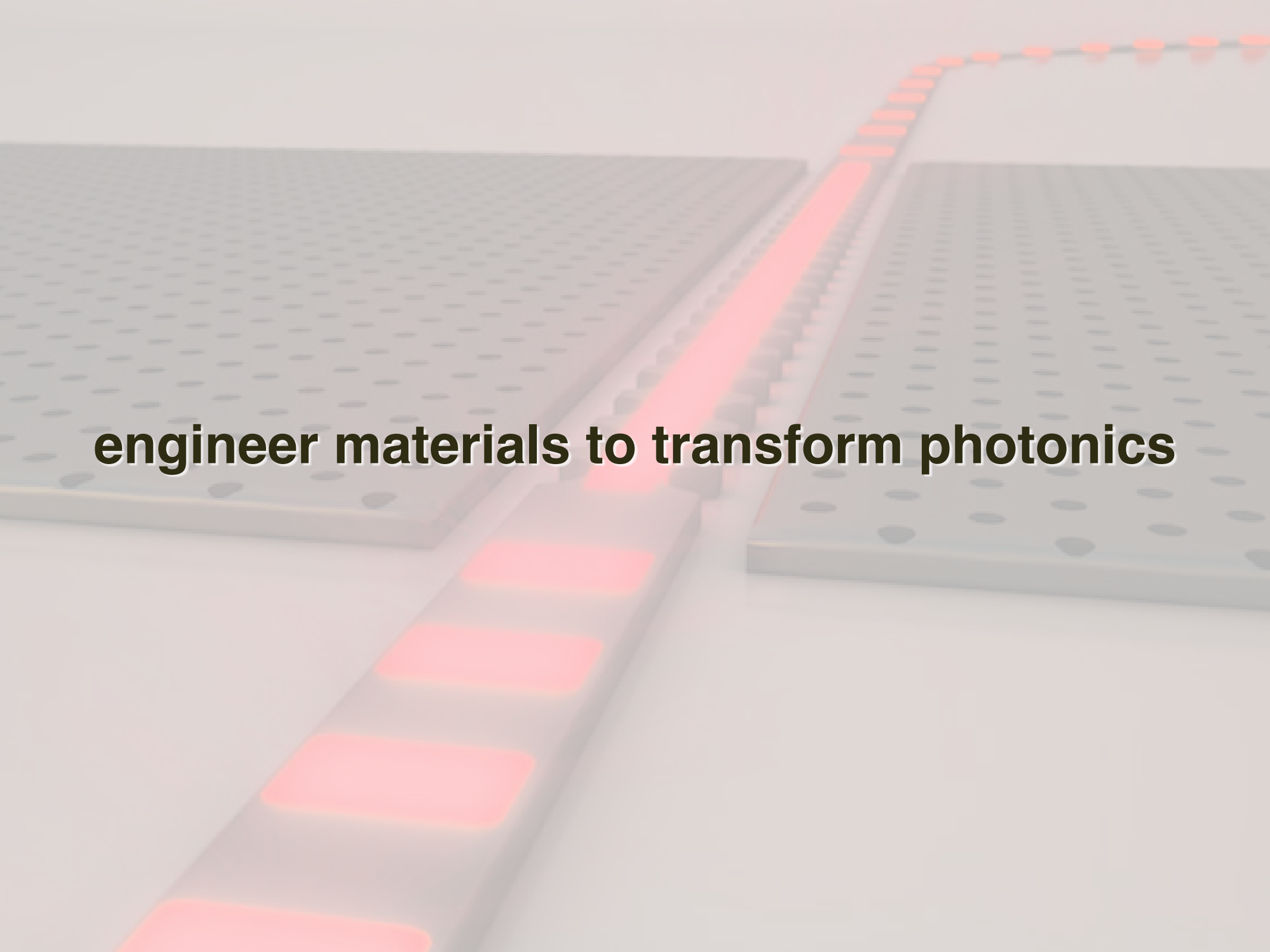
Justin R. Gagnon,[1,†] Orad Reshef,[1,*,†] Daniel H. G. Espinosa,[2] M. Zahirul Alam,[1] Daryl I. Vulis,[3] Erik N. Knall,[3] Jeremy Upham,[1] Yang Li,[3,4] Ksenia Dolgaleva,[1,2] Eric Mazur,[3] and Robert W. Boyd[1,2,5]

[1]*Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada*
[2]*School of Electrical Engineering and Computer Science, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada*
[3]*John A. Paulson School of Engineering and Applied Sciences, Harvard University, 9 Oxford Street, Cambridge, Massachusetts 02138, USA*
[4]*State Key Laboratory of Precision Measurement Technology and Instrument, Department of Precision Instrument, Tsinghua University, 100084 Beijing, China*
[5]*Institute of Optics and Department of Physics and Astronomy, University of Rochester, 500 Wilson Blvd, Rochester, New York 14627, USA*

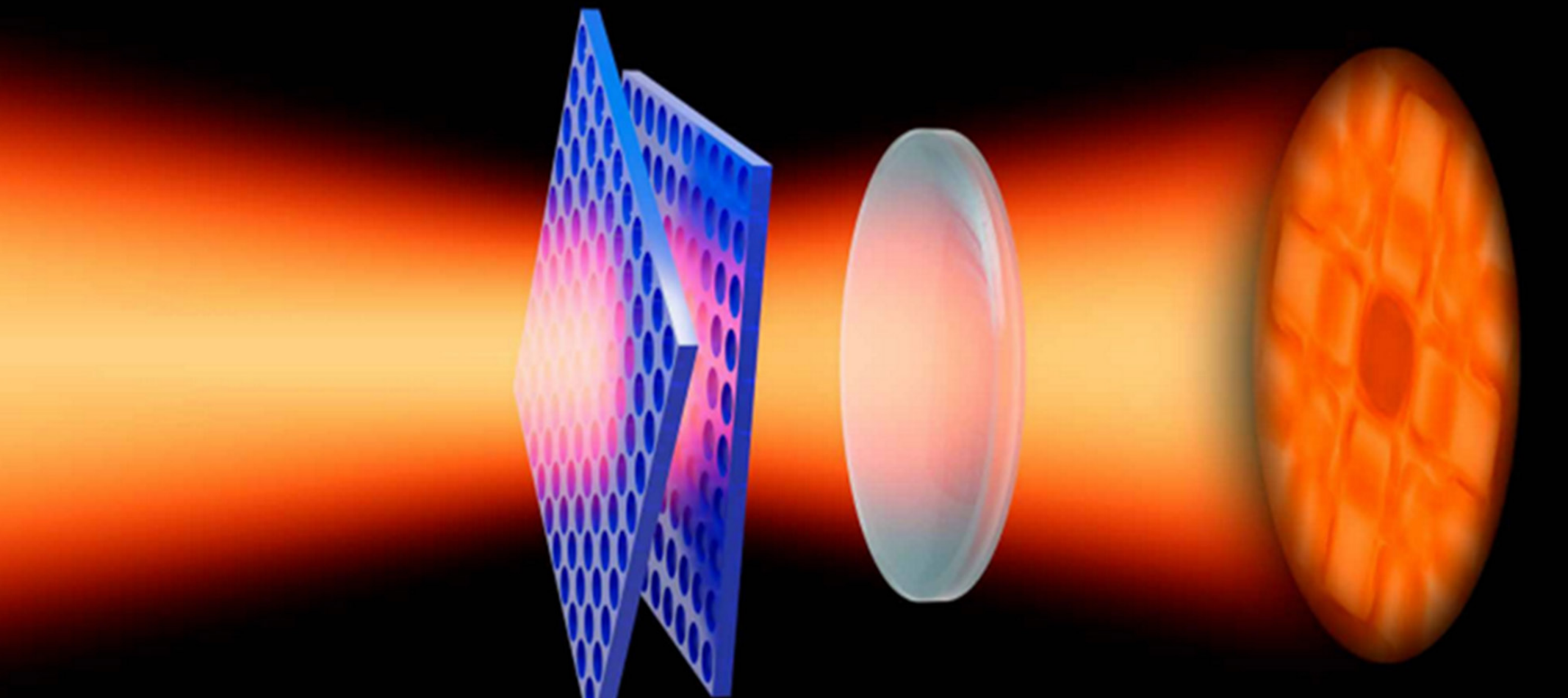
(Received 1 July 2021; accepted 4 April 2022; published 17 May 2022)

The utility of all parametric nonlinear optical processes is hampered by phase-matching requirements. Quasi-phase-matching, birefringent phase matching, and higher-order-mode phase matching have all been developed to address this constraint, but the methods demonstrated to date suffer from the inconvenience of only being phase matched for a single, specific arrangement of beams, typically copropagating, resulting in cumbersome experimental configurations and large footprints for integrated devices. Here, we experimentally demonstrate that these phase-matching requirements may be satisfied in a parametric nonlinear optical process for multiple, if not all, configurations of input and output beams when using low-index media. Our measurement constitutes the first experimental observation of direction-independent phase matching for a medium sufficiently long for phase matching to be relevant. We demonstrate four-wave mixing from spectrally distinct co- and counterpropagating pump and probe beams, the backward [illegible] and excitation by an out-of-plane probe beam. These results explicitly [illegible] additional phase-matching constraints, which can [illegible] adding to the

1 zero index 2 fabrication 3 results


engineer materials to transform photonics

Friday May 12, 15:00



FF3D.5: Direct Imaging of Band Structure in Twisted Bilayer Photonic Crystal Slabs

Group Members:

Prof. Yang Li
Dr. Haoning Tang
Fan Du
Dr. Sara Muñoz
Dr. Orad Reshef,
Dr. Daryl Vulis
Mei Yin
Lysander Christakis
Dr. Olivia Mello
Dr. Clayton DeVault
Prof. Michael Lobet
Xueqi Ni
Vishantak Srikrishna
Mingjie Zhang
Alex Raun
Prof. Evelyn Hu
Zin Lin
Justin Gagnon
Cleaven Chia
Dr. Stephen Carr
Shota Kita
Beicheng Lou

Collaborators:

Prof. Bob Boyd
Prof. Nader Engheta
Prof. Alan Wilner
Prof. Shanhui Fan
Prof. Marko Loncar

National Science Foundation
DARPA
Harvard Center for Nanoscale Systems
Harvard Quantum Initiative

mazur.harvard.edu

Follow me! @eric_mazur