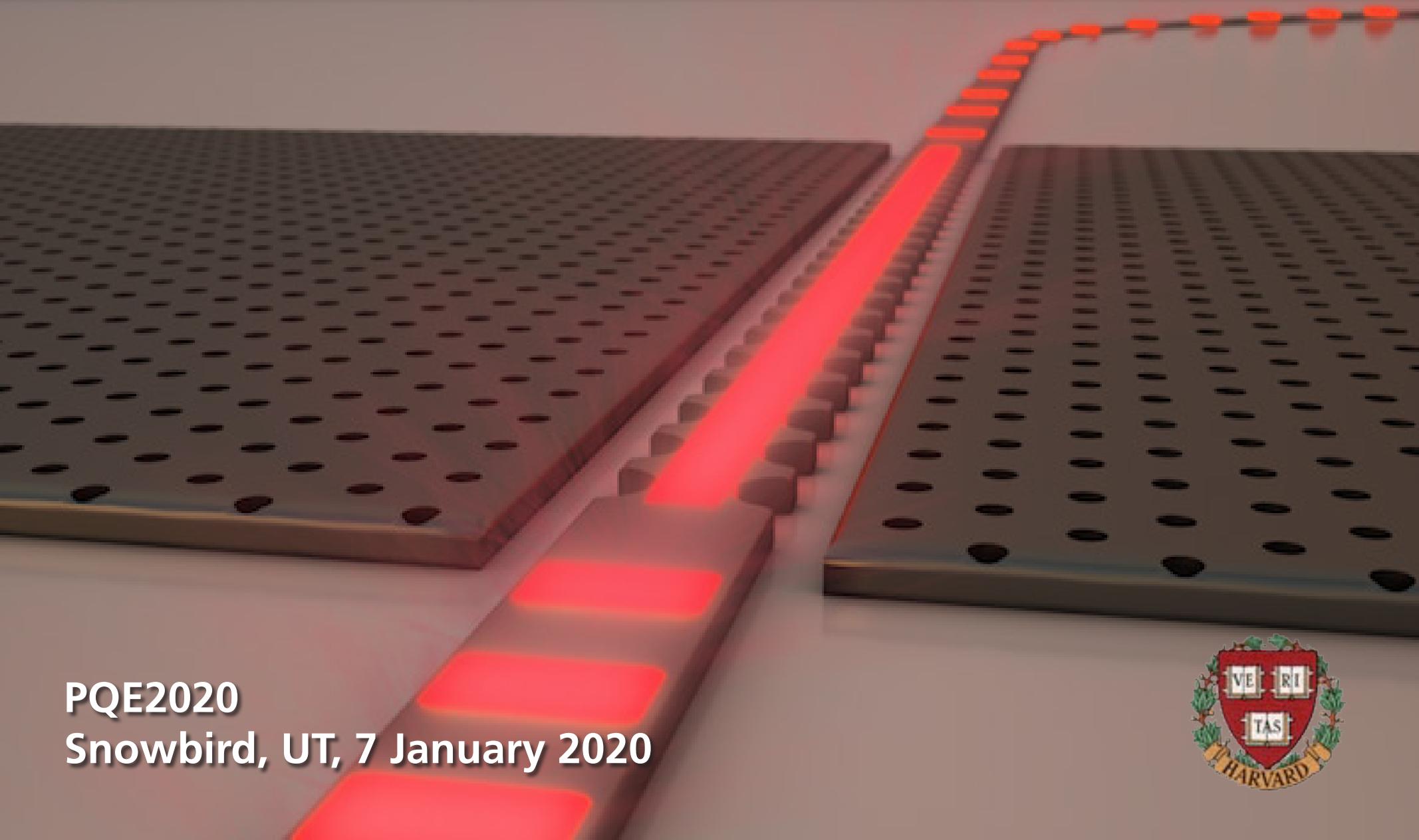


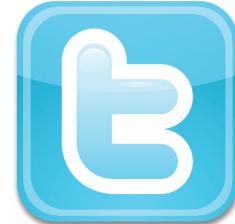
Extreme optics with zero index metamaterials



PQE2020
Snowbird, UT, 7 January 2020



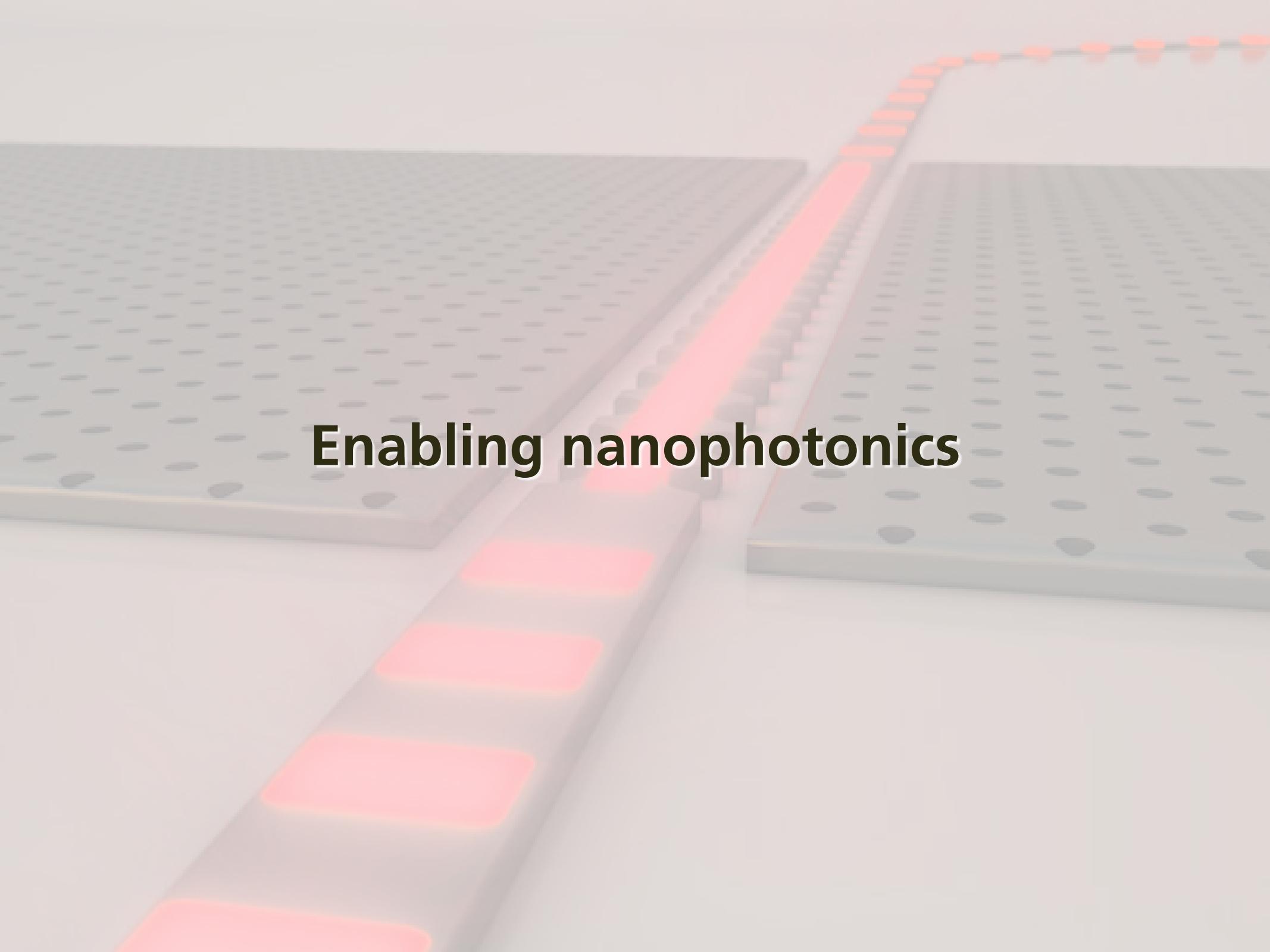
Extreme optics with zero index metamaterials



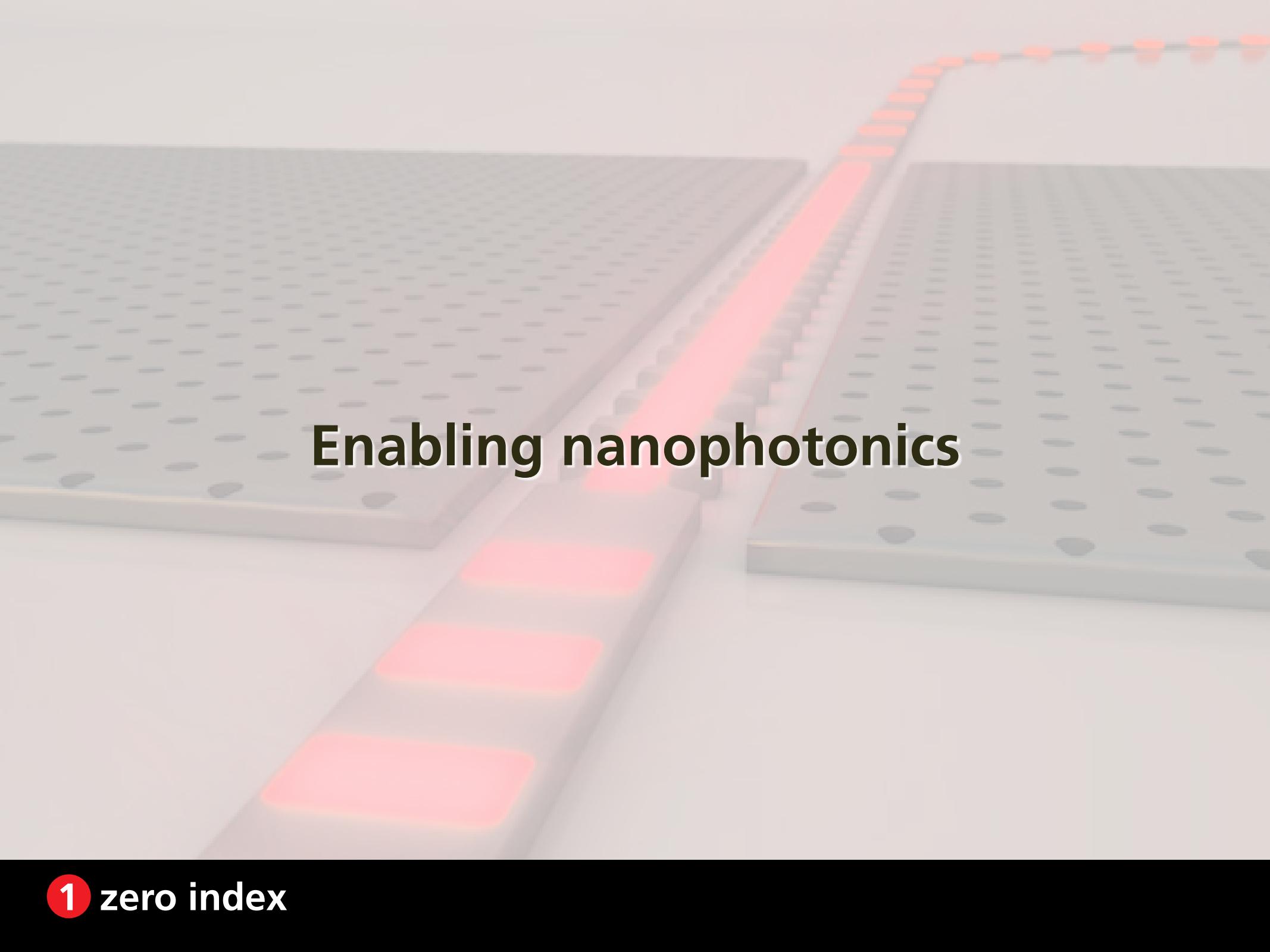
@eric_mazur

PQE2020
Snowbird, UT, 7 January 2020



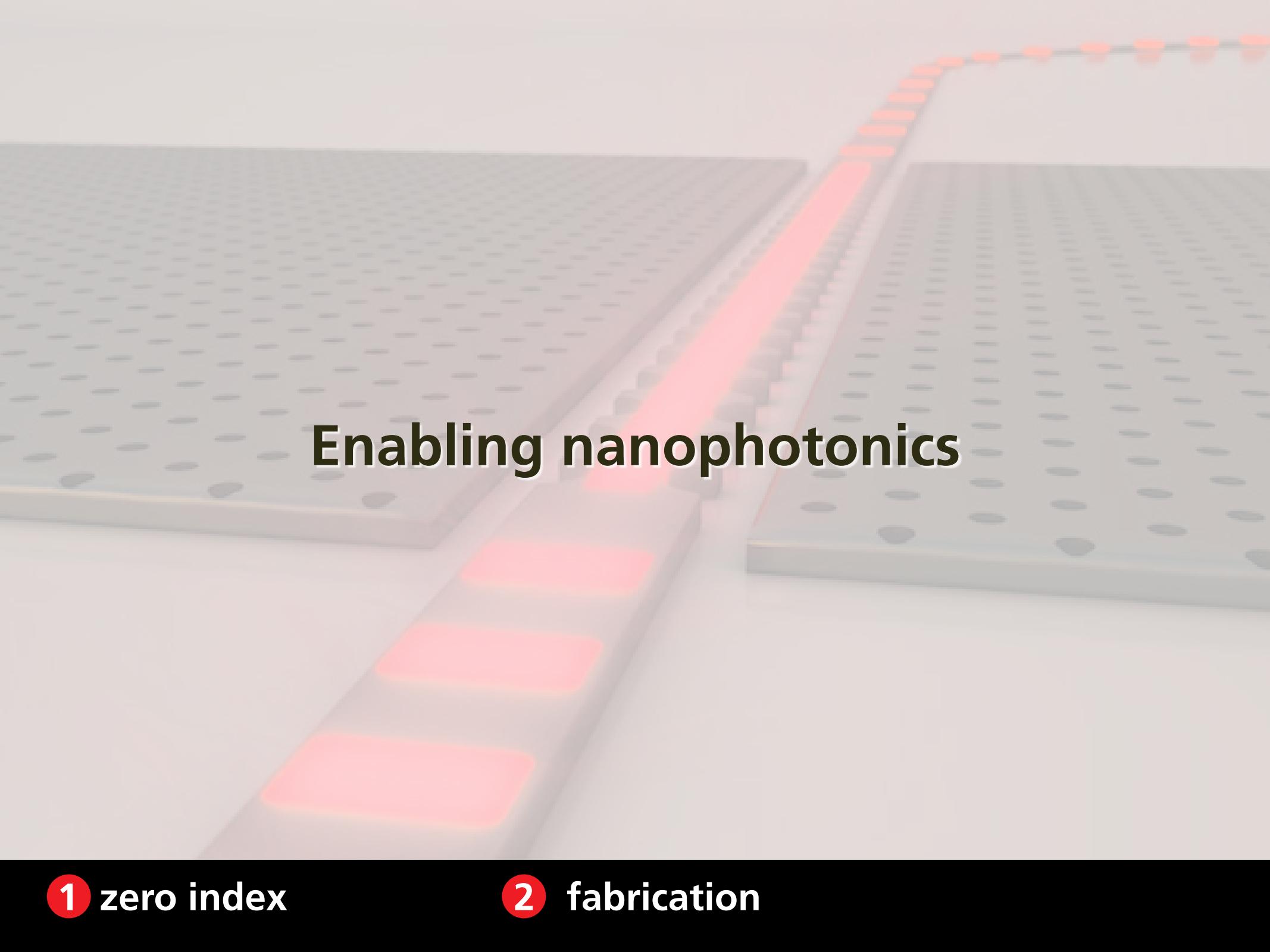
A grayscale background image showing a complex nanophotonic circuit. The circuit consists of a series of interconnected waveguides and resonators, represented by a grid of small, light-gray rectangles. Several specific features are highlighted with a vibrant red color: a central vertical column of three large rectangular resonators, a diagonal line of four smaller rectangular resonators extending from the bottom-left towards the top-right, and a curved line of five small circular resonators at the top right.

Enabling nanophotonics



Enabling nanophotonics

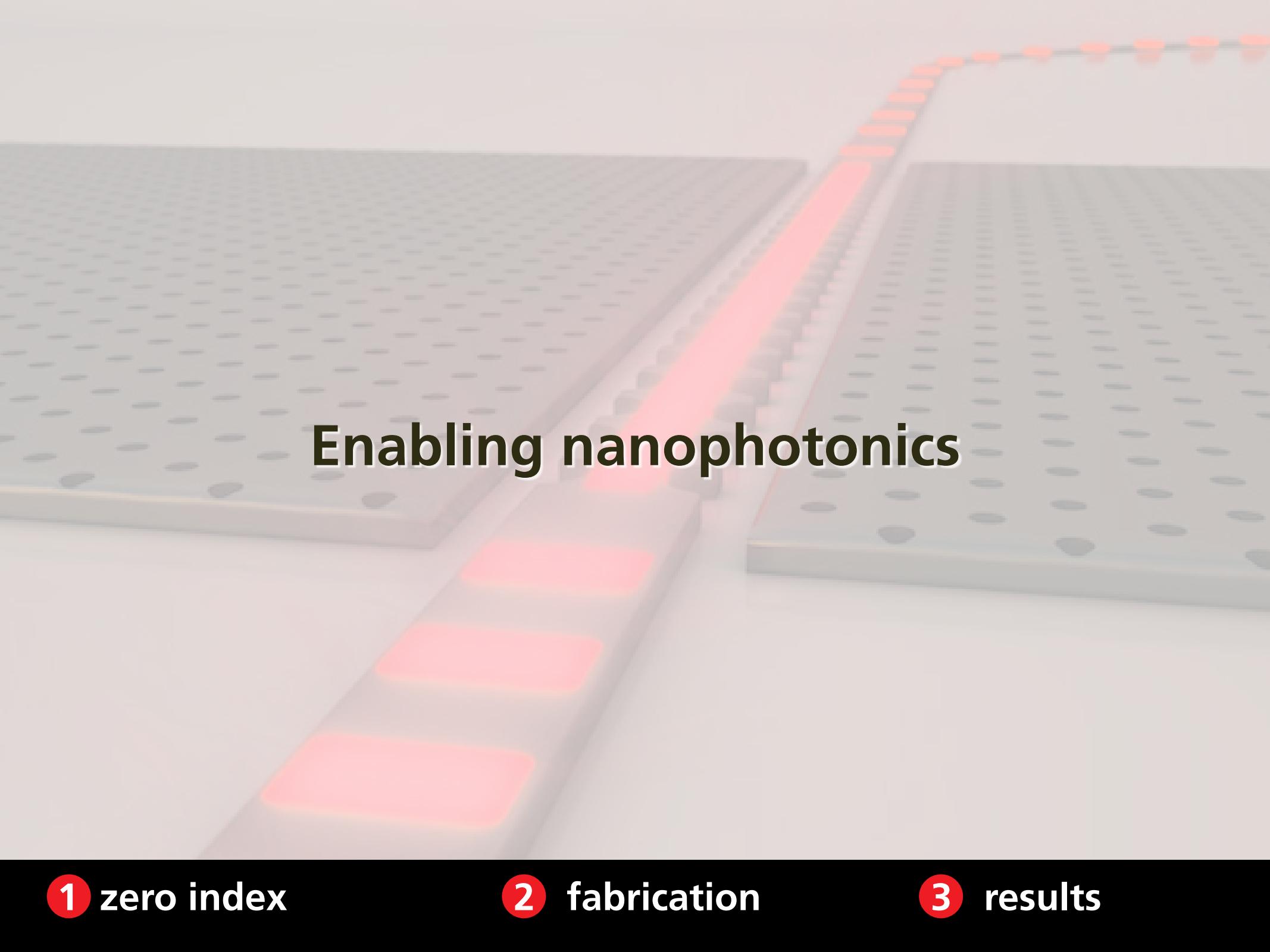
1 zero index



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

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

1 zero index

wave equation

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

solution

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

where

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

1 zero index

wave equation

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

solution

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

where

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

1 zero index

wave equation

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

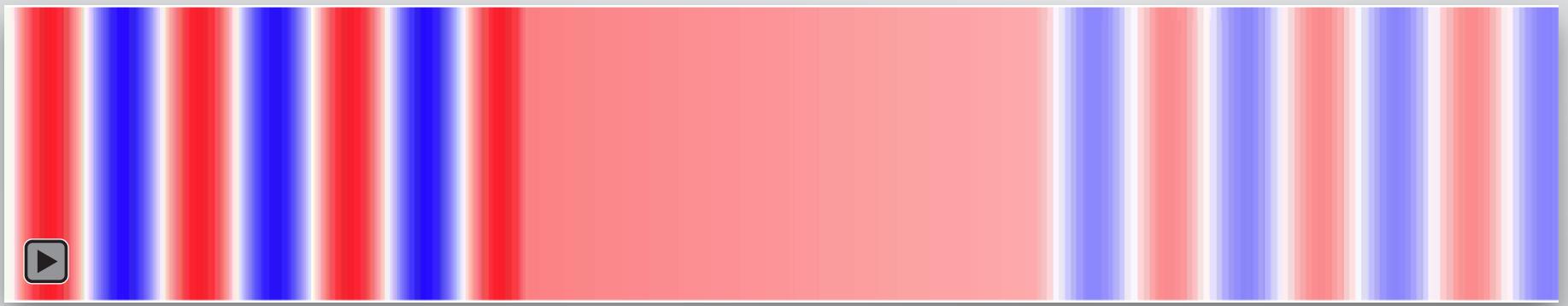
solution

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

where

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

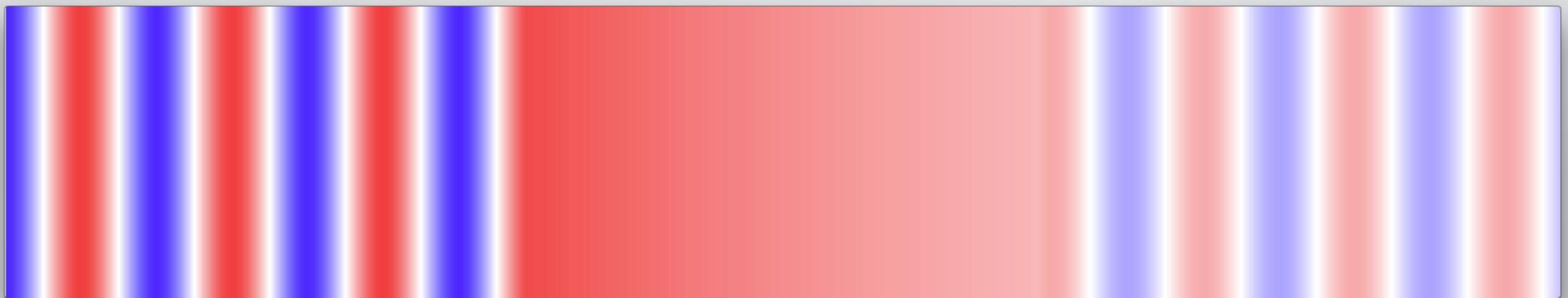
1 zero index



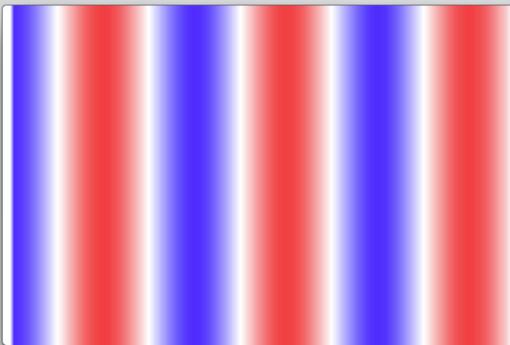
1 zero index

“Superluminal”?

What about causality?



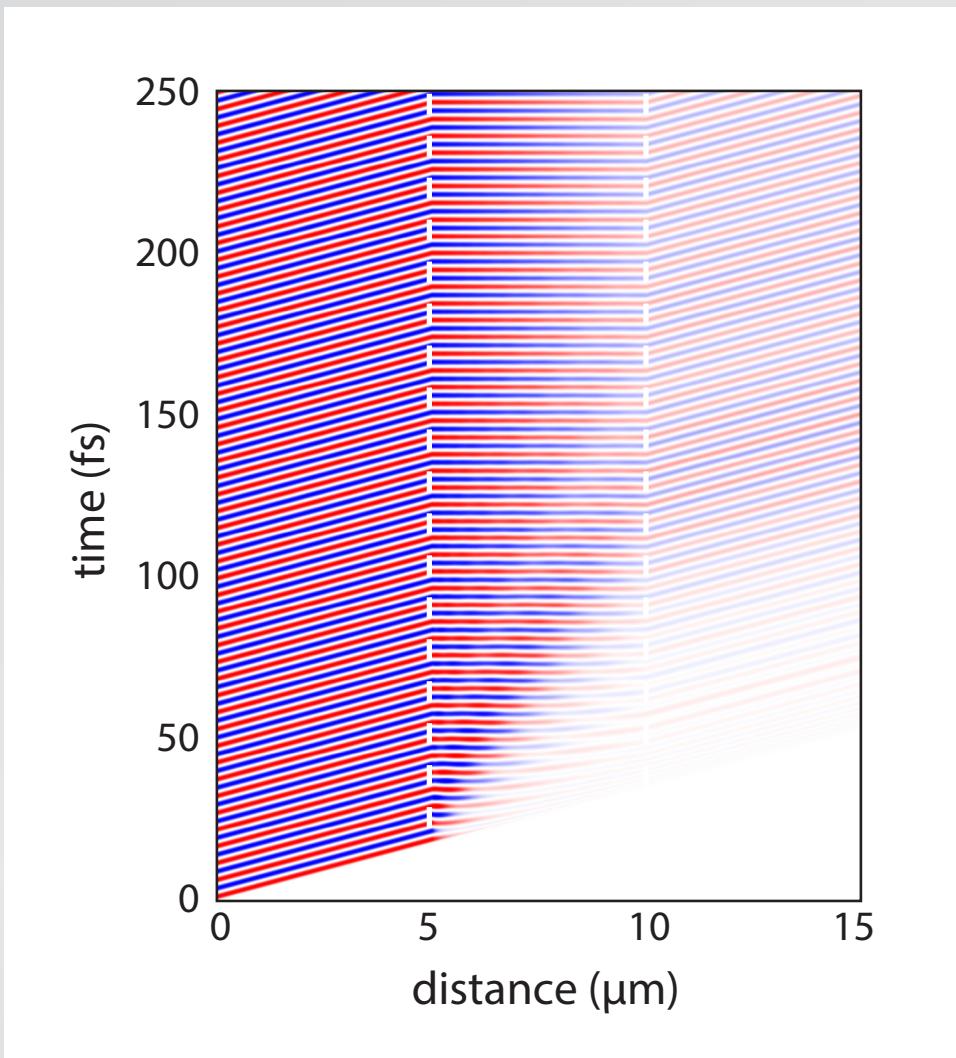
What about causality?



What about causality?



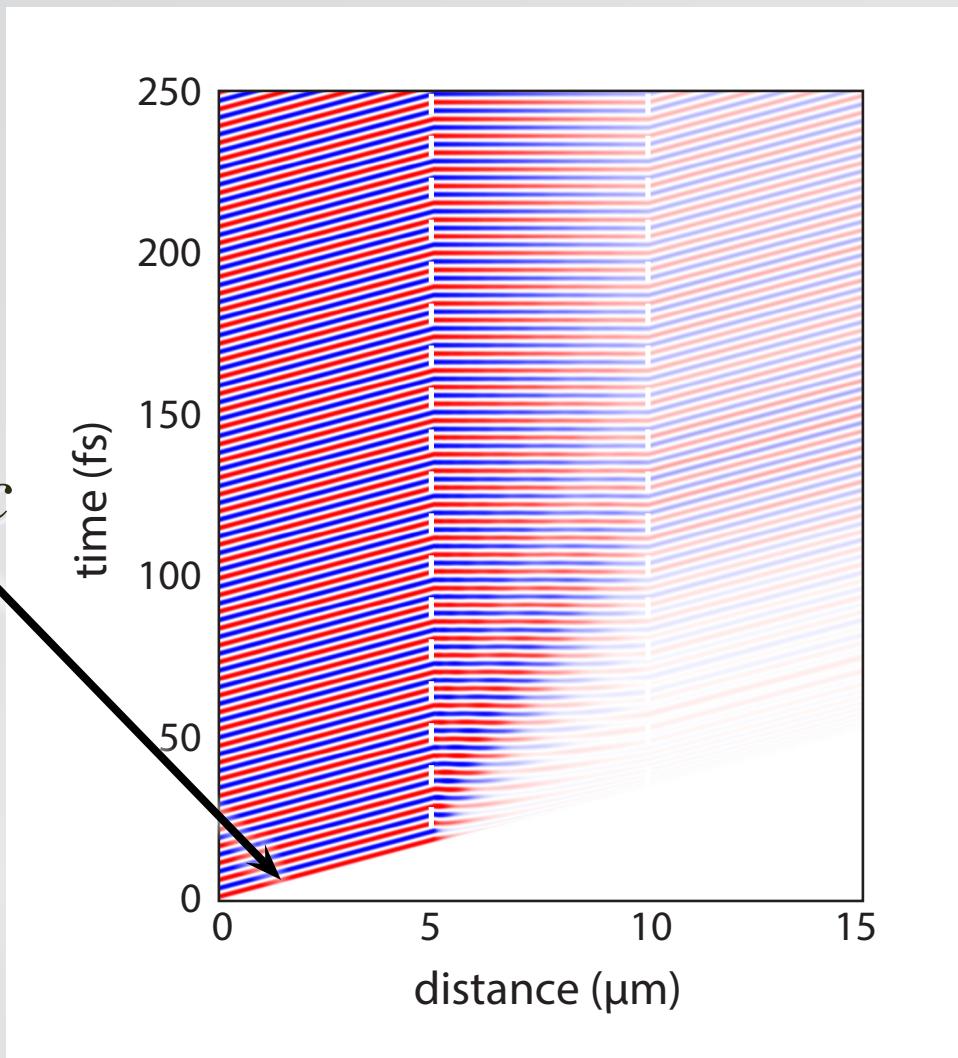
What about causality?



1 zero index

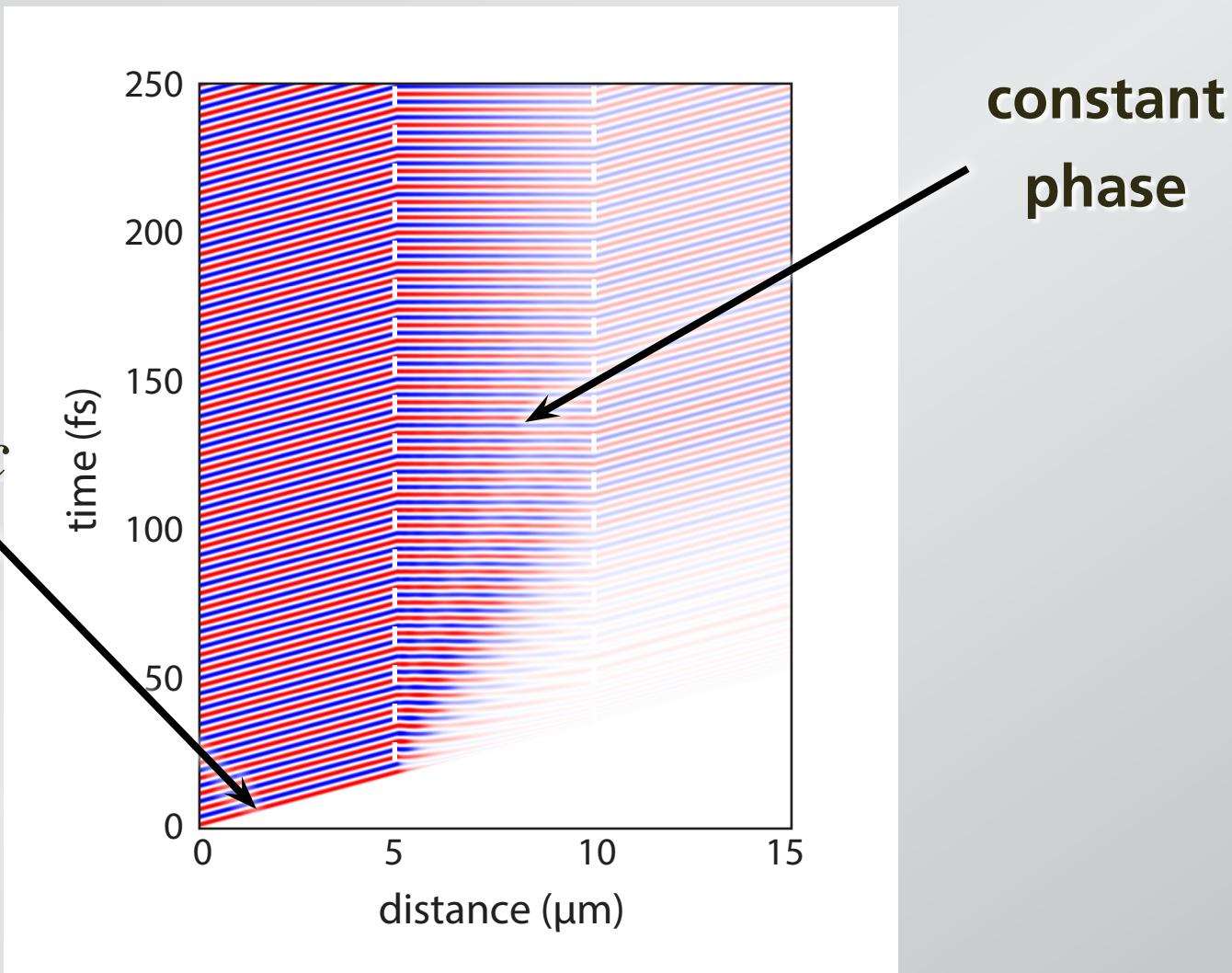
What about causality?

speed of light c



What about causality?

speed of light c



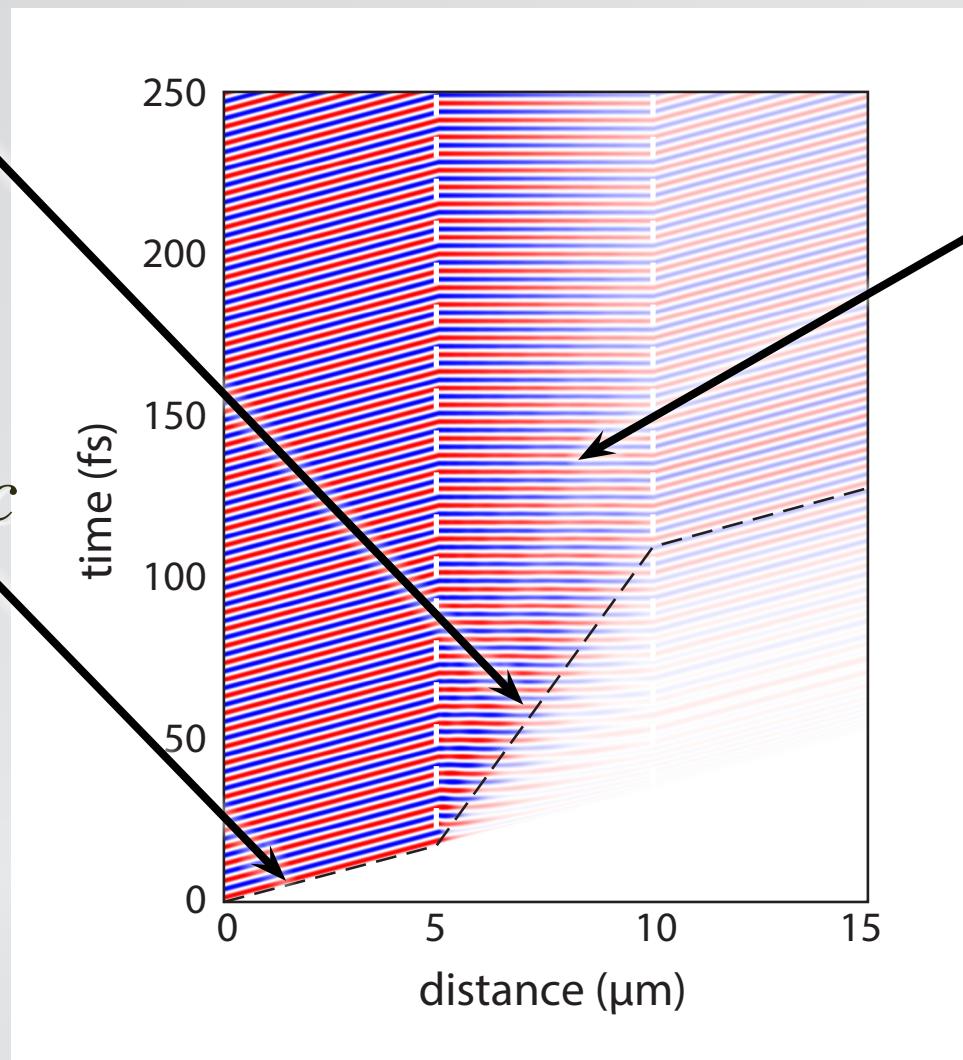
What about causality?

group velocity

$$v_g < c$$

speed of light c

constant
phase



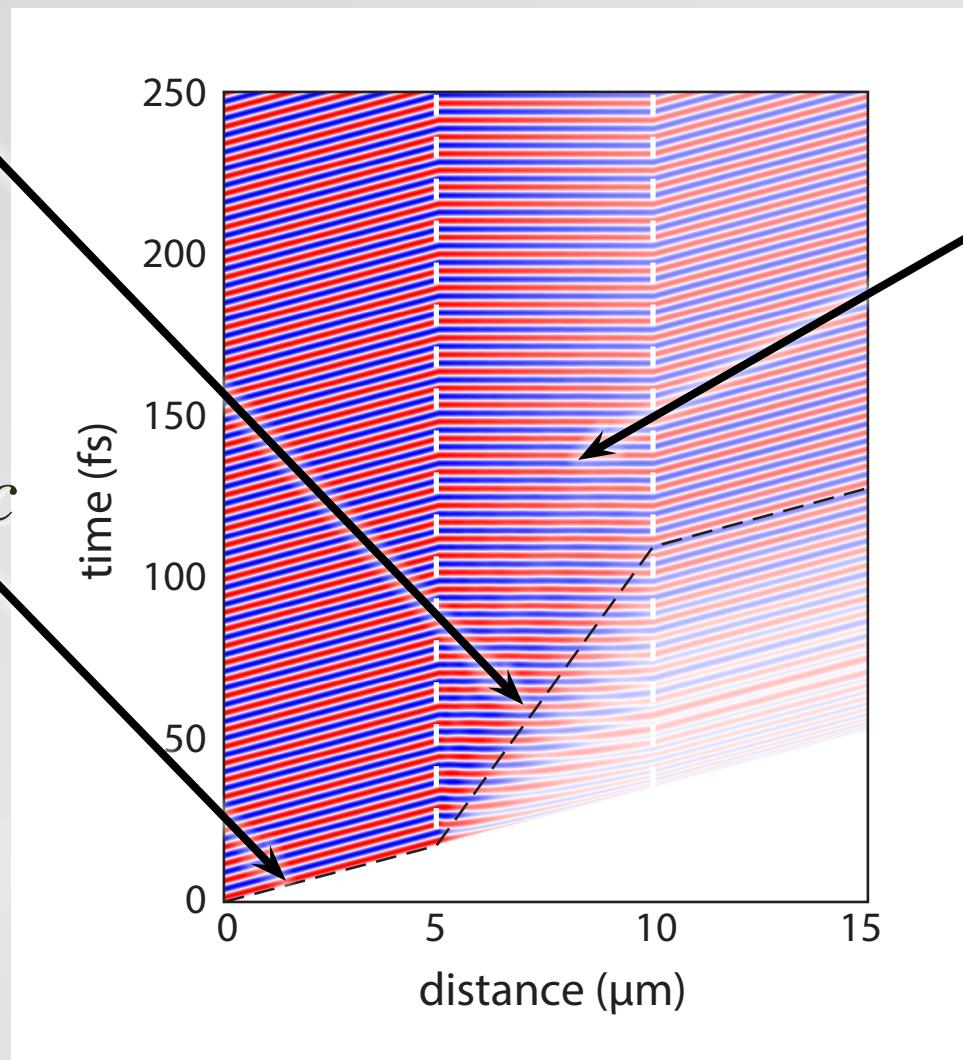
What about causality?

group velocity

$$v_g < c$$

speed of light c

constant
phase



What about causality?

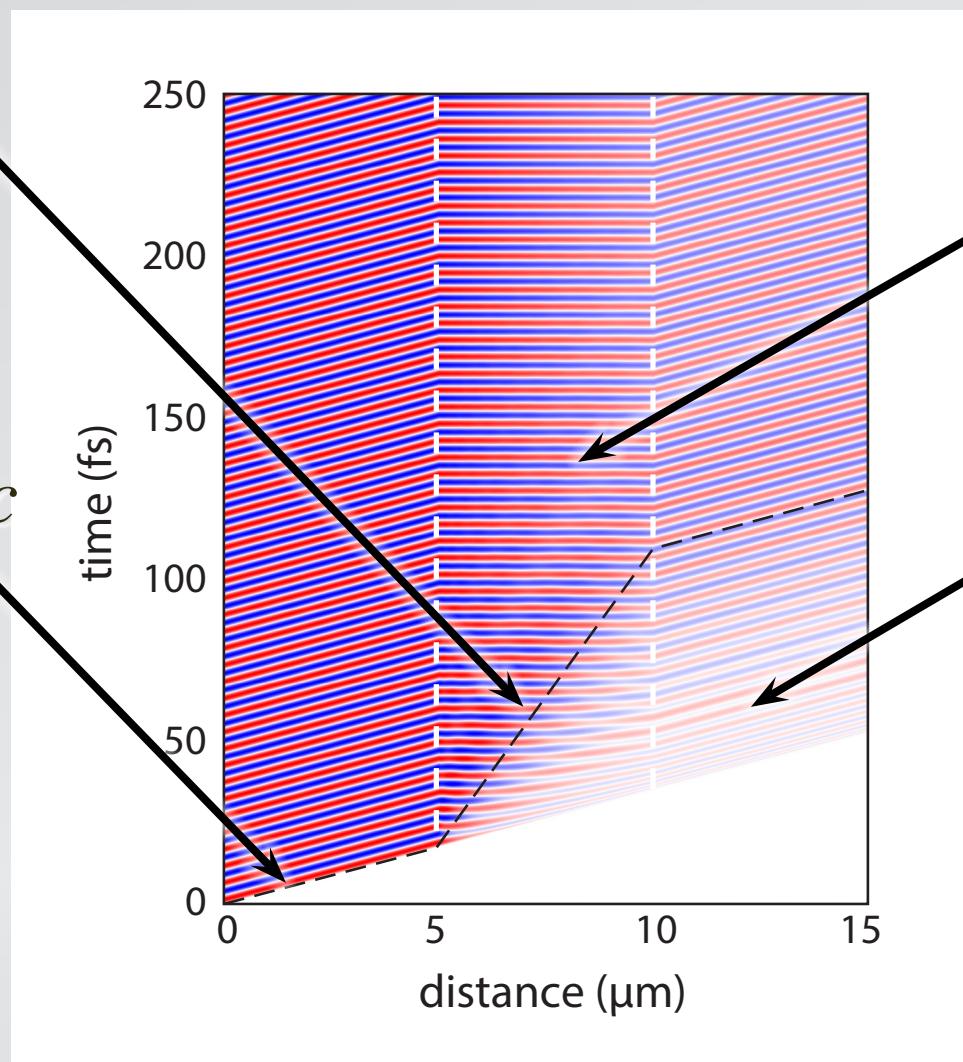
group velocity

$$v_g < c$$

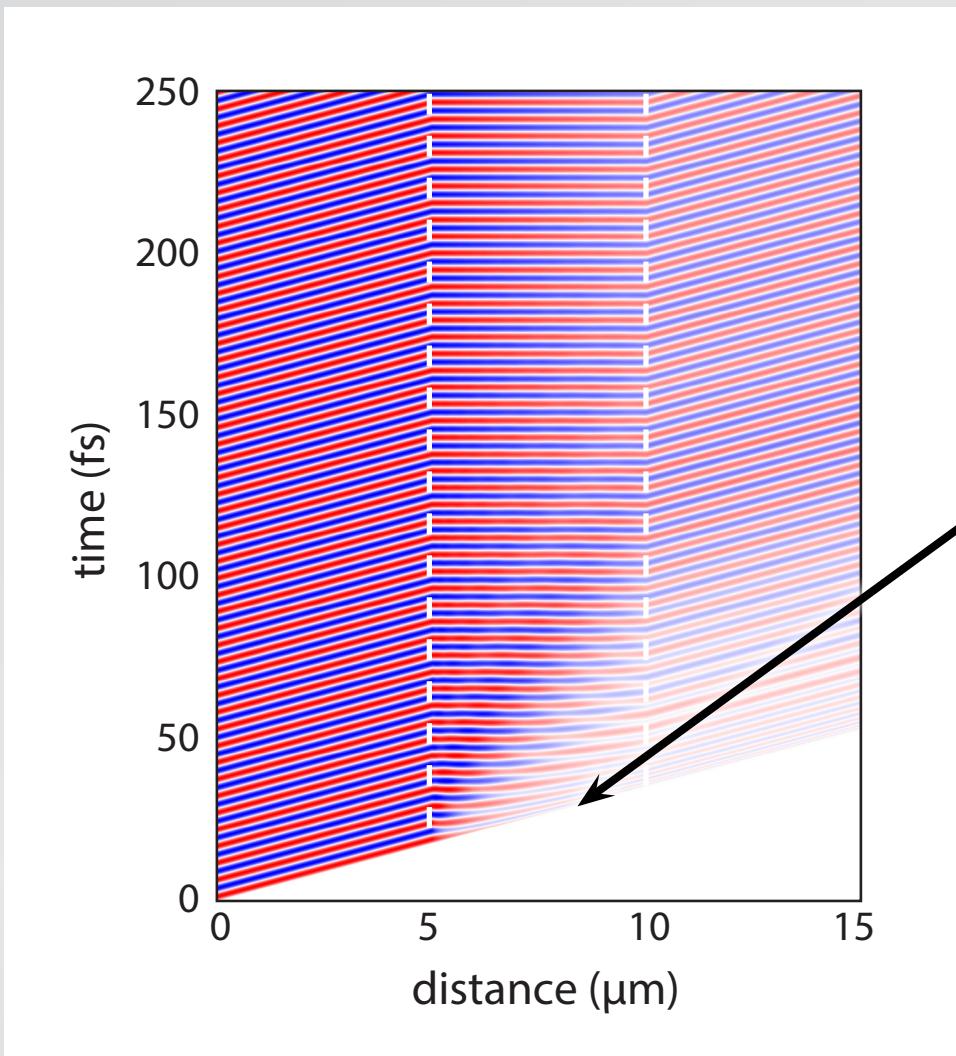
speed of light c

constant
phase

high-frequency
precursors



What about causality?



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

What about causality?



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

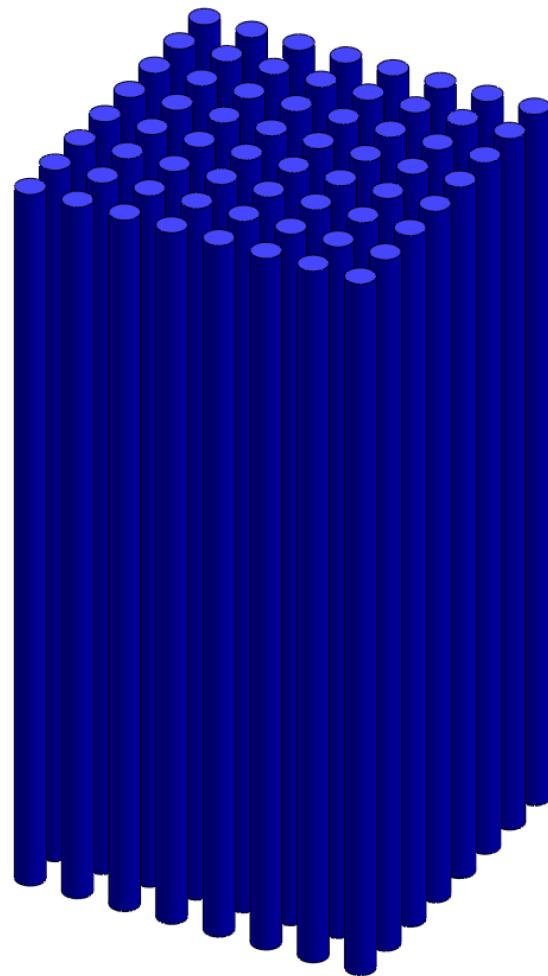
$$R = \frac{Z - 1}{Z + 1}$$

where

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

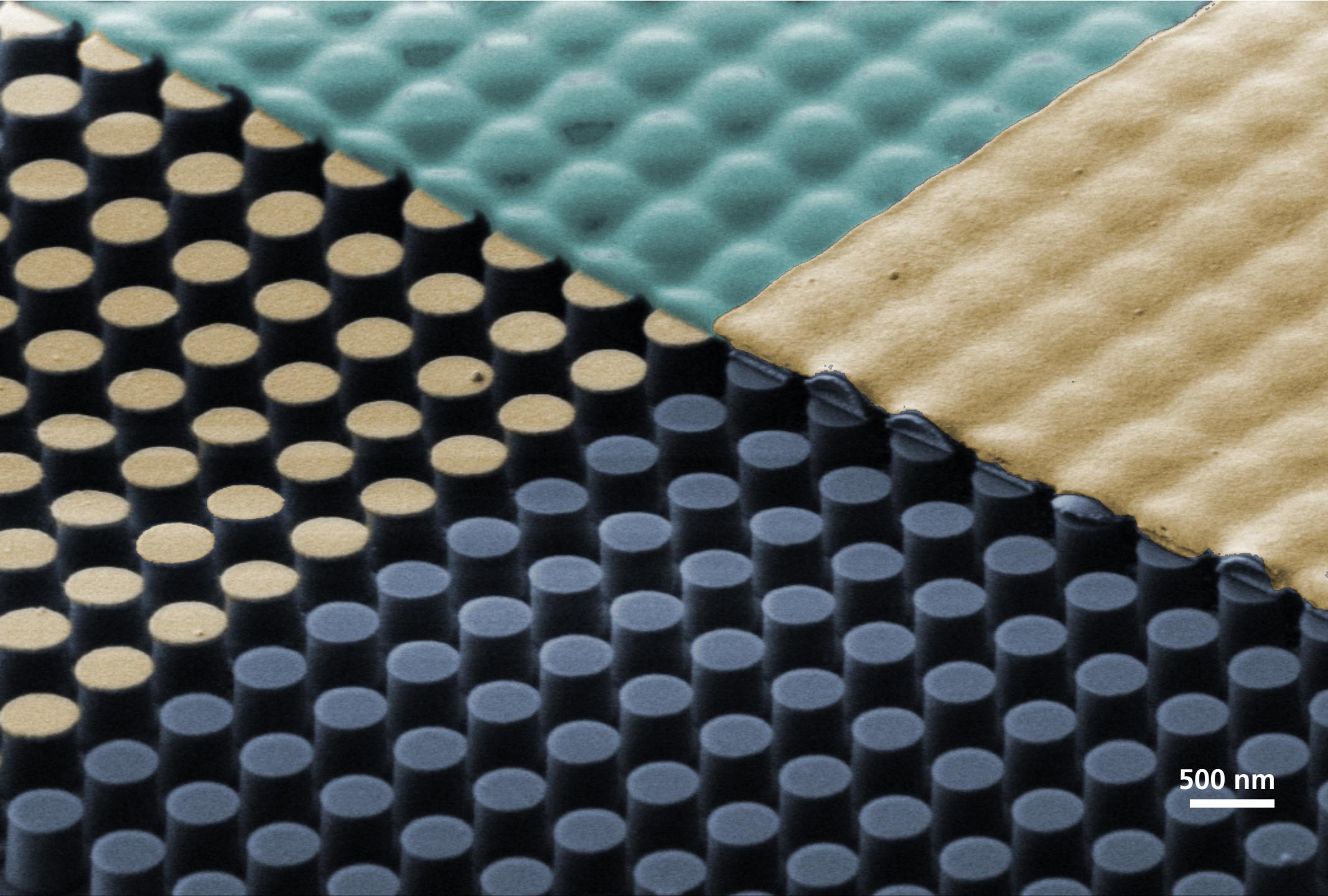
1 zero index

How to fabricate?



1 zero index

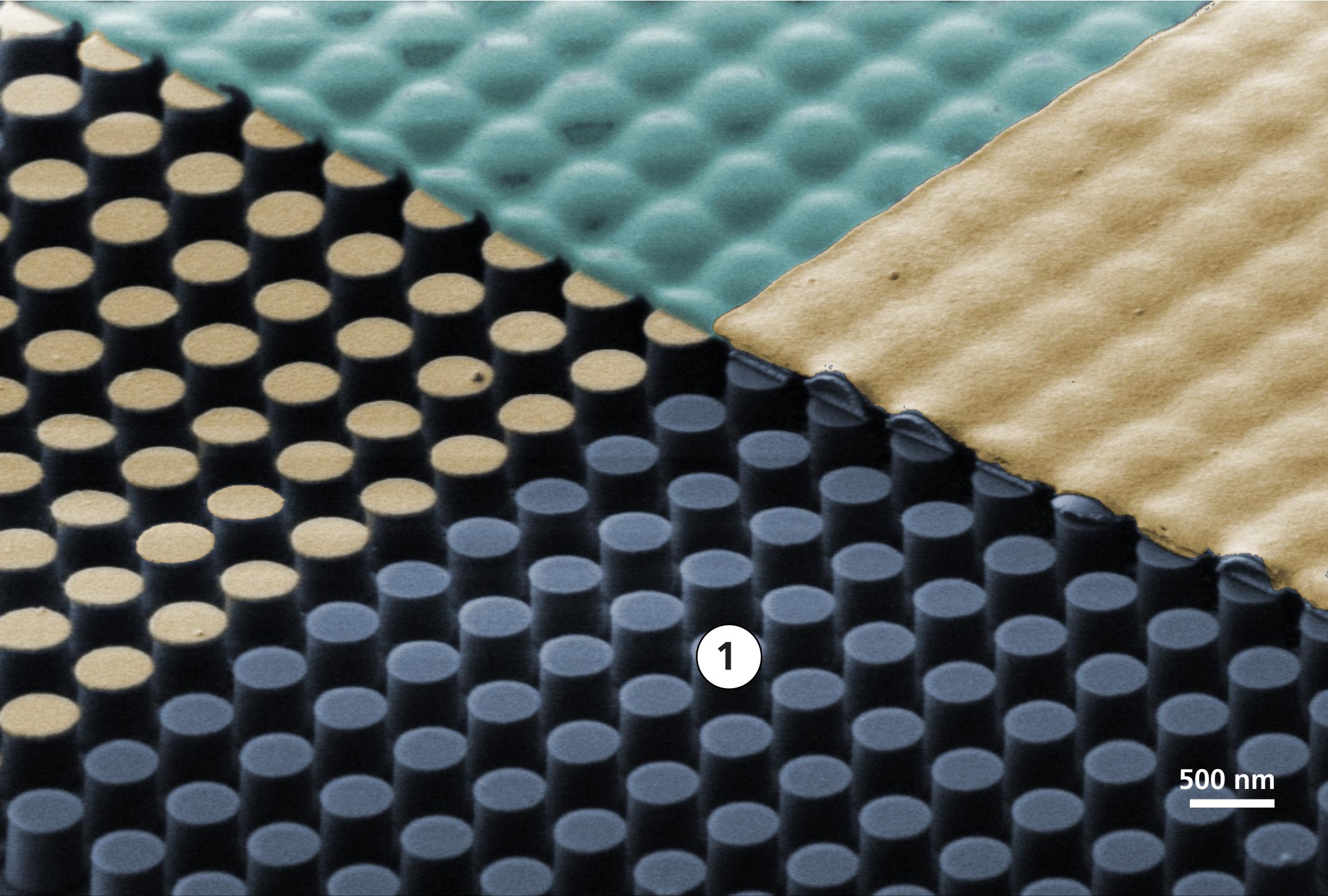
2 fabrication



1 zero index

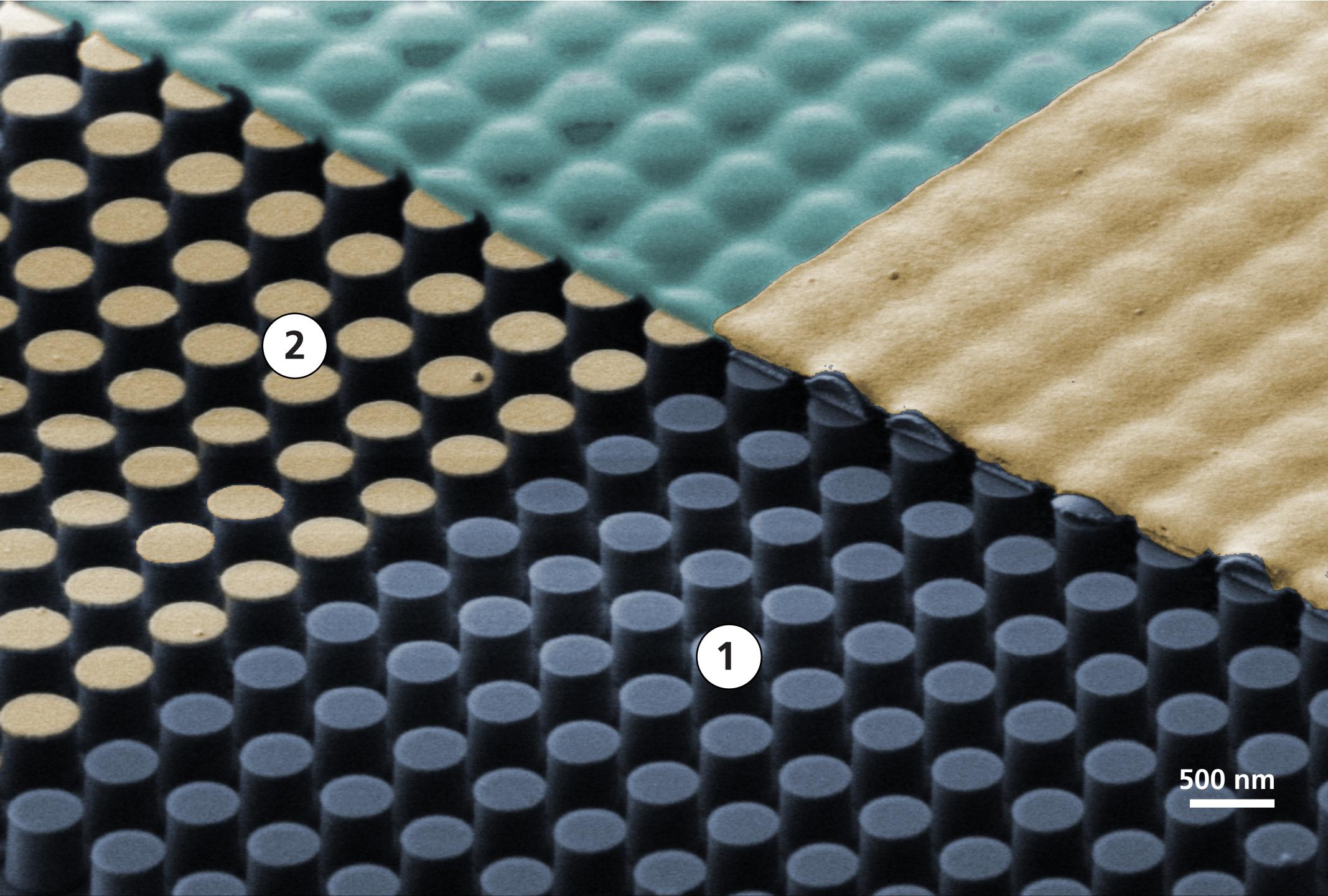
2 fabrication

500 nm



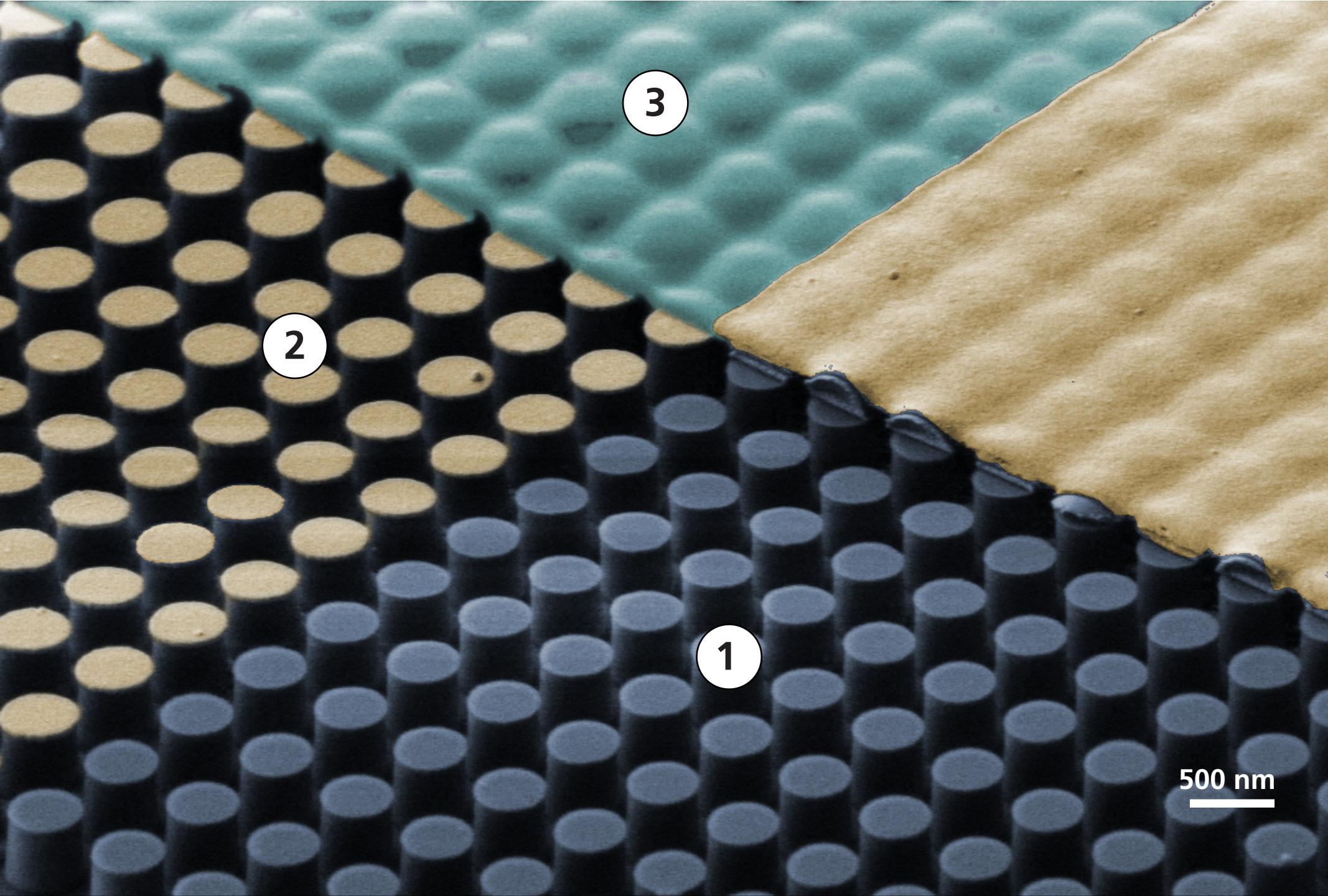
1 zero index

2 fabrication



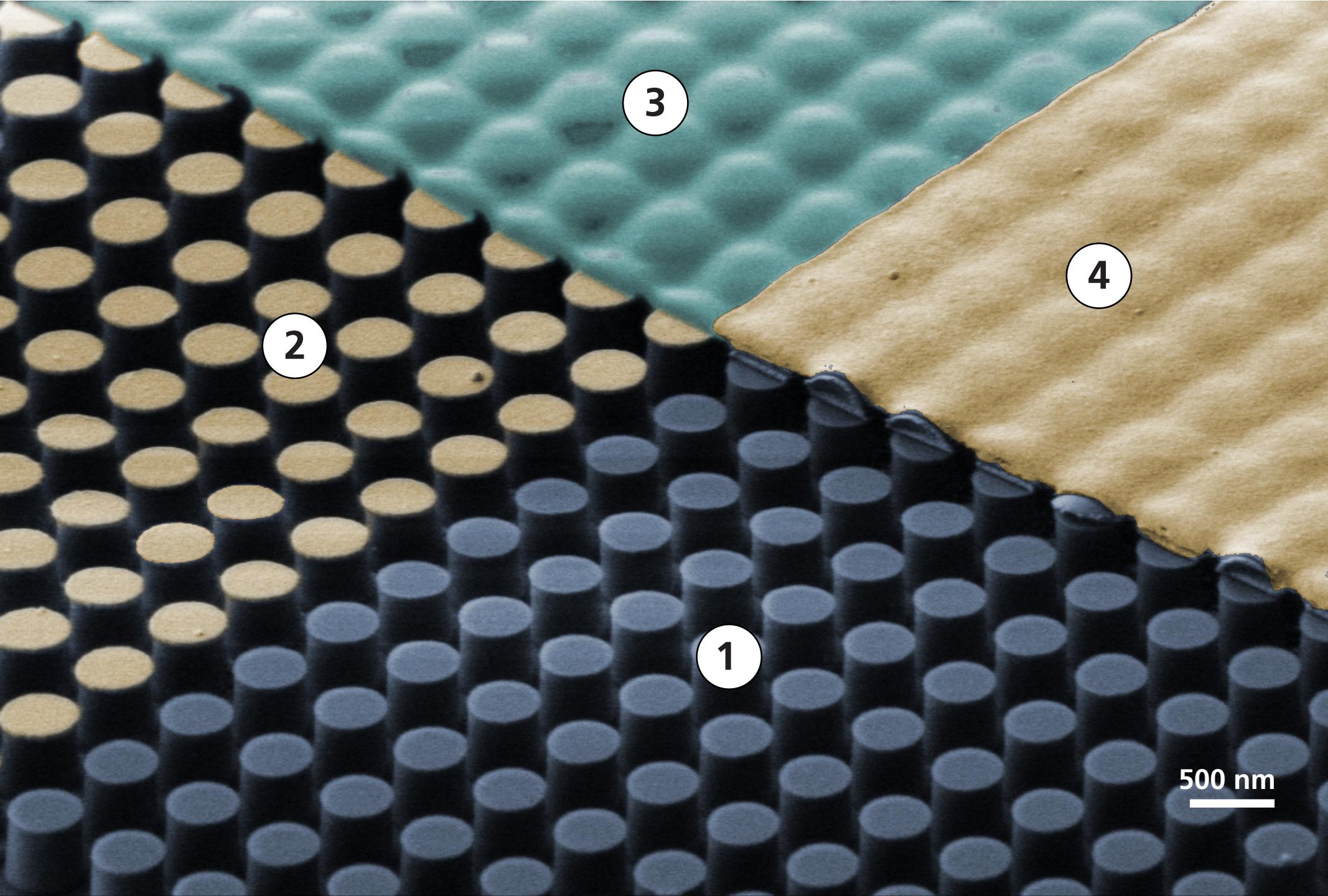
1 zero index

2 fabrication



1 zero index

2 fabrication



1 zero index

2 fabrication

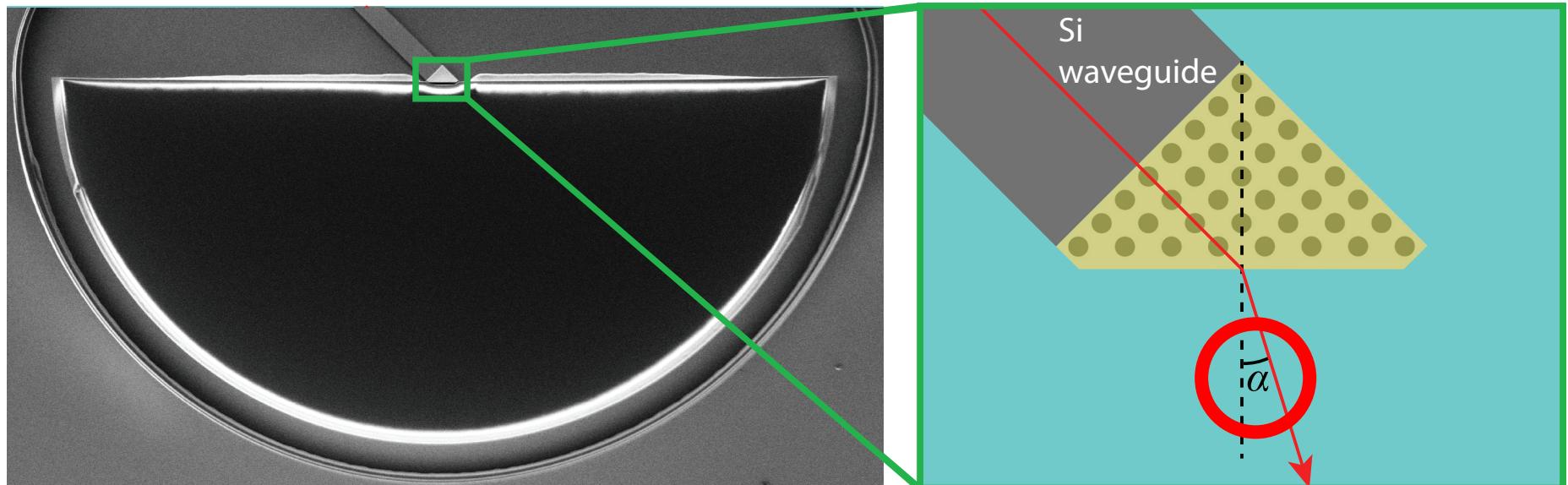
500 nm

Can make this in any shape!

1 zero index

2 fabrication

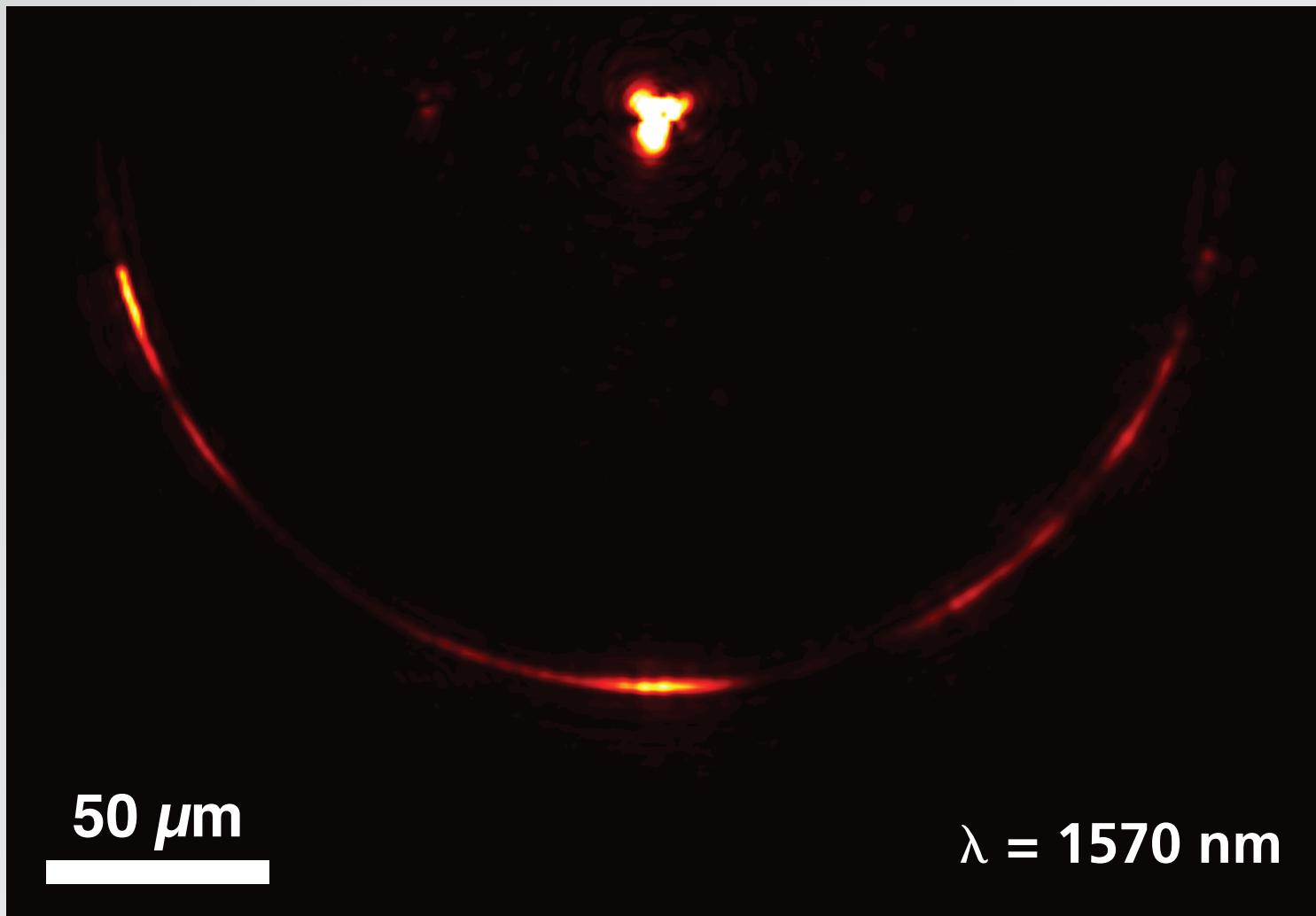
On-chip zero-index prism



1 zero index

2 fabrication

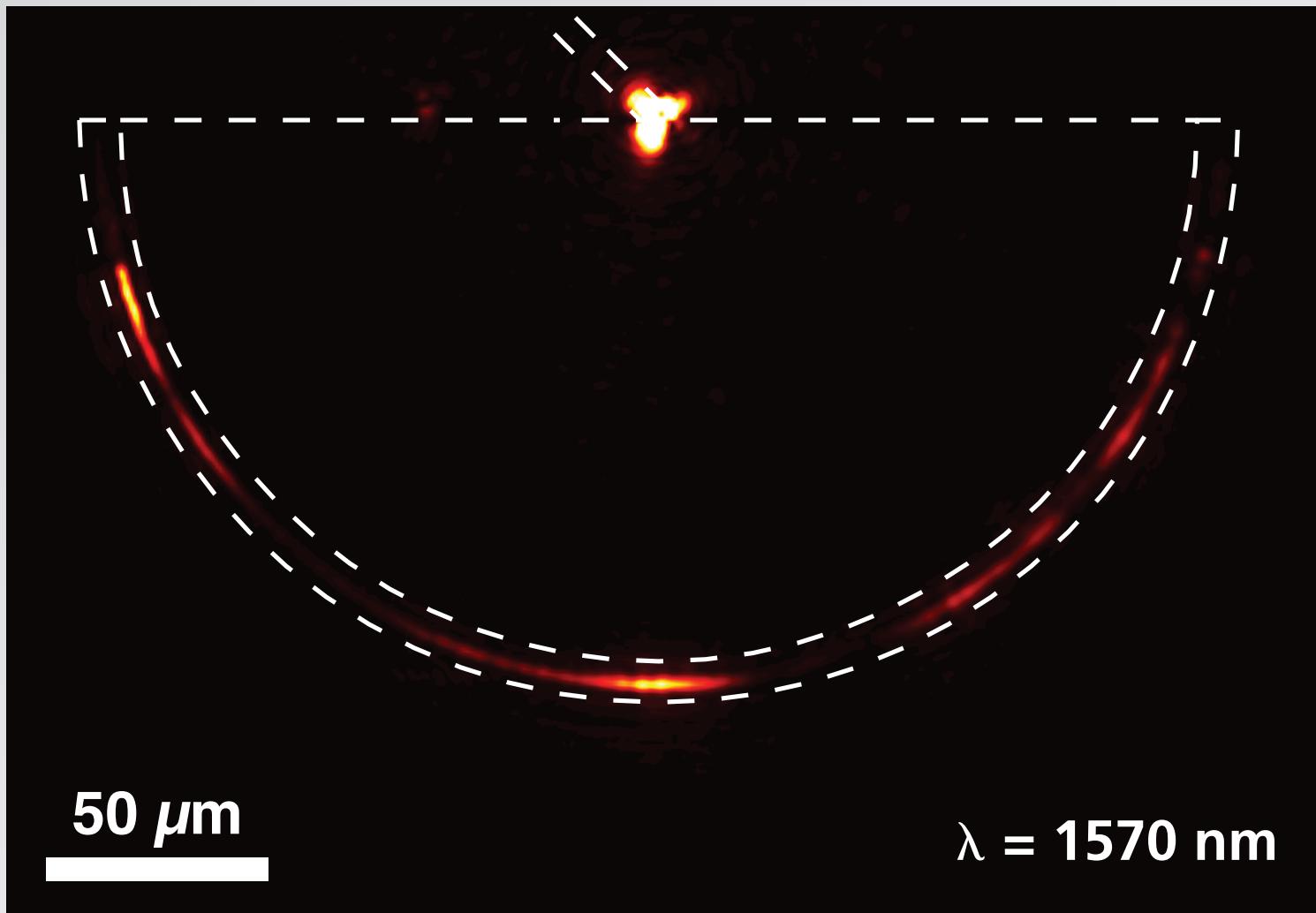
3 results



1 zero index

2 fabrication

3 results



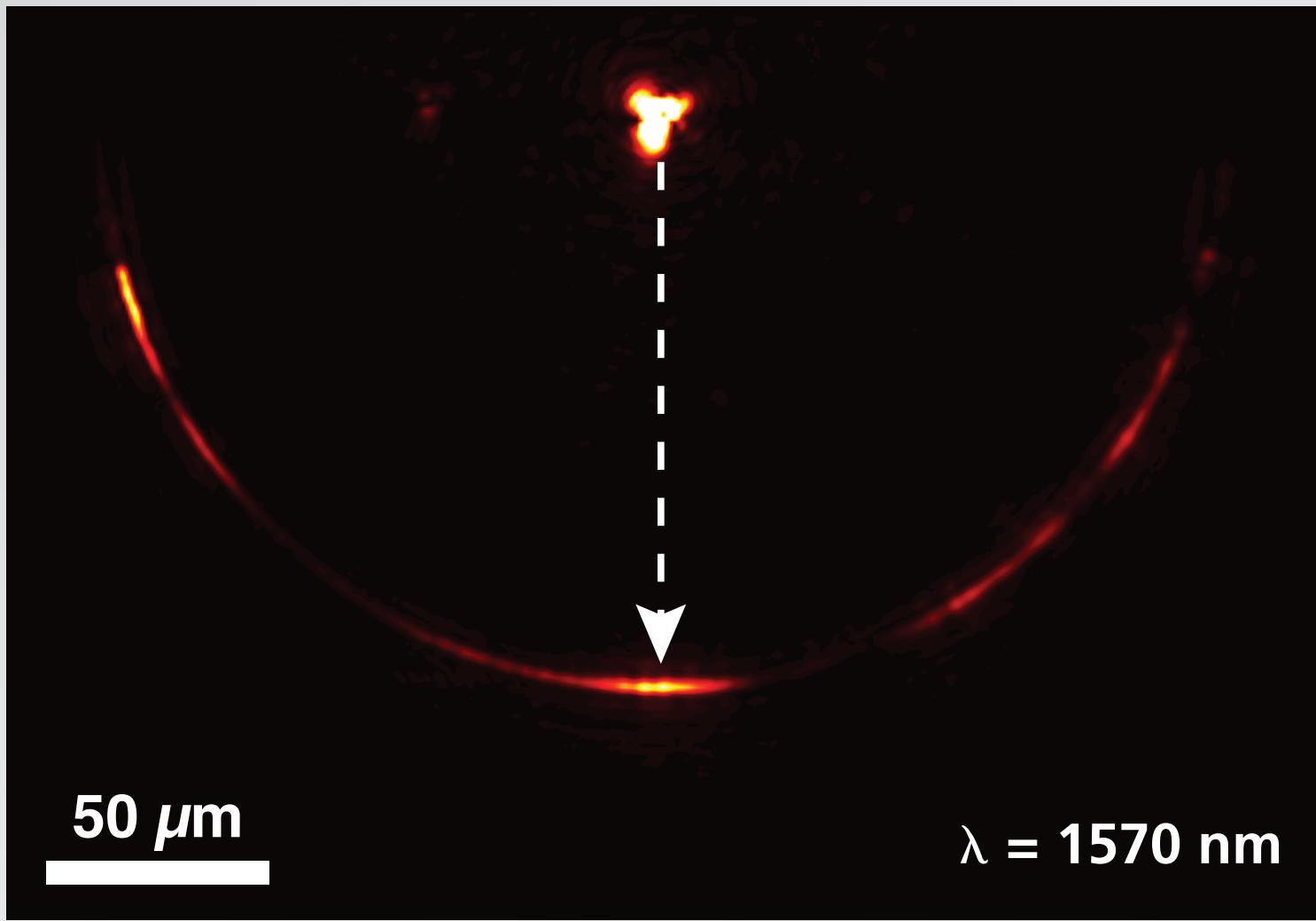
50 μm

$\lambda = 1570 \text{ nm}$

1 zero index

2 fabrication

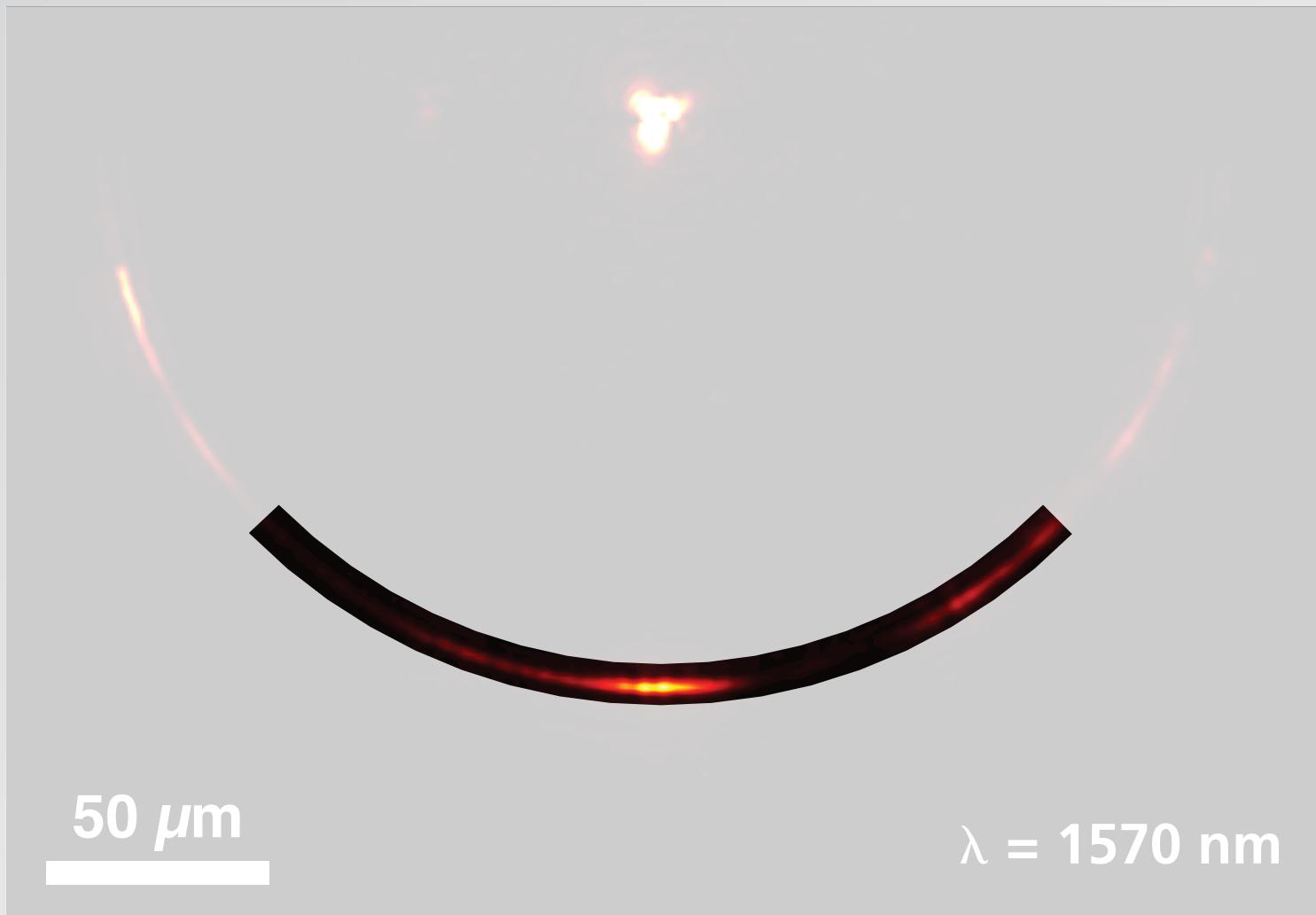
3 results



1 zero index

2 fabrication

3 results

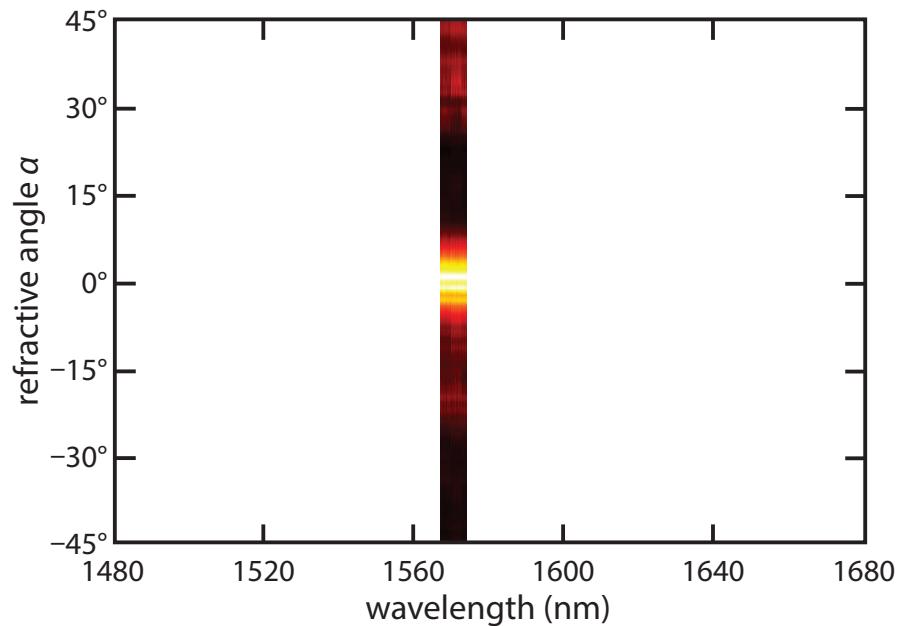


1 zero index

2 fabrication

3 results

Wavelength dependence of refraction angle

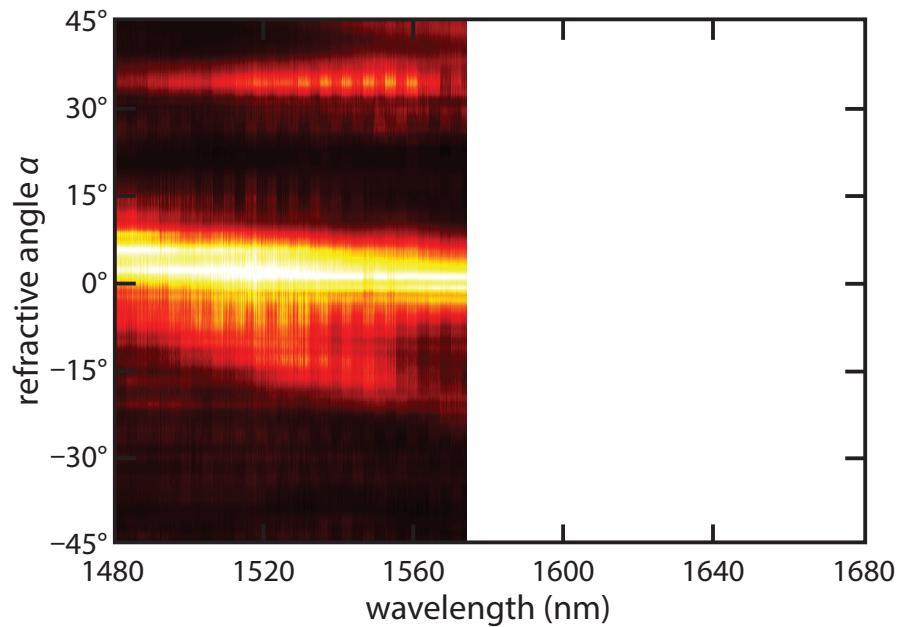


1 zero index

2 fabrication

3 results

Wavelength dependence of refraction angle

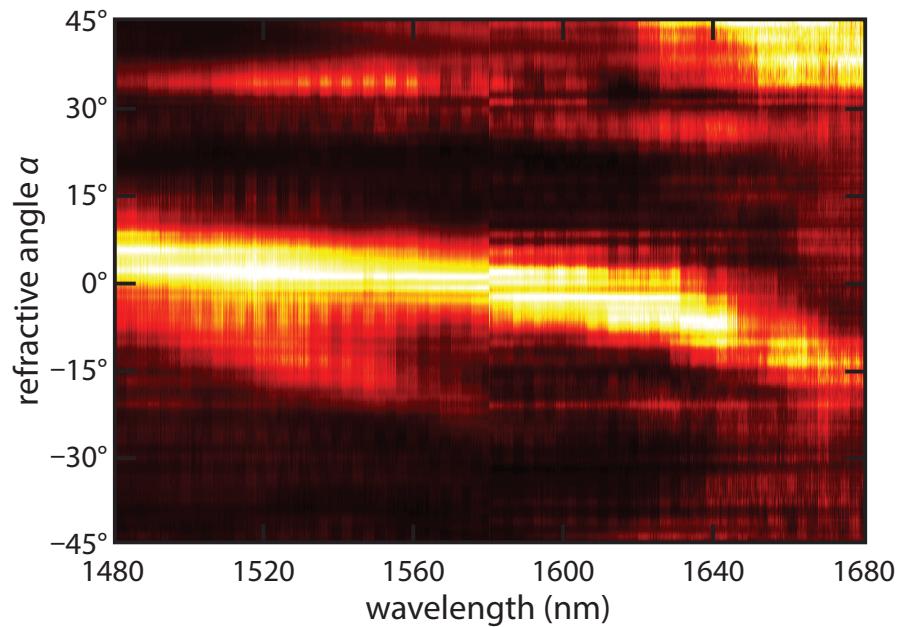


1 zero index

2 fabrication

3 results

Wavelength dependence of refraction angle

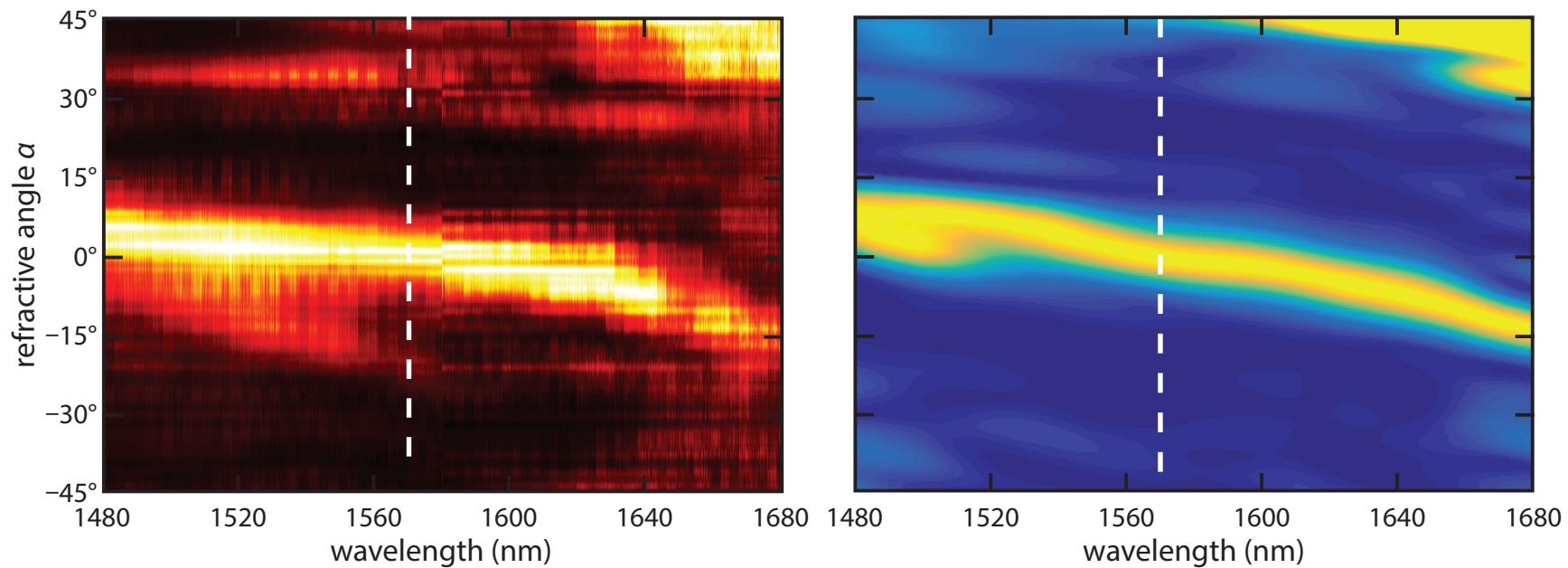


1 zero index

2 fabrication

3 results

Wavelength dependence of refraction angle

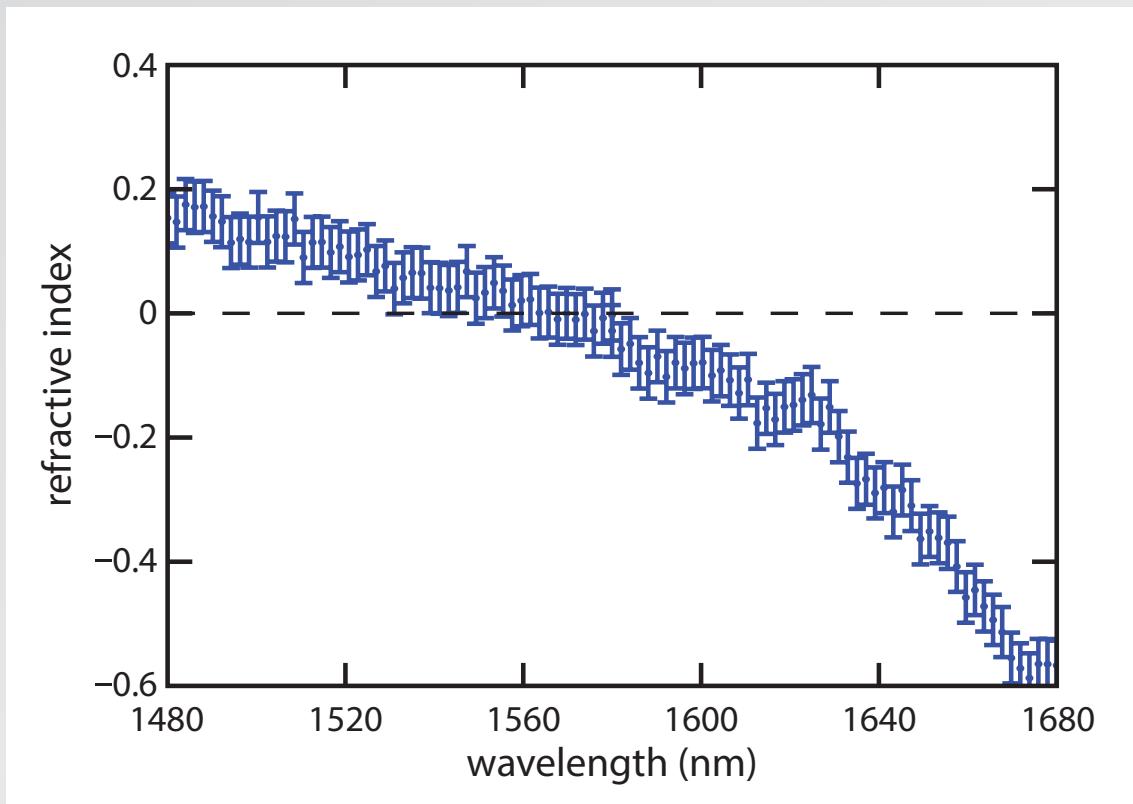


1 zero index

2 fabrication

3 results

Wavelength dependence of index

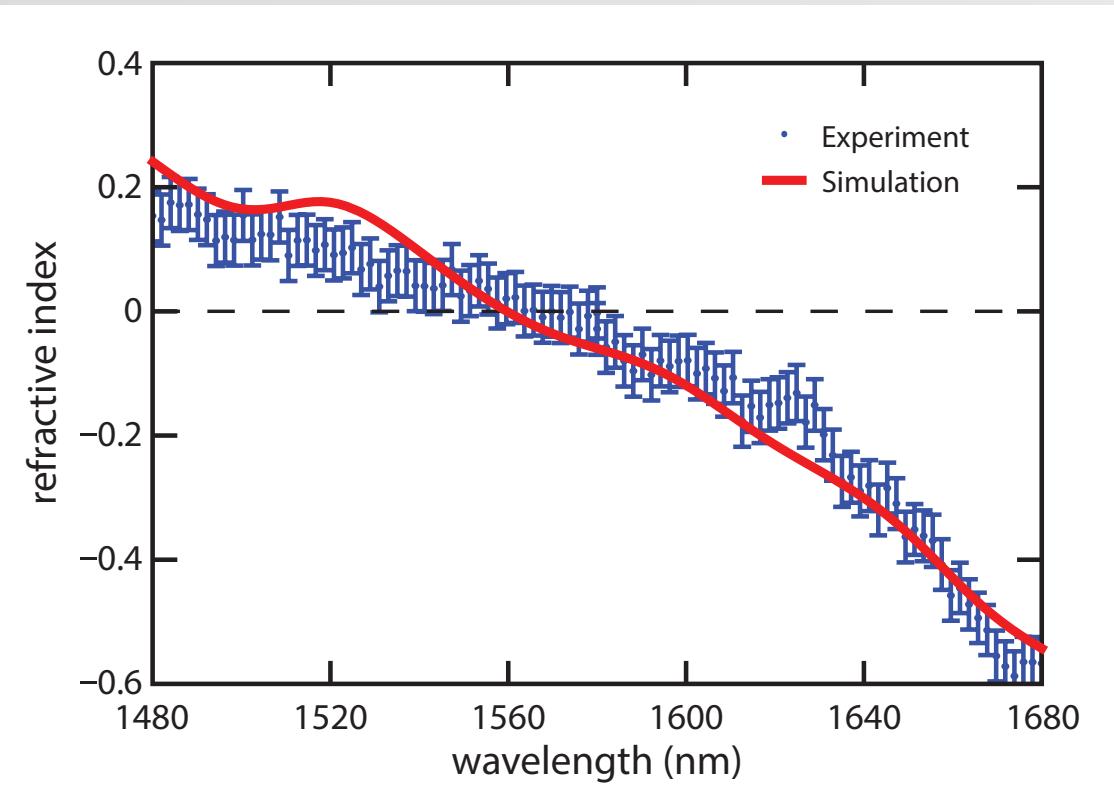


1 zero index

2 fabrication

3 results

Wavelength dependence of index

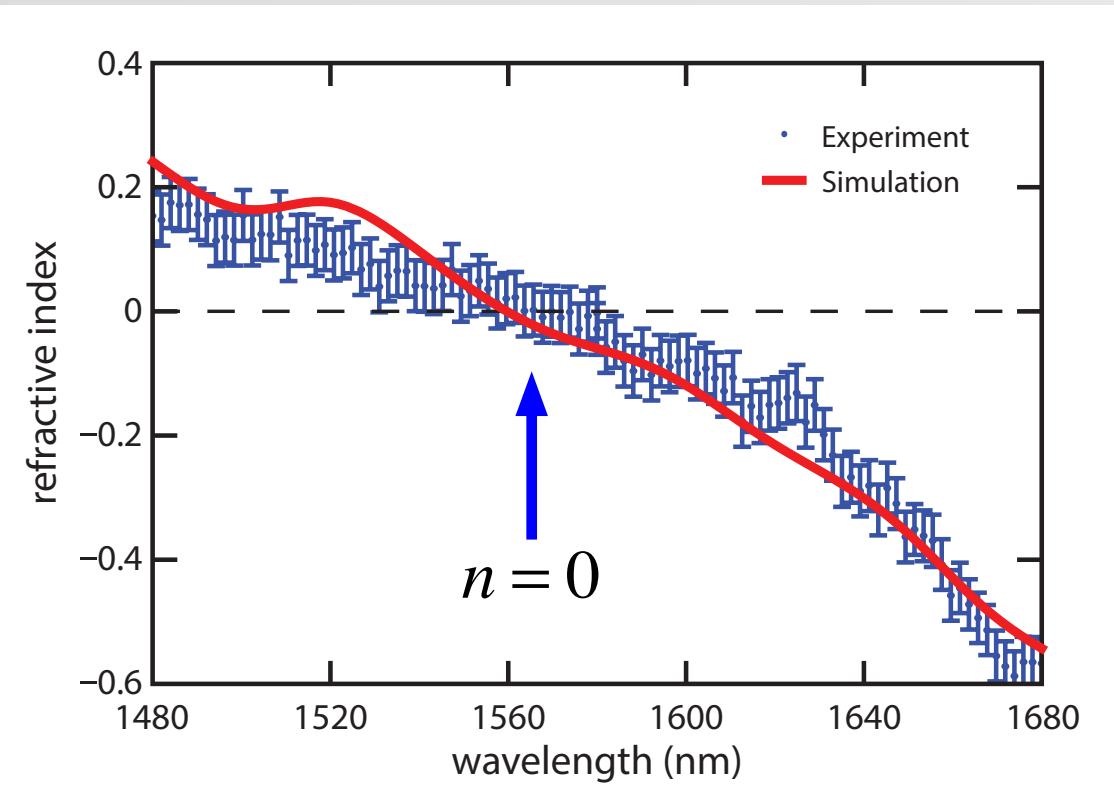


1 zero index

2 fabrication

3 results

Wavelength dependence of index



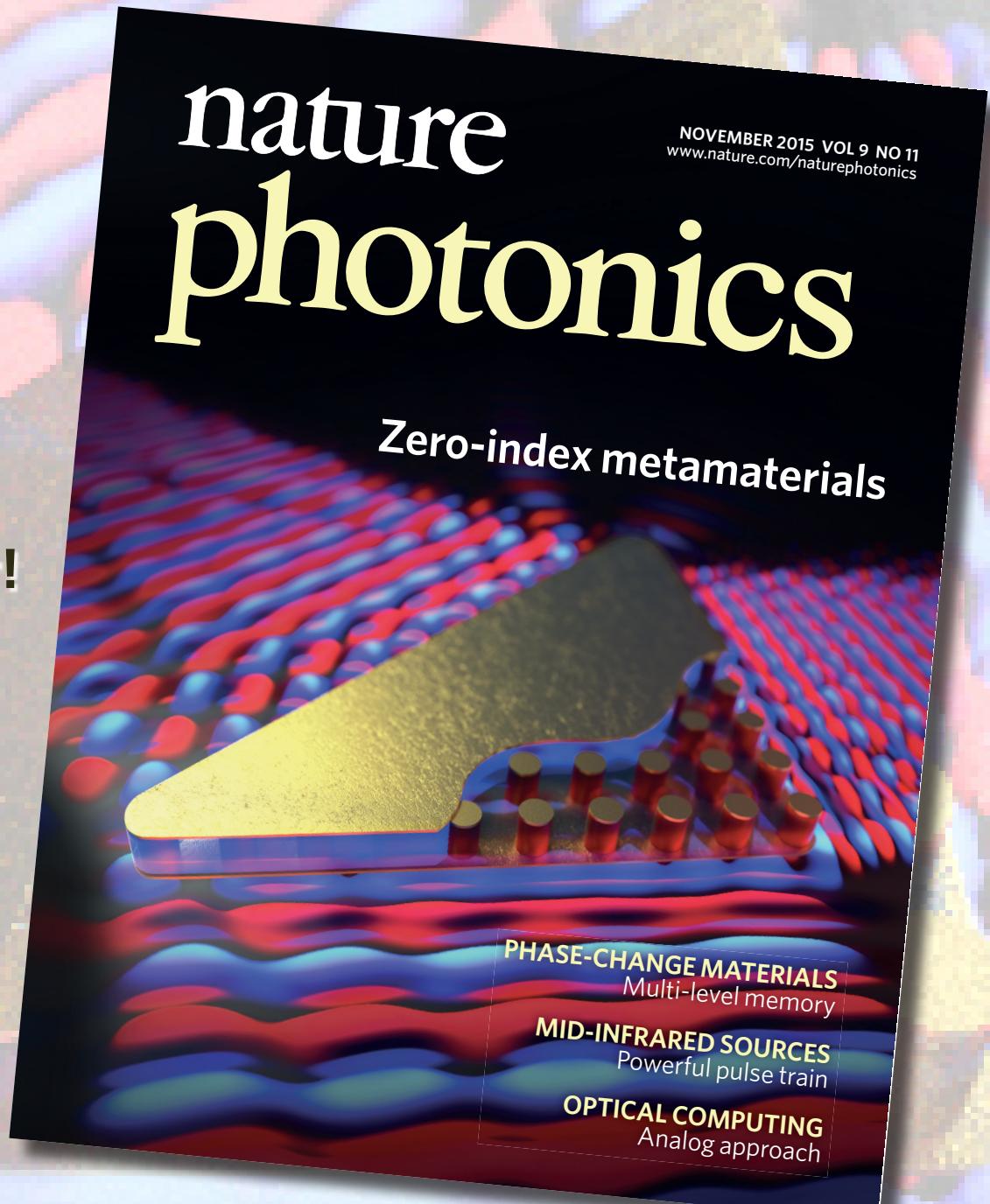
1 zero index

2 fabrication

3 results



More info: download paper!



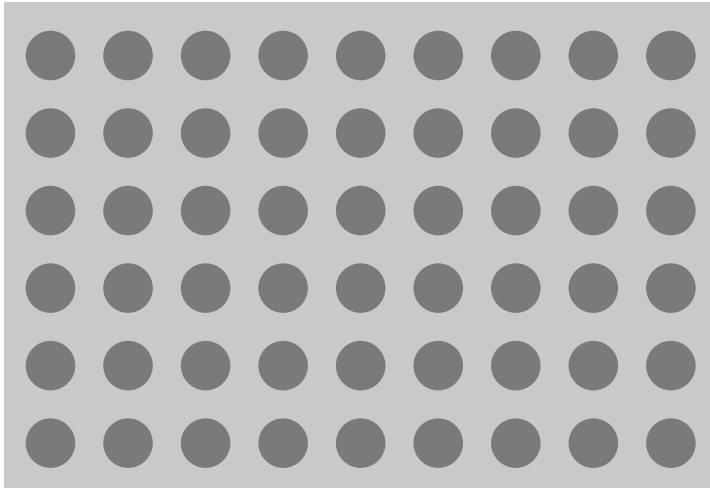
1 zero index

2 fabrication

3 results

simplify fabrication

pillar array



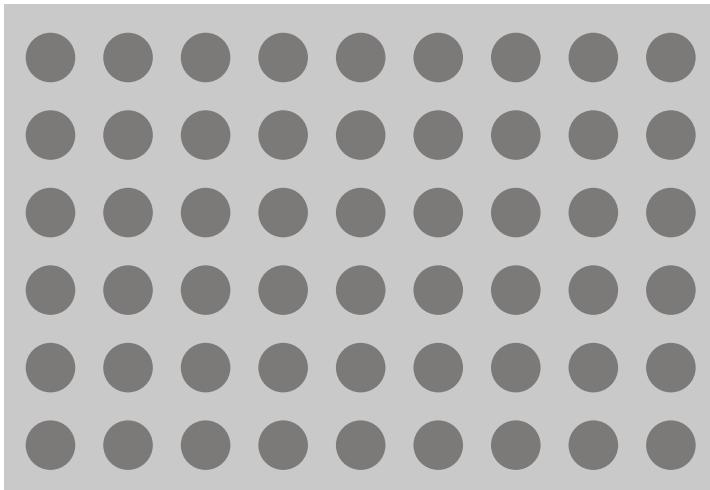
1 zero index

2 fabrication

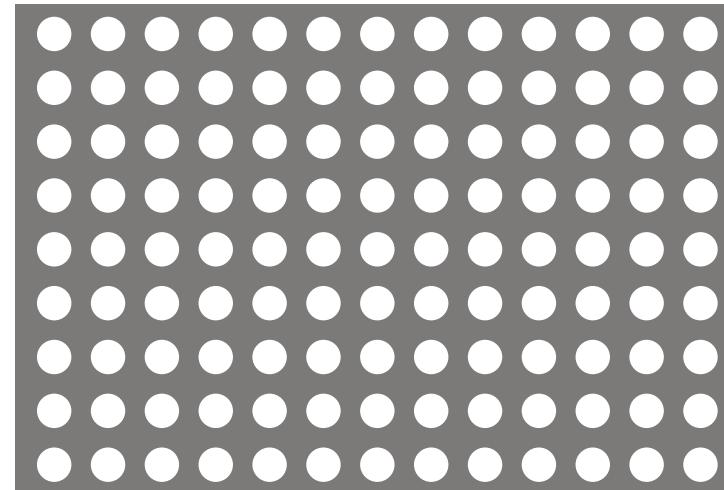
3 results

simplify fabrication

pillar array



airhole array

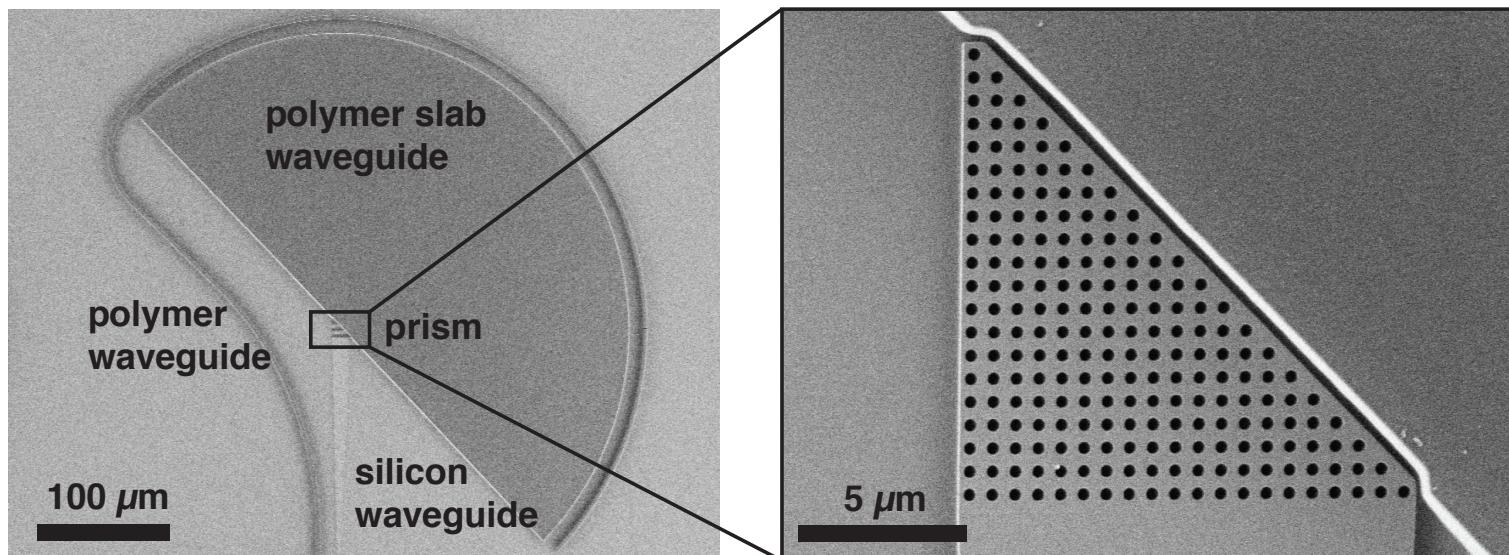


1 zero index

2 fabrication

3 results

simplify fabrication



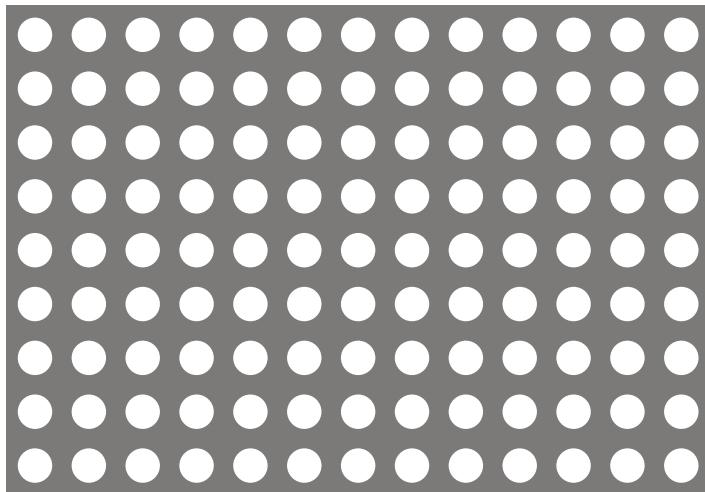
1 zero index

2 fabrication

3 results

simplify further!

airhole array



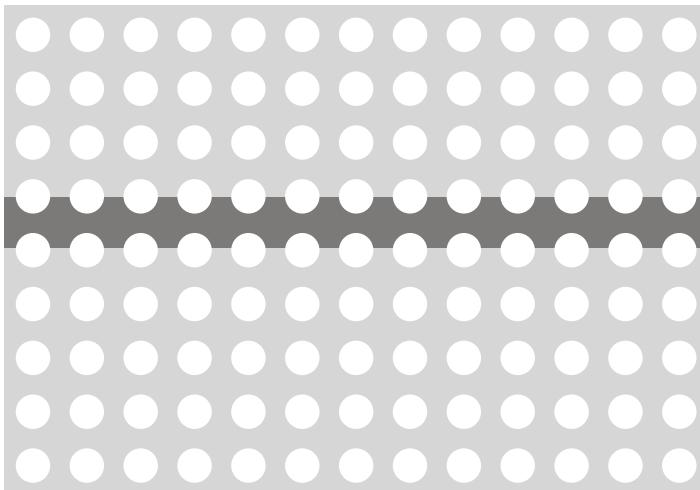
1 zero index

2 fabrication

3 results

simplify further!

airhole array



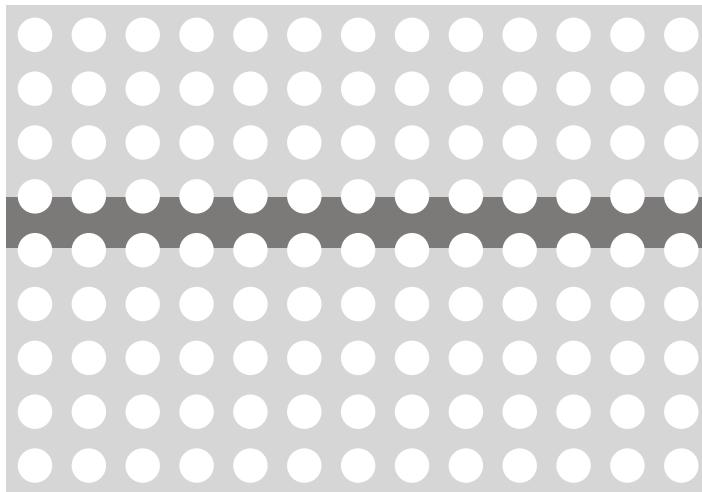
1 zero index

2 fabrication

3 results

simplify further!

airhole array



1D ZIM waveguide



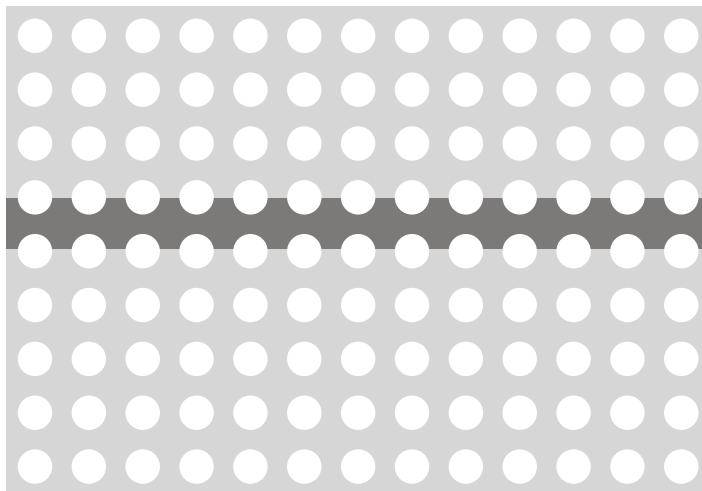
1 zero index

2 fabrication

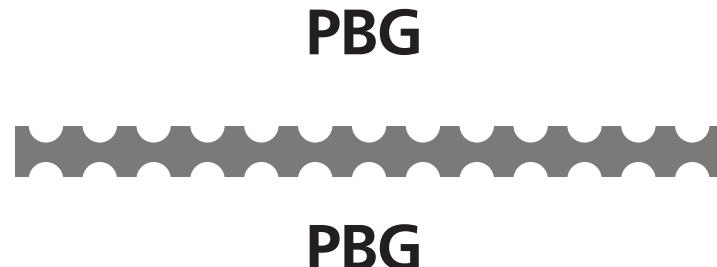
3 results

simplify further!

airhole array



1D ZIM waveguide

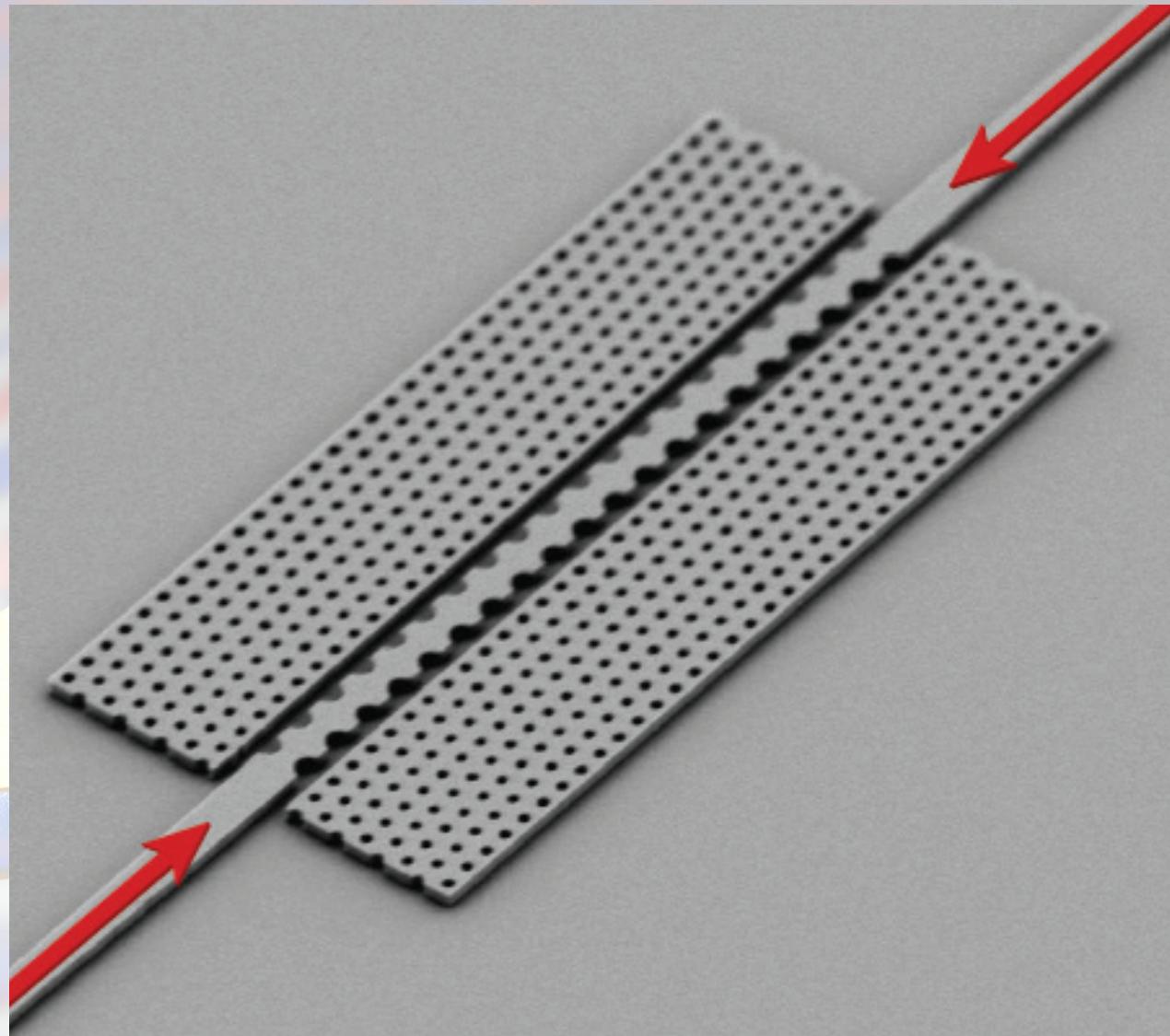


1 zero index

2 fabrication

3 results

look at standing waves

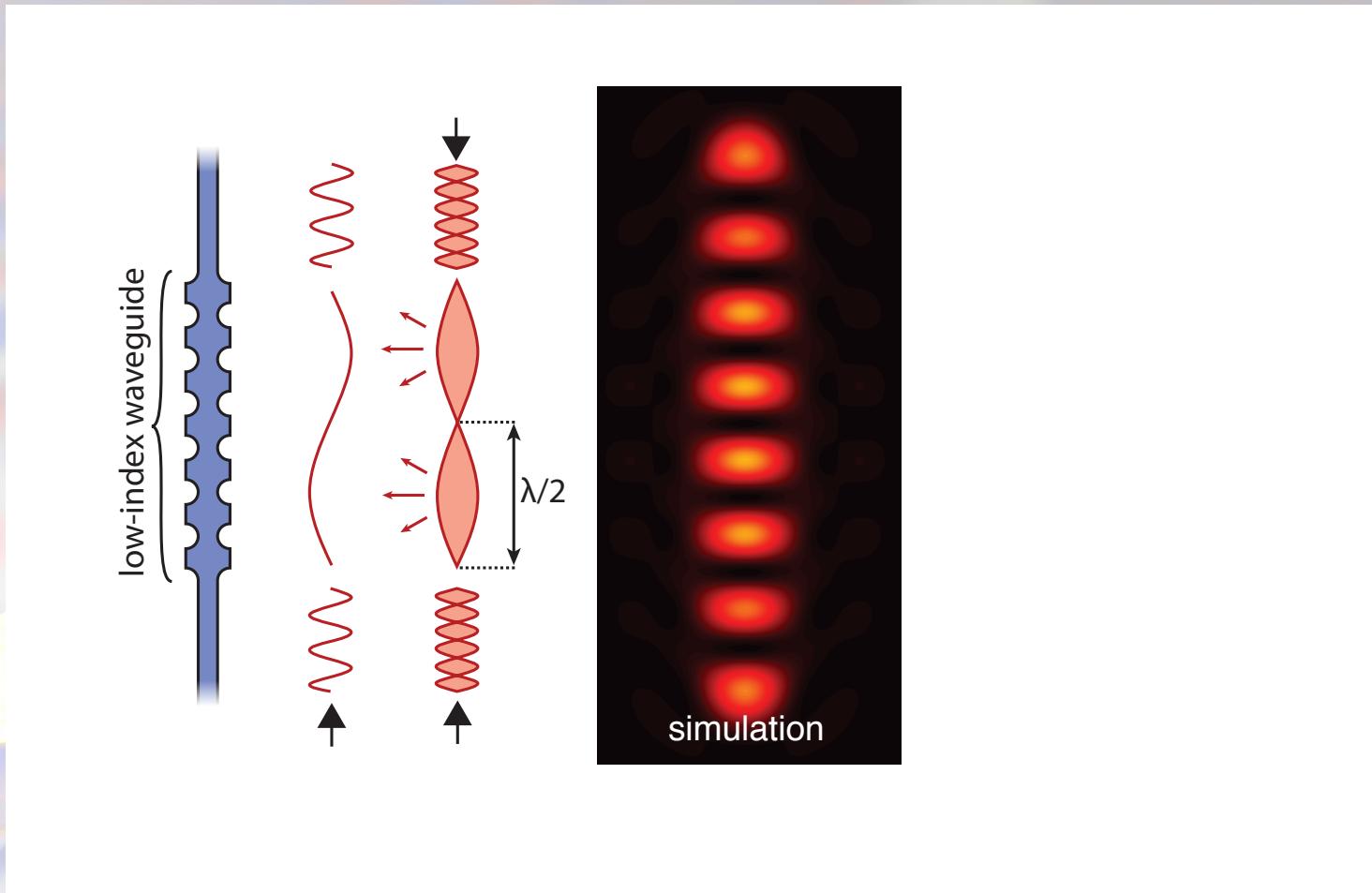


1 zero index

2 fabrication

3 results

look at standing waves

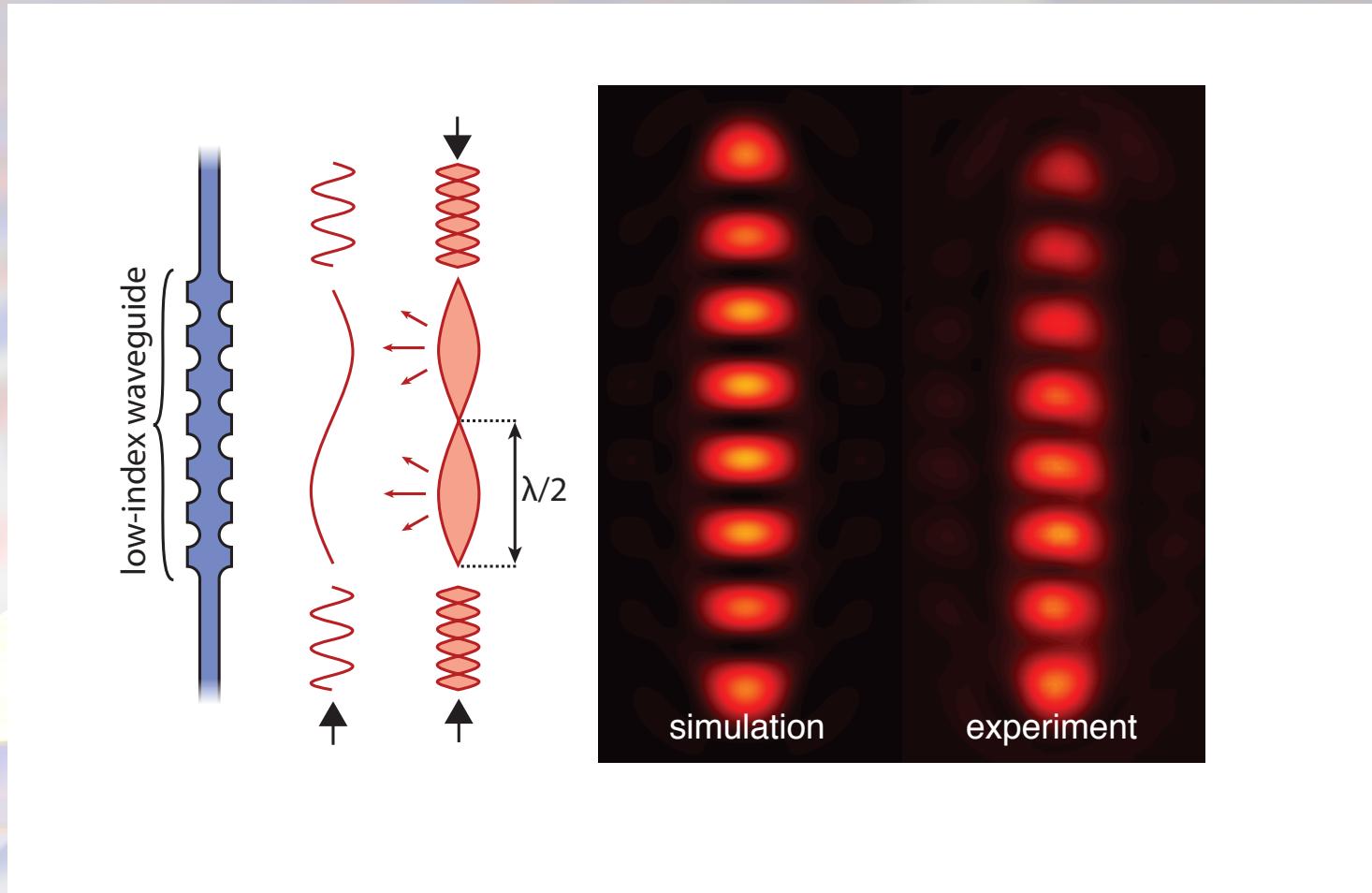


1 zero index

2 fabrication

3 results

look at standing waves

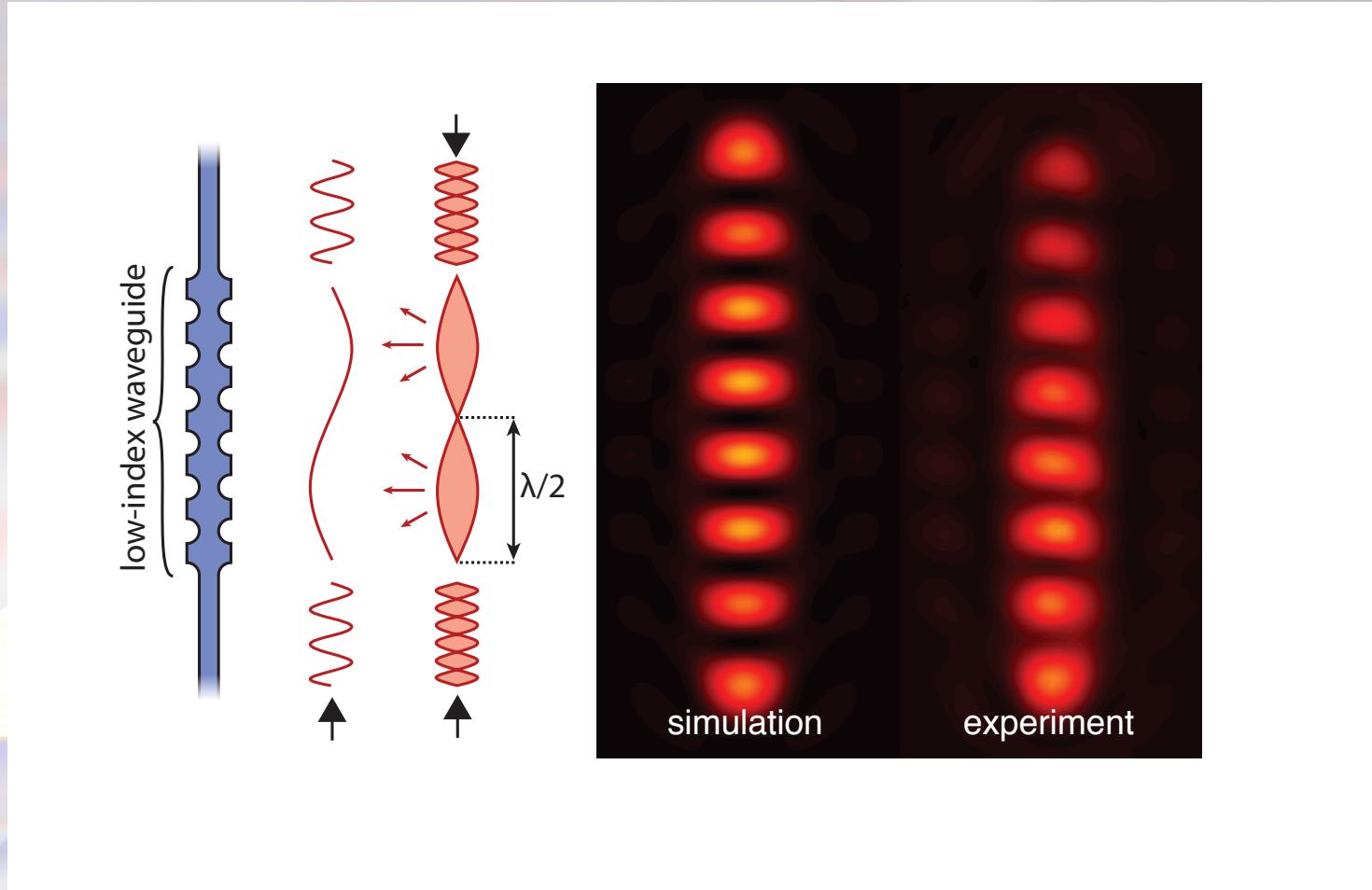


1 zero index

2 fabrication

3 results

direct observation of effective wavelength!!

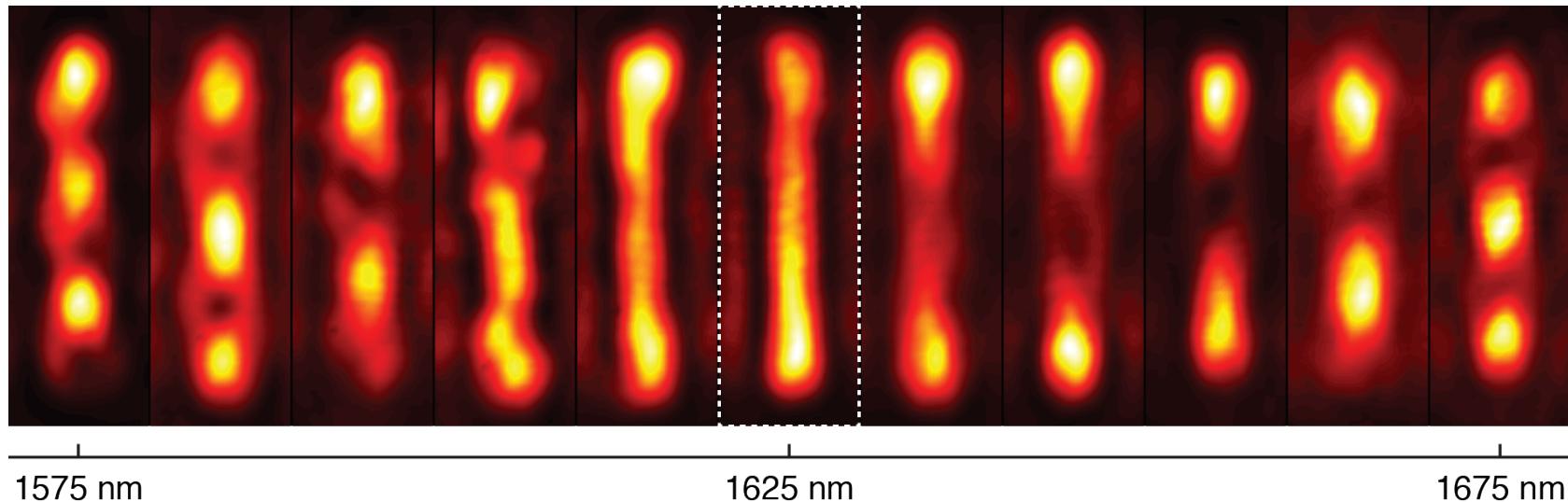


1 zero index

2 fabrication

3 results

look at standing waves

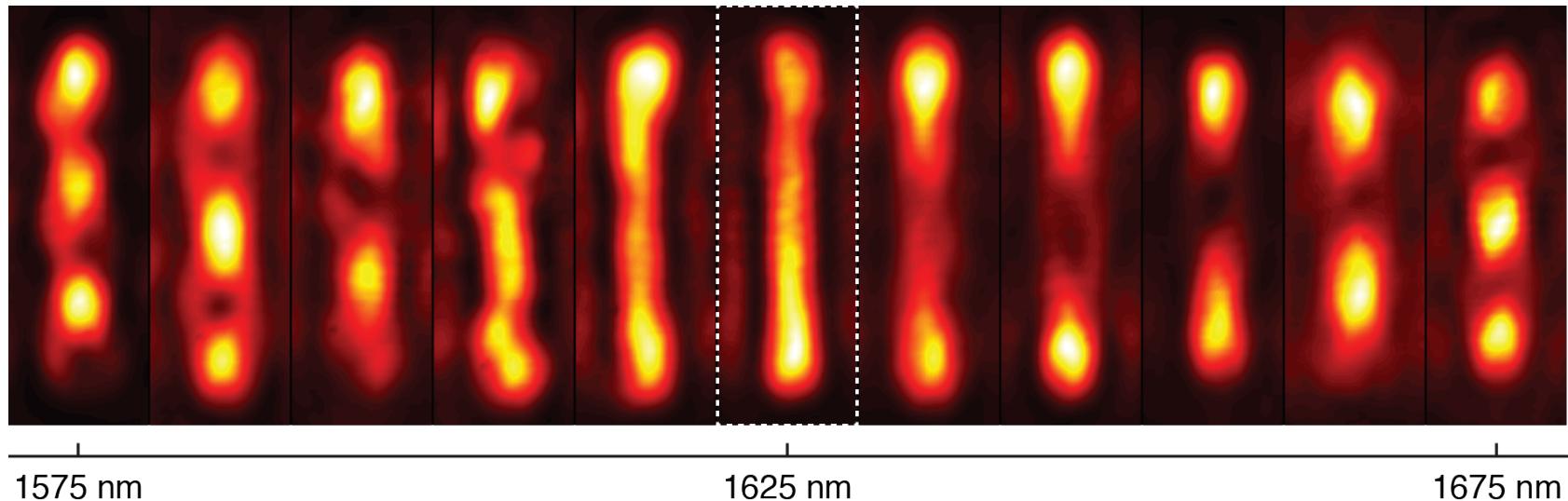


1 zero index

2 fabrication

3 results

look at standing waves



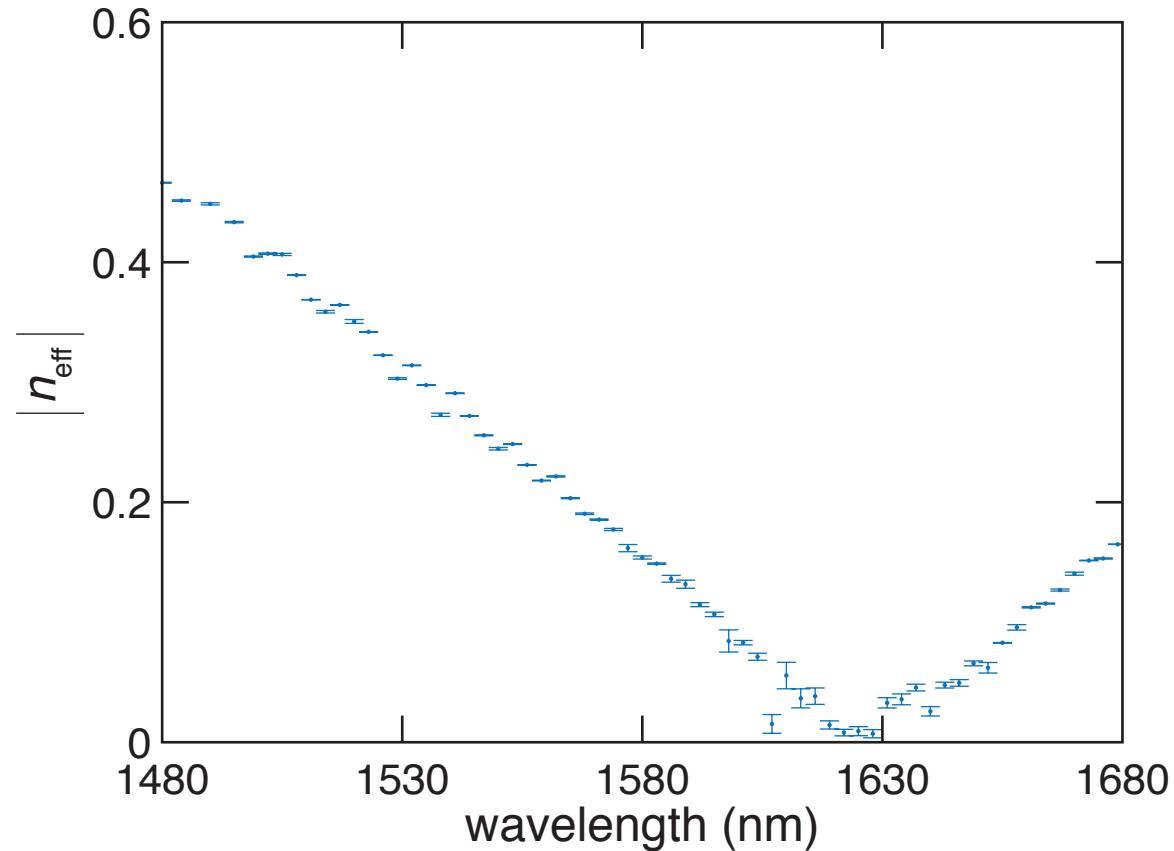
$$| n_{\text{eff}} | = \frac{\lambda_0}{\lambda_{\text{eff}}}$$

1 zero index

2 fabrication

3 results

comparison of experiment and simulation

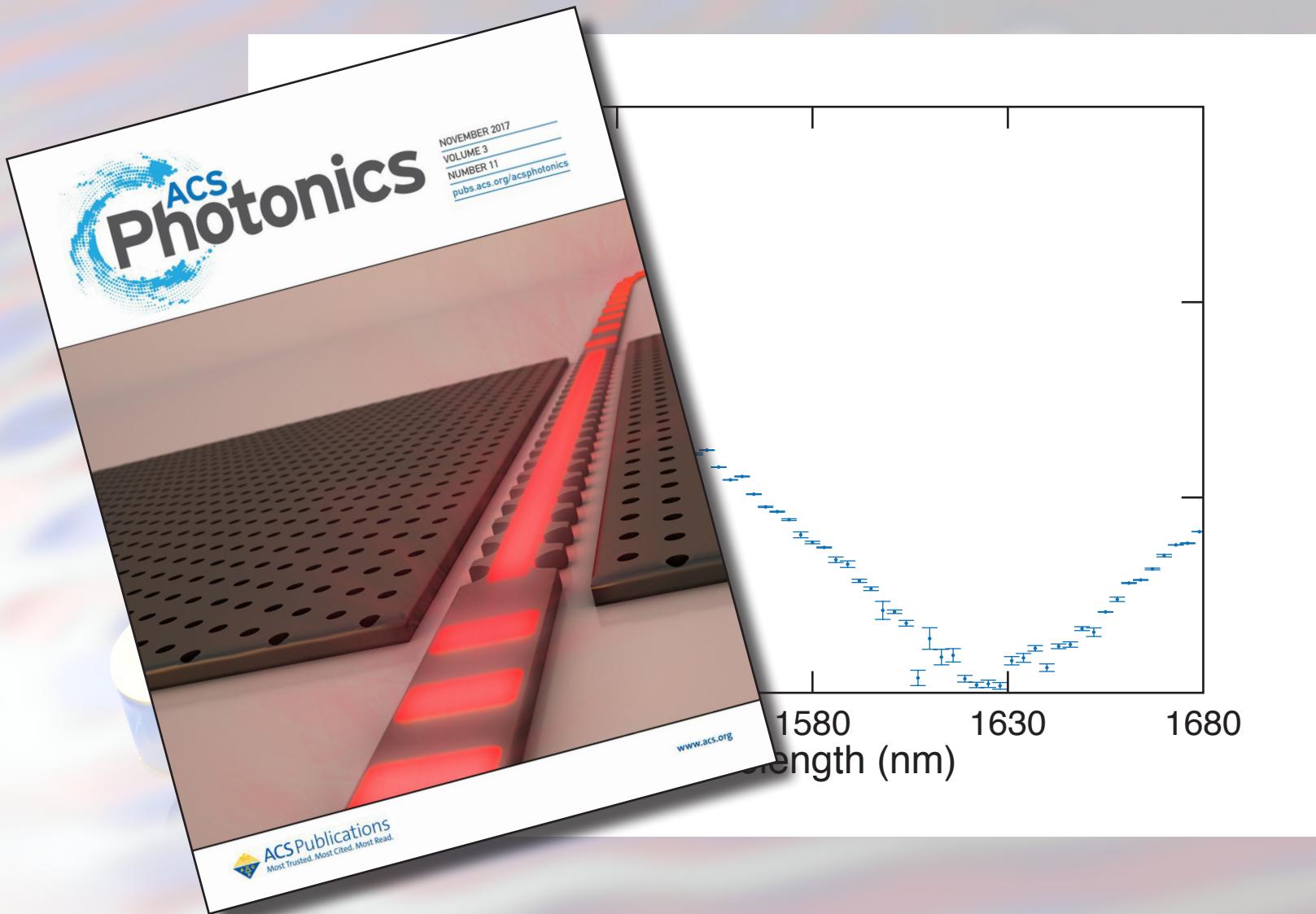


1 zero index

2 fabrication

3 results

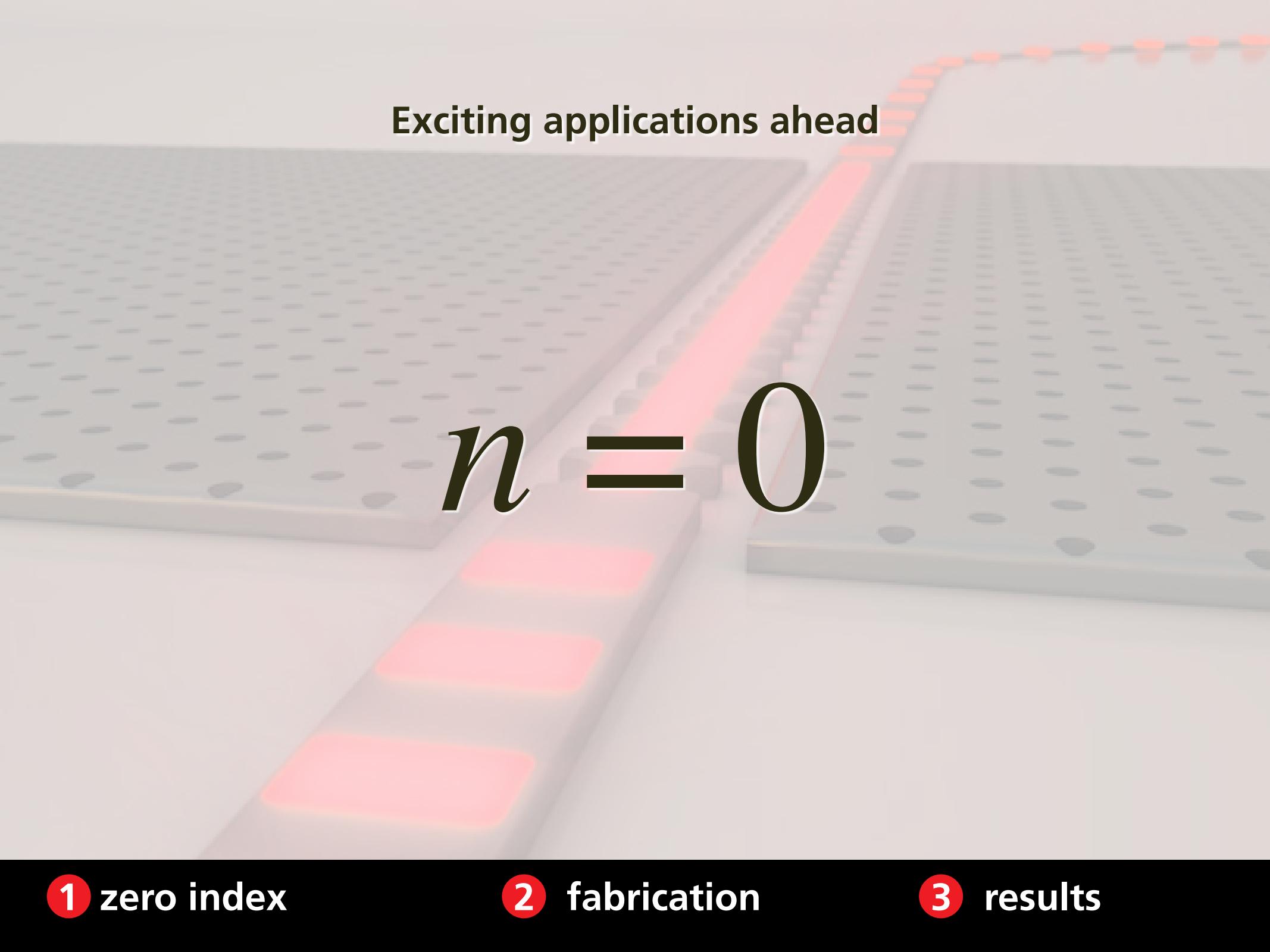
comparison of experiment and simulation



1 zero index

2 fabrication

3 results



Exciting applications ahead

$$n = 0$$

1 zero index

2 fabrication

3 results

Exciting applications ahead

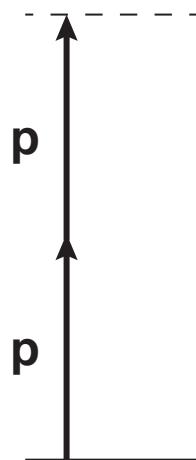
$$n \approx n_0 + \frac{\chi_R^{(3)}}{2n_0} |E(\omega)|^2$$

1 zero index

2 fabrication

3 results

four-wave mixing

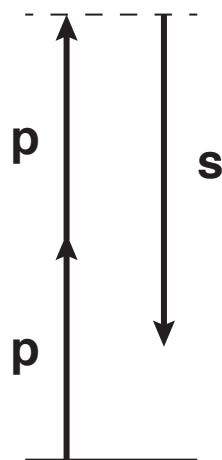


1 zero index

2 fabrication

3 results

four-wave mixing

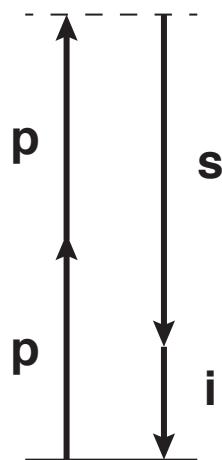


1 zero index

2 fabrication

3 results

four-wave mixing



1 zero index

2 fabrication

3 results

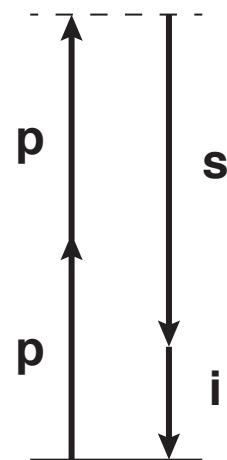
four-wave mixing

energy
conservation

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

momentum
conservation

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



1 zero index

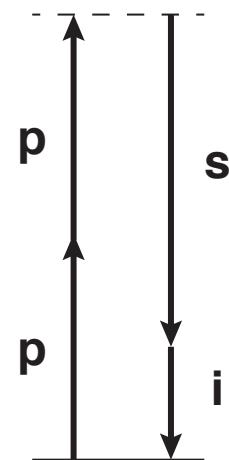
2 fabrication

3 results

four-wave mixing

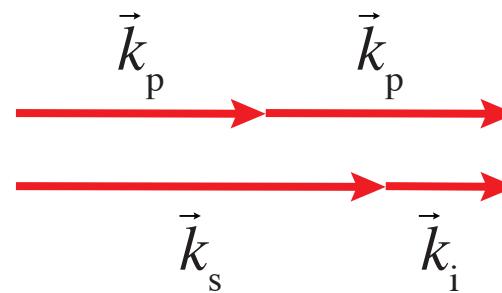
energy
conservation

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



momentum
conservation

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



phase matching

1 zero index

2 fabrication

3 results

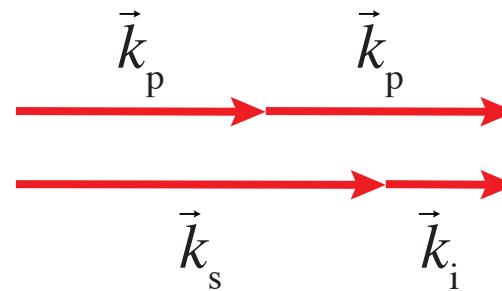
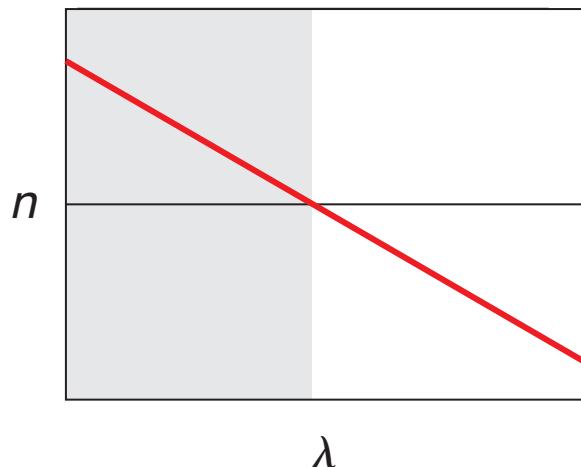
four-wave mixing

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

1 zero index

2 fabrication

3 results

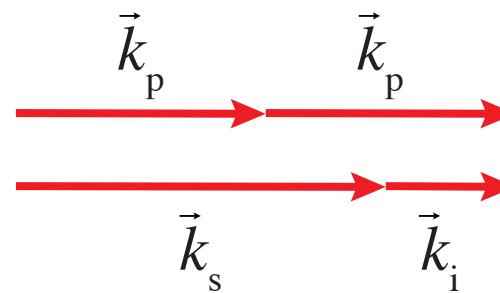
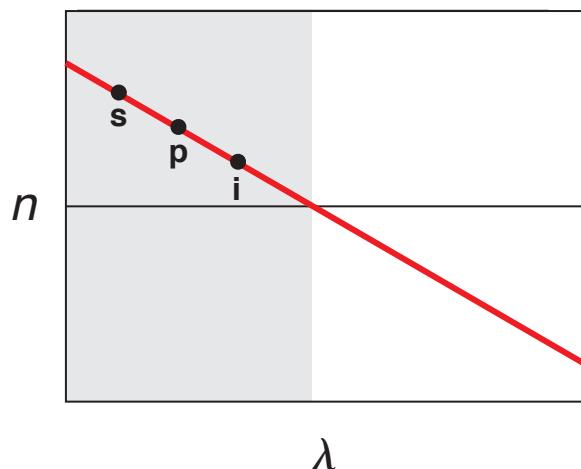
four-wave mixing

energy
conservation

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

momentum
conservation

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



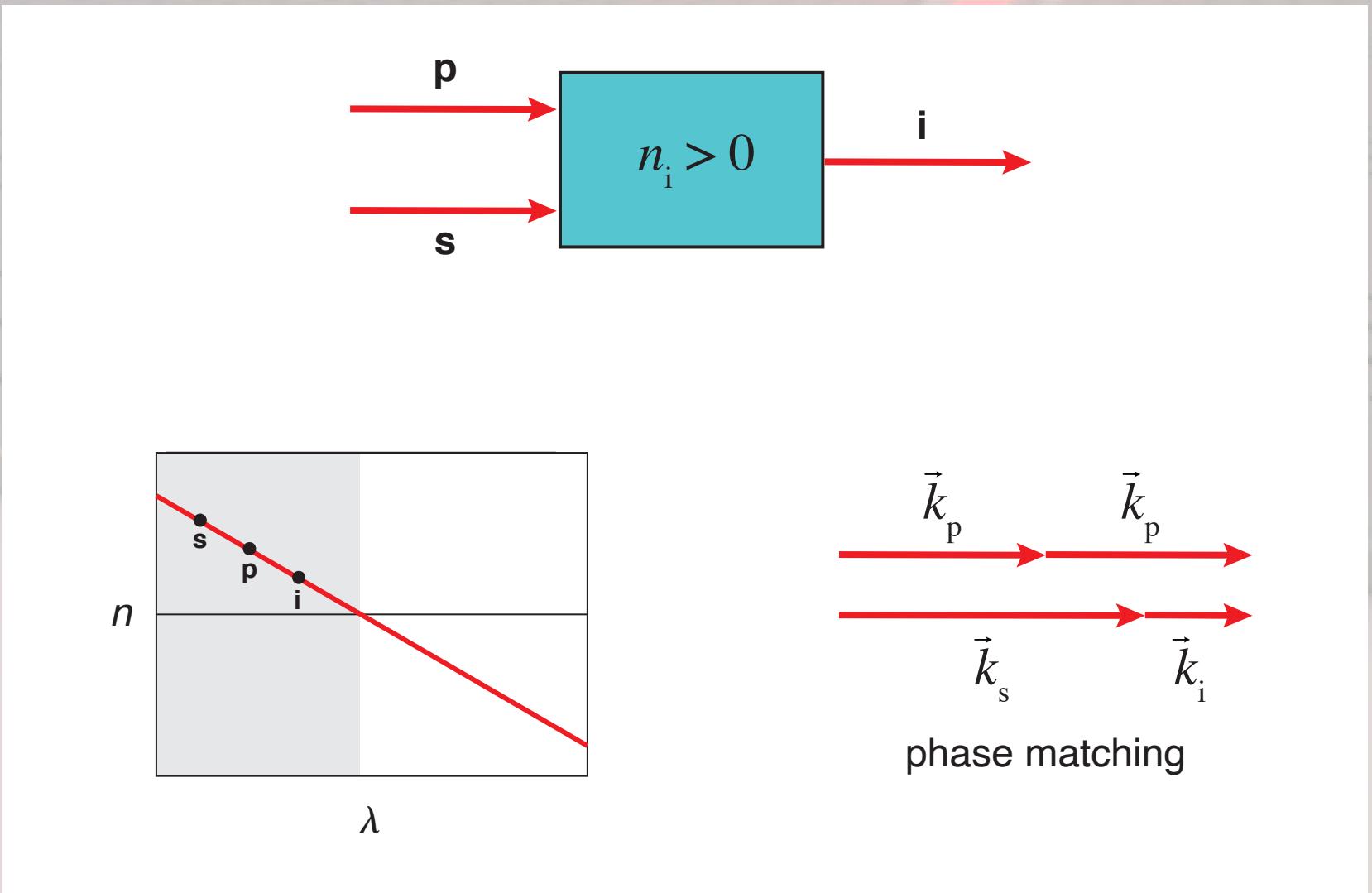
phase matching

1 zero index

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3 results

four-wave mixing

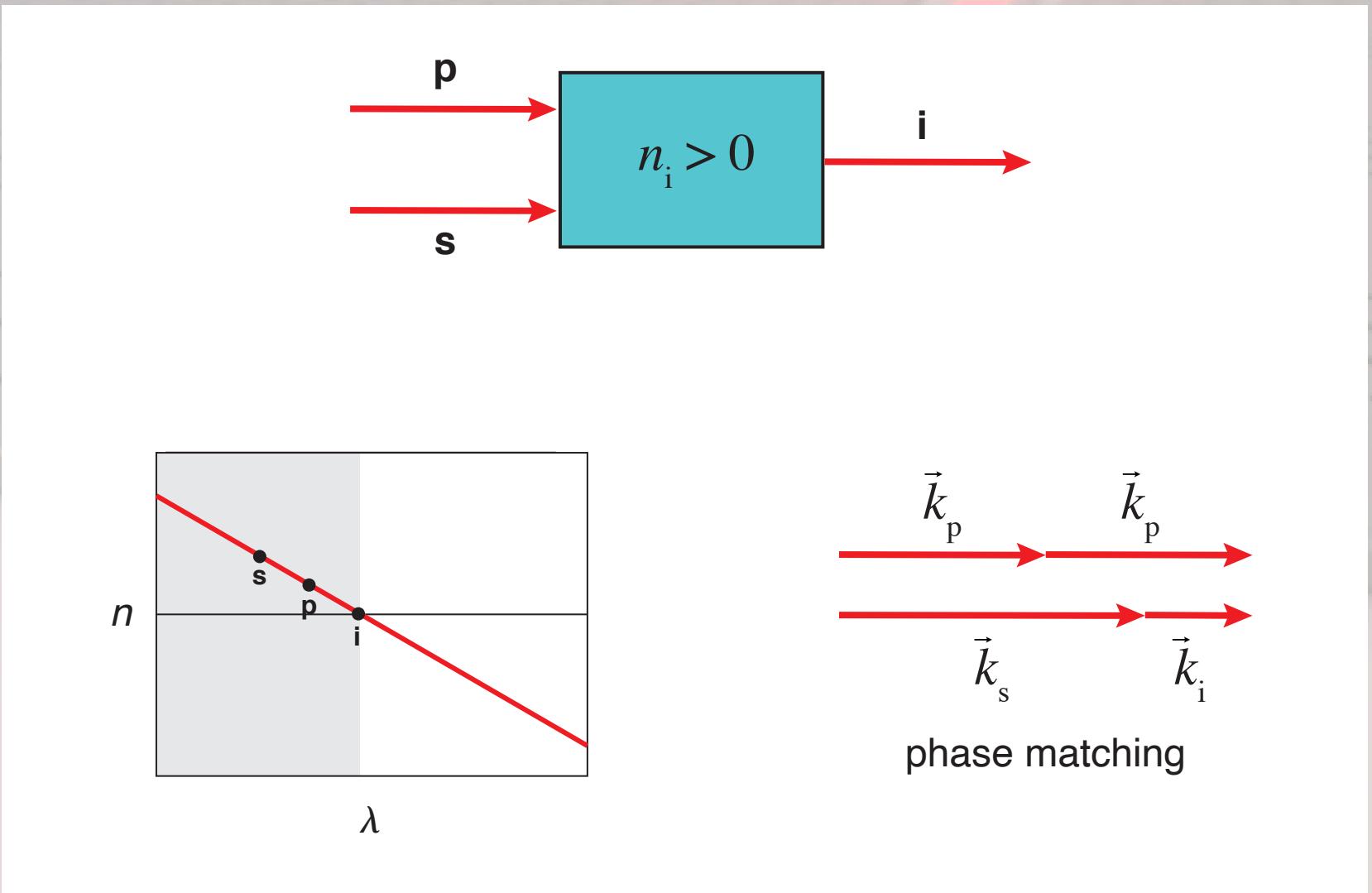


1 zero index

2 fabrication

3 results

four-wave mixing

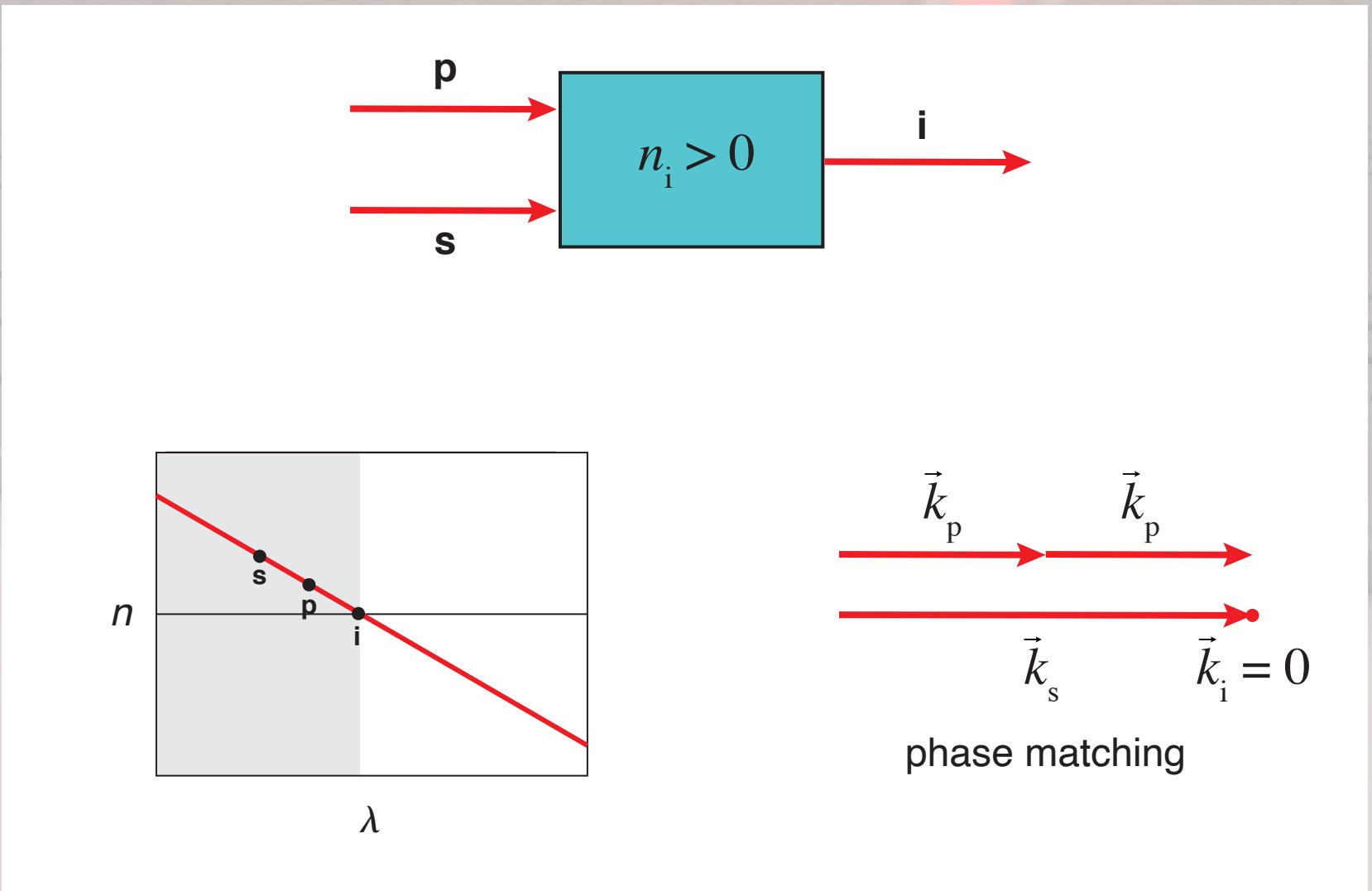


1 zero index

2 fabrication

3 results

four-wave mixing

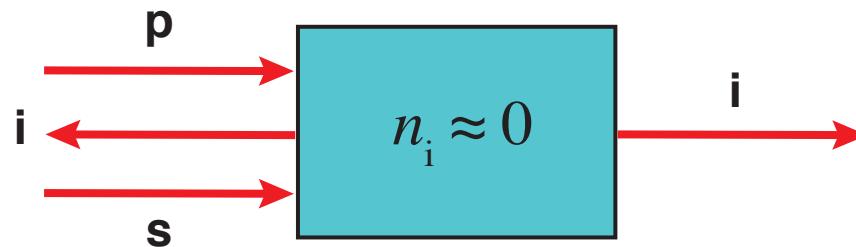


1 zero index

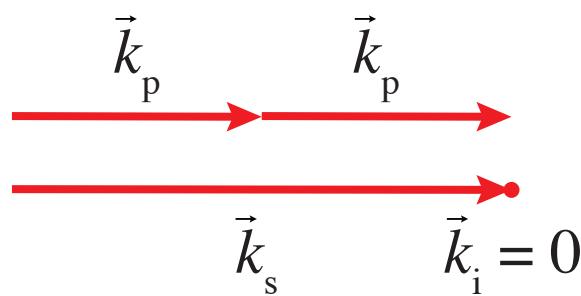
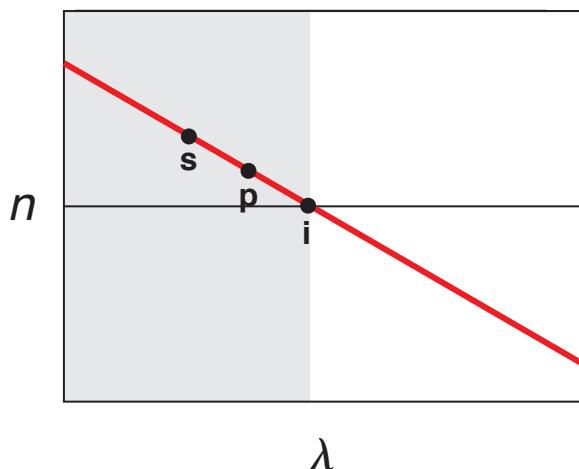
2 fabrication

3 results

four-wave mixing



forward and backward



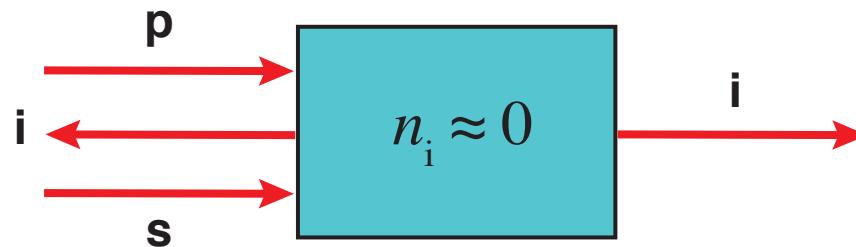
phase matching

1 zero index

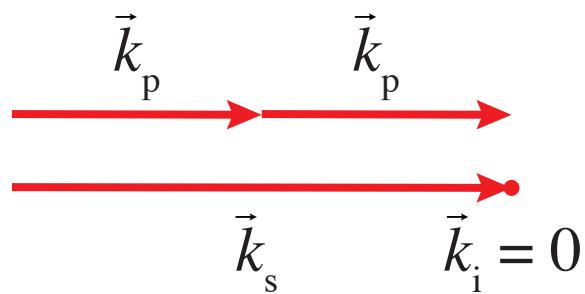
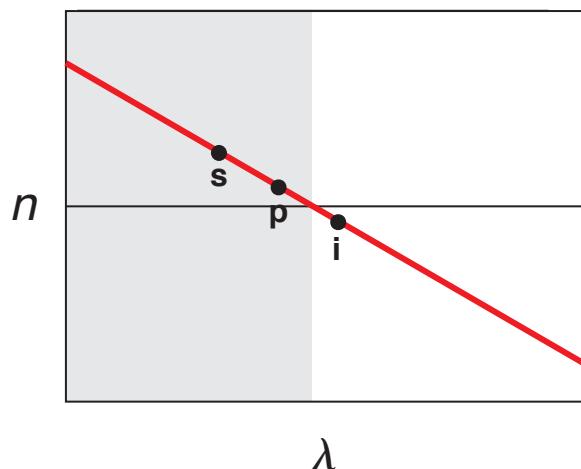
2 fabrication

3 results

four-wave mixing



forward and backward



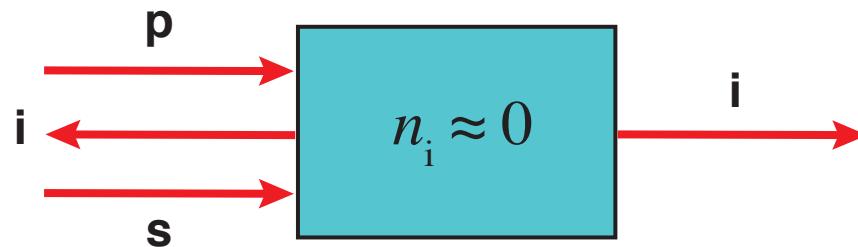
phase matching

1 zero index

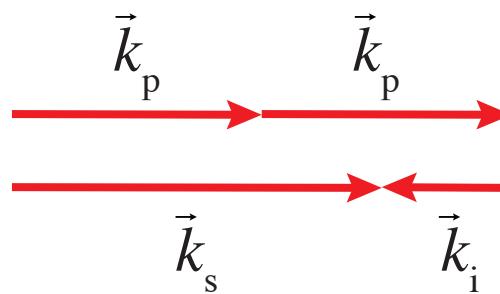
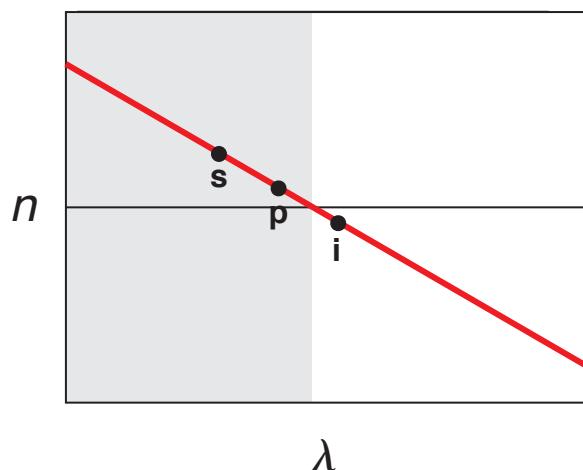
2 fabrication

3 results

four-wave mixing



forward and backward



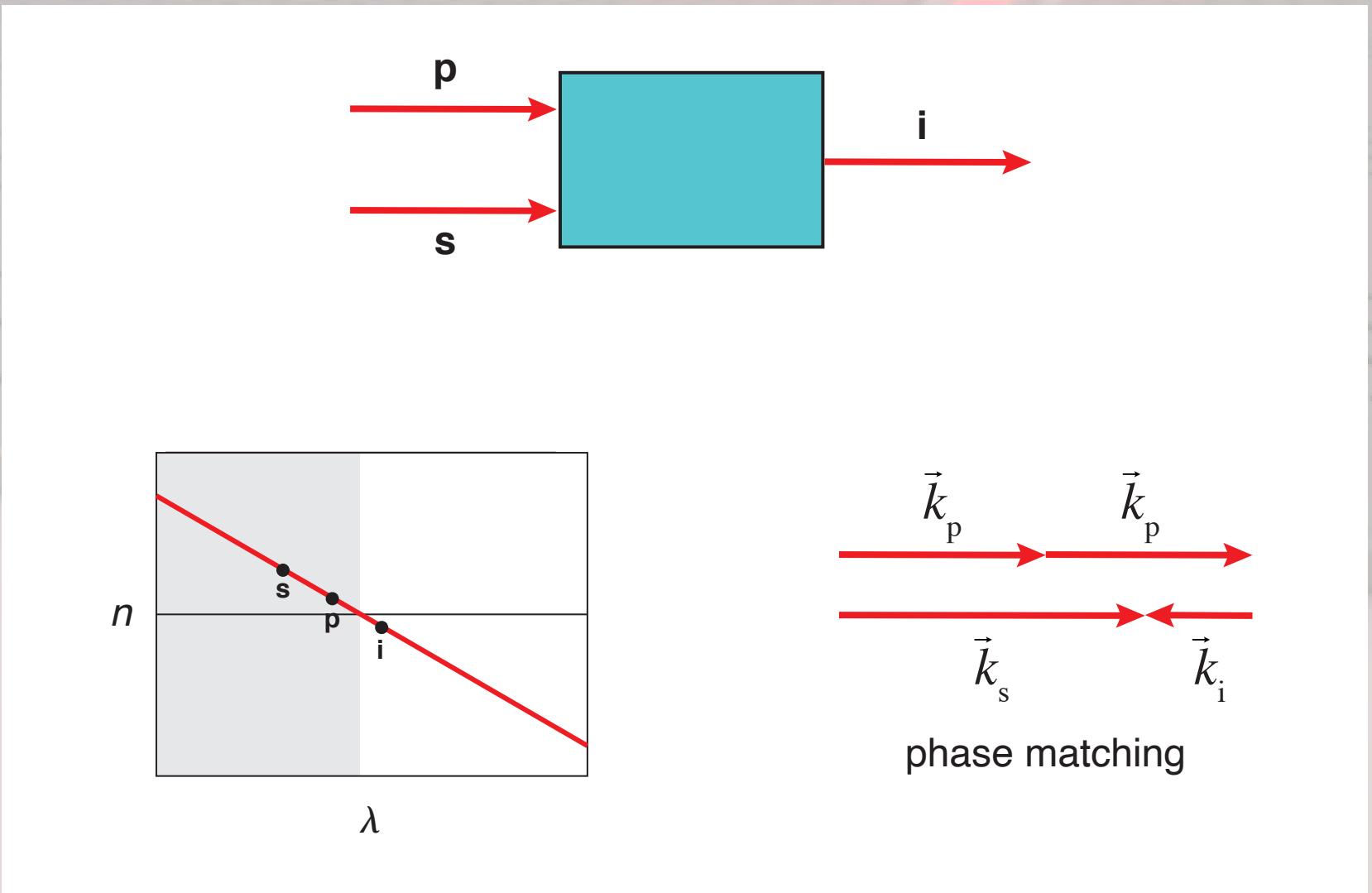
phase matching

1 zero index

2 fabrication

3 results

four-wave mixing

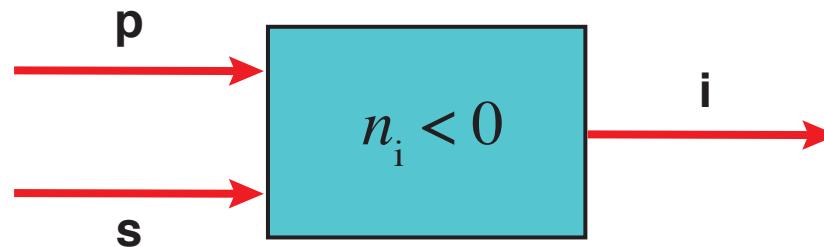


1 zero index

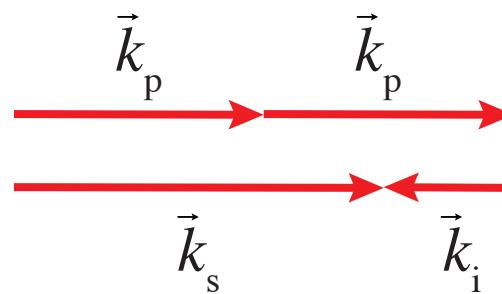
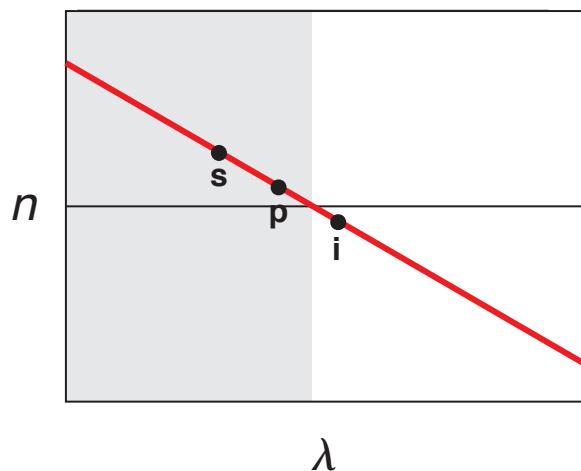
2 fabrication

3 results

four-wave mixing



forward only



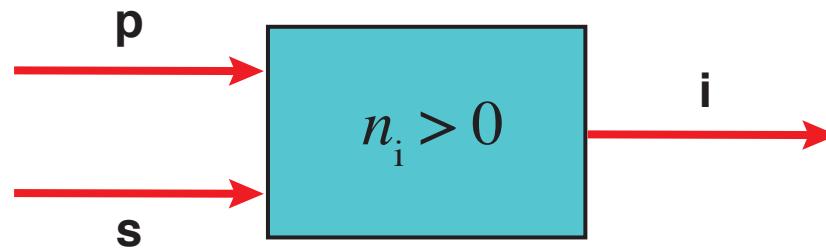
phase matching

1 zero index

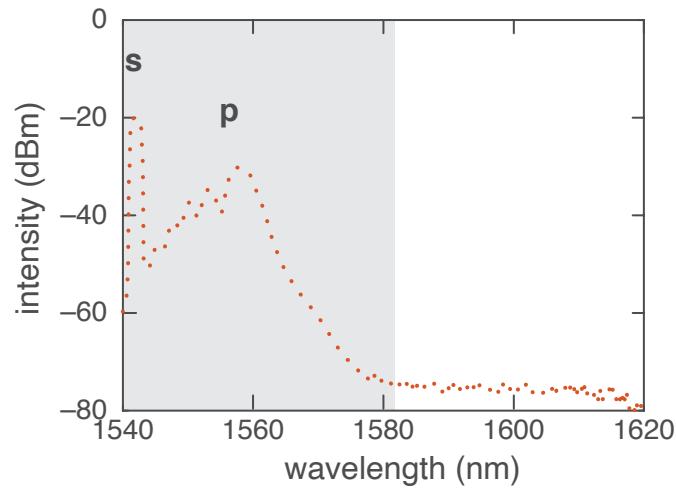
2 fabrication

3 results

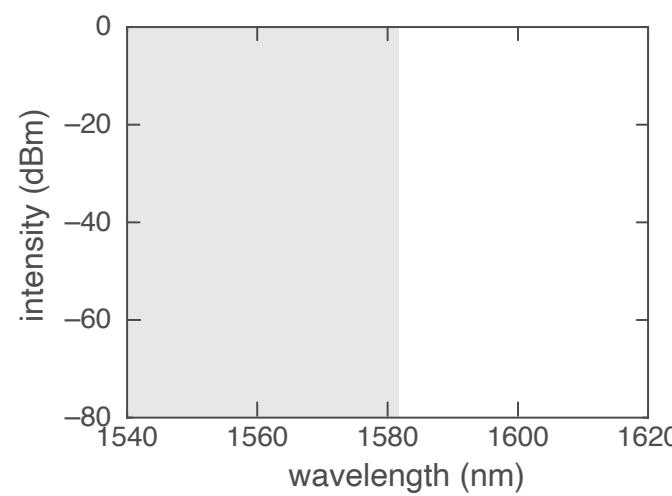
four-wave mixing



backward



forward

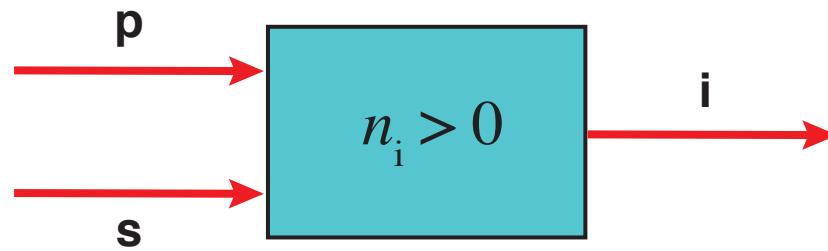


1 zero index

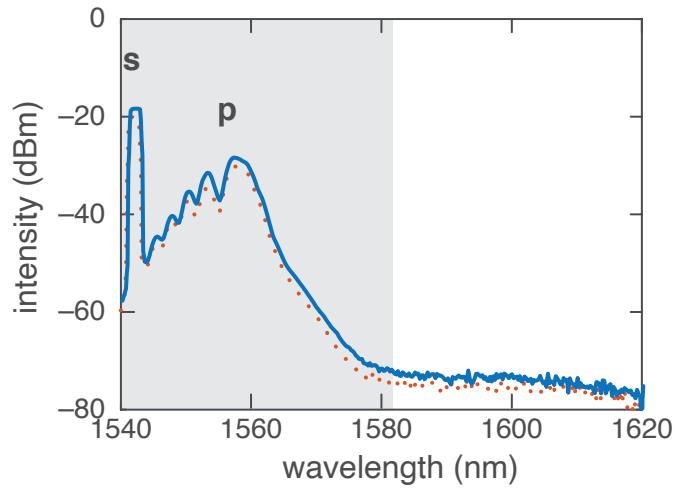
2 fabrication

3 results

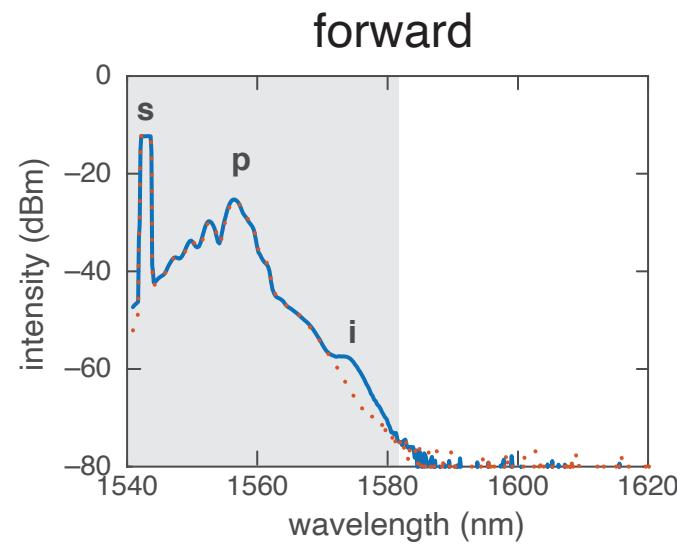
four-wave mixing



backward



forward

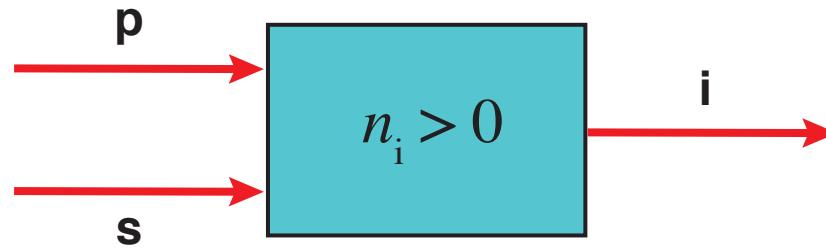


1 zero index

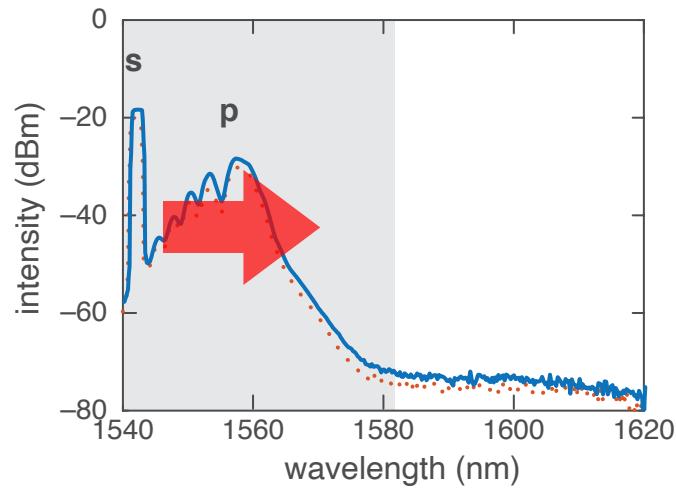
2 fabrication

3 results

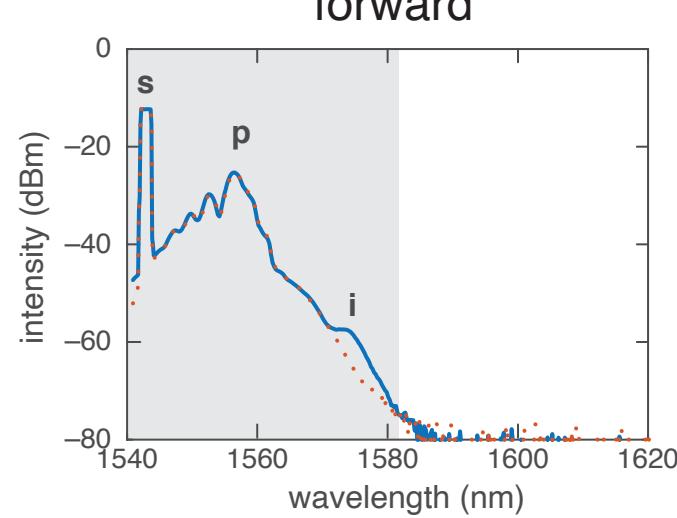
four-wave mixing



backward



forward

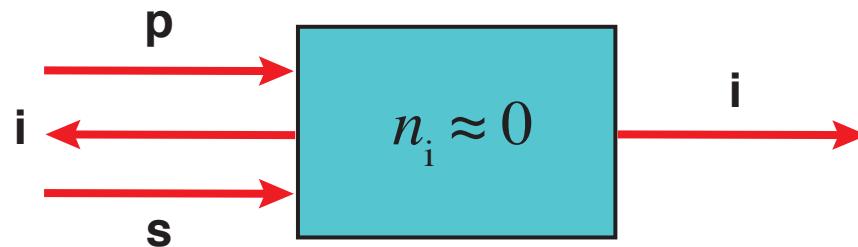


1 zero index

2 fabrication

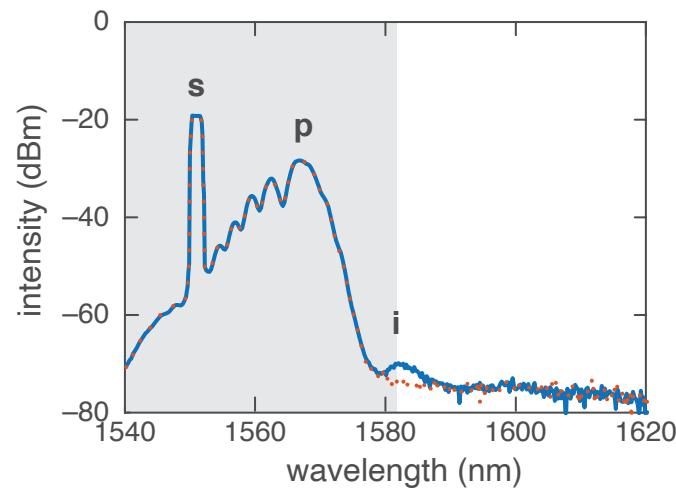
3 results

four-wave mixing

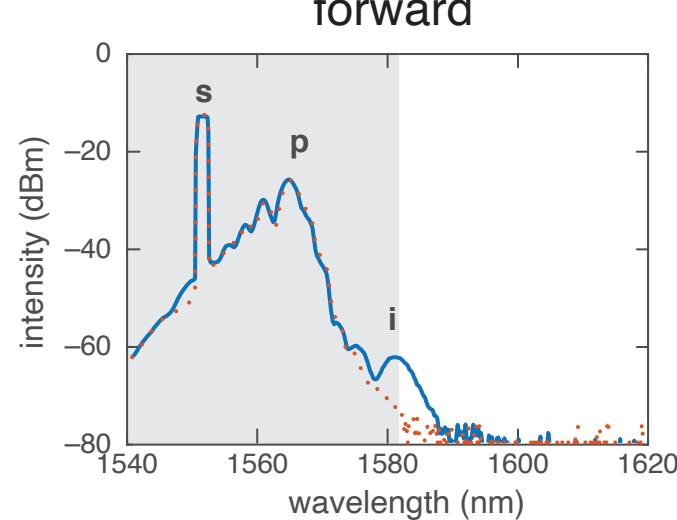


forward and backward

backward



forward

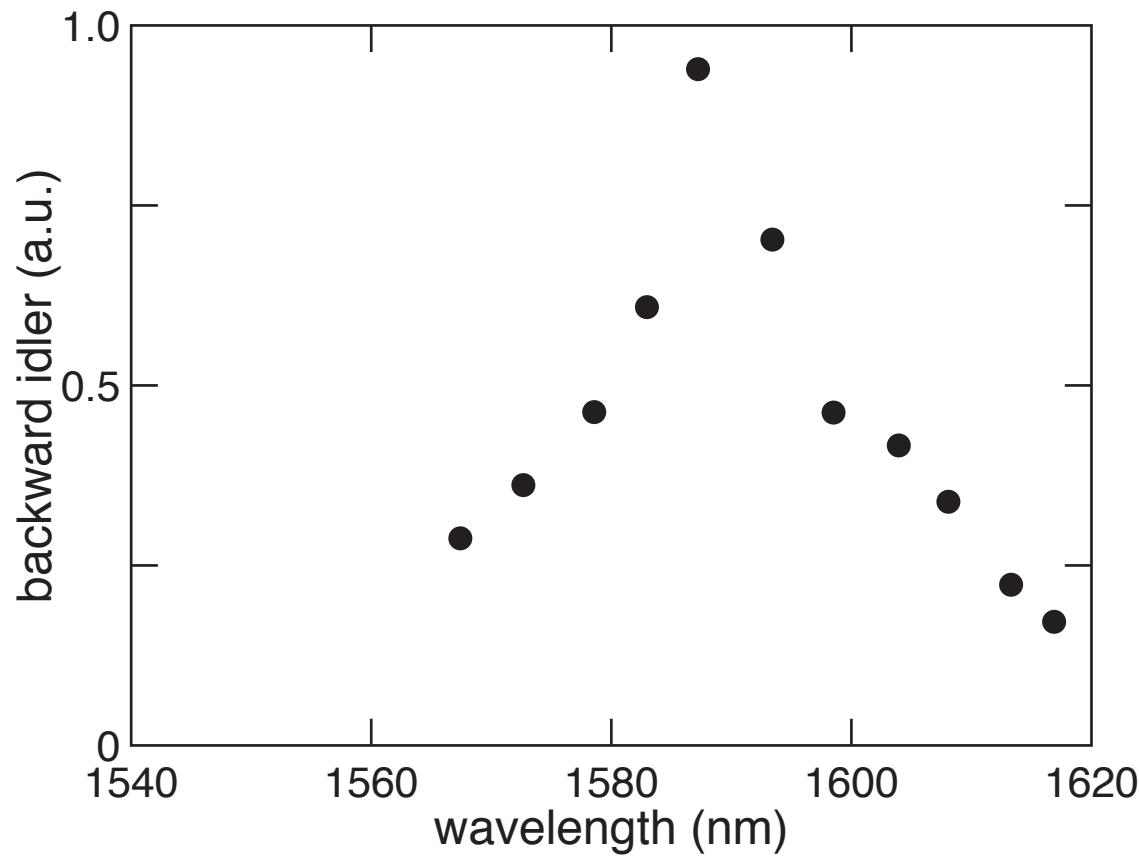


1 zero index

2 fabrication

3 results

backward idler intensity

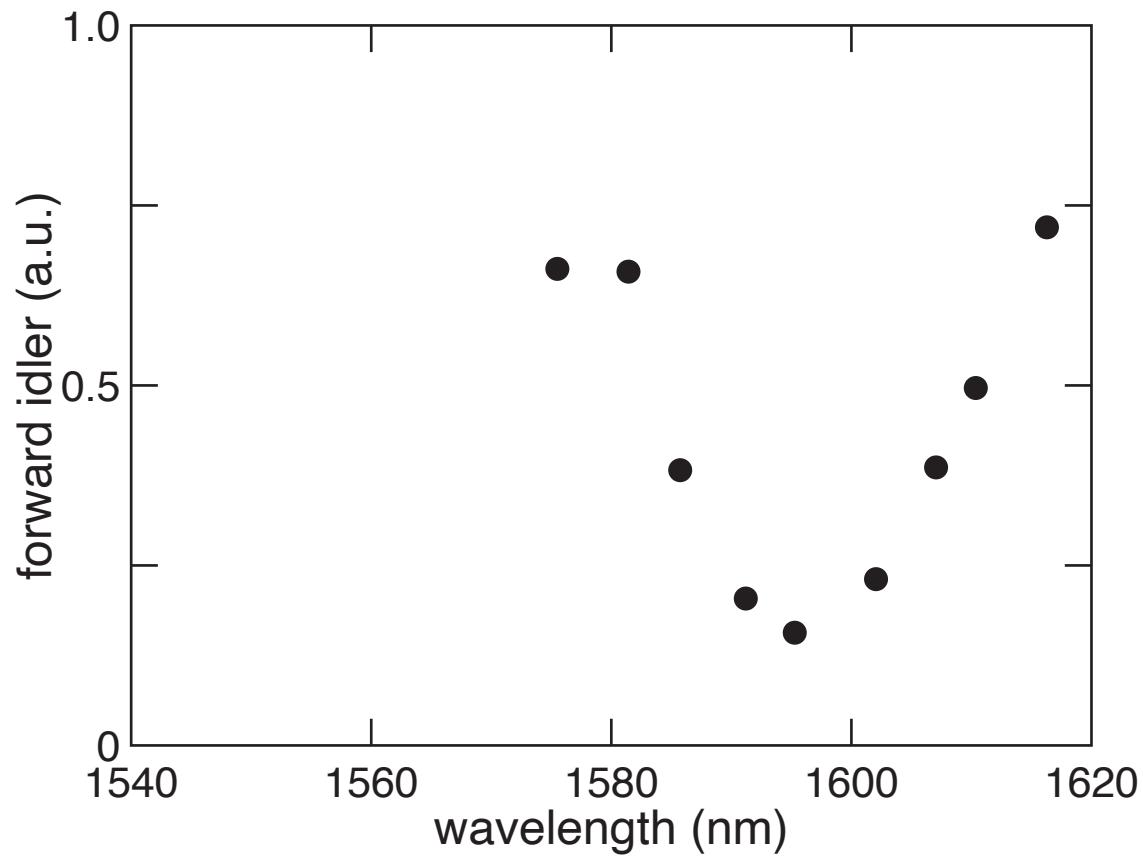


1 zero index

2 fabrication

3 results

forward idler intensity



1 zero index

2 fabrication

3 results



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1 zero index

2 fabrication

3 results