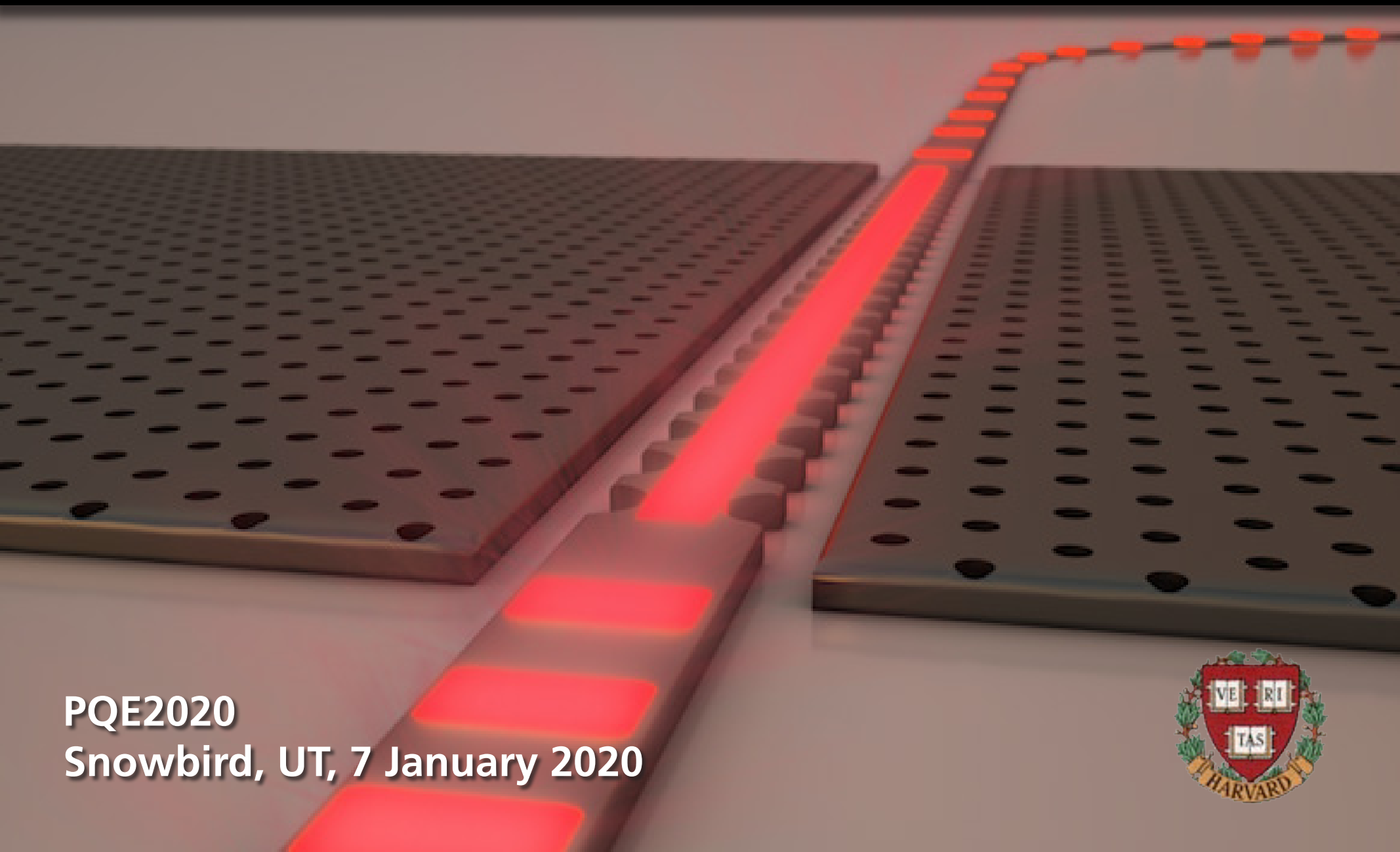
Extreme optics with zero index metamaterials



PQE2020
Snowbird, UT, 7 January 2020

Extreme optics with zero index metamaterials

@eric__mazur

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Snowbird, UT, 7 January 2020

Enabling nanophotonics

Enabling nanophotonics

Enabling nanophotonics

1 zero index

2 fabrication

Enabling nanophotonics

1 zero index 2 fabrication 3 results

wave equation

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

solution

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

where

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

wave equation

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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

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

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

where

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

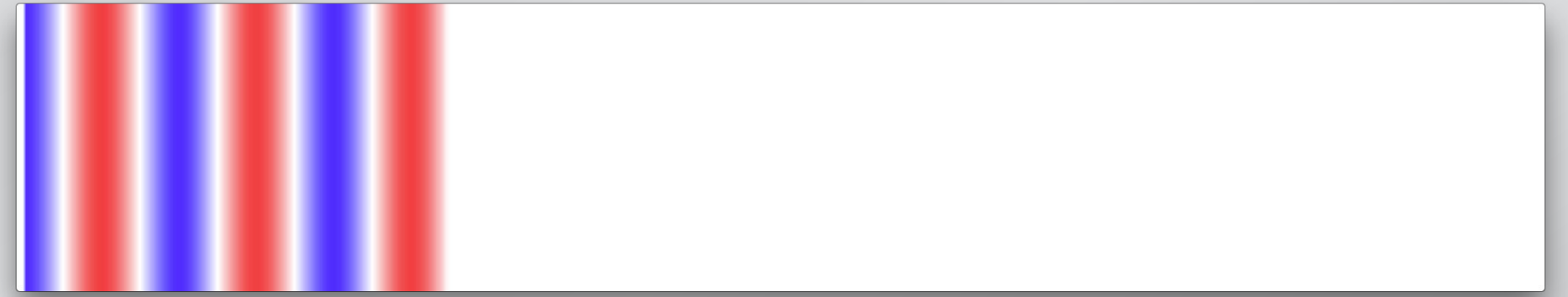
1 zero index

1 zero index

“Superluminal”?!

What about causality?

What about causality?



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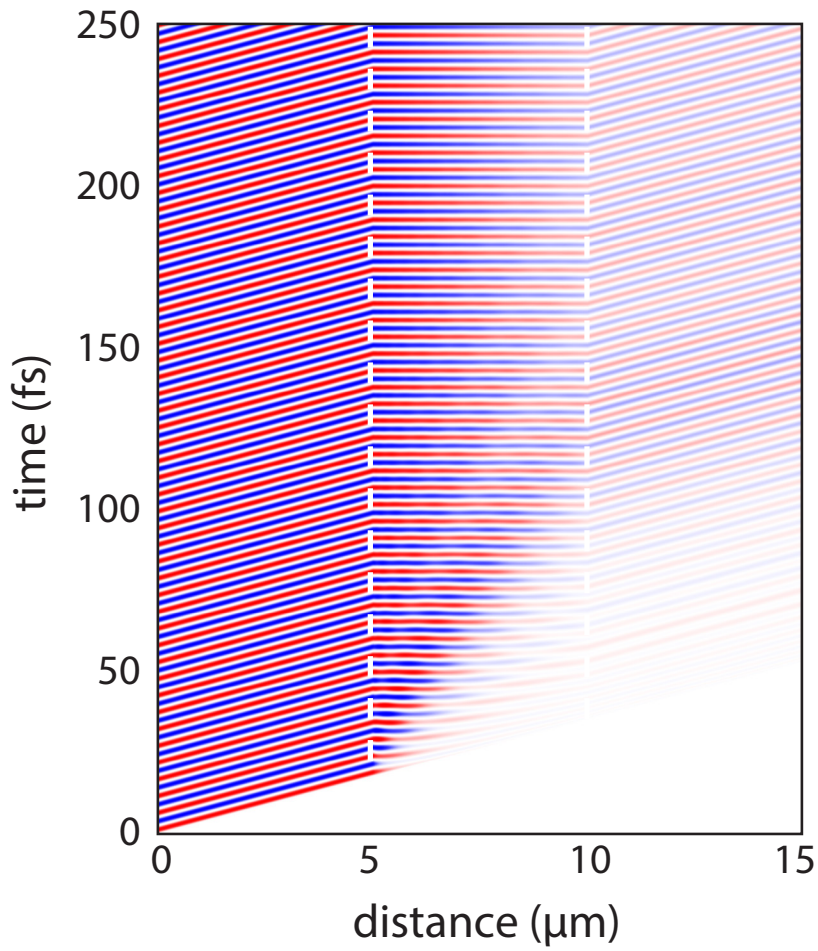
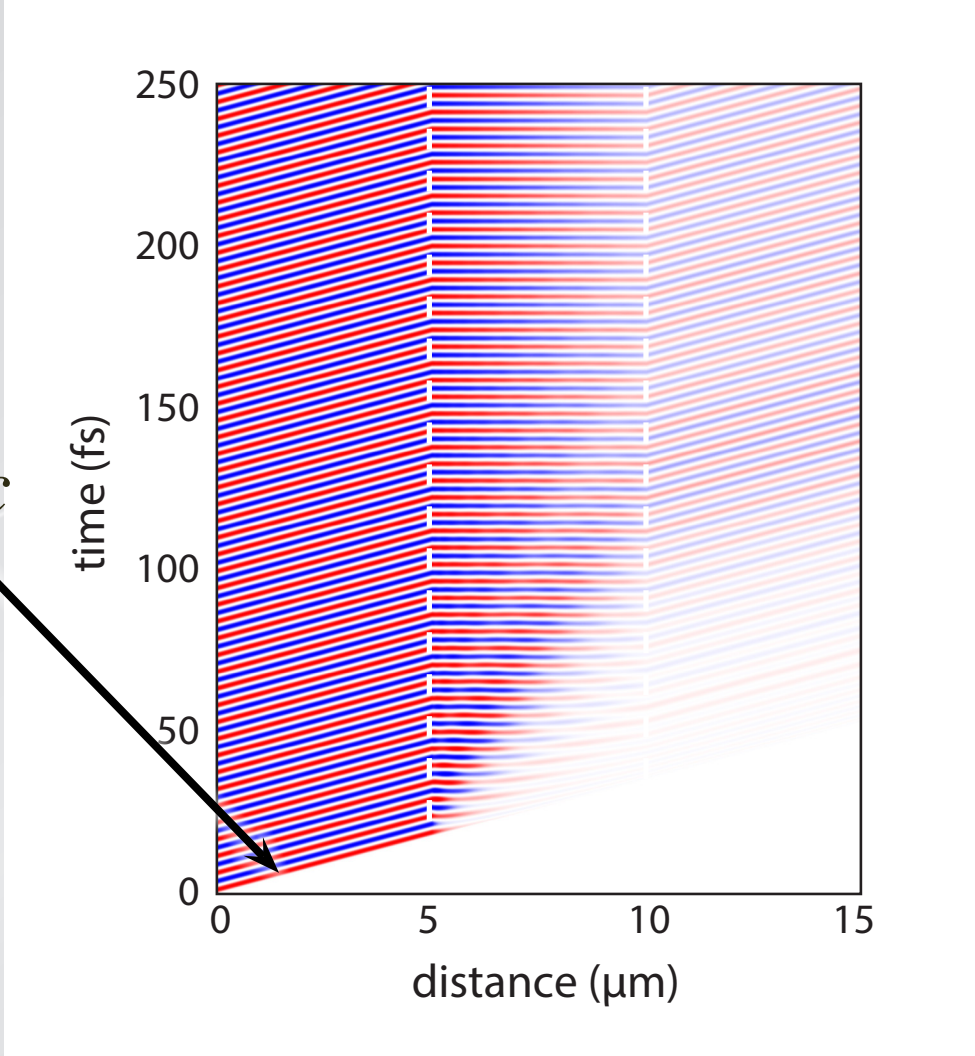


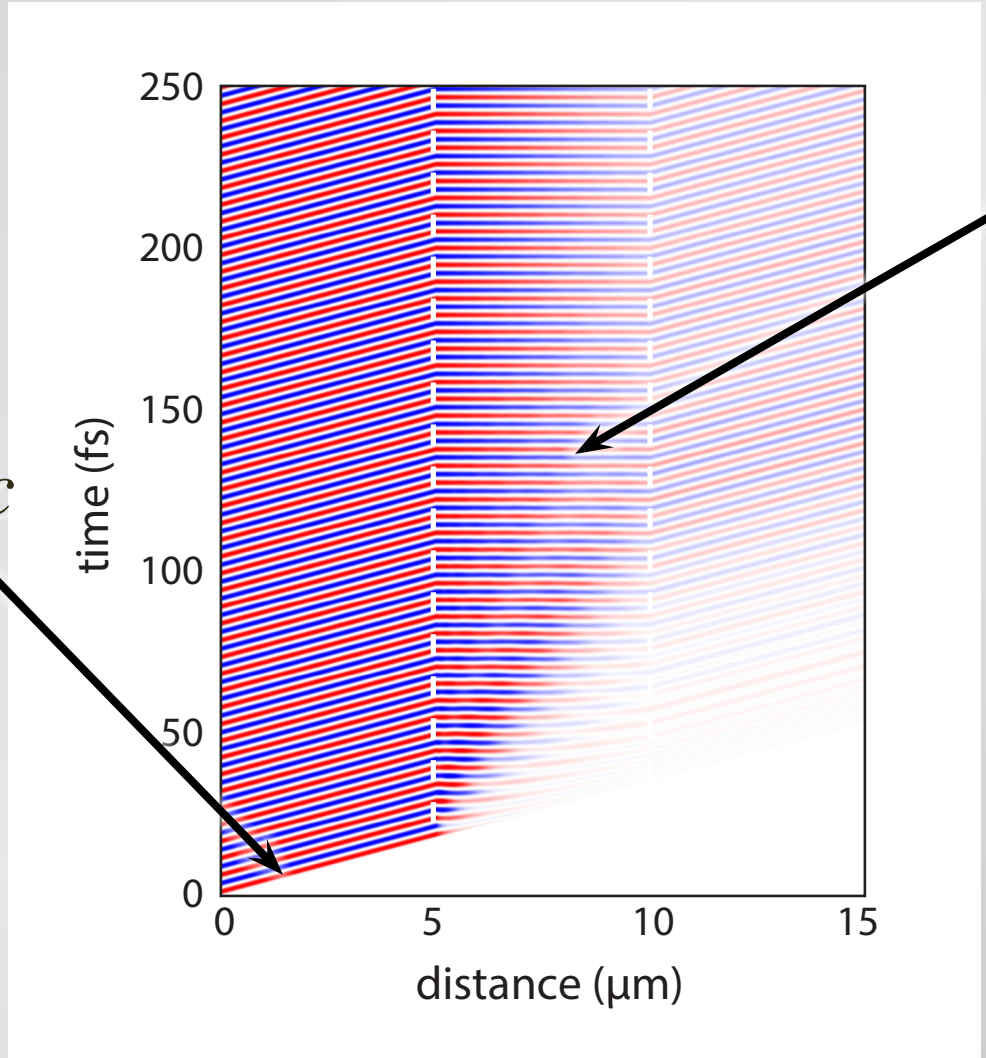
1 zero index

What about causality?

speed of light c



What about causality?



constant phase

speed of light c

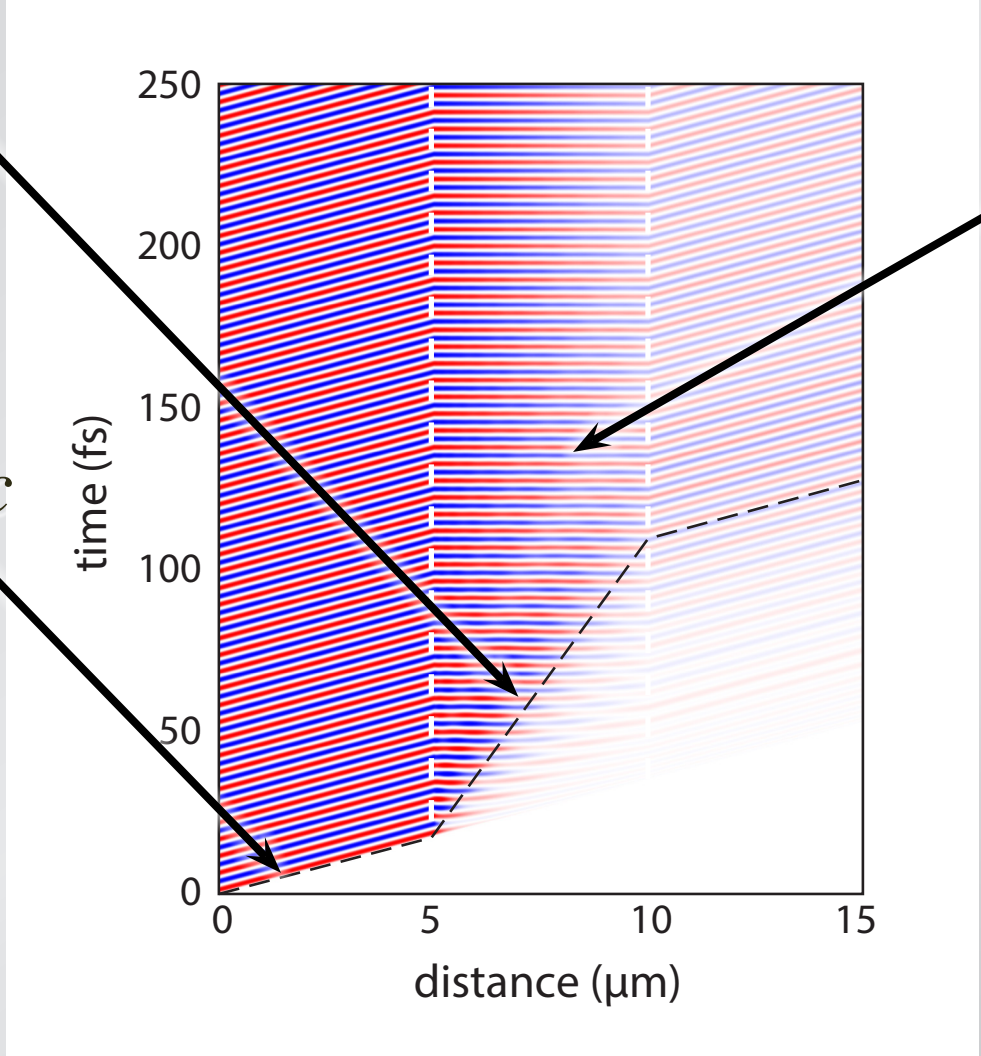
1 zero index

What about causality?

group velocity

$v_g < c$

speed of light c



constant phase

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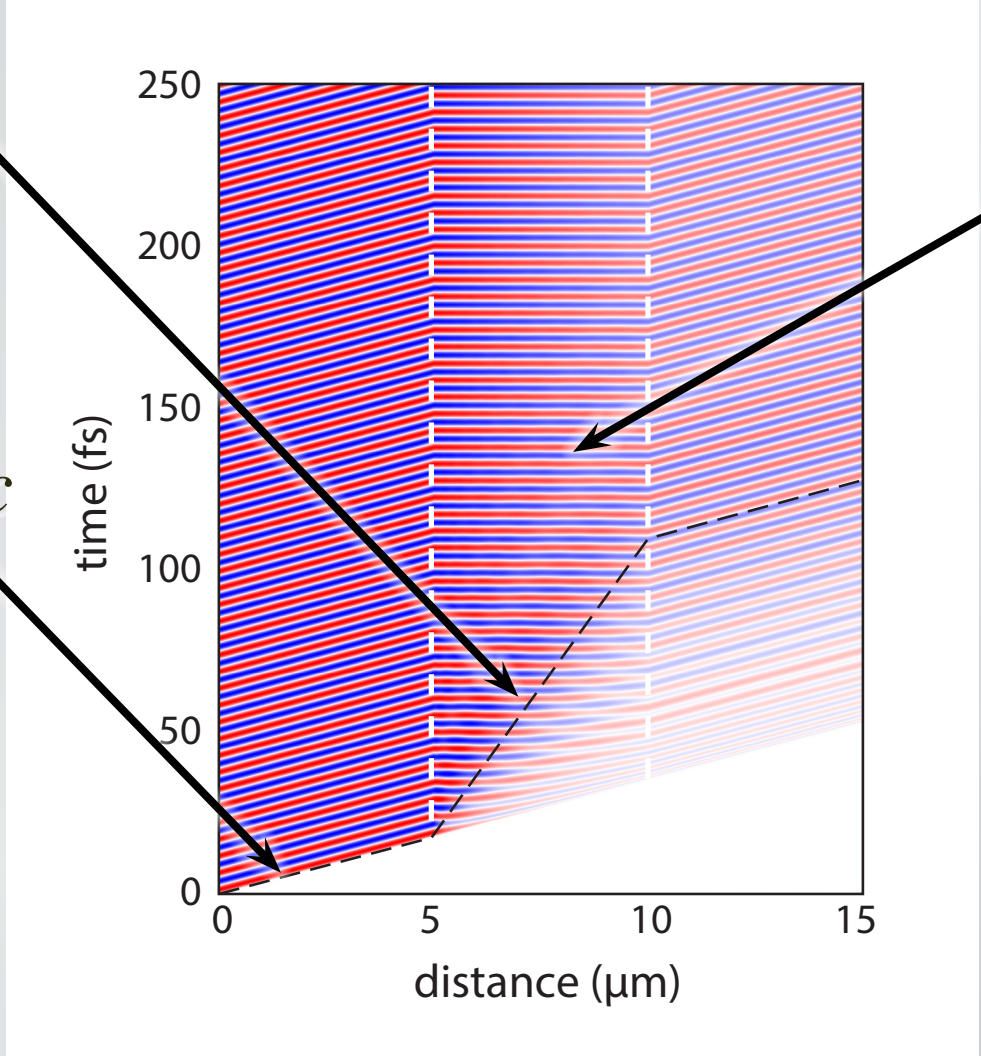

constant phase

1 zero index

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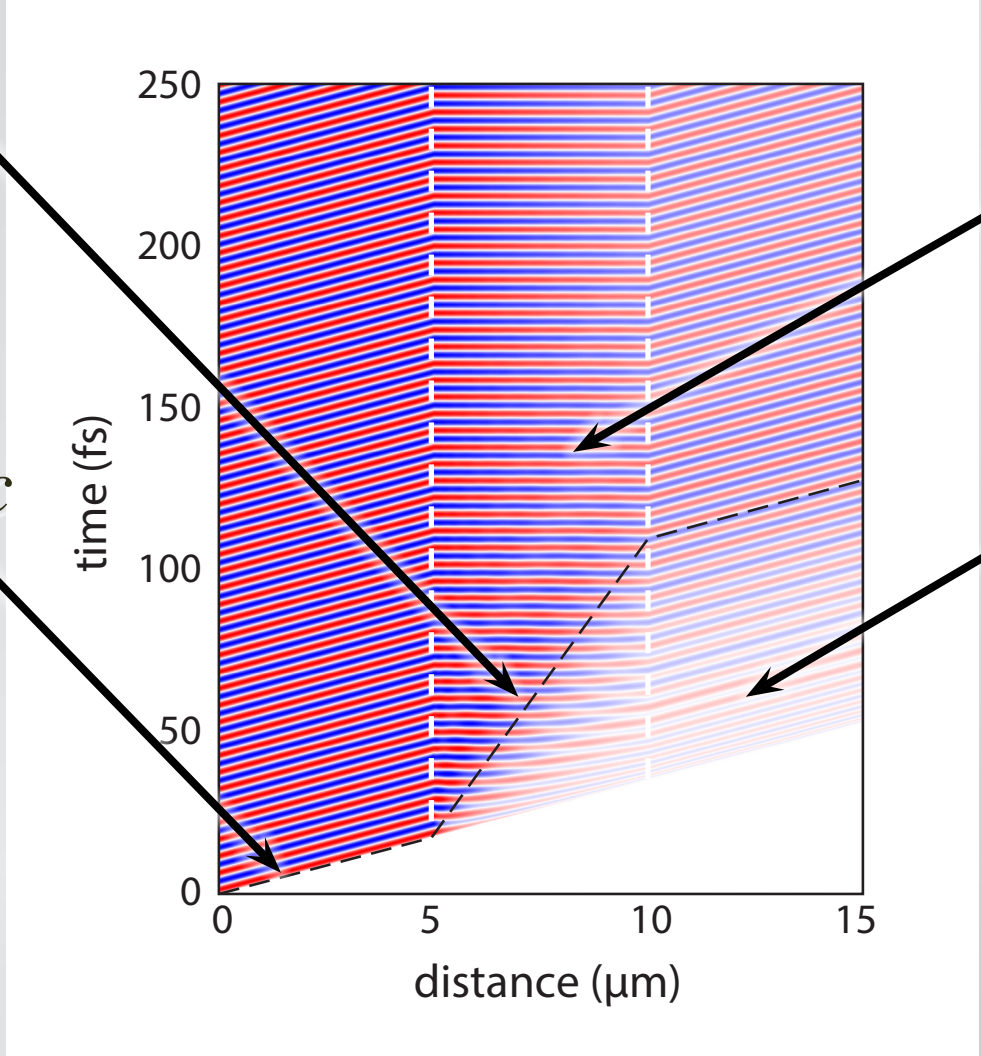
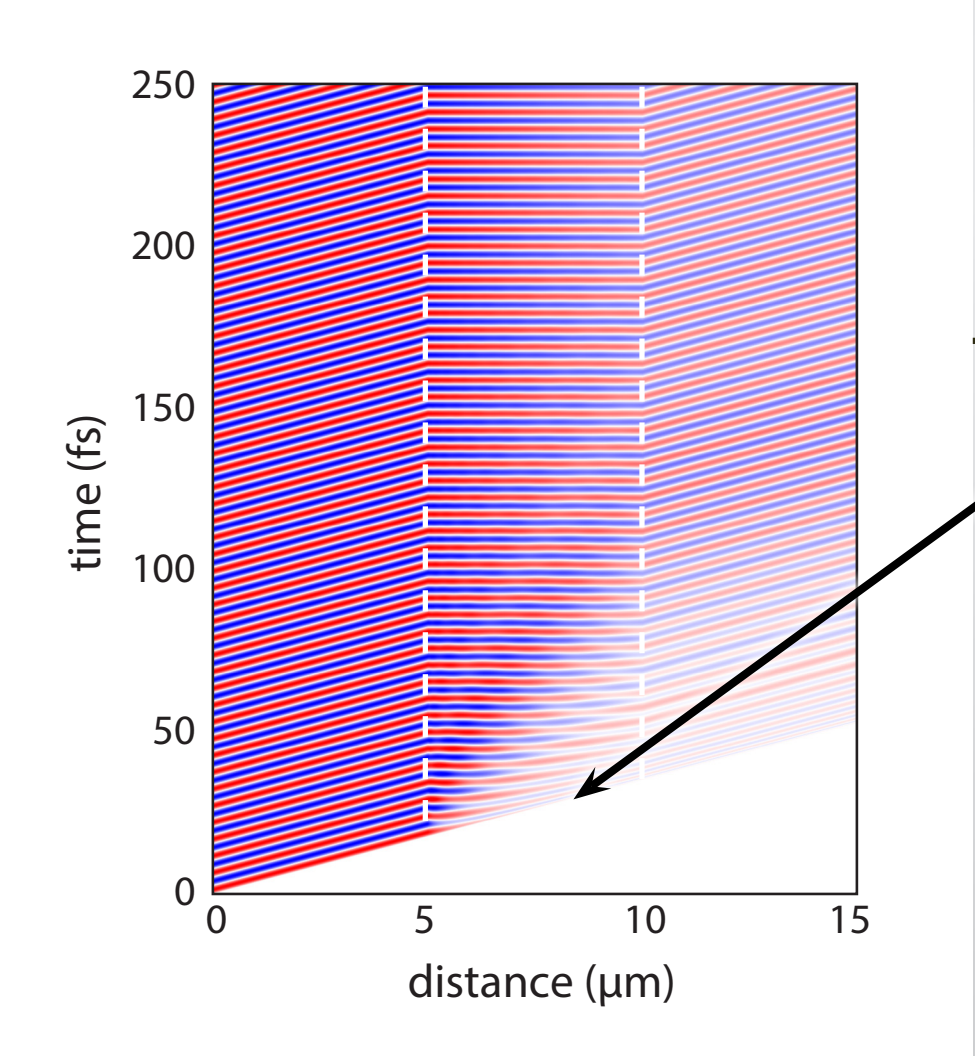


constant phase

high-frequency precursors

1 zero index

What about causality?



signal *always* travels at speed c!

What about causality?

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?

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

but ϵ and μ also determine reflectivity

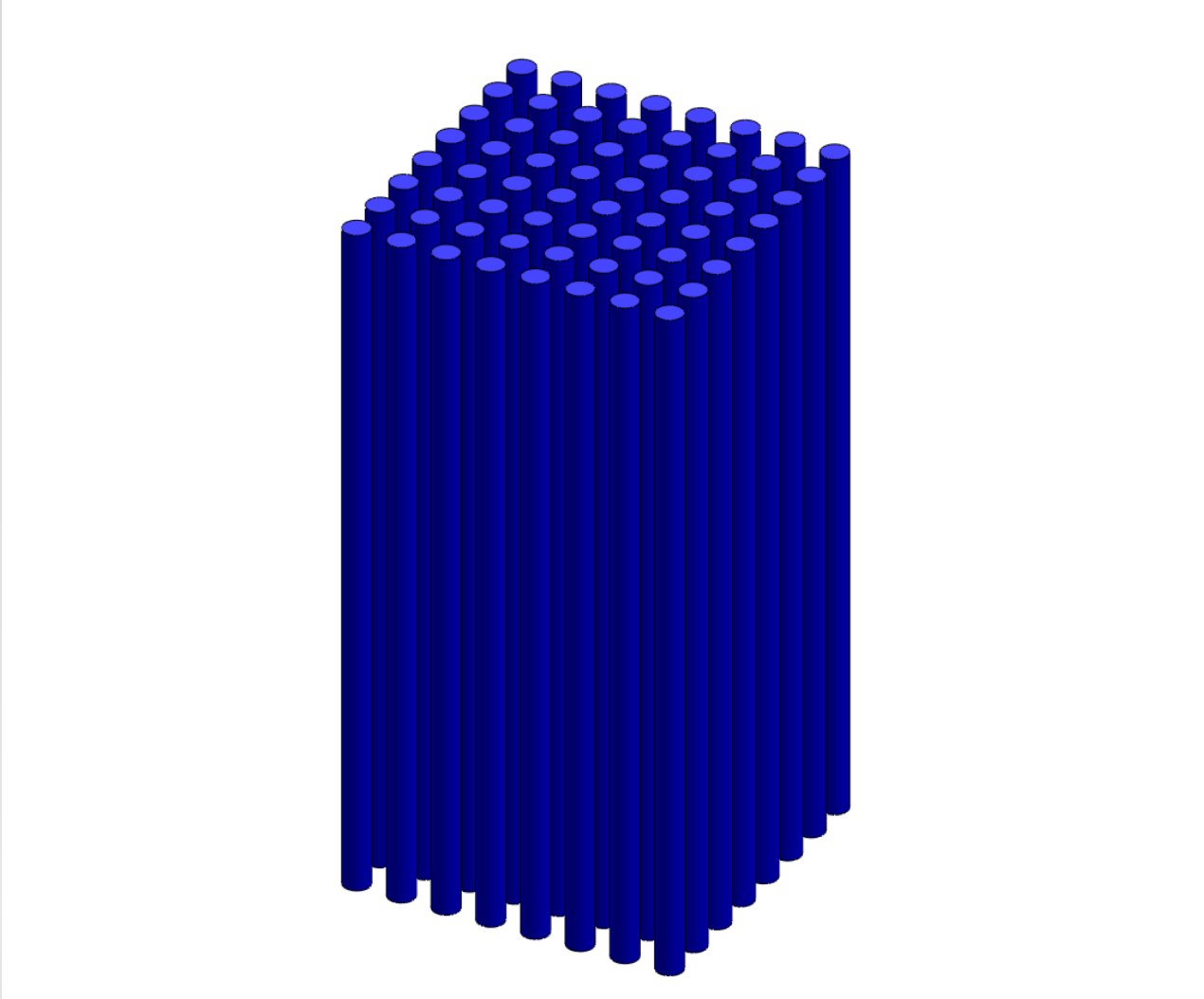
$$R = \frac{Z-1}{Z+1}$$

where

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

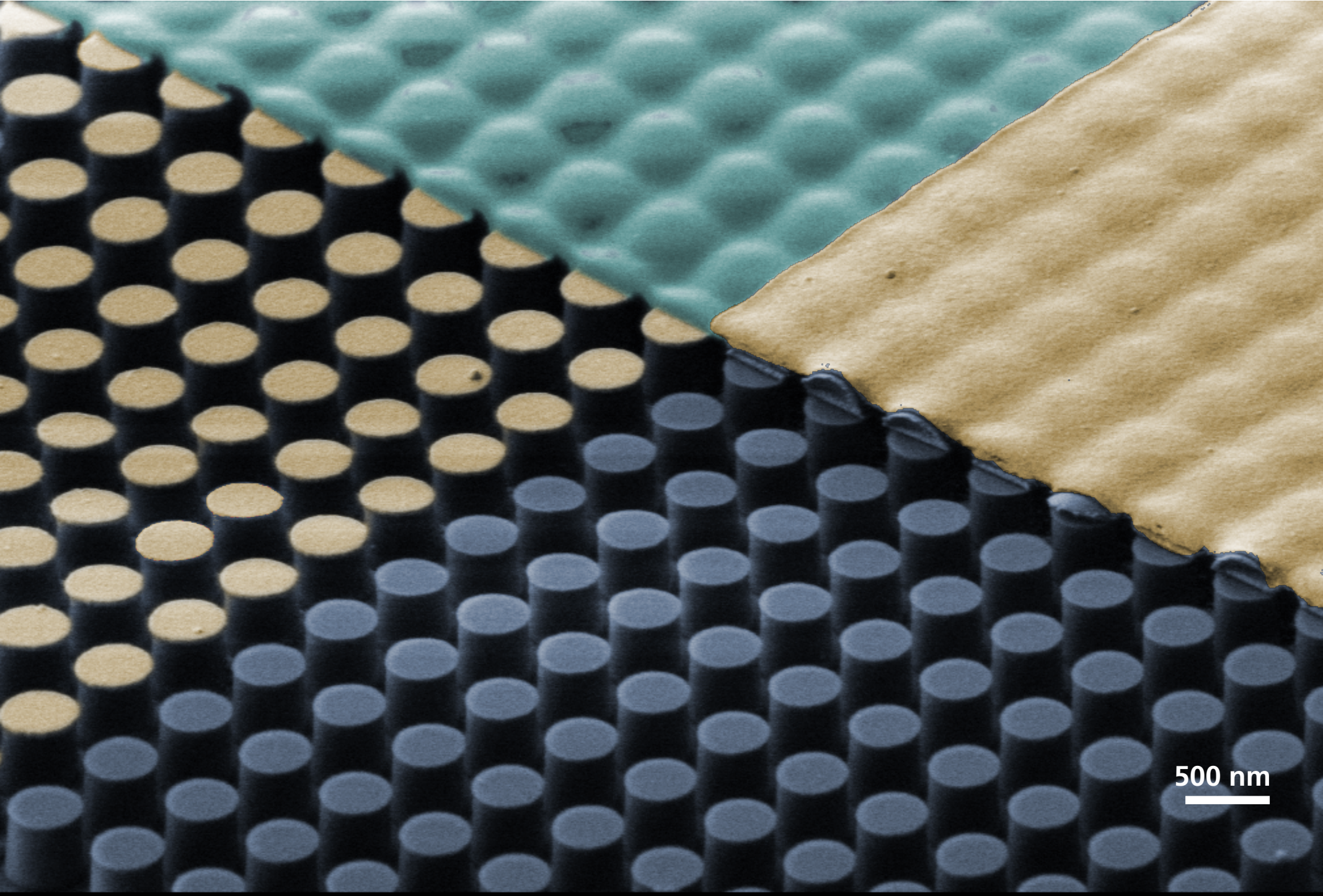
finite!

How to fabricate?



1 zero index

2 fabrication



1 zero index

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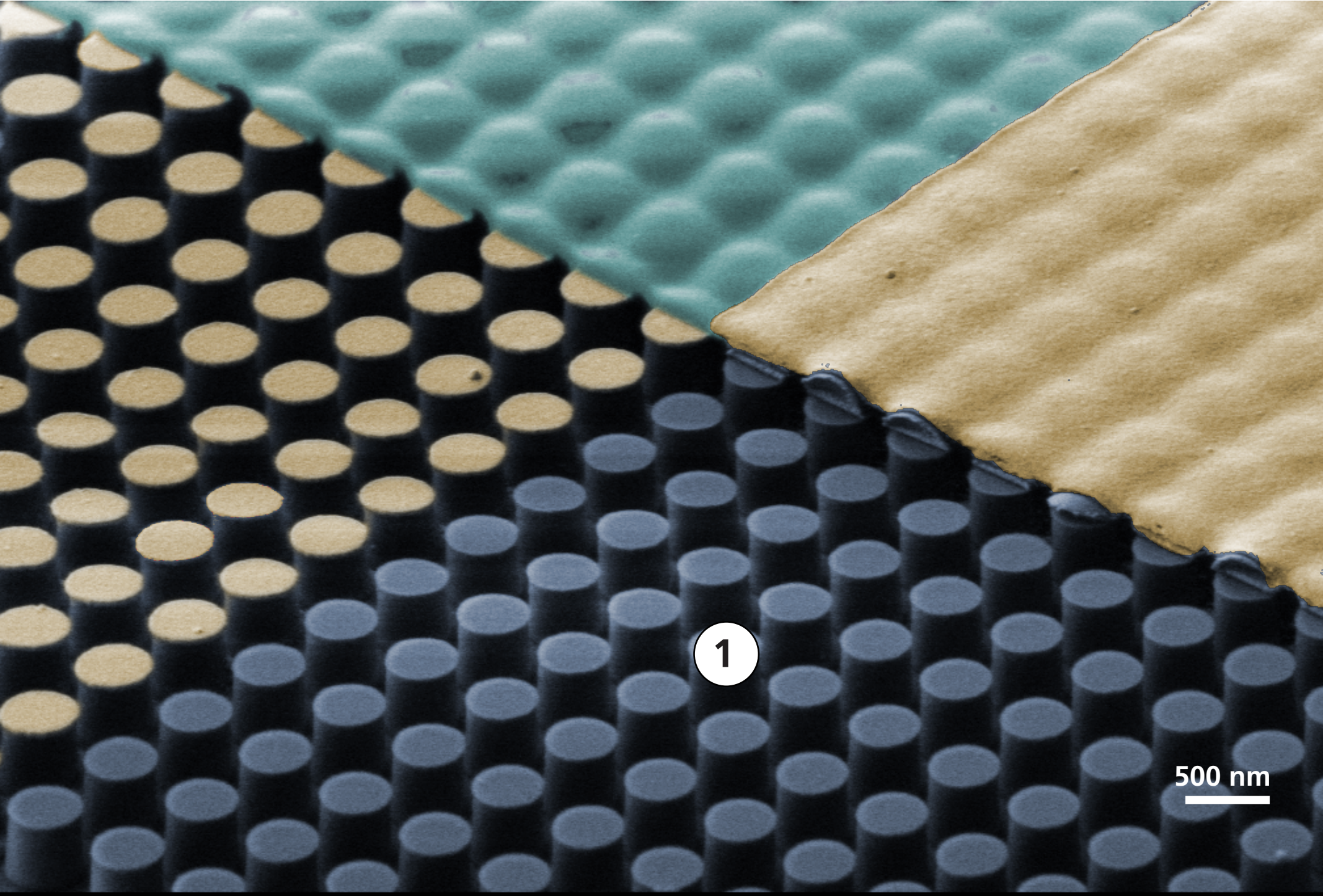

1 zero index

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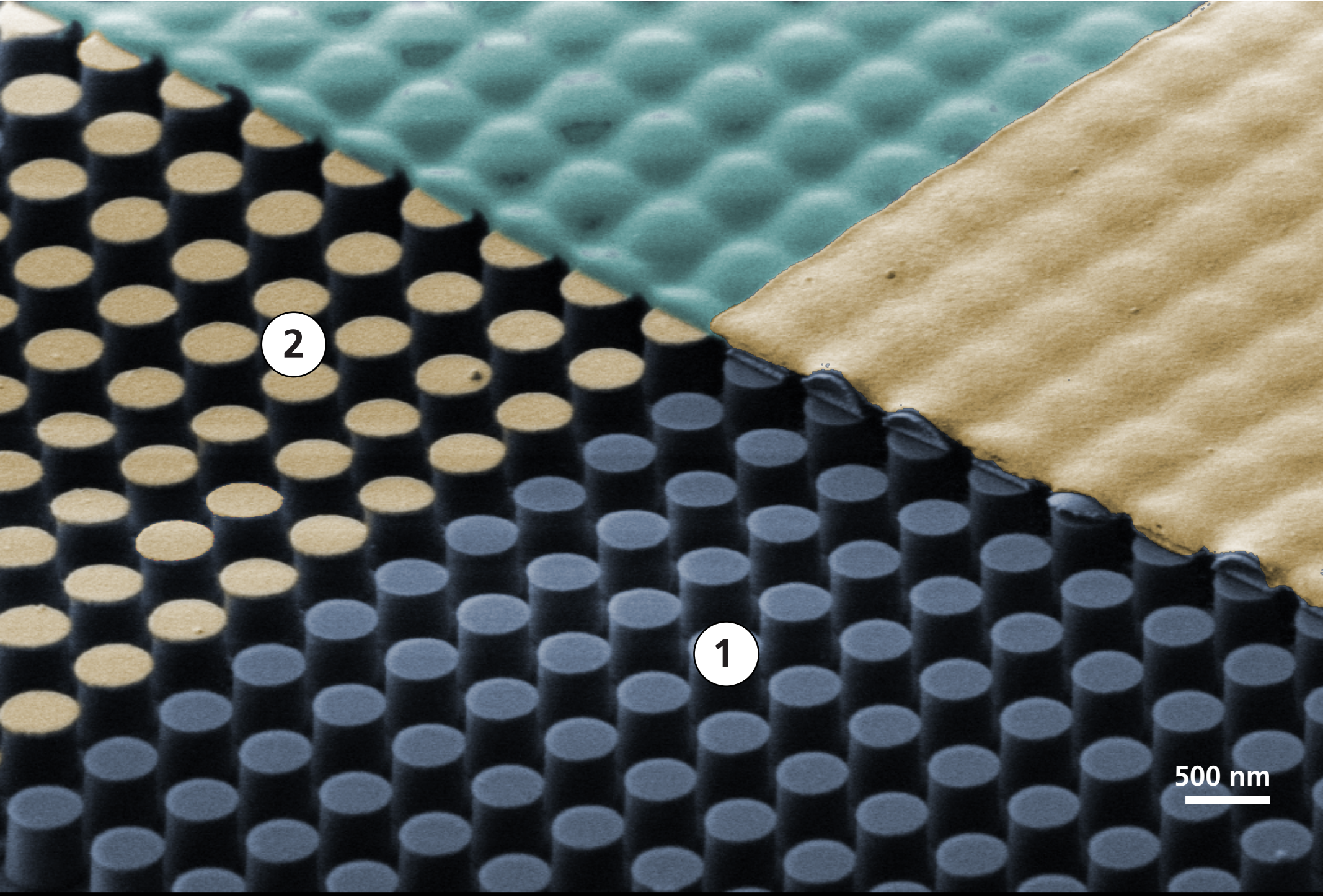

1 zero index

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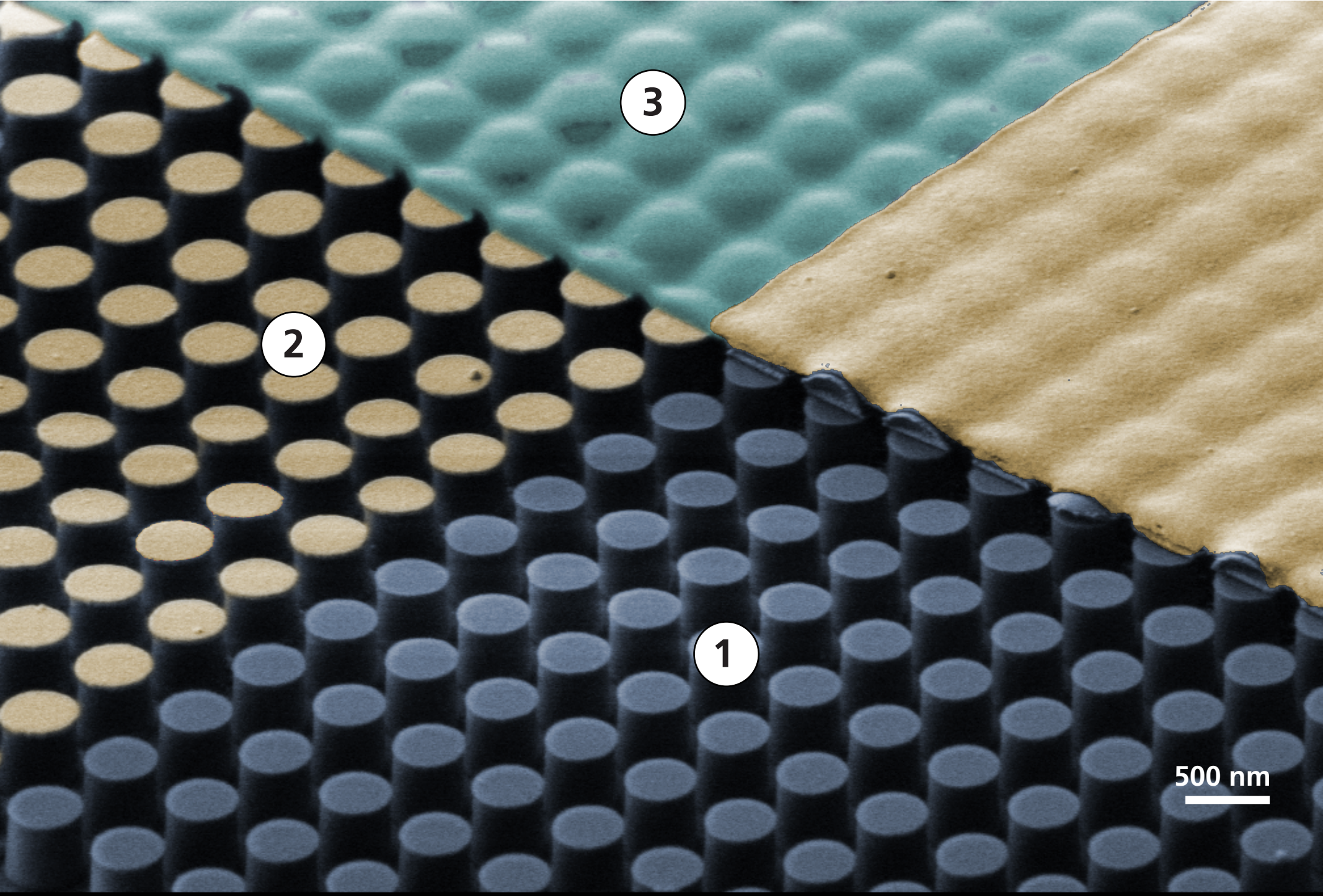
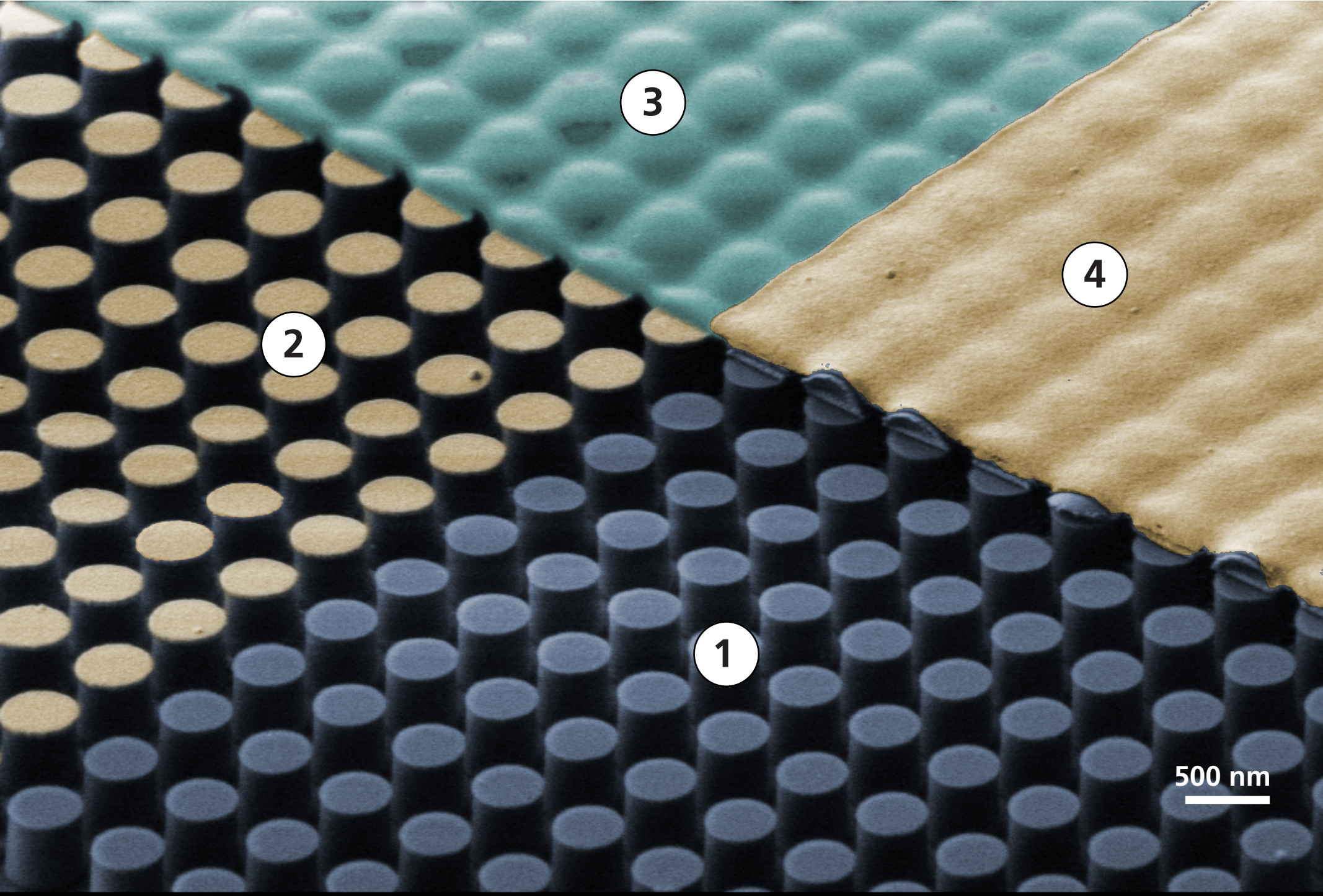


1 zero index

2 fabrication

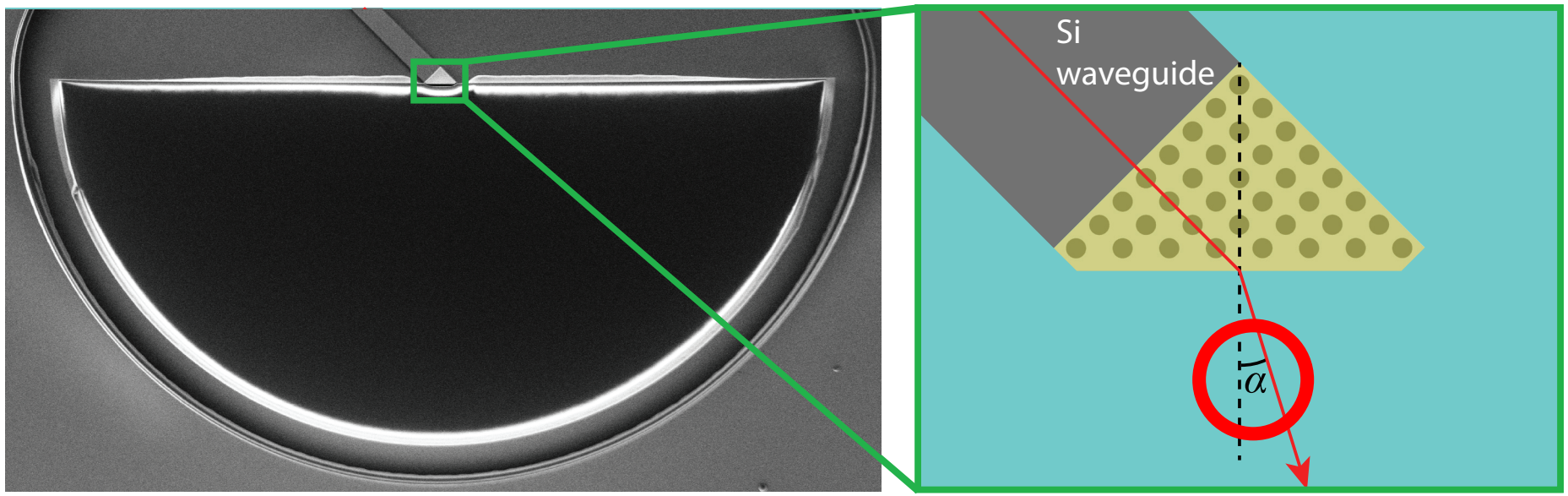


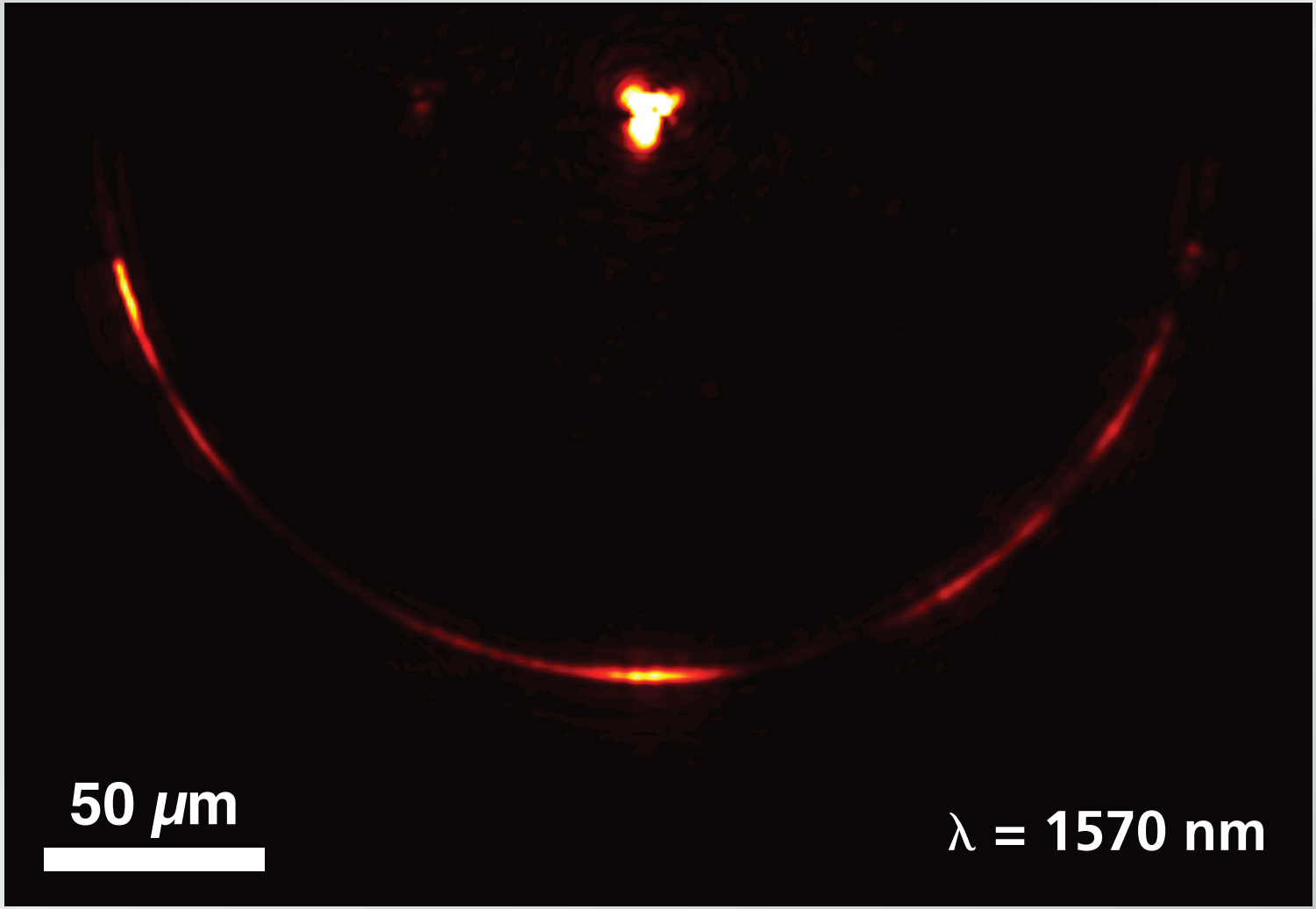
1 zero index

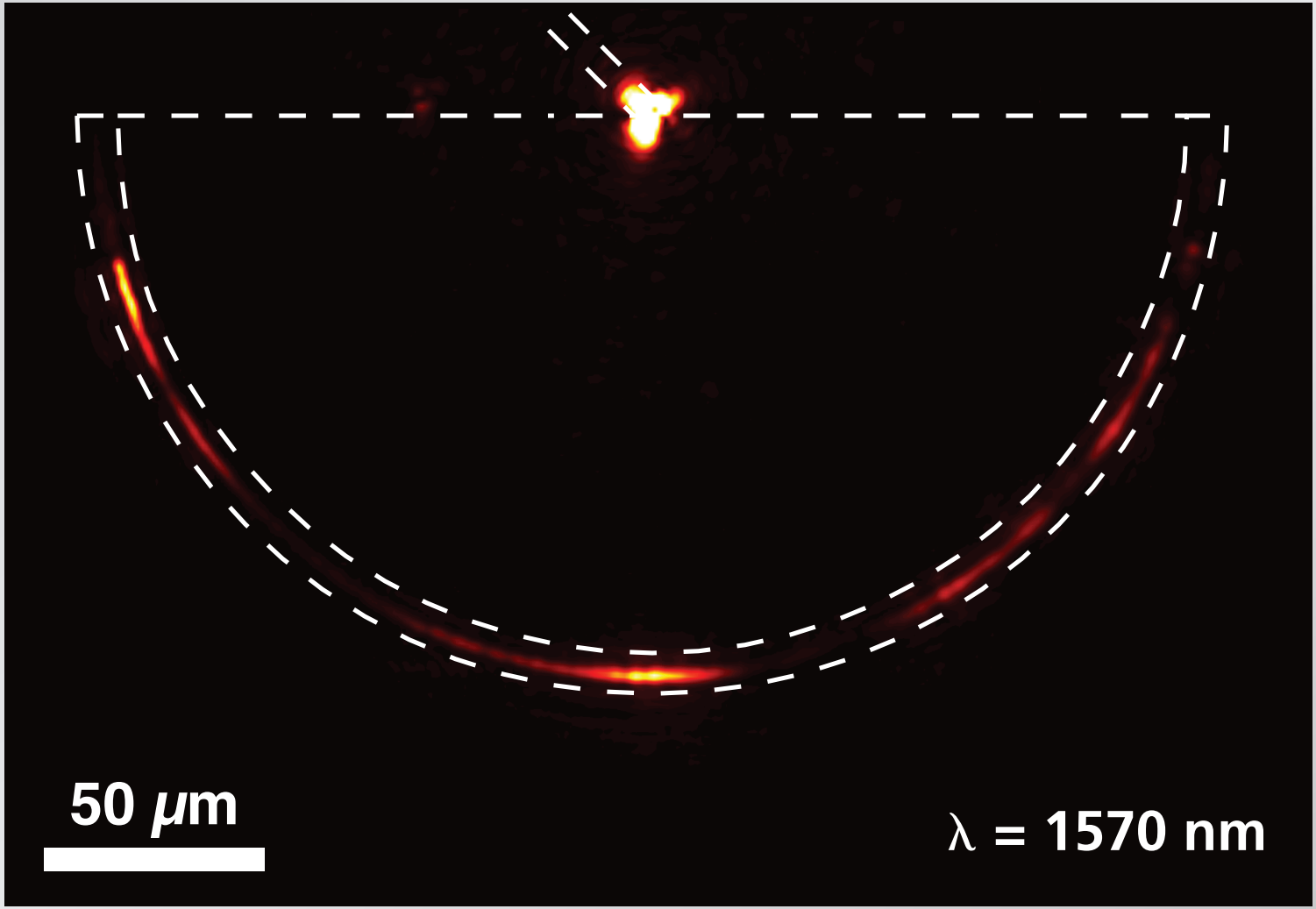
2 fabrication

Can make this in any shape!

On-chip zero-index prism




50 μm
λ = 1570 nm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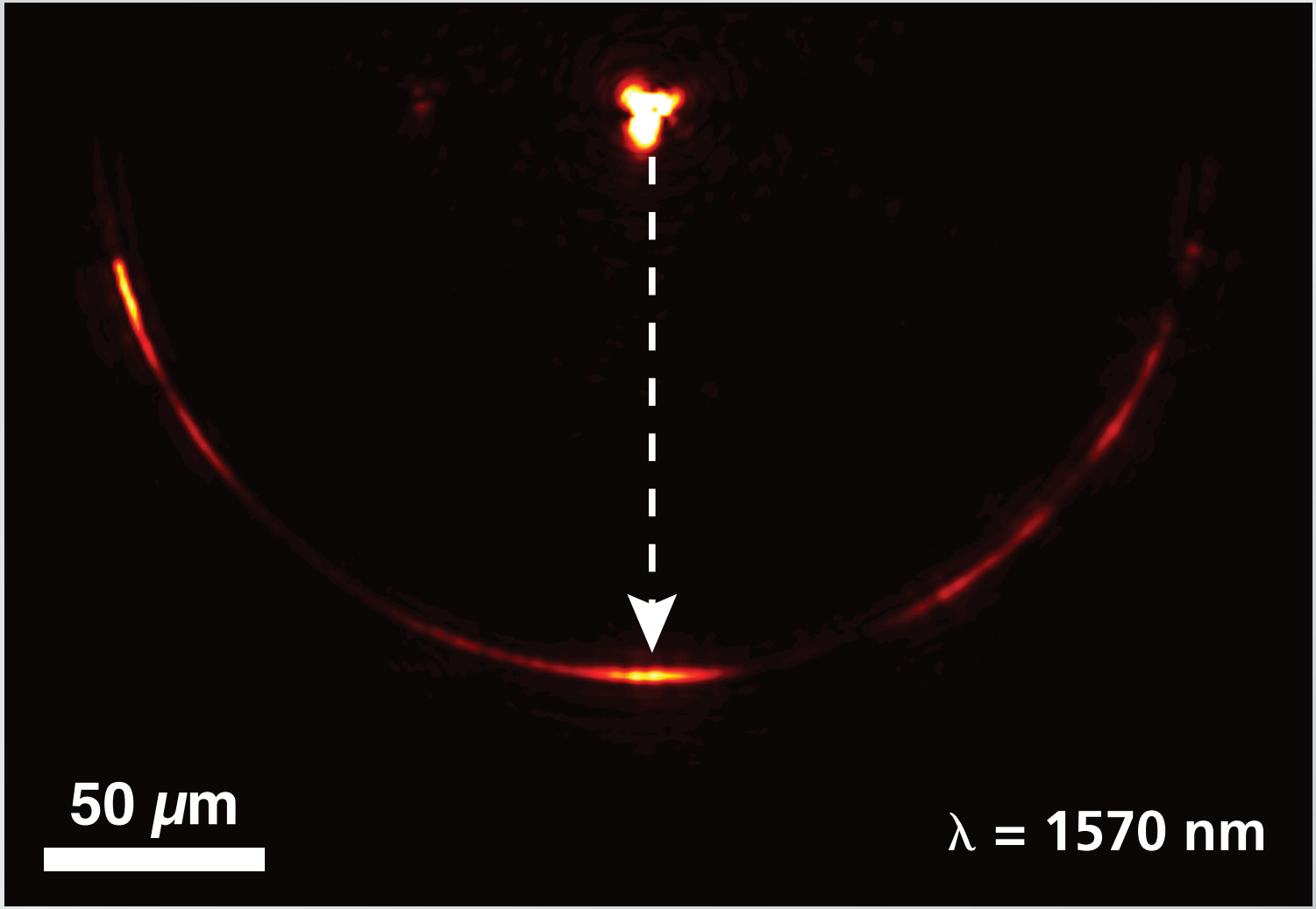
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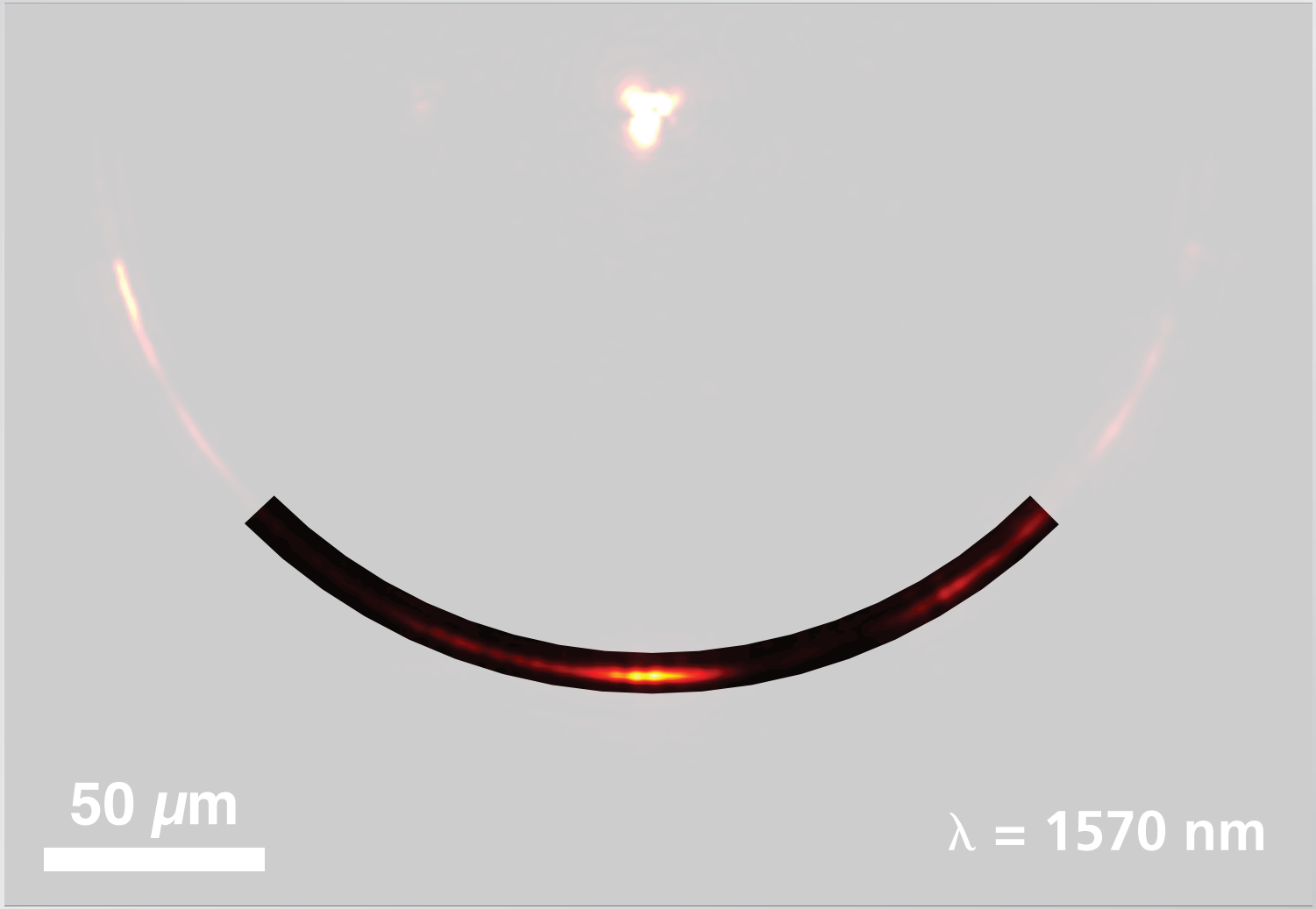
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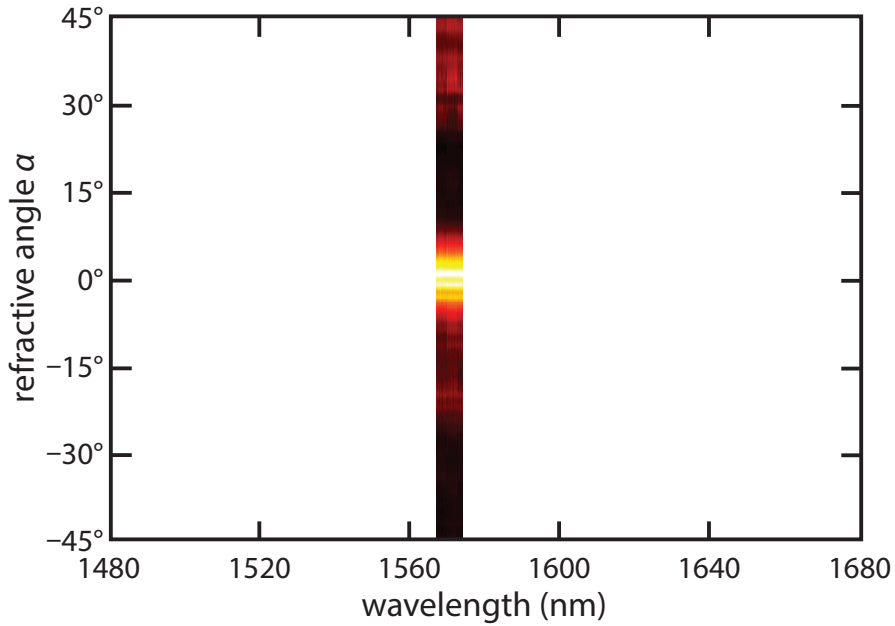
Wavelength dependence of refraction angle



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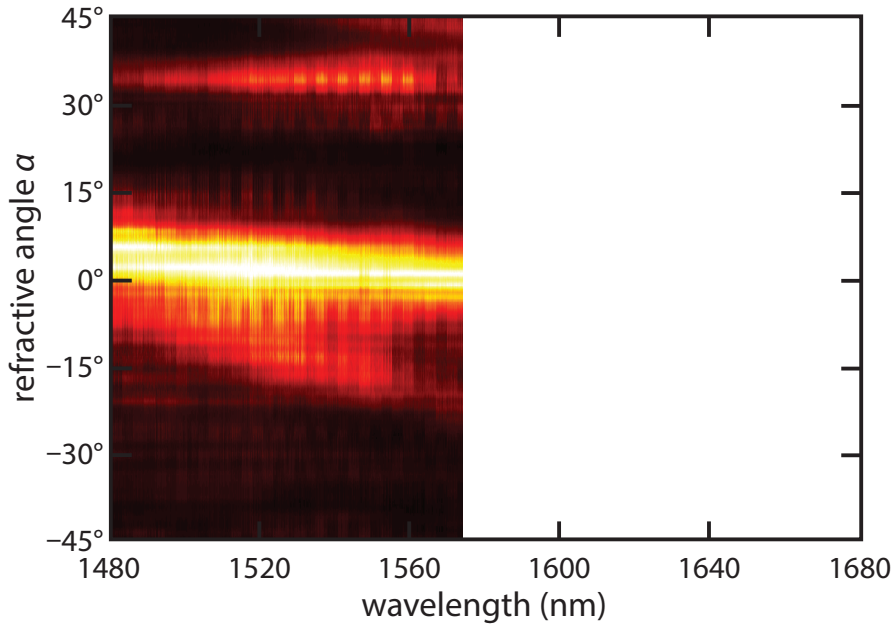

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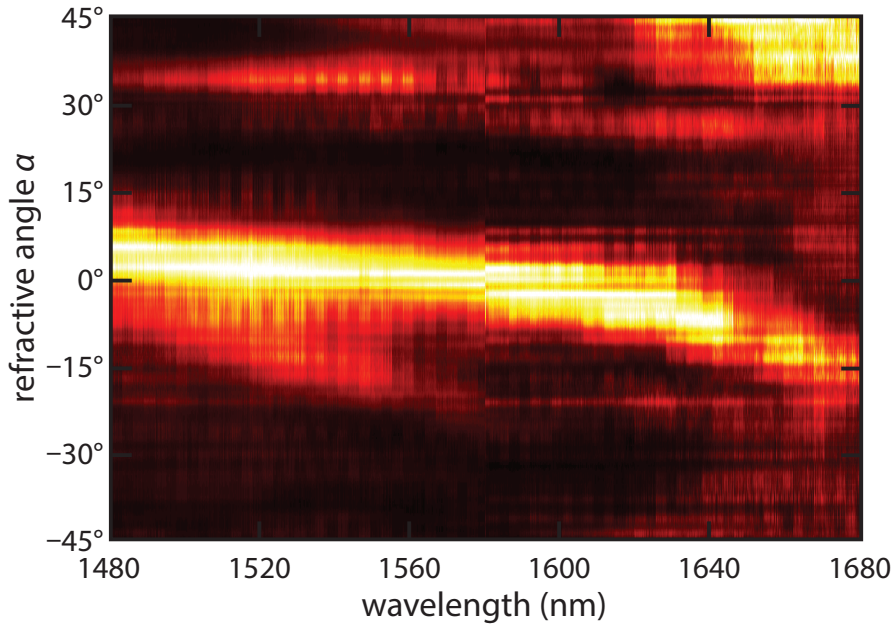
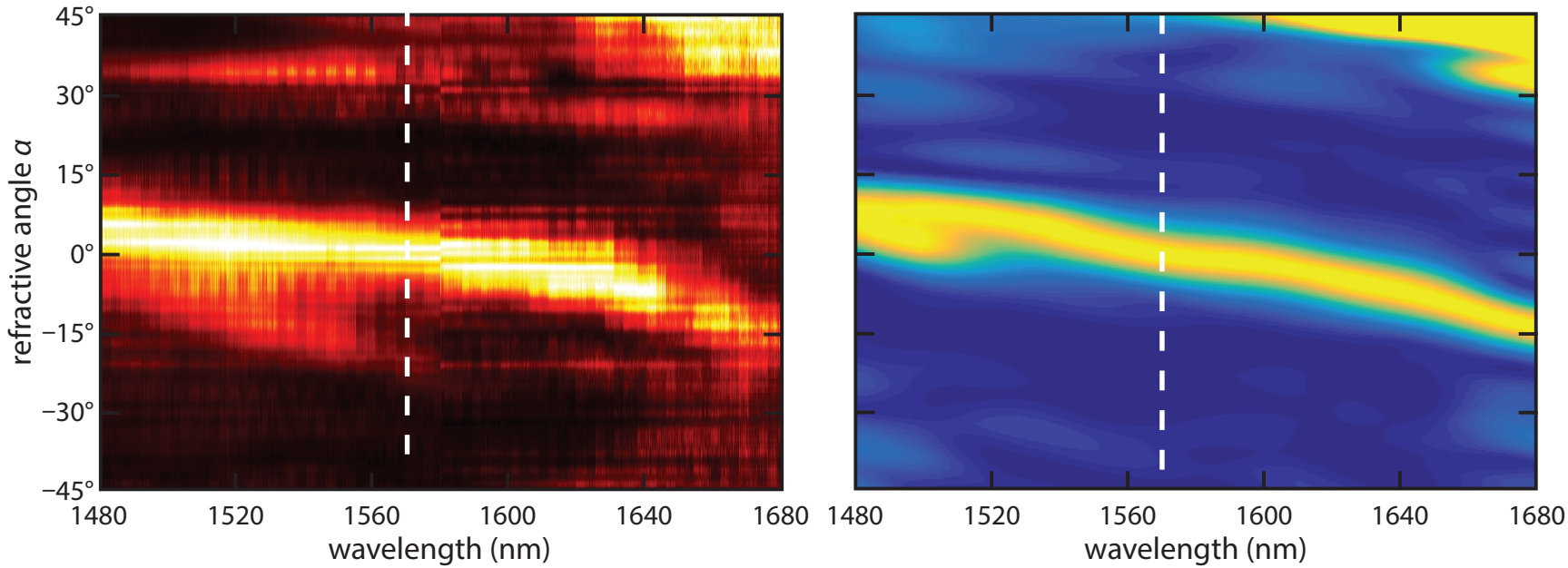
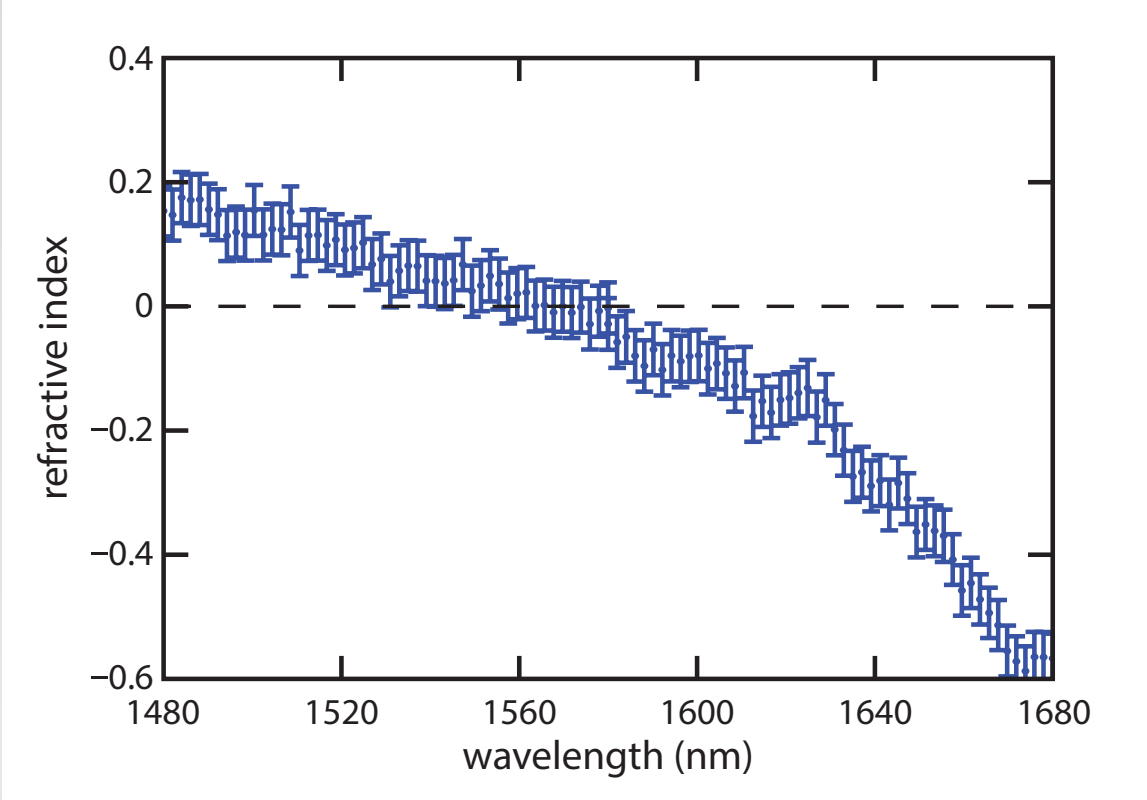


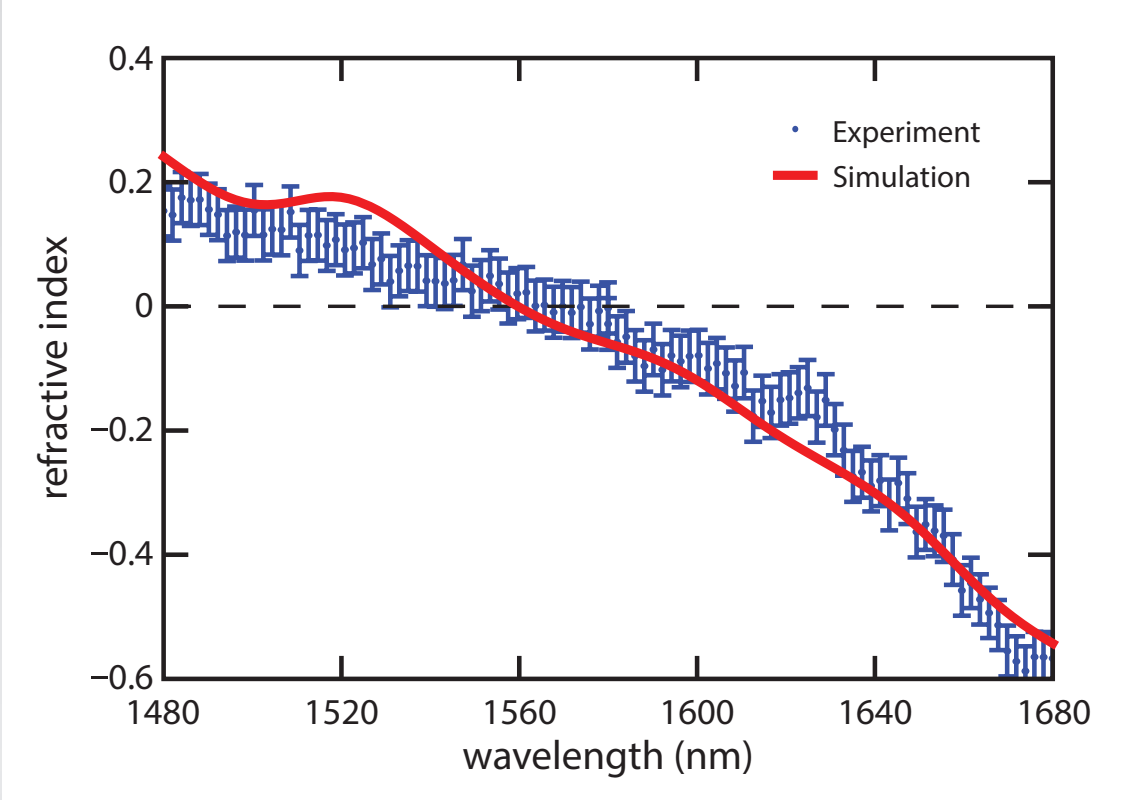
Wavelength dependence of refraction angle



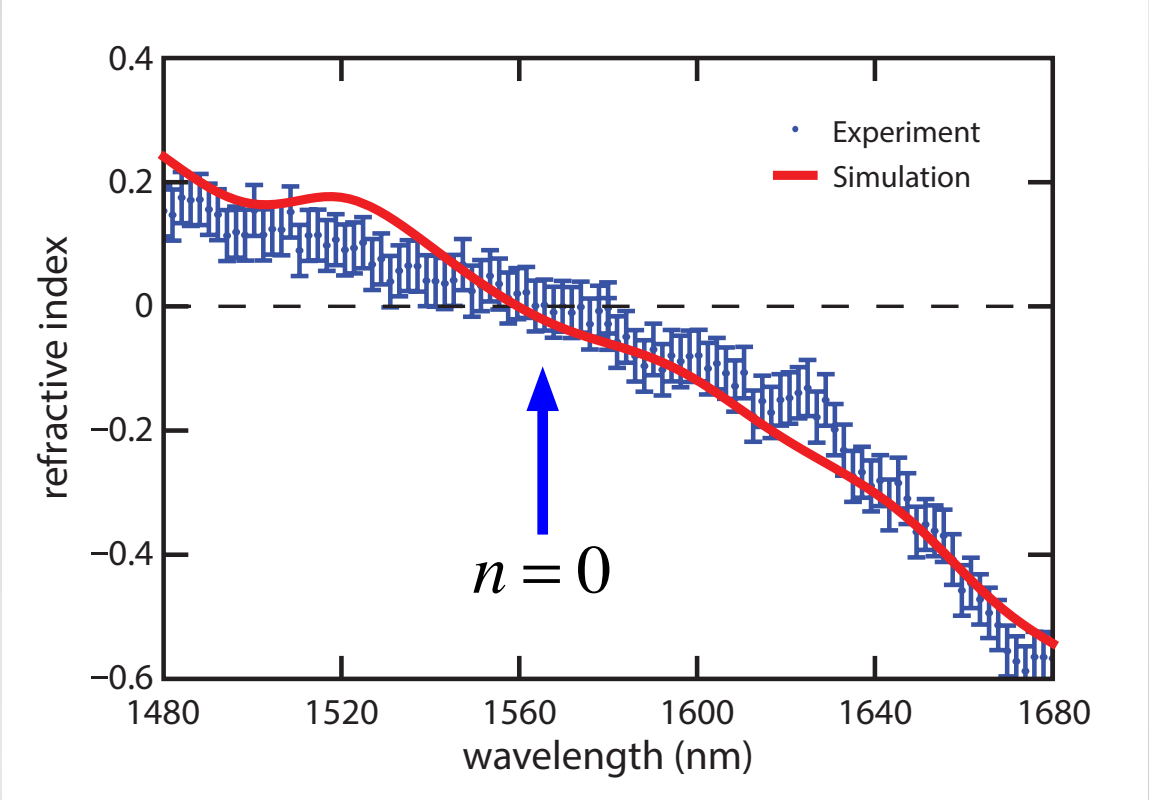
Wavelength dependence of index



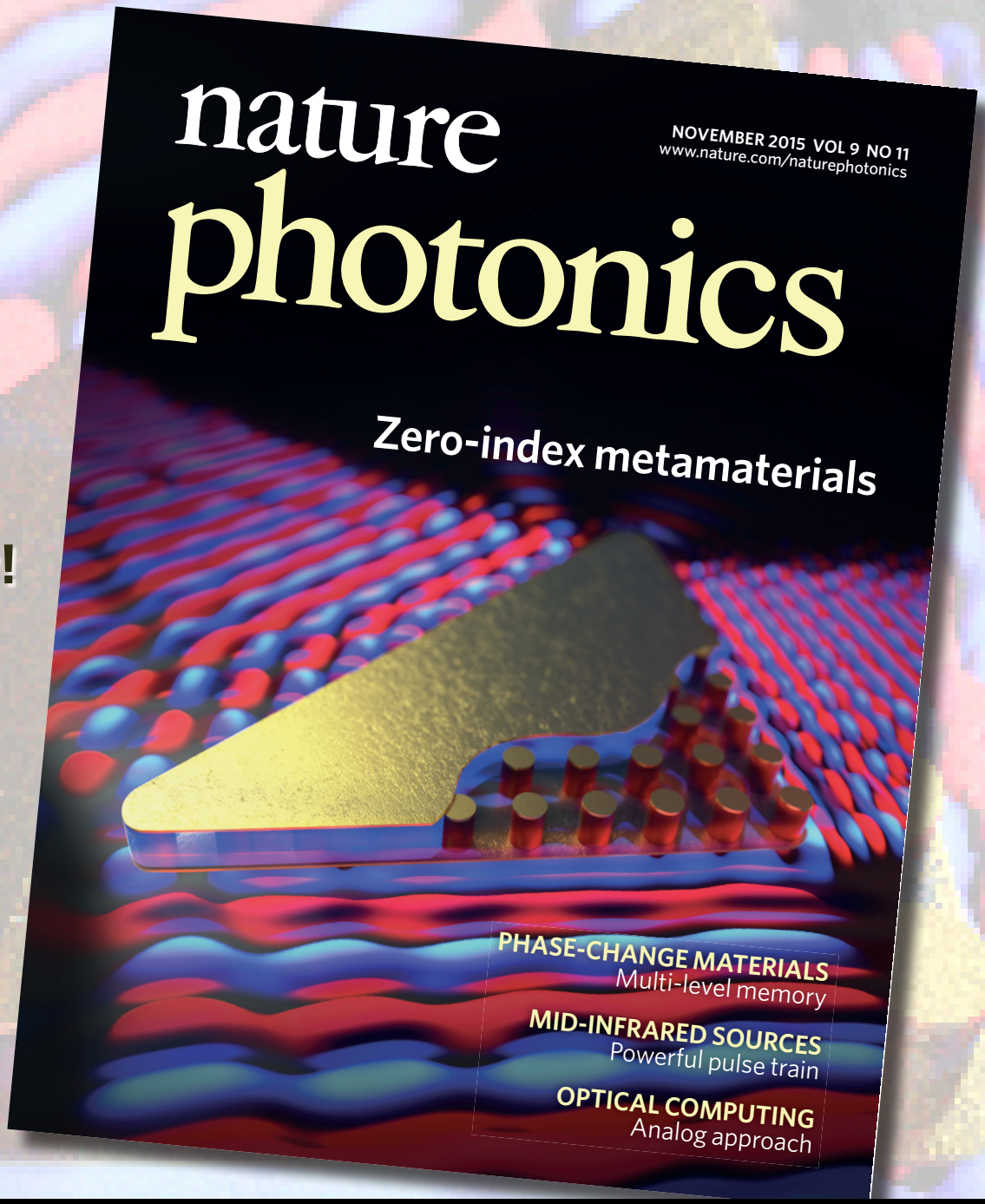
Wavelength dependence of index



Wavelength dependence of index



More info: download paper!



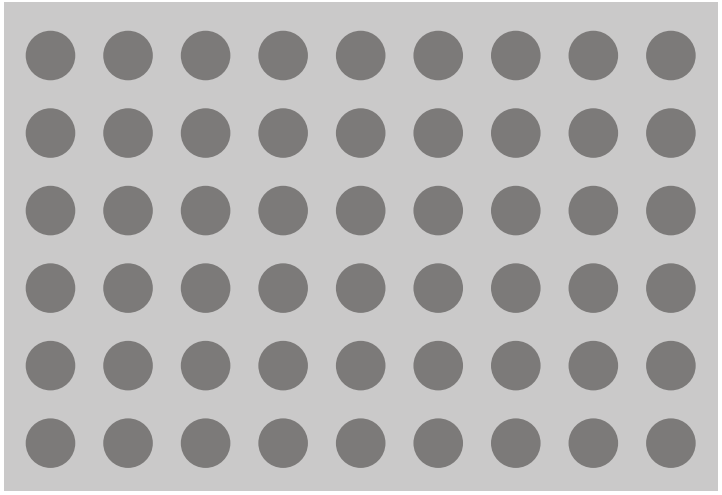
1 zero index

2 fabrication

3 results

simplify fabrication

pillar array



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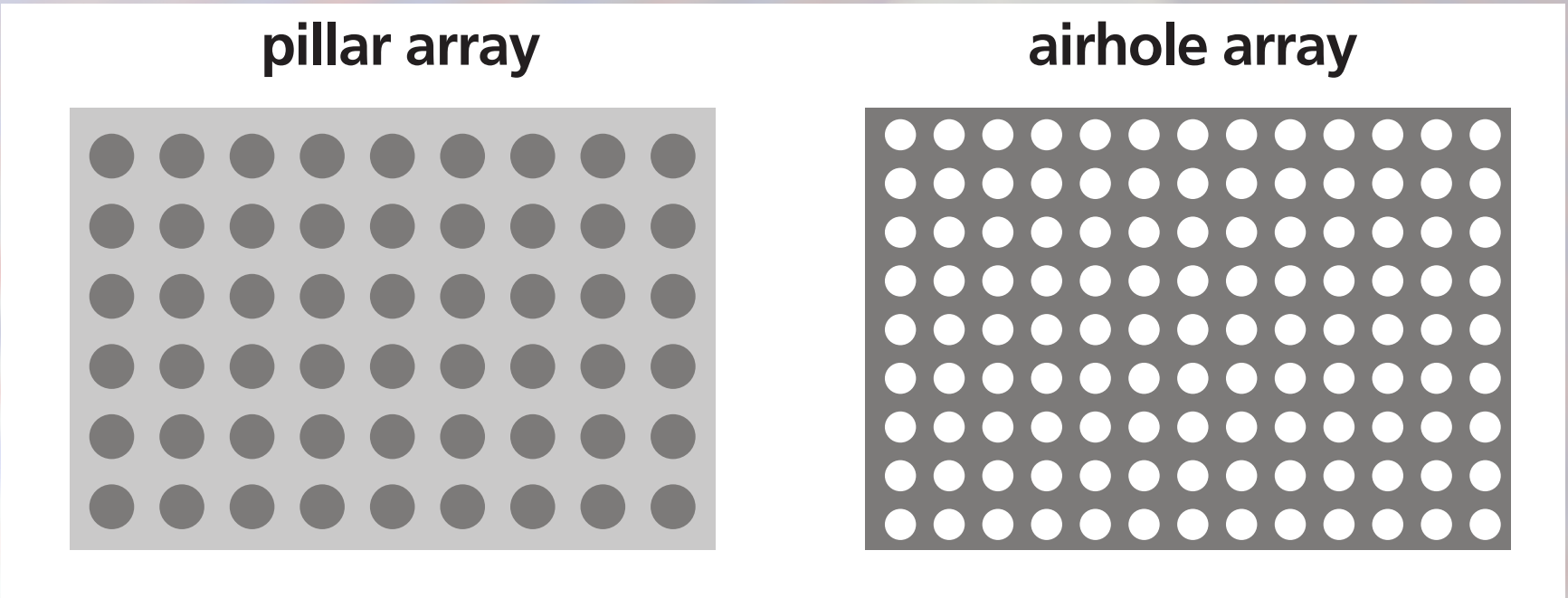
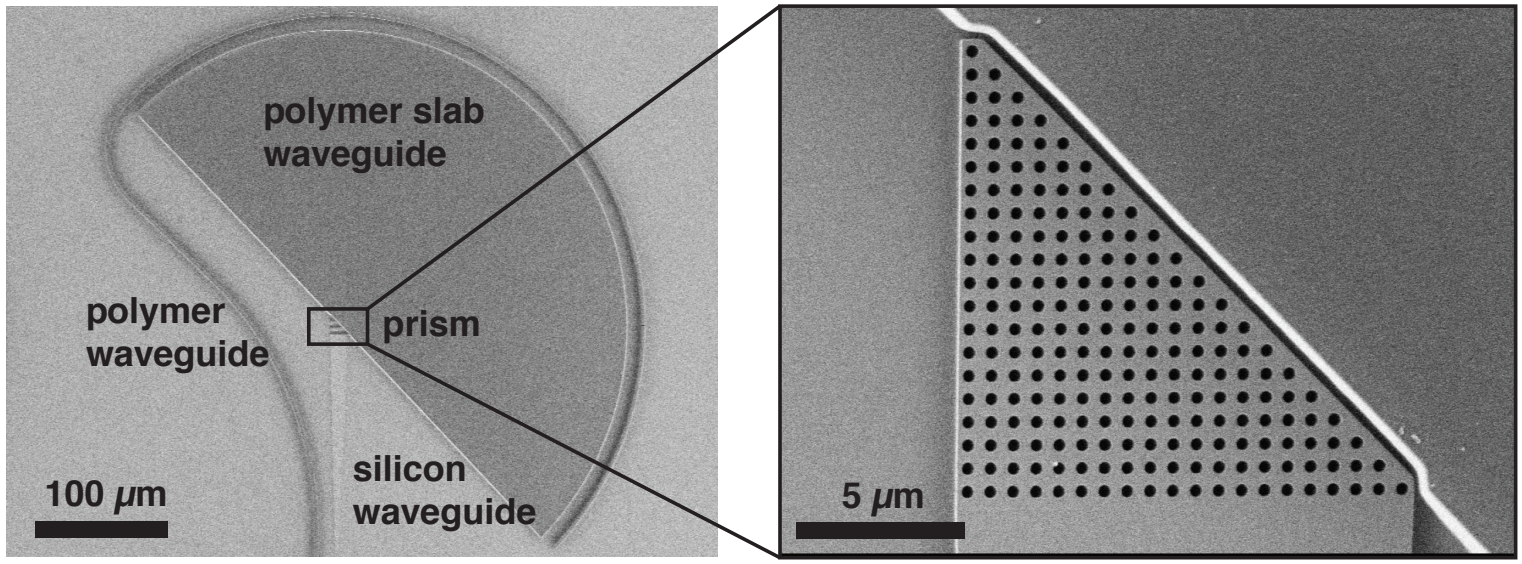
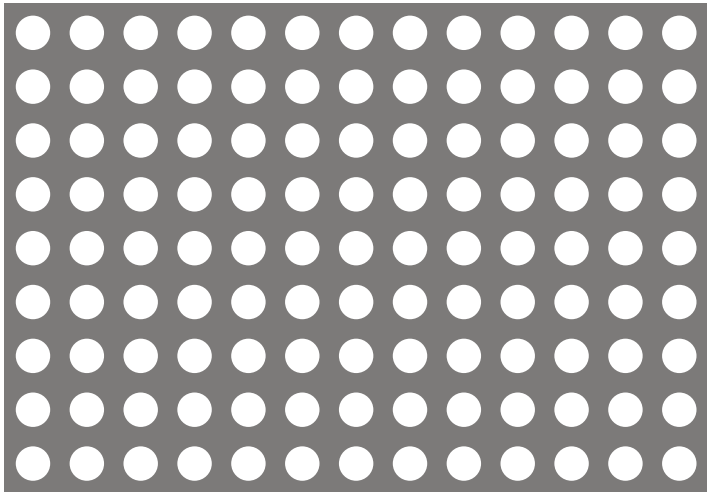


simplify fabrication



simplify further!

airhole array



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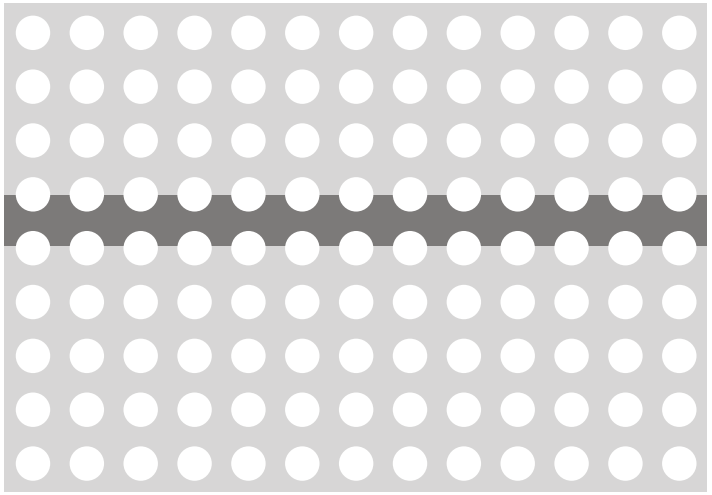

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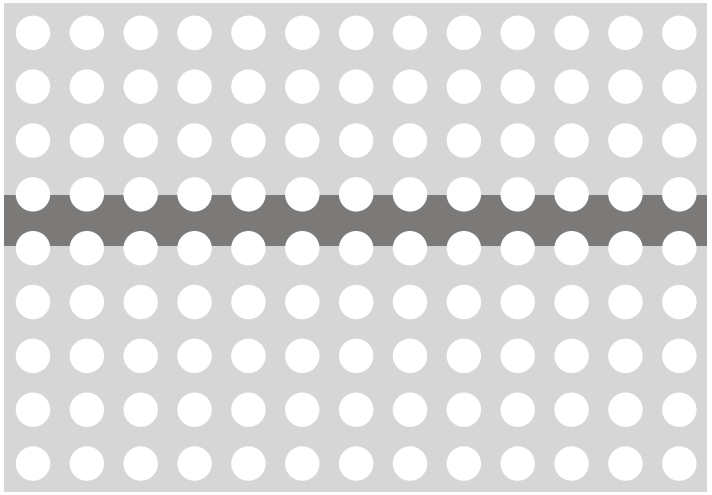
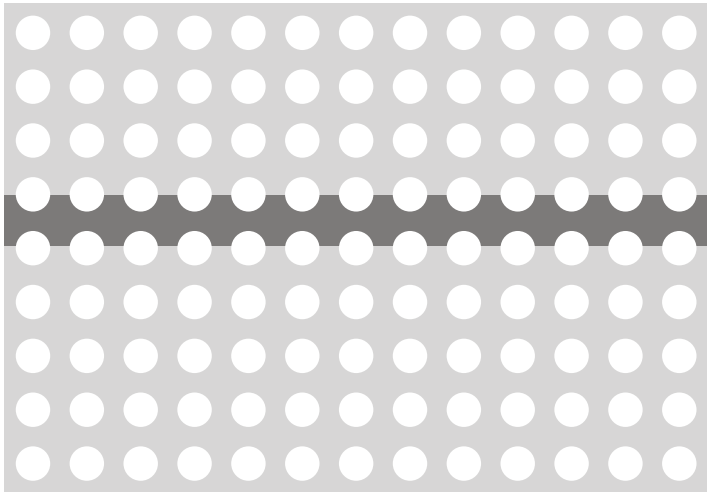


1D ZIM waveguide

simplify further!

airhole array



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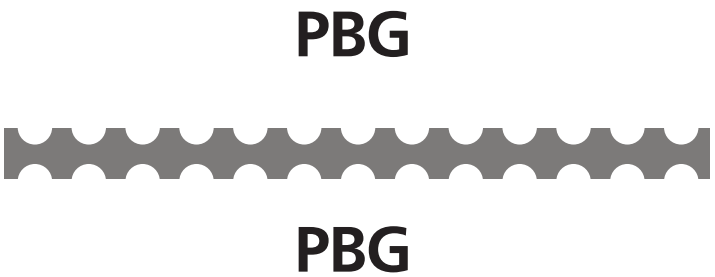
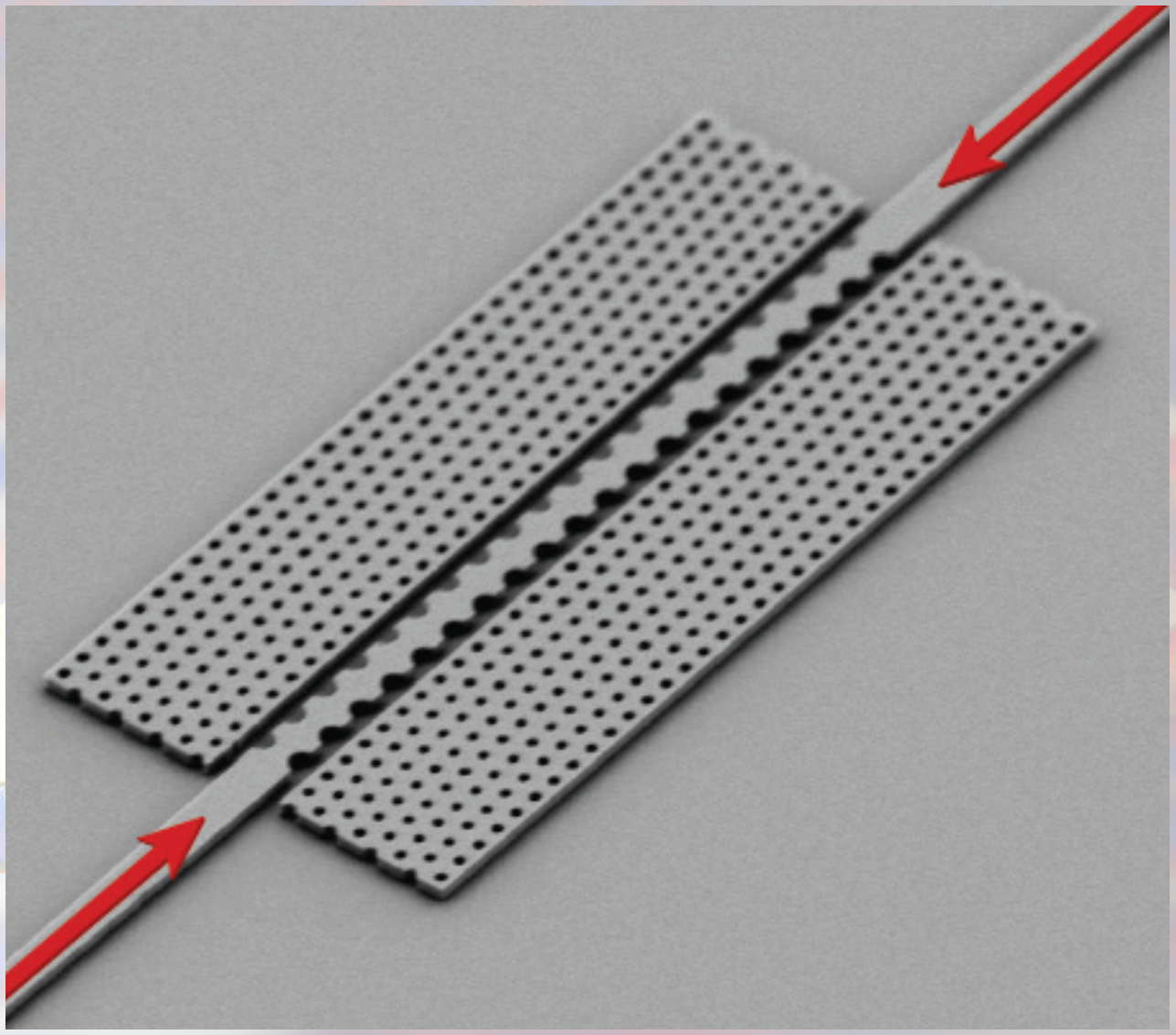


look at standing waves



1 zero index 2 fabrication 3 results

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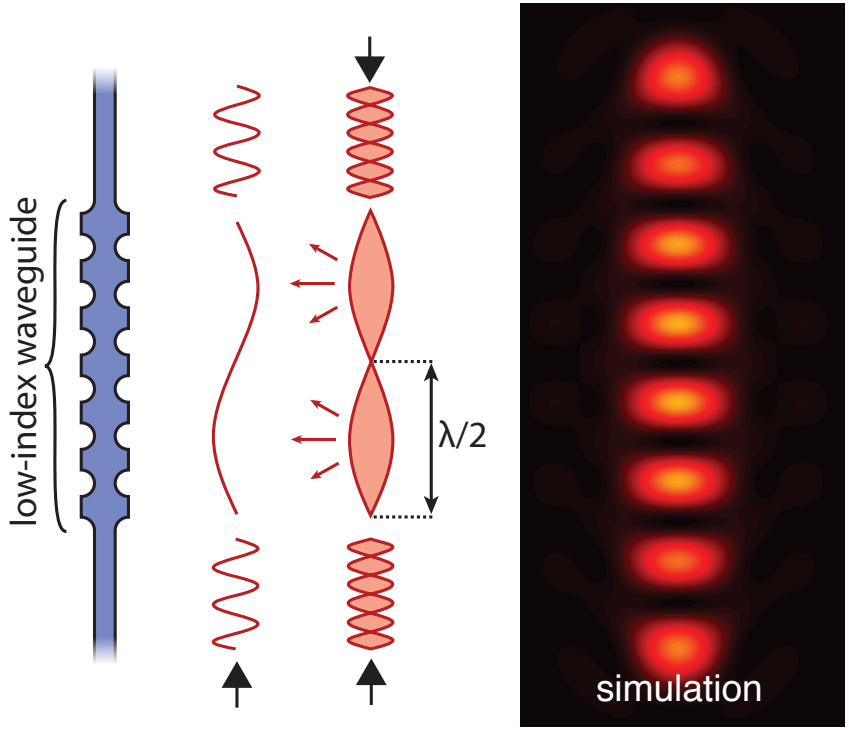

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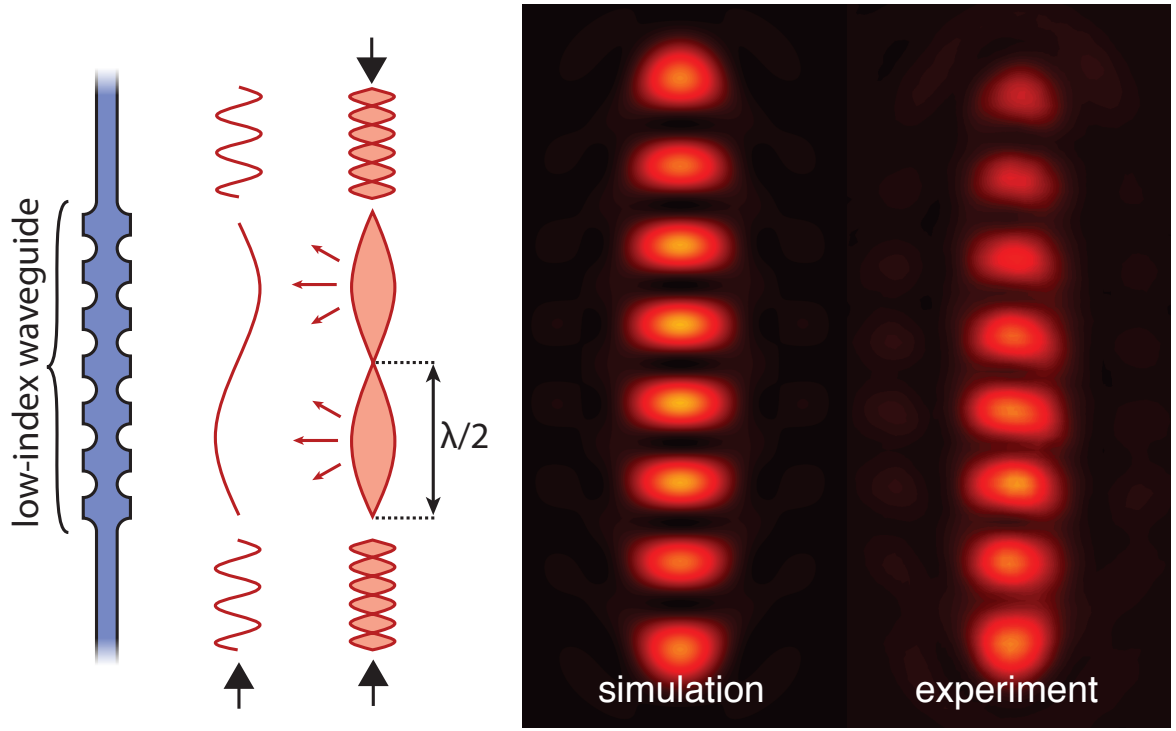
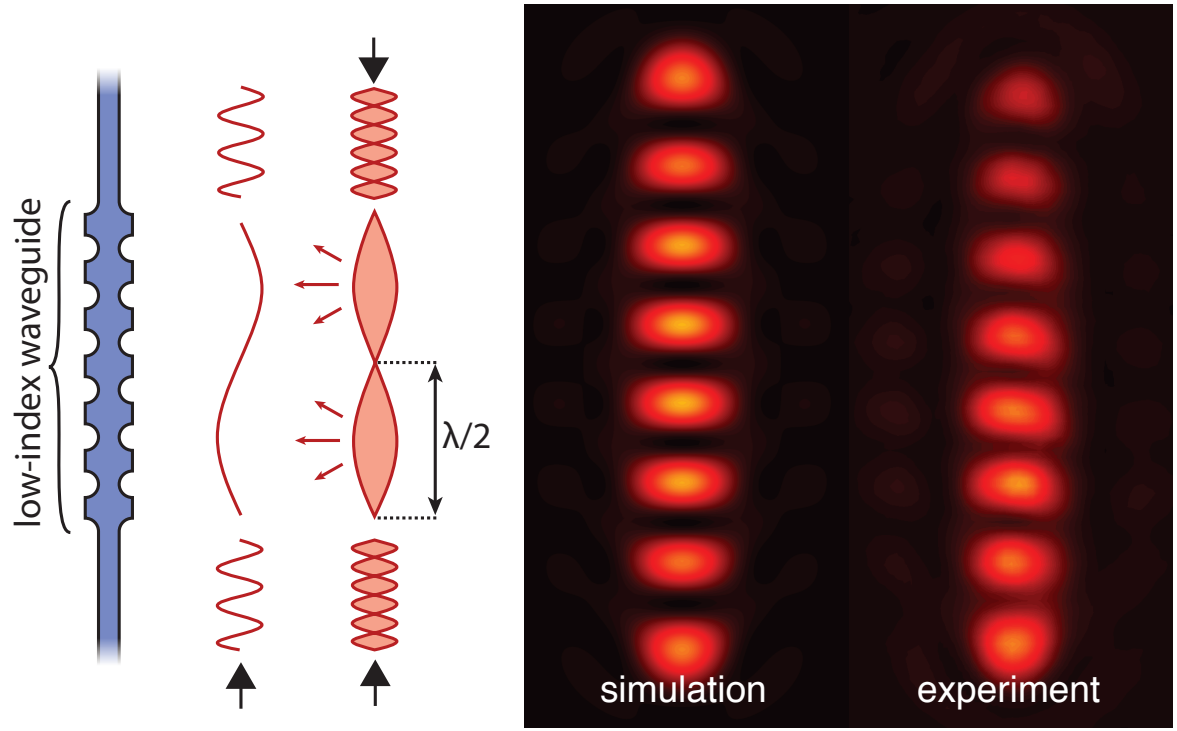
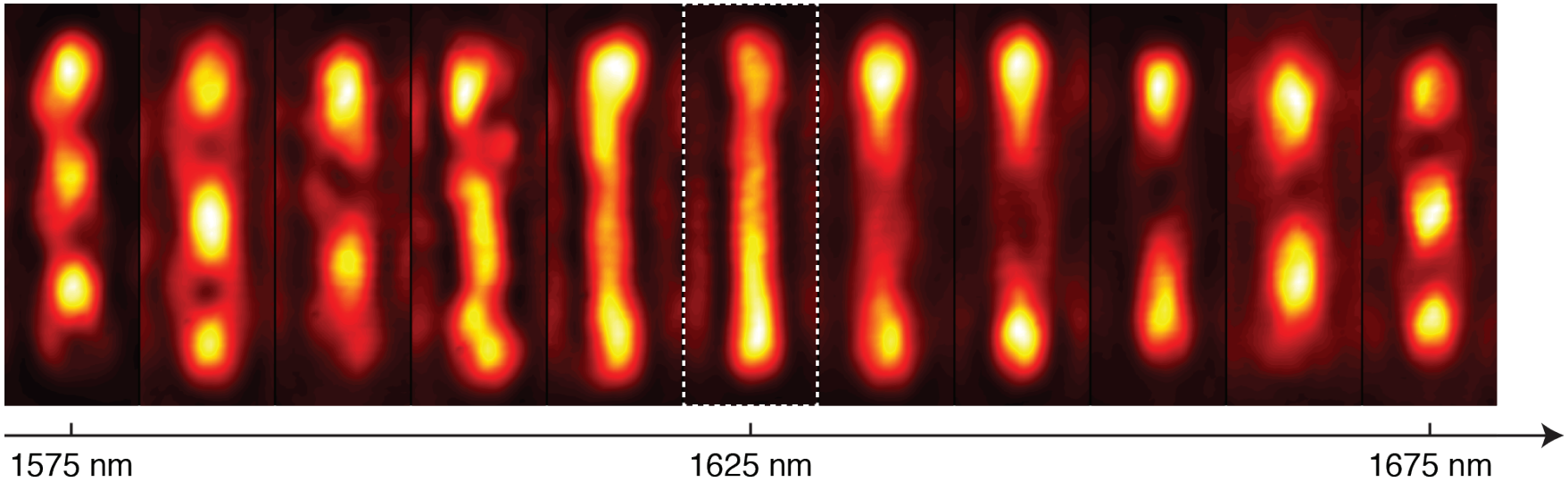


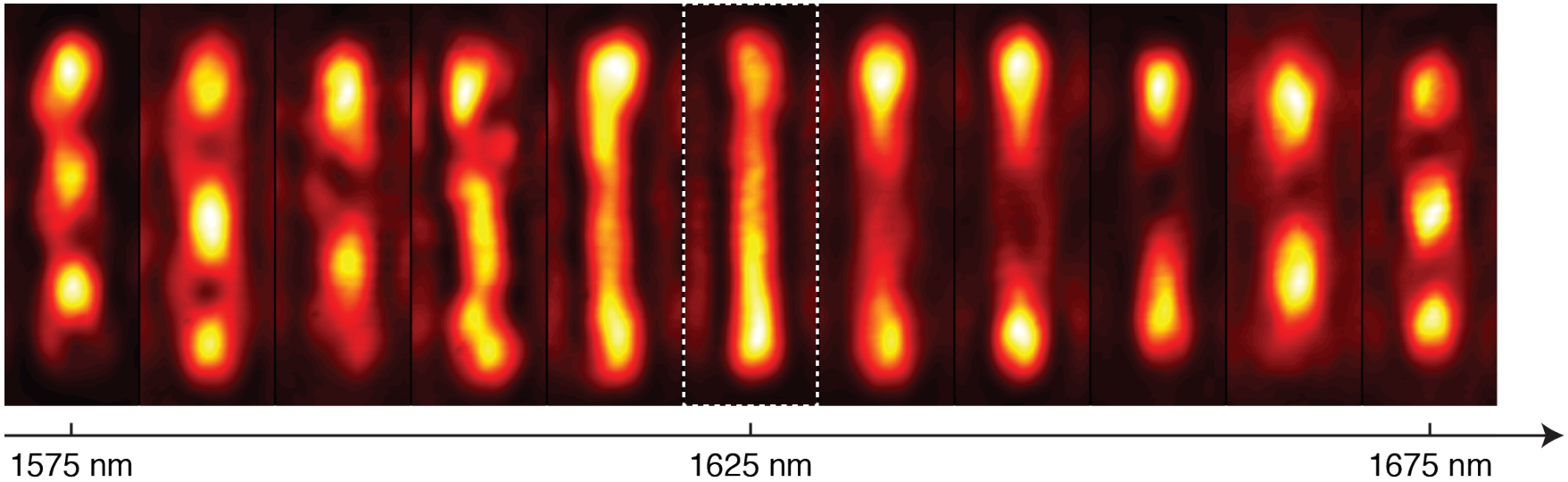
direct observation of effective wavelength!!



look at standing waves

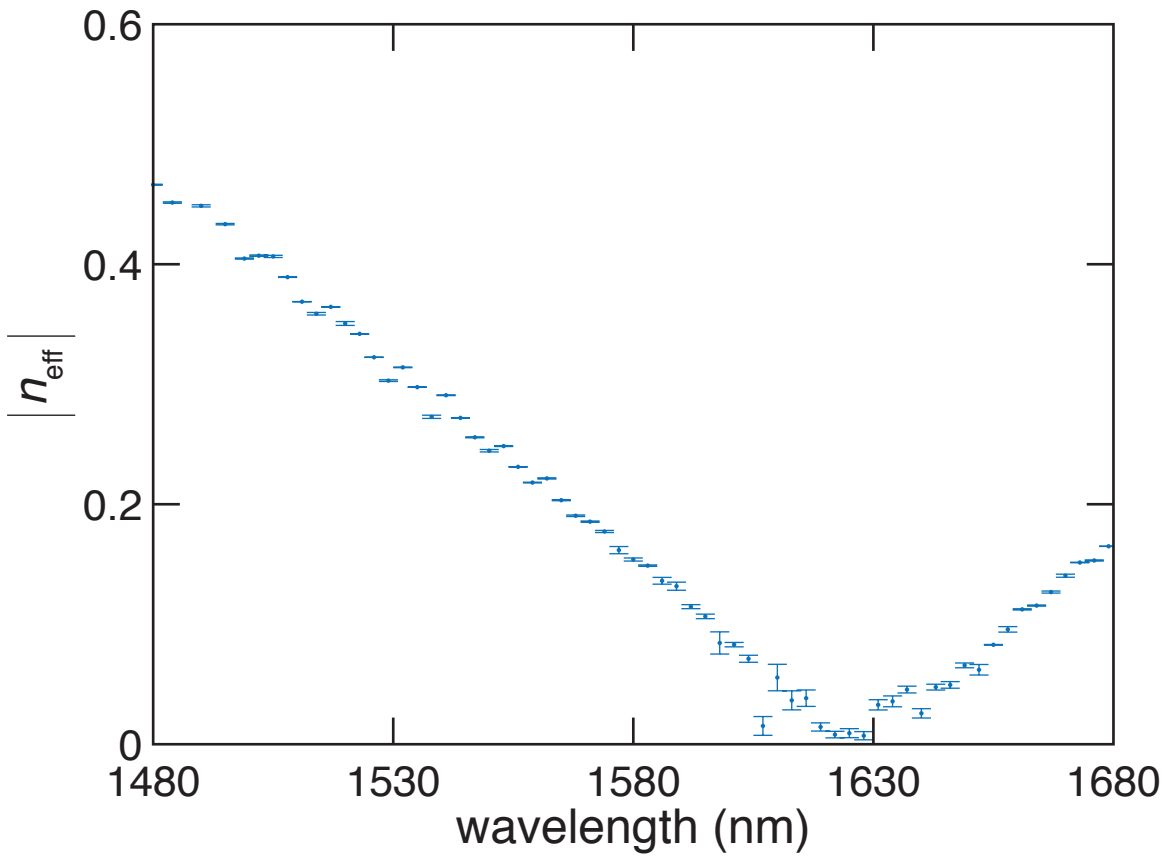


look at standing waves



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

comparison of experiment and simulation



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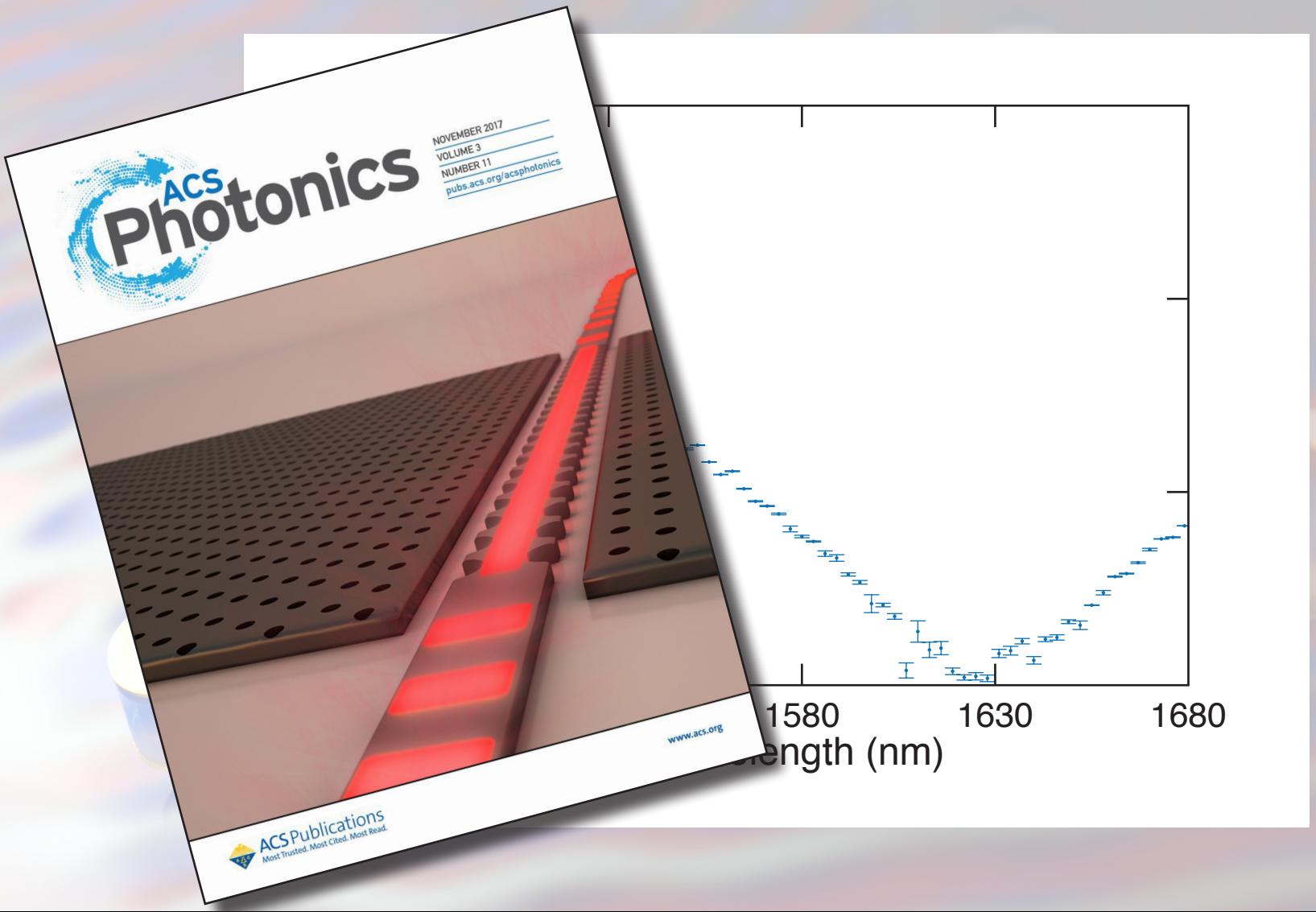

1 zero index

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Exciting applications ahead

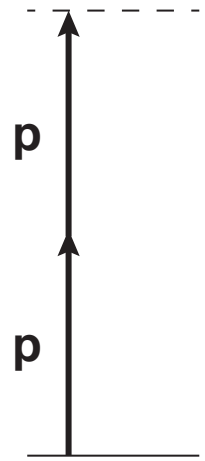
$$n = 0$$

1 zero index 2 fabrication 3 results

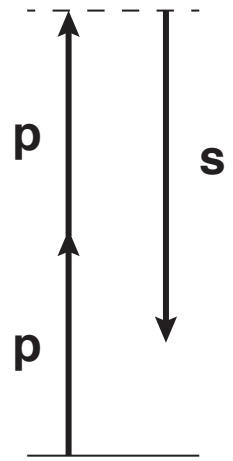
Exciting applications ahead

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

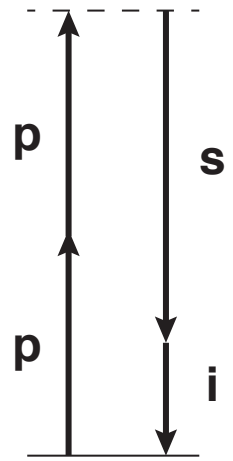
four-wave mixing



four-wave mixing



four-wave mixing



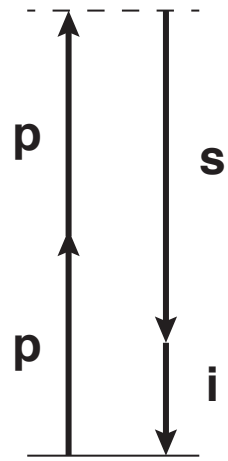
four-wave mixing

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

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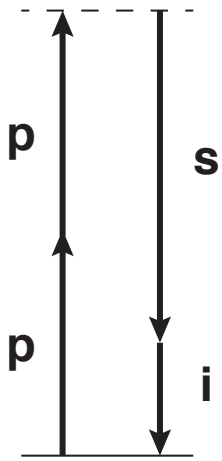
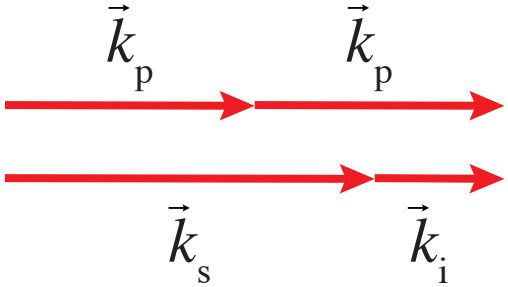


momentum conservation

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

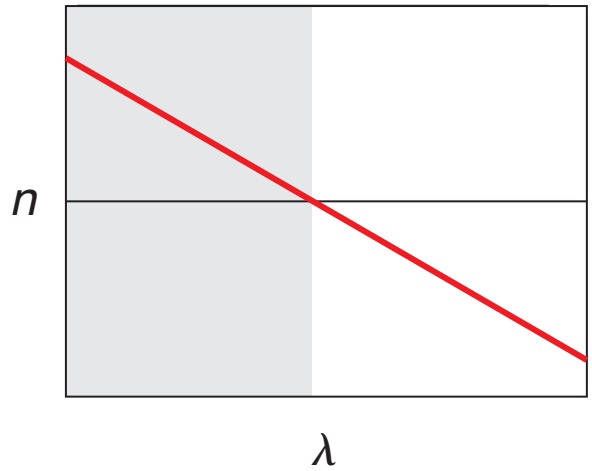


phase matching

four-wave mixing

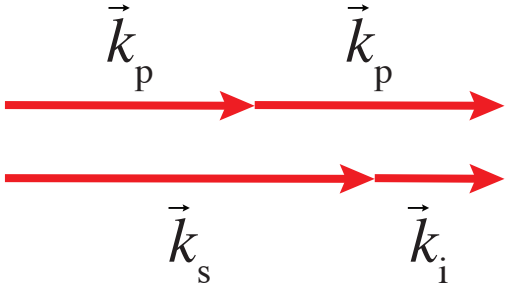
energy conservation

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



momentum conservation

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

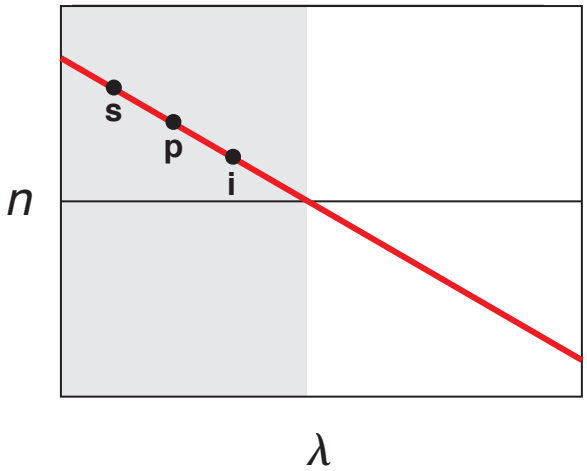


phase matching

four-wave mixing

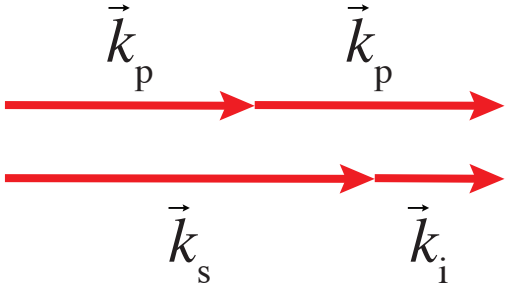
energy conservation

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



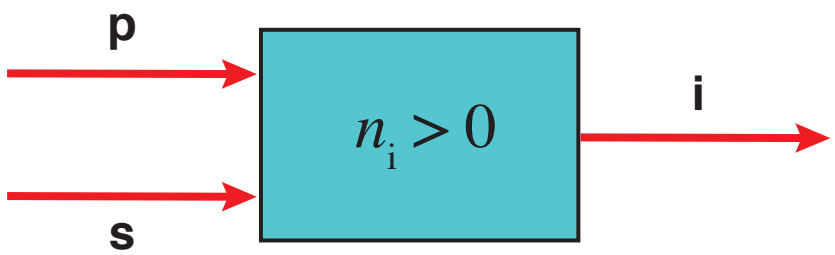
momentum conservation

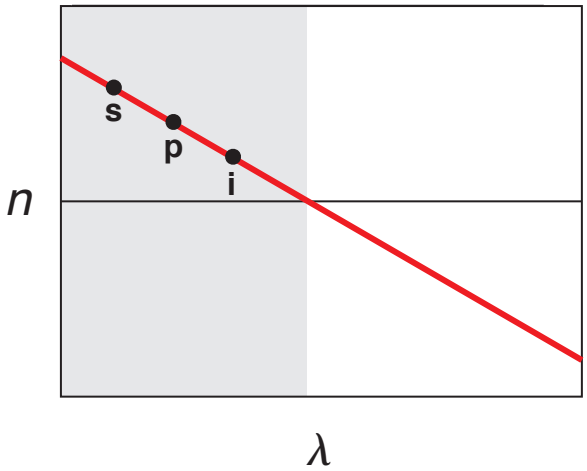
$$\Delta k = 2\vec{k}_p - \vec{k}_s - \vec{k}_i = 0$$

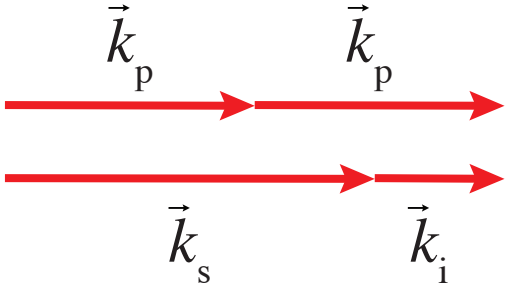


phase matching

four-wave mixing

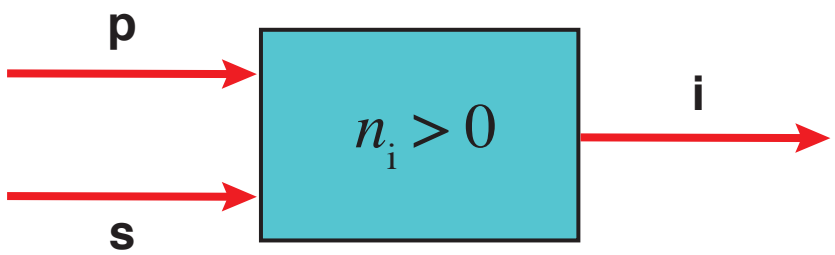


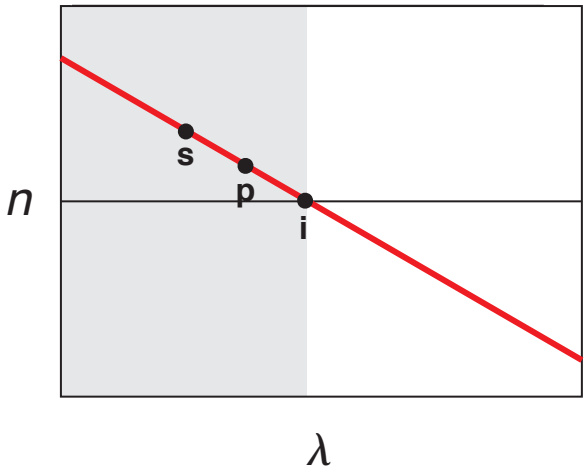


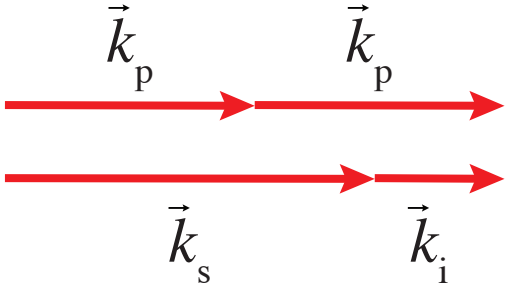


phase matching

four-wave mixing

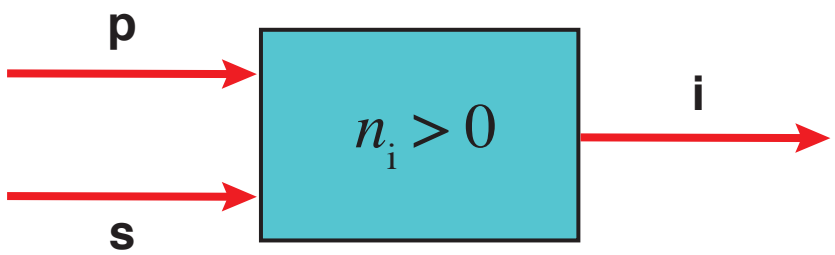


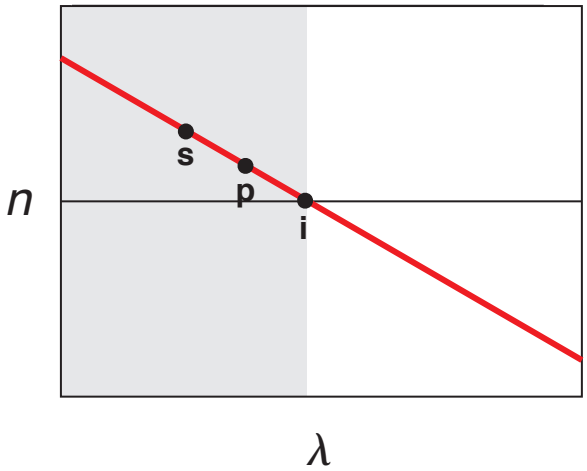


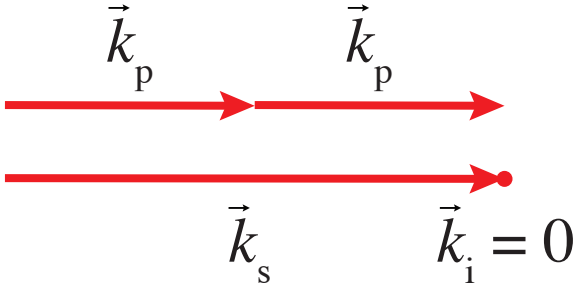


phase matching

four-wave mixing

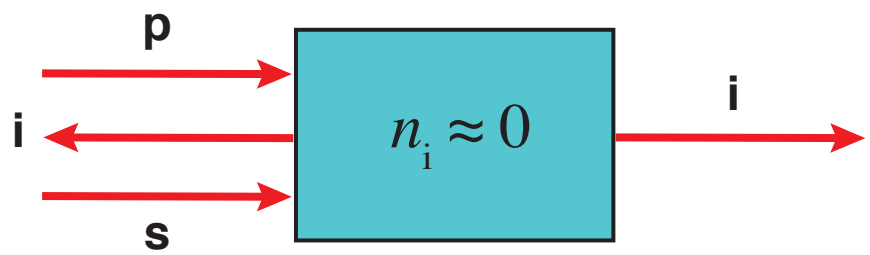




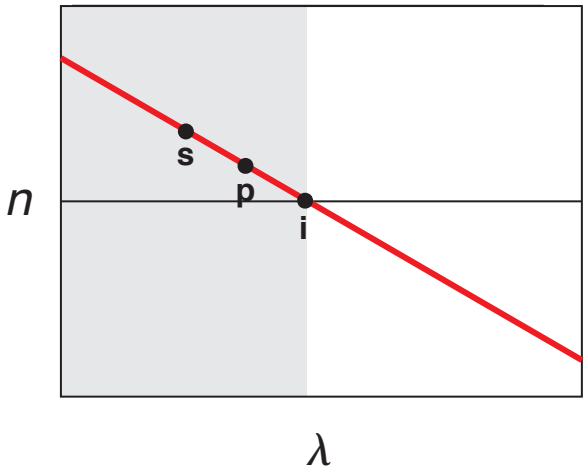


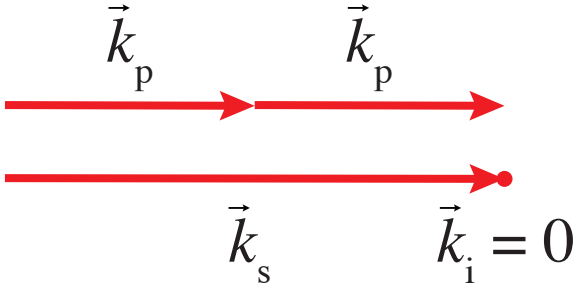
phase matching

four-wave mixing



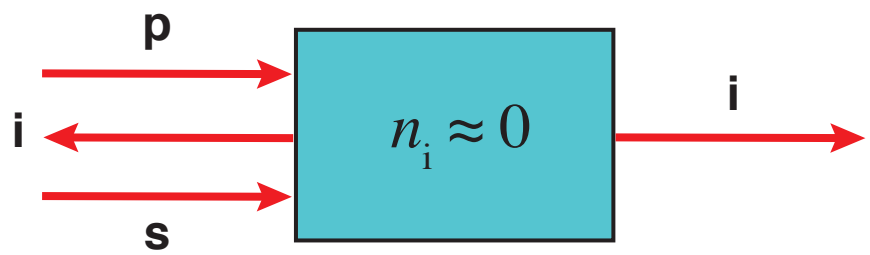
forward and backward



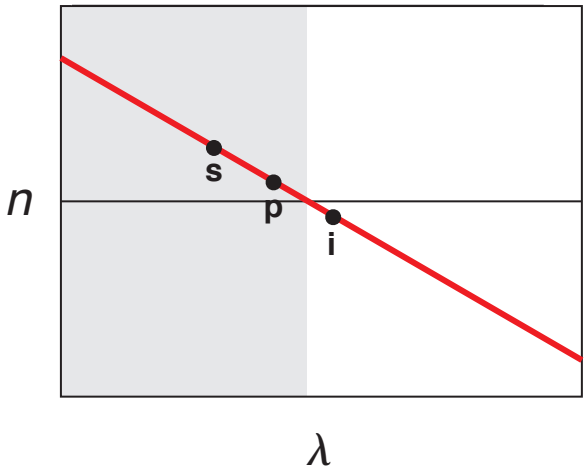


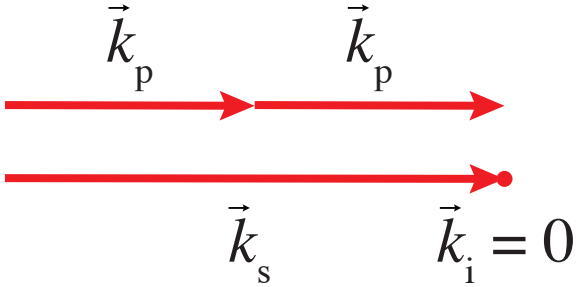
phase matching

four-wave mixing



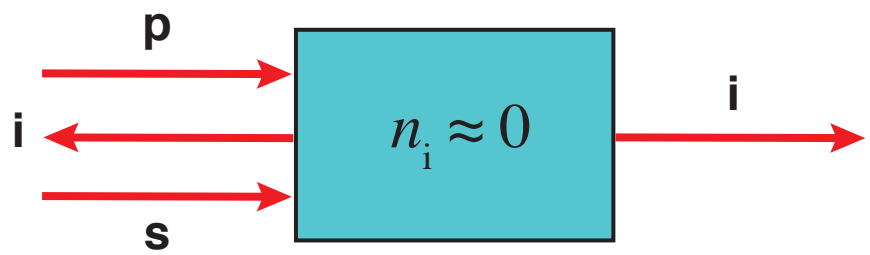
forward and backward



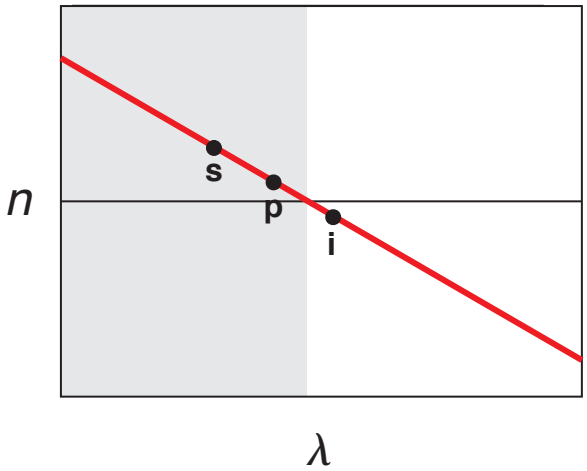


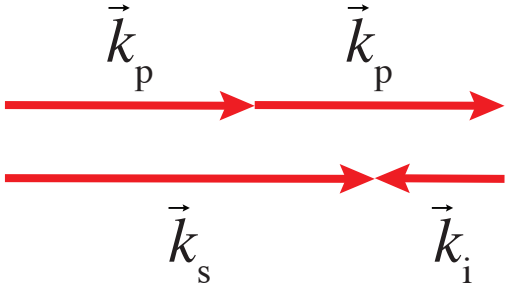
phase matching

four-wave mixing



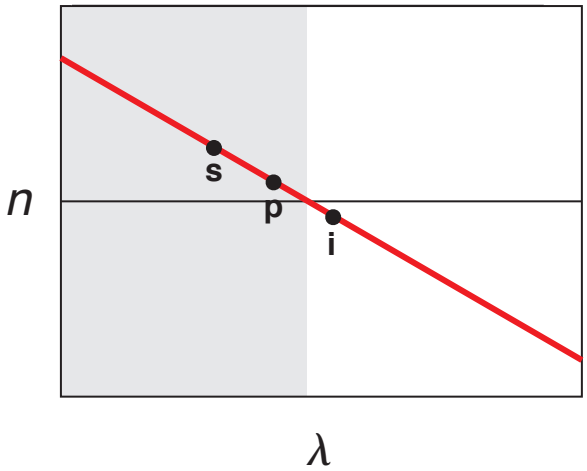
forward and backward

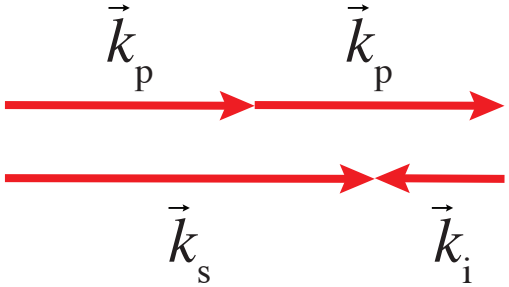




phase matching

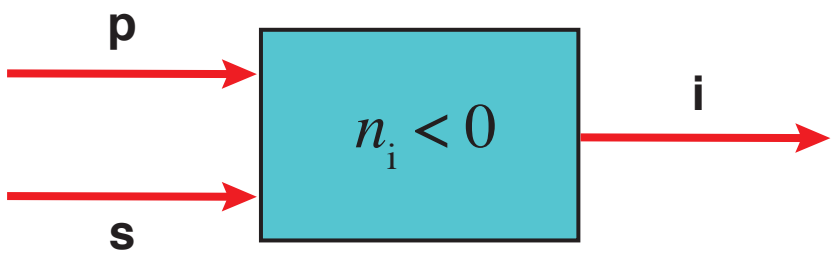
four-wave mixing



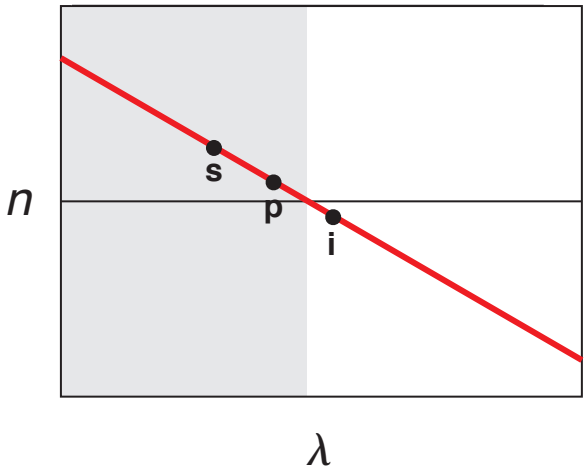


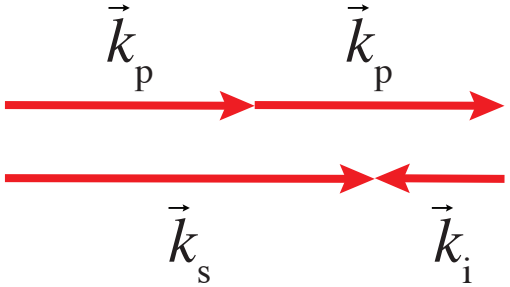
phase matching

four-wave mixing



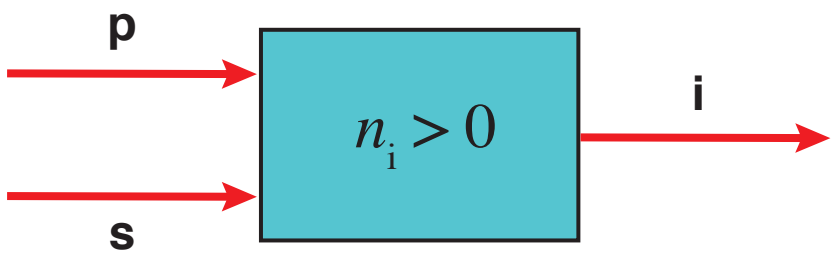
forward only

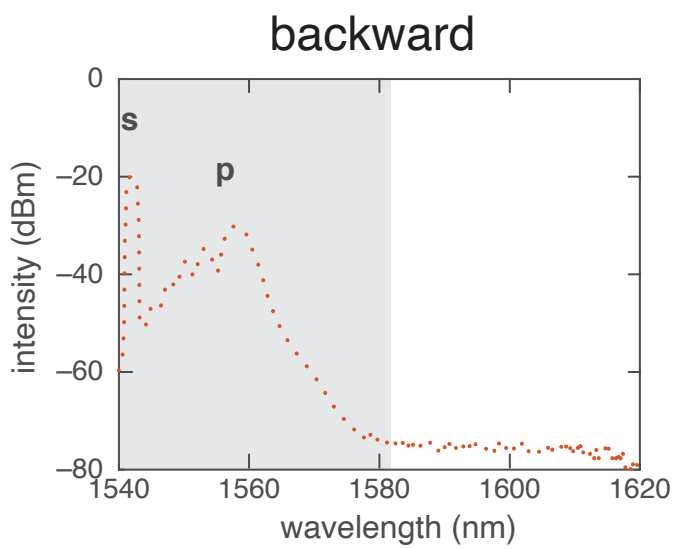


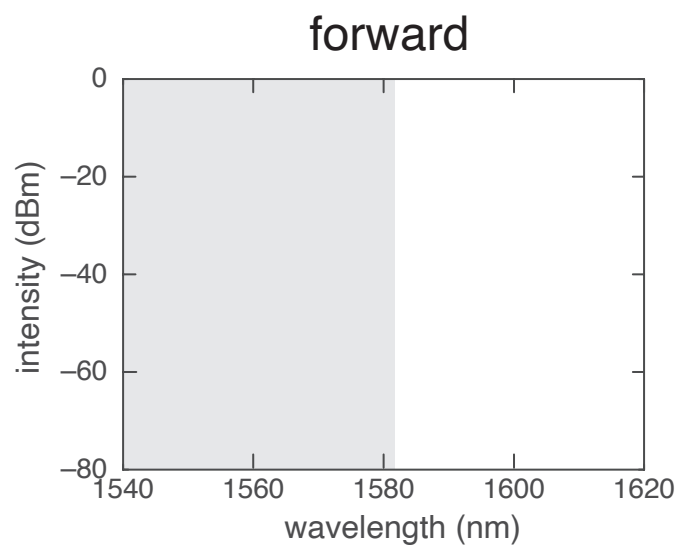


phase matching

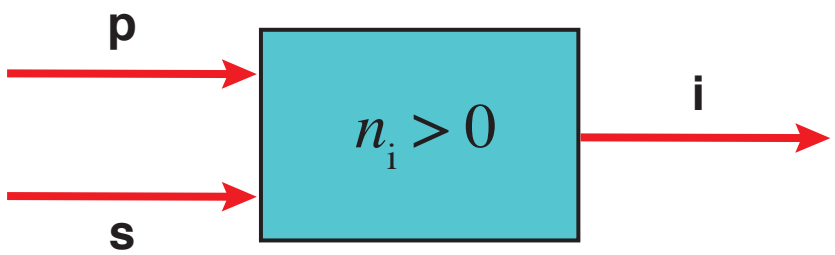
four-wave mixing

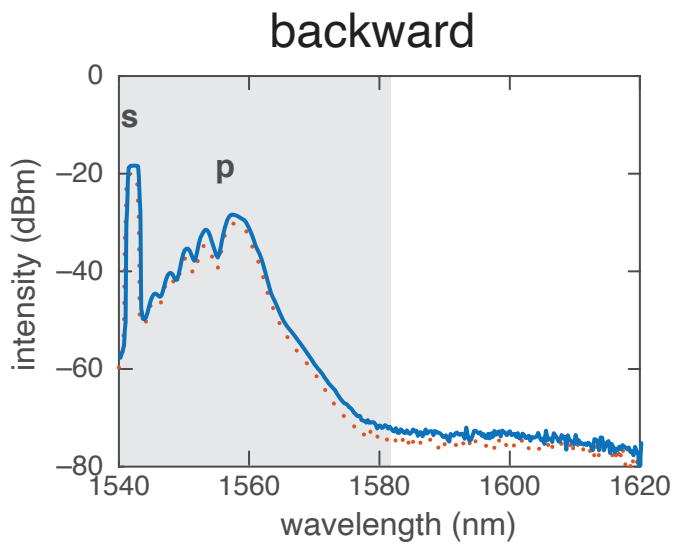


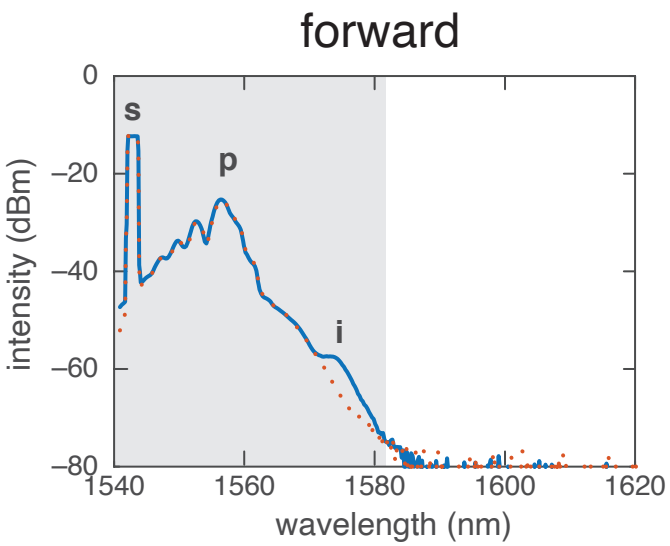




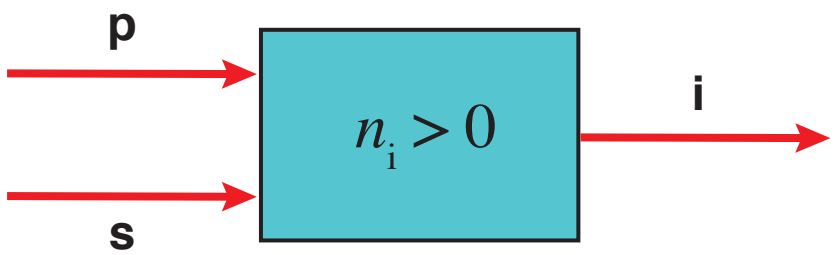
four-wave mixing

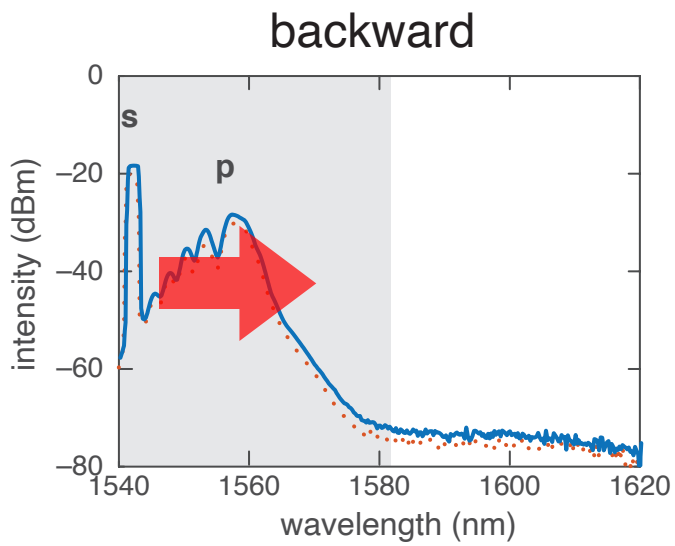


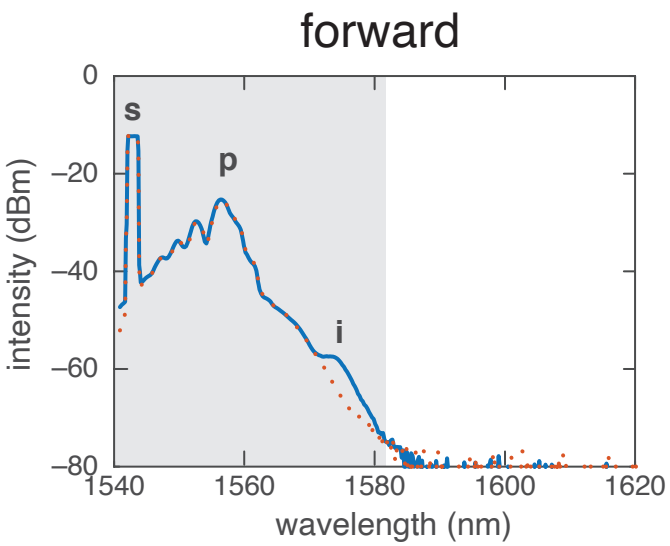




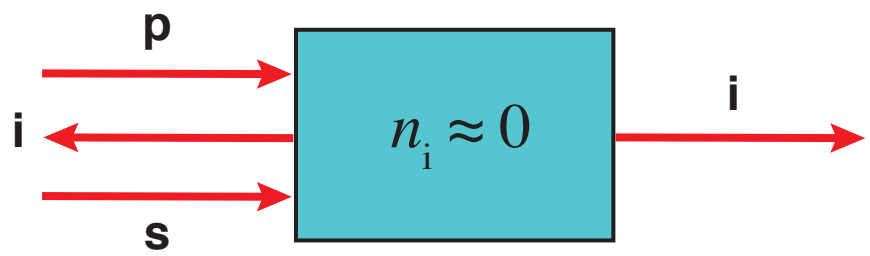
four-wave mixing



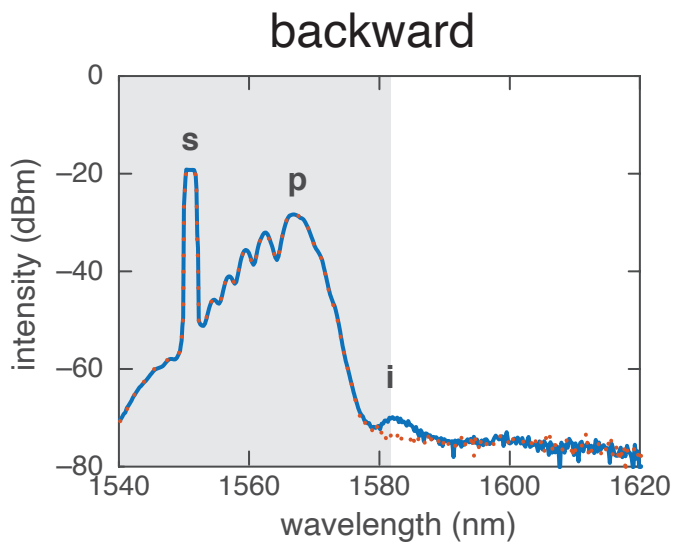


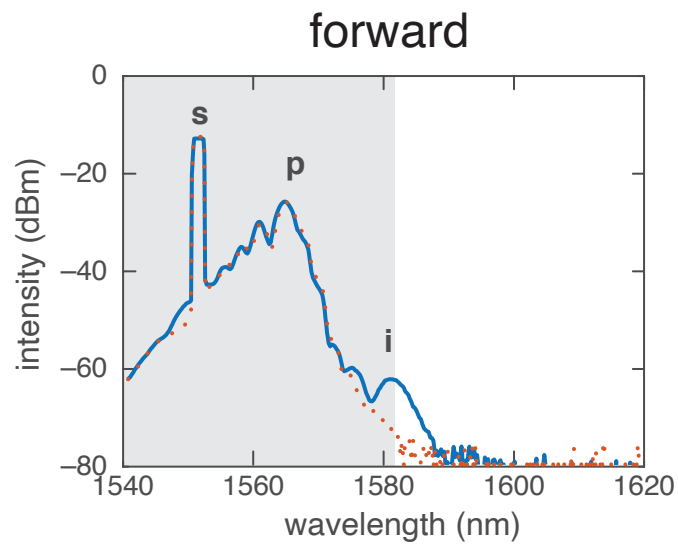


four-wave mixing

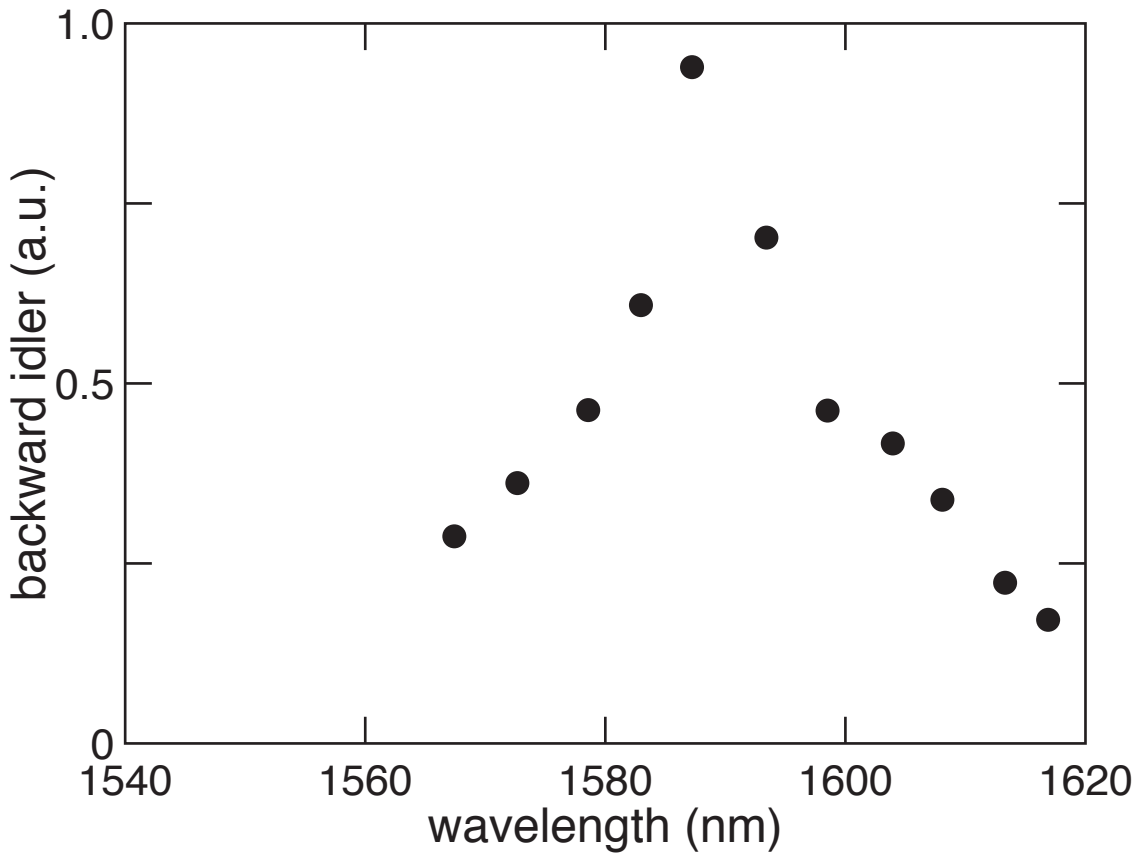


forward and backward

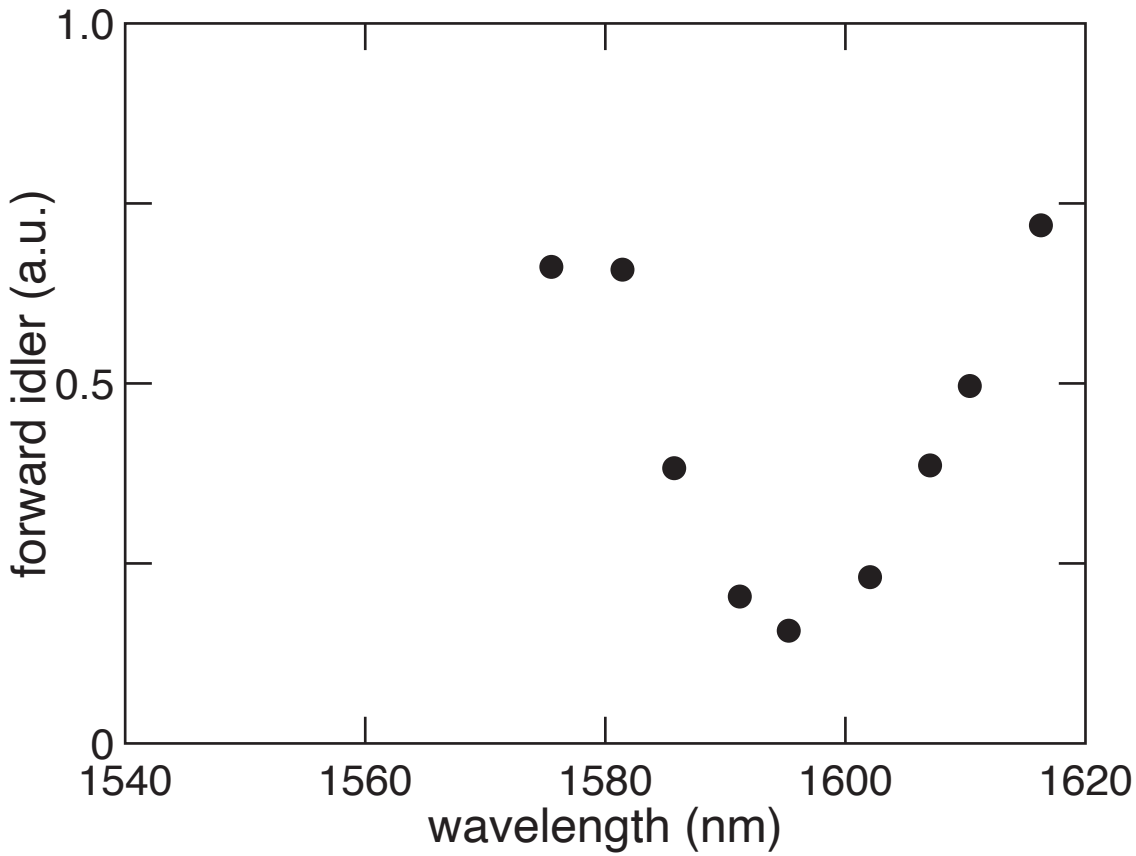




backward idler intensity



forward idler intensity



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