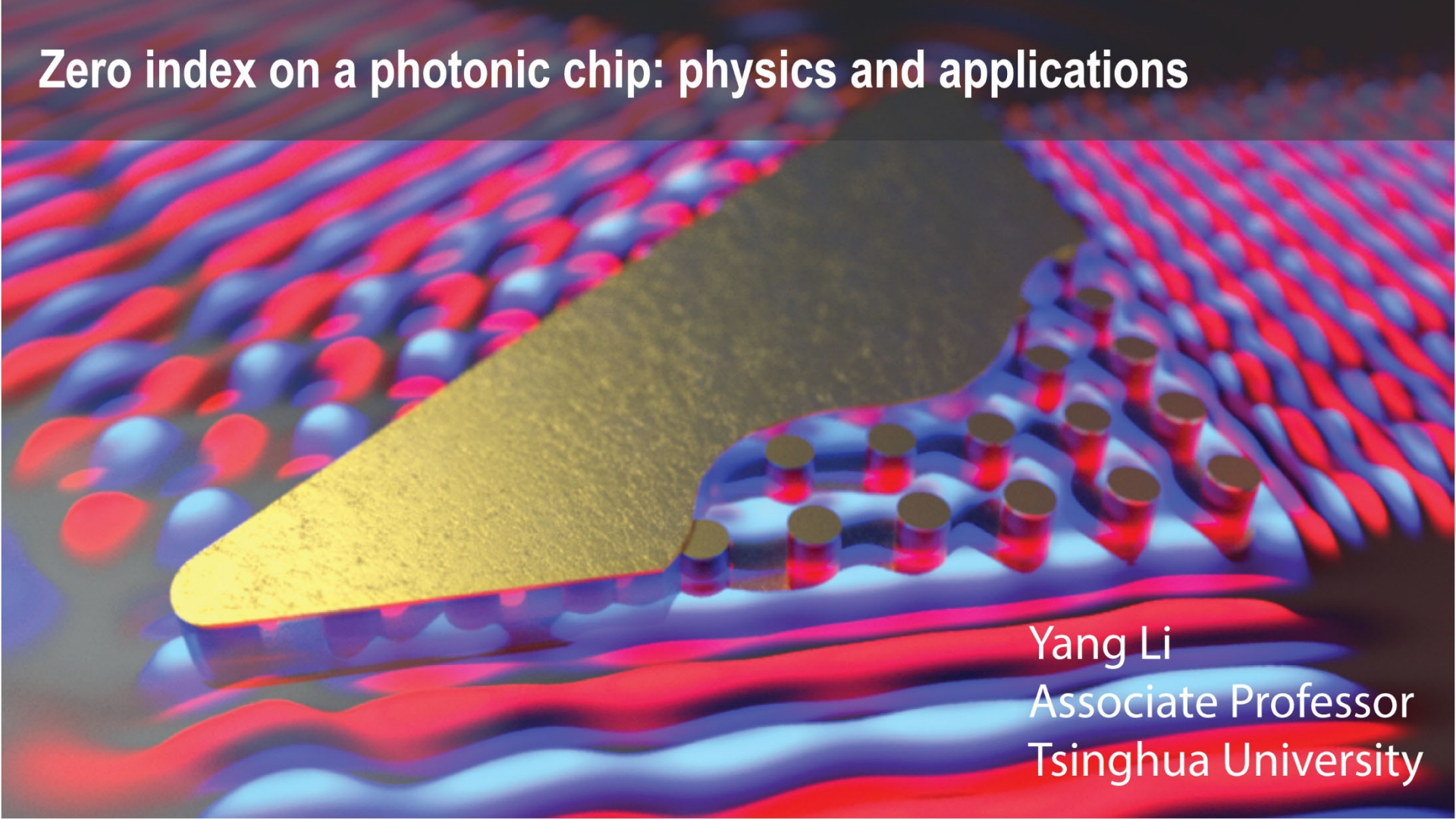
# Zero index on a photonic chip: physics and applications



Yang Li
Associate Professor
Tsinghua University

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G. Dolling, *et al.*, *Opt. Express* (2006)

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# 1 Zero index

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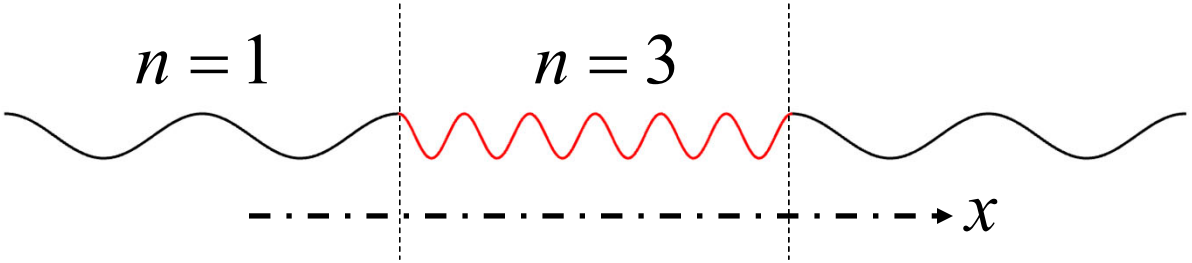

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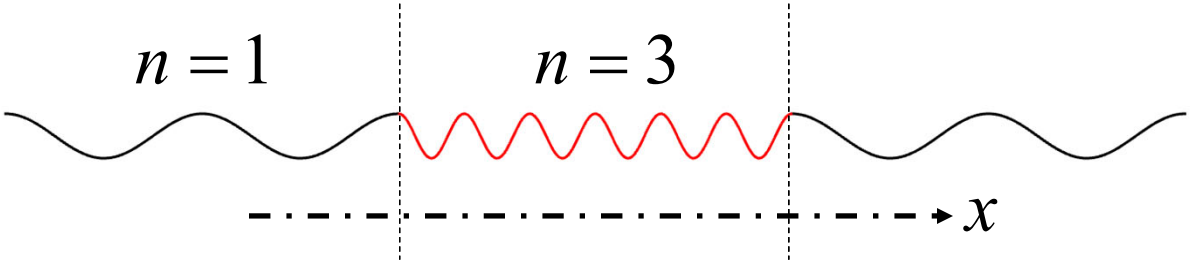


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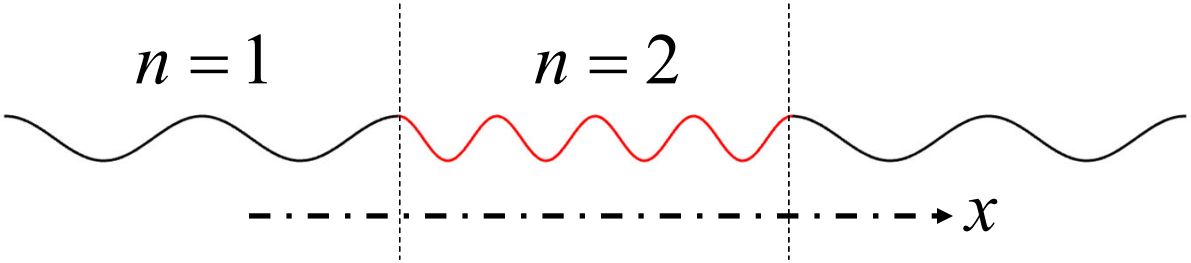


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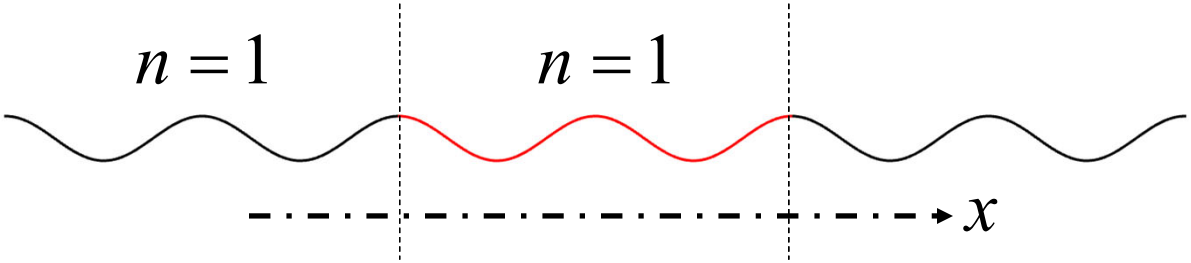


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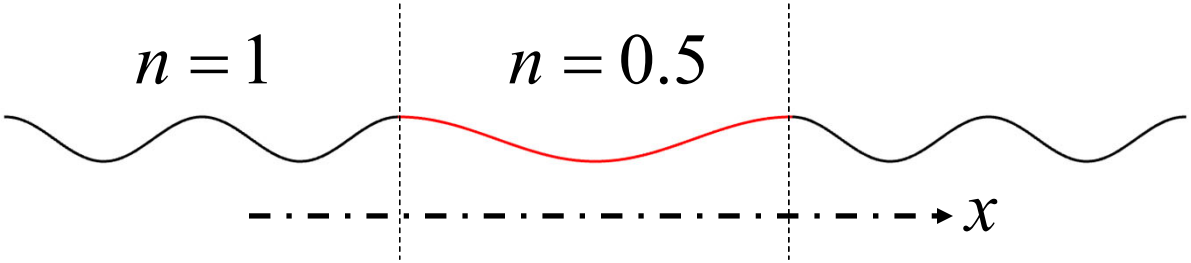


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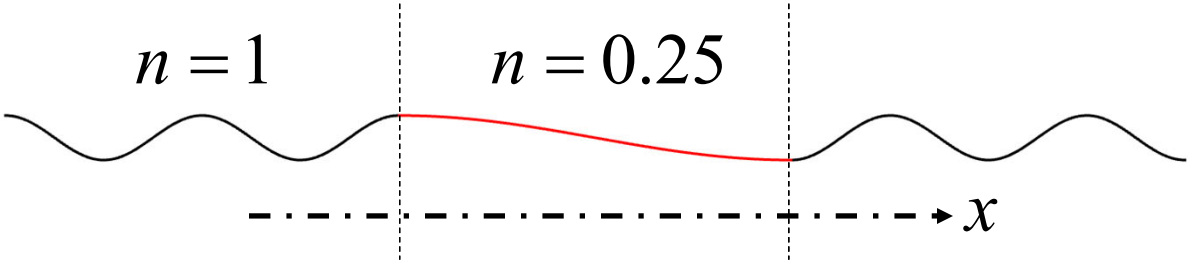


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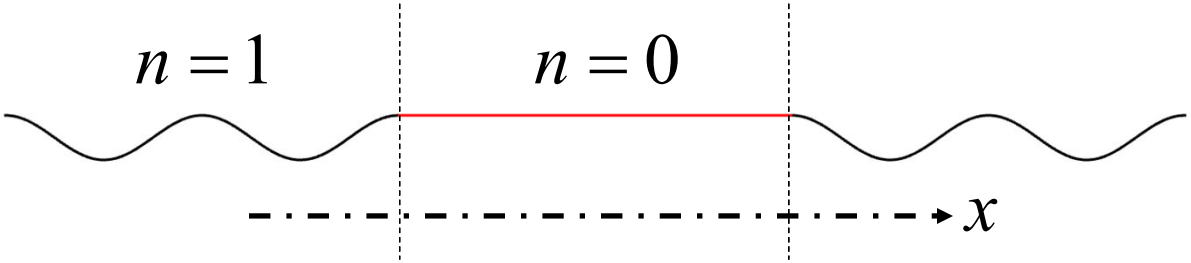


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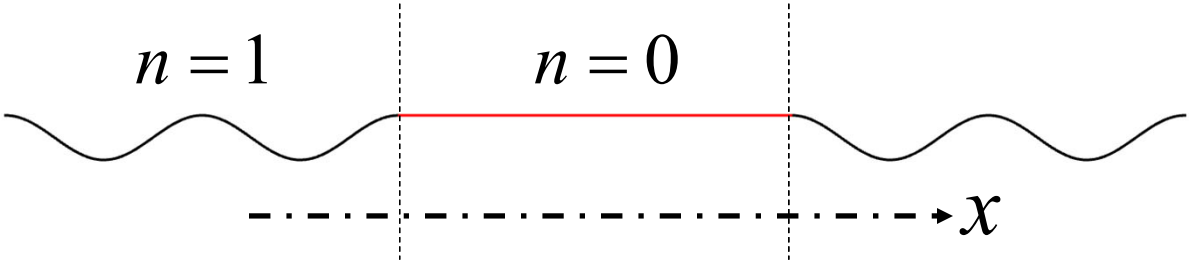


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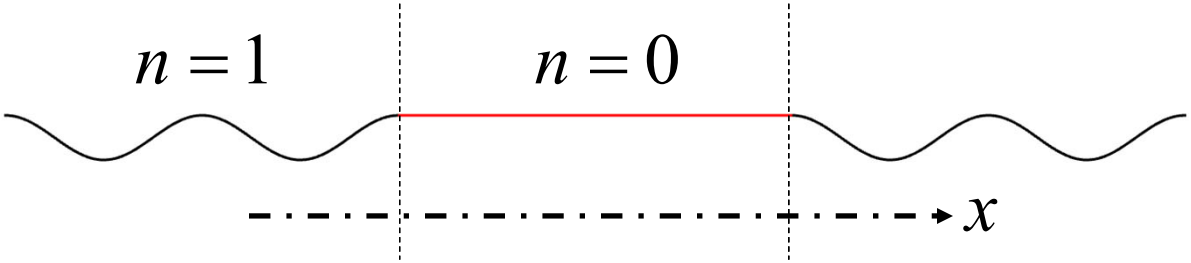


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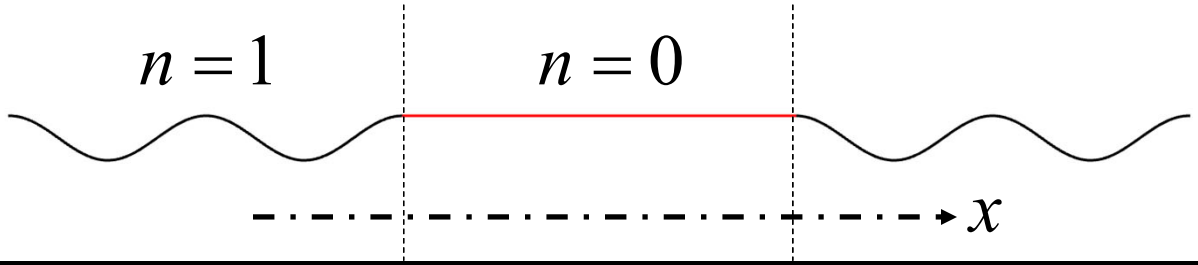

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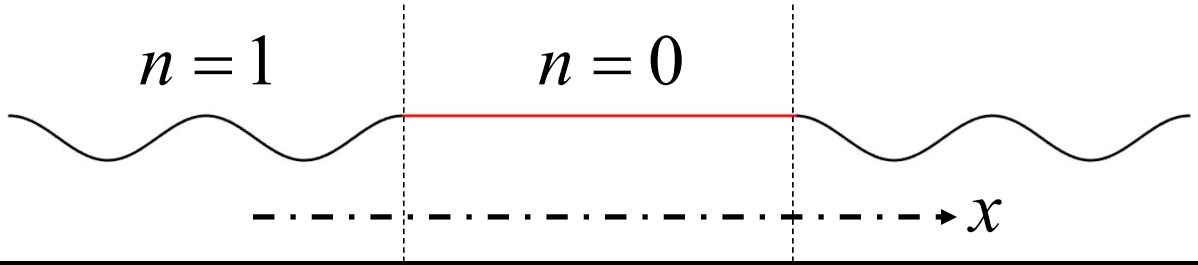

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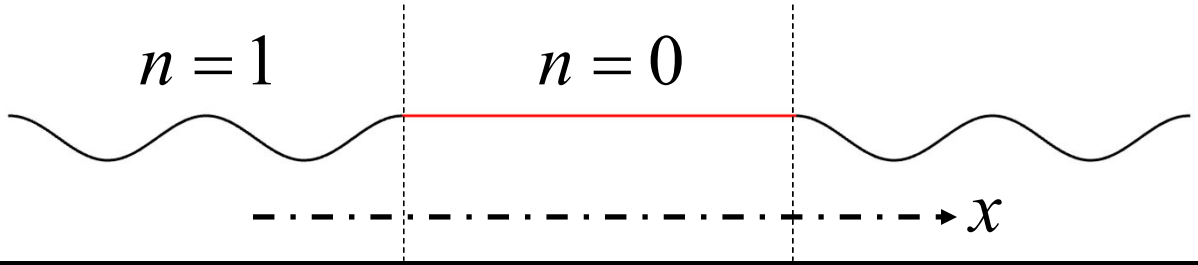
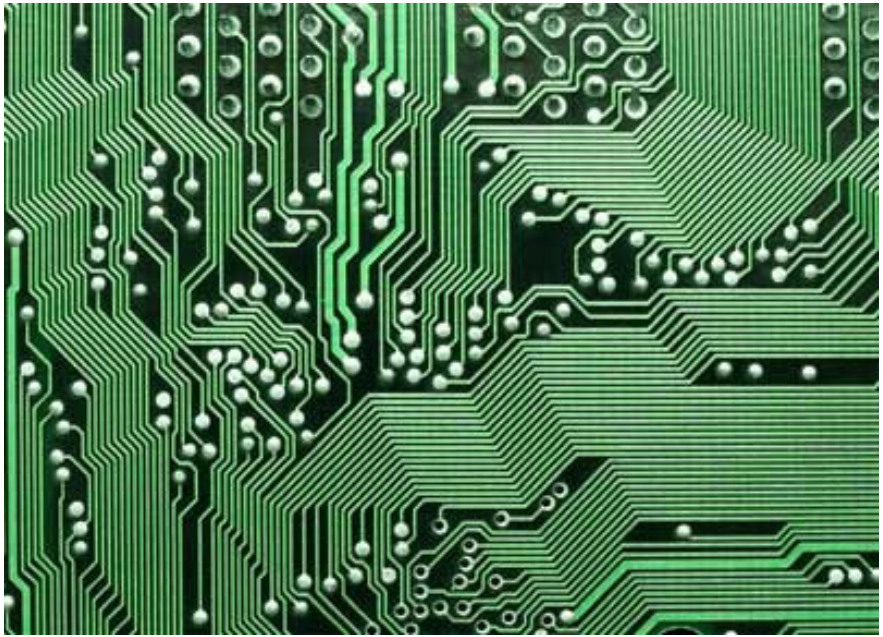


# Zero index: applications in interconnects for integrated optics



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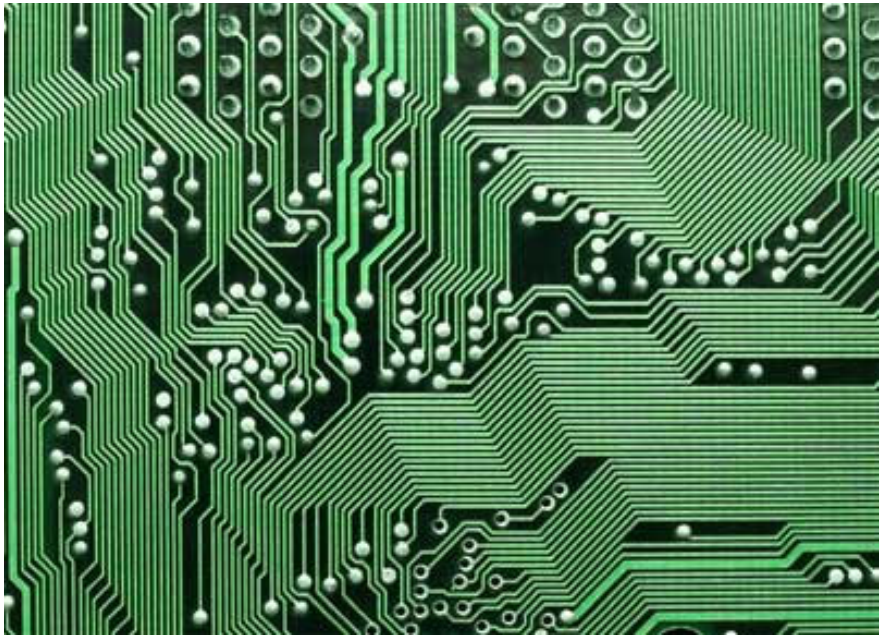

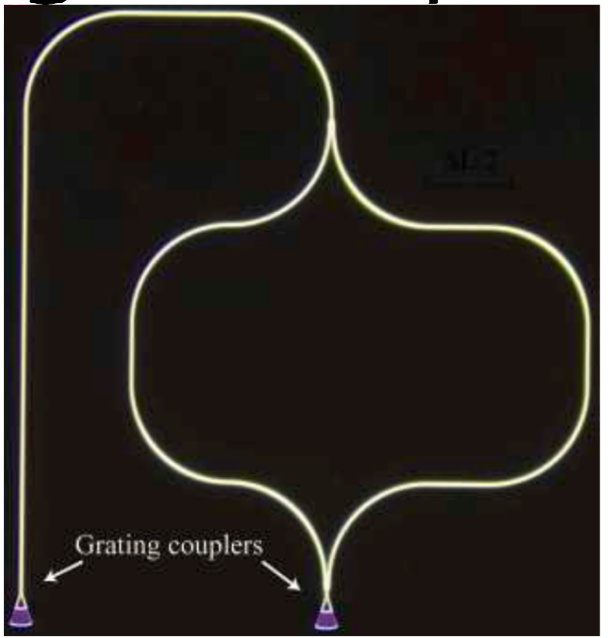

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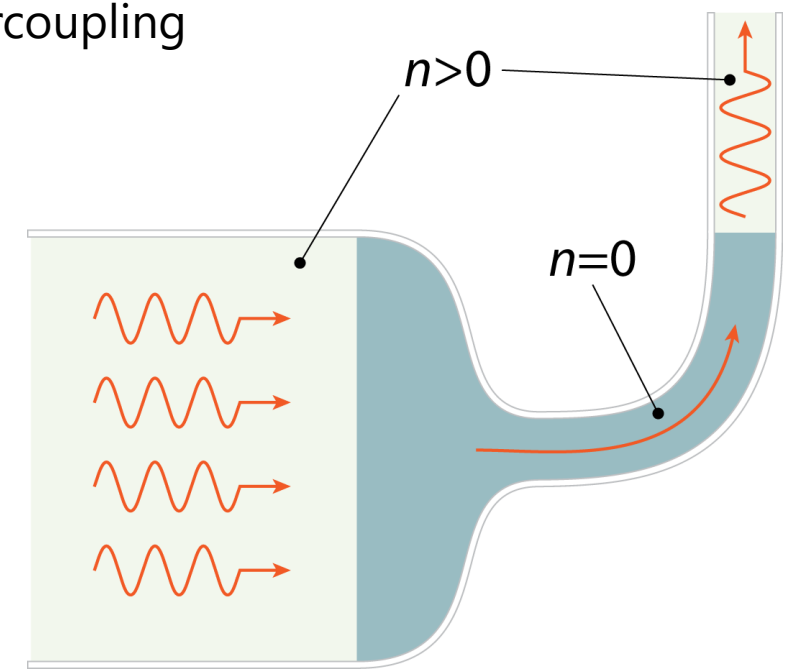
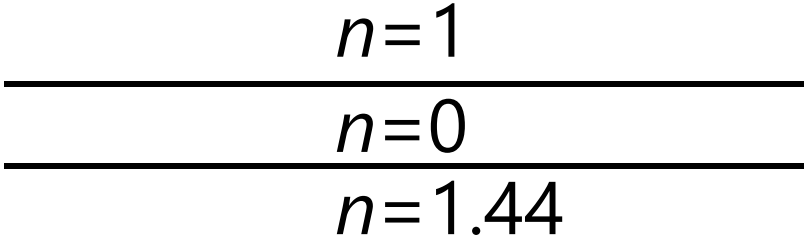
Supercoupling



# Zero index: applications in beam steering and holography



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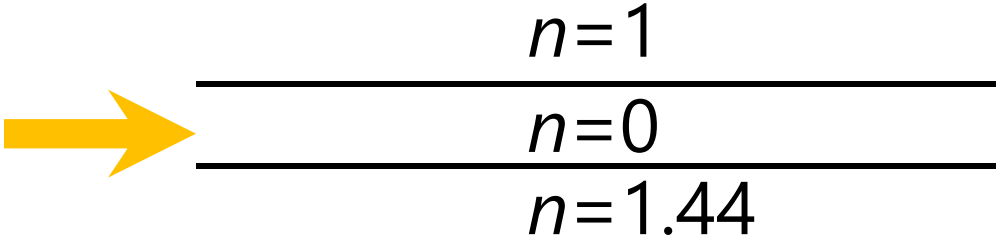

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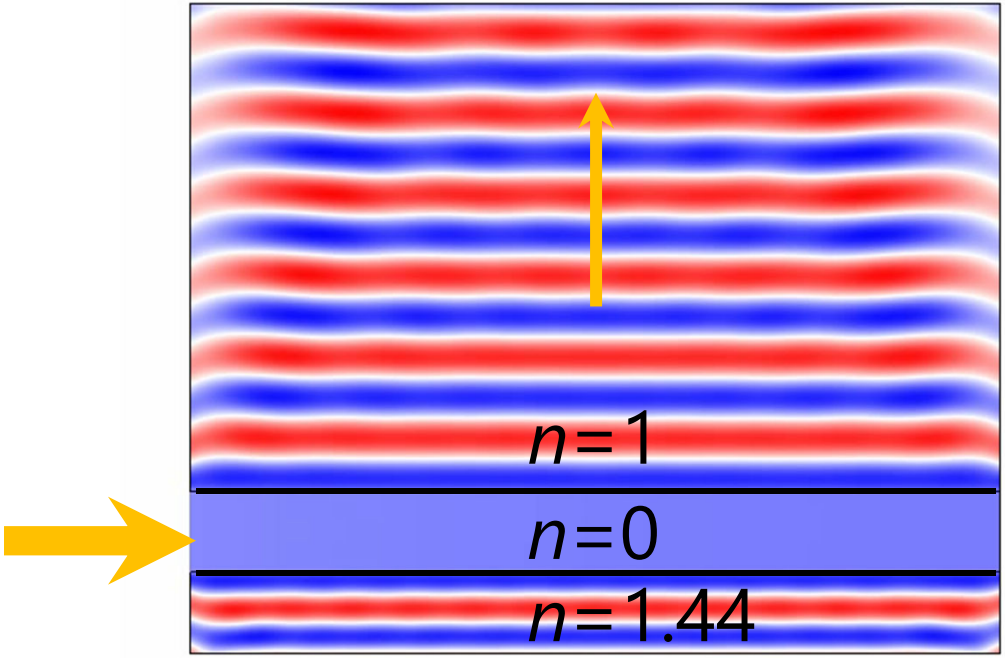

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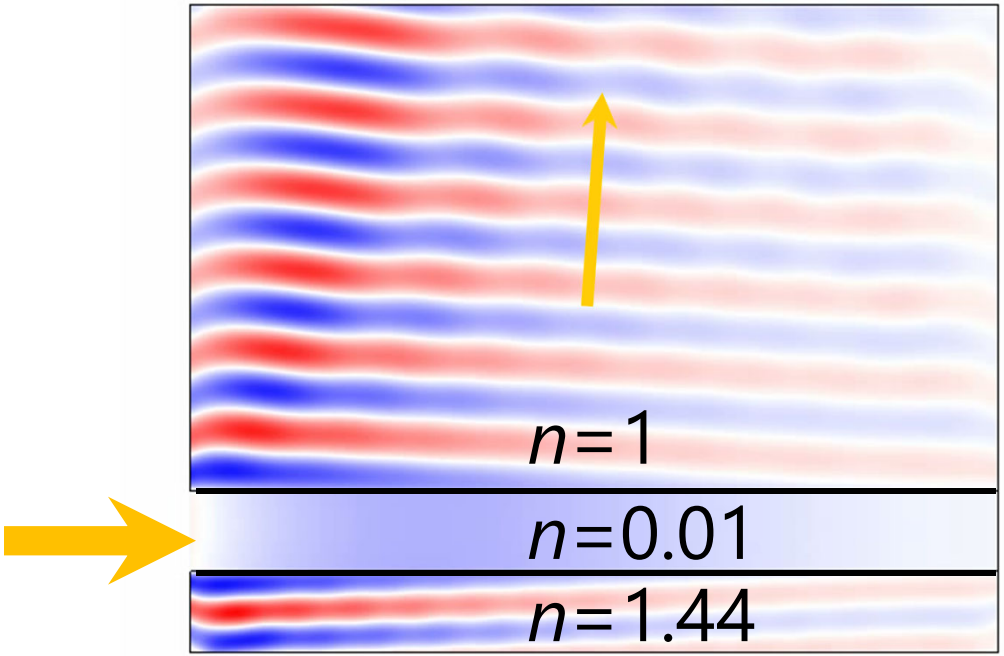

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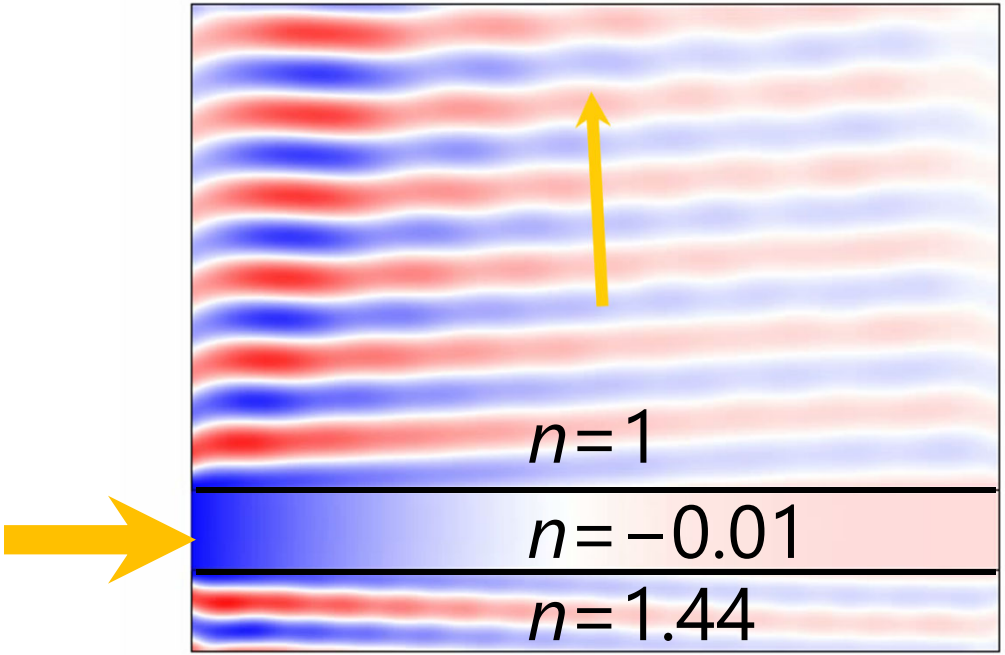

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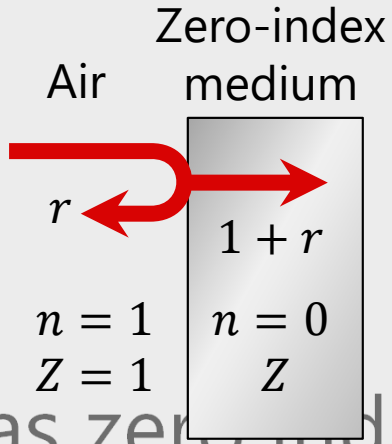

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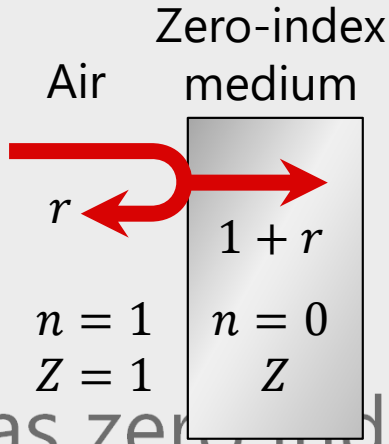


Reflection coefficient (to air):

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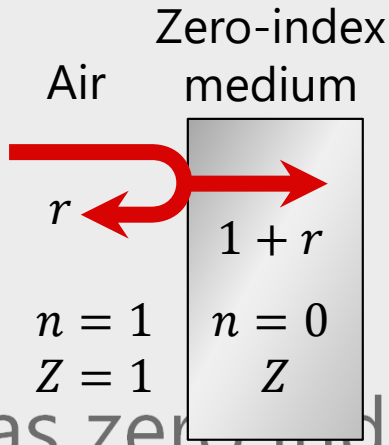


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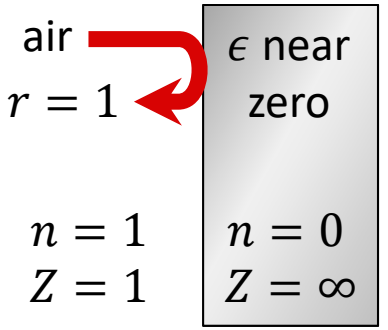


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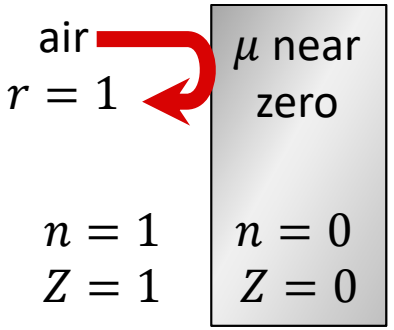


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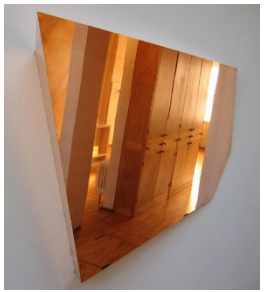

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**Poor impedance matching ☹**

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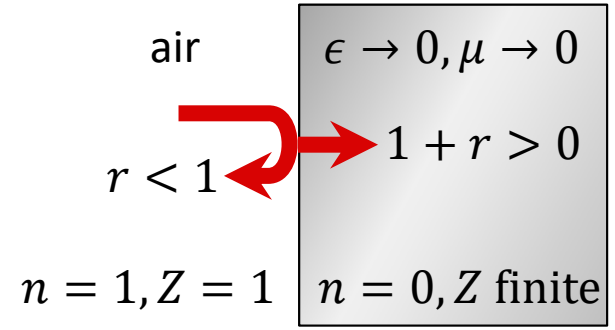

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**Good impedance matching ☺**

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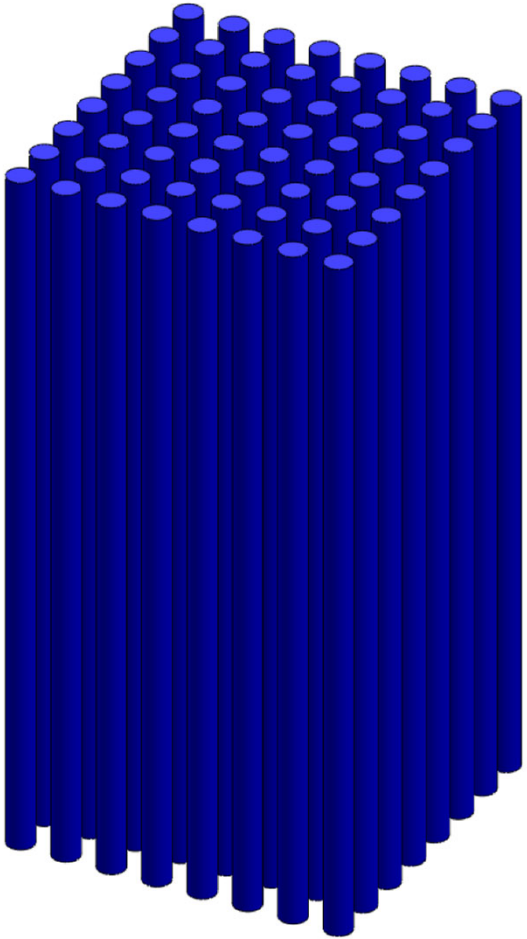
$r < 1$ → $1 + r > 0$

$n = 1, Z = 1$ | $n = 0, Z$ finite

But, how?



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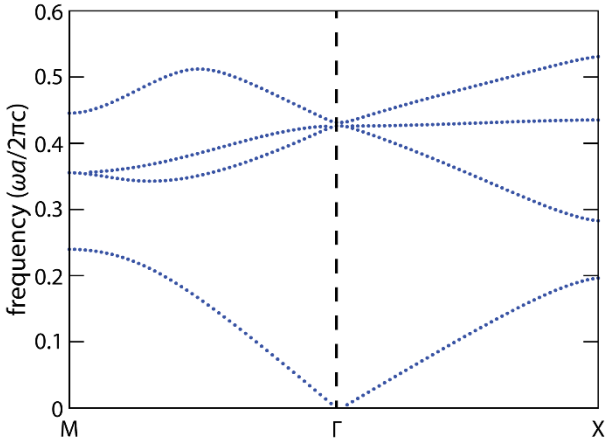


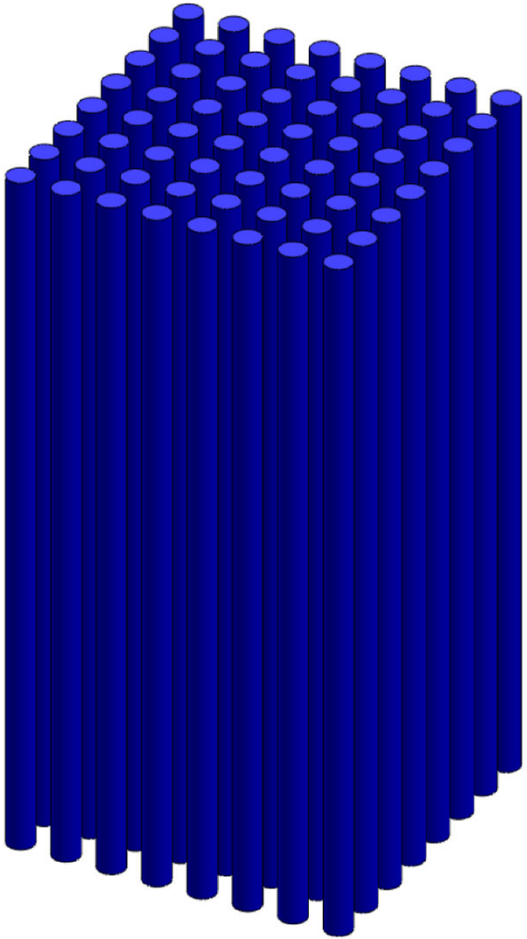

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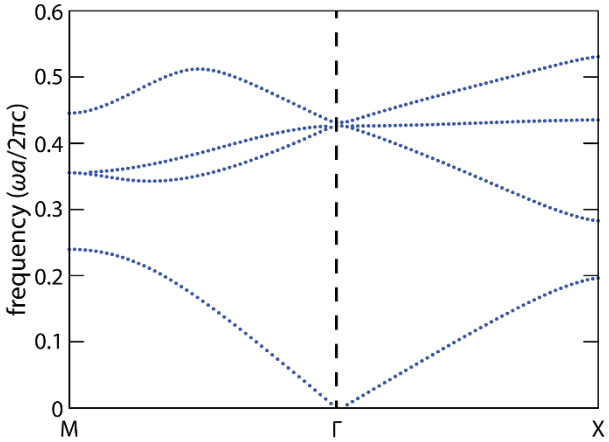


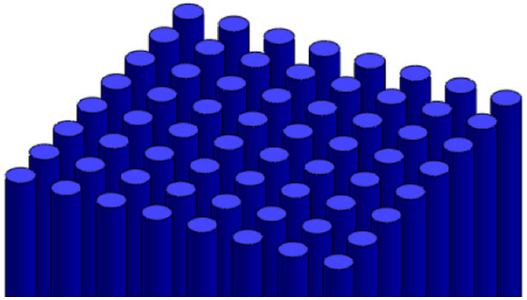

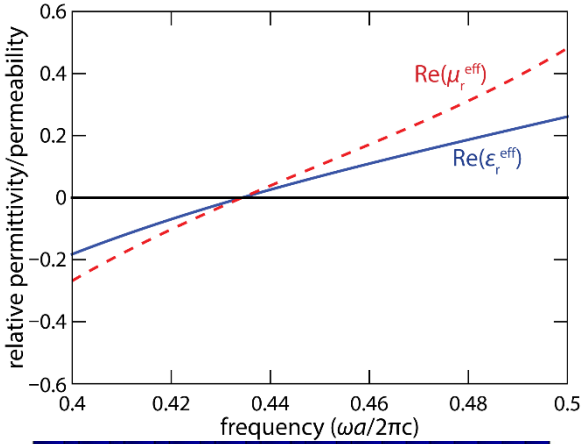


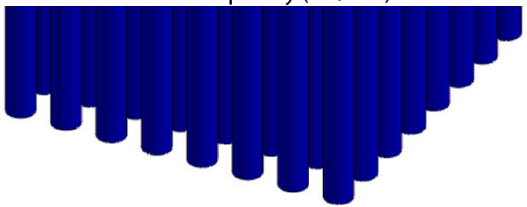

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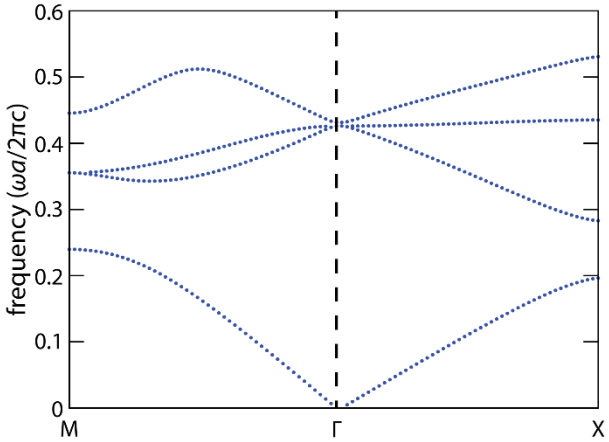
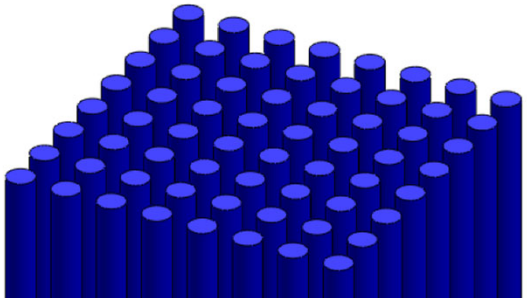
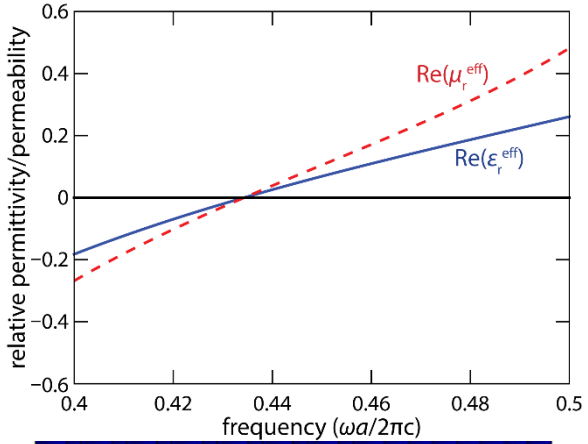
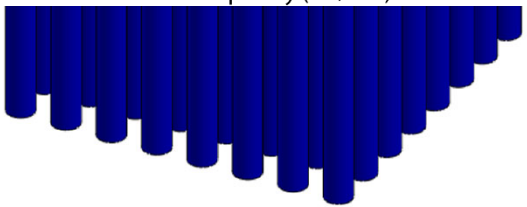
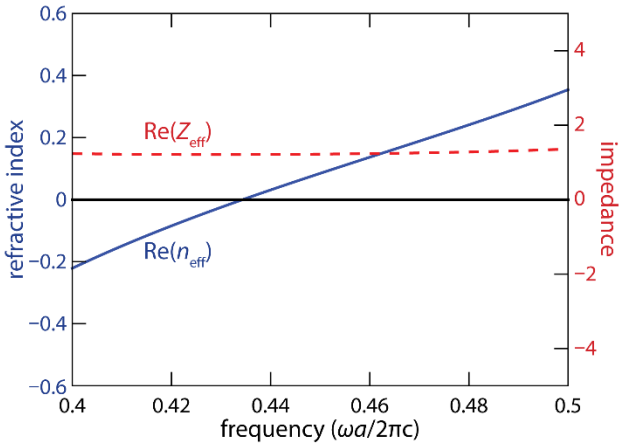







M. Notomi, Phys. Rev. B (2000)

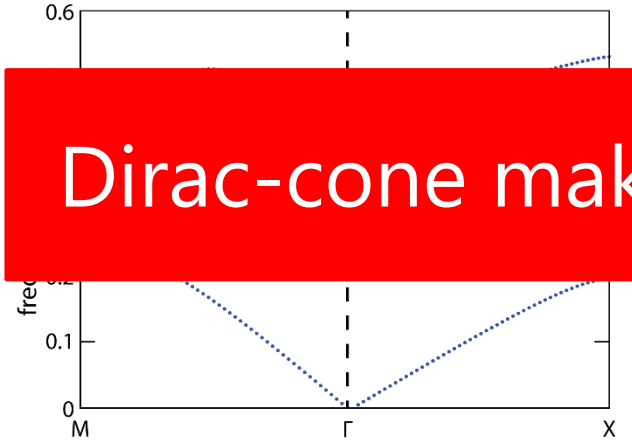
K. Sakoda, Opt. Express (2012)

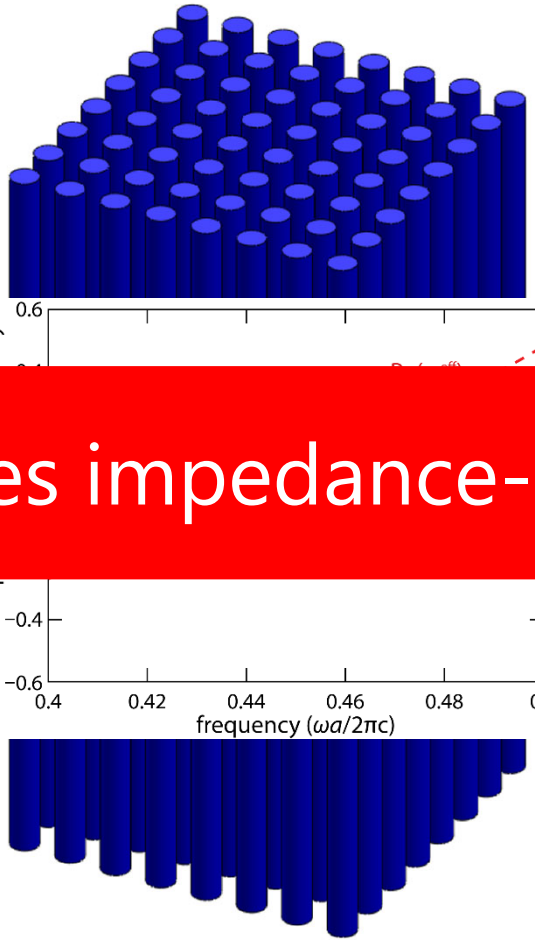
X. Q. Huang, *et al.*, Nature Mater. (2011)

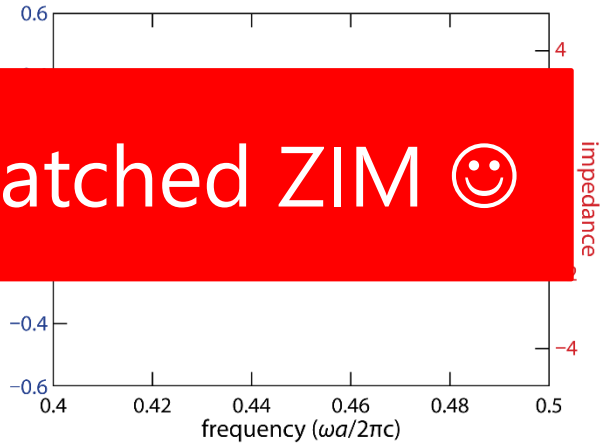
P. Moitra, *et al.*, Nature Photon. (2013)

**1 Zero index**

**2 Design**




# Dirac-cone makes impedance-matched ZIM ☺

M. Notomi, Phys. Rev. B (2000)

K. Sakoda, Opt. Express (2012)

X. Q. Huang, *et al.*, Nature Mater. (2011)

P. Moitra, *et al.*, Nature Photon. (2013)

**1 Zero index**

**2 Design**

# Peer instruction

1 Zero index

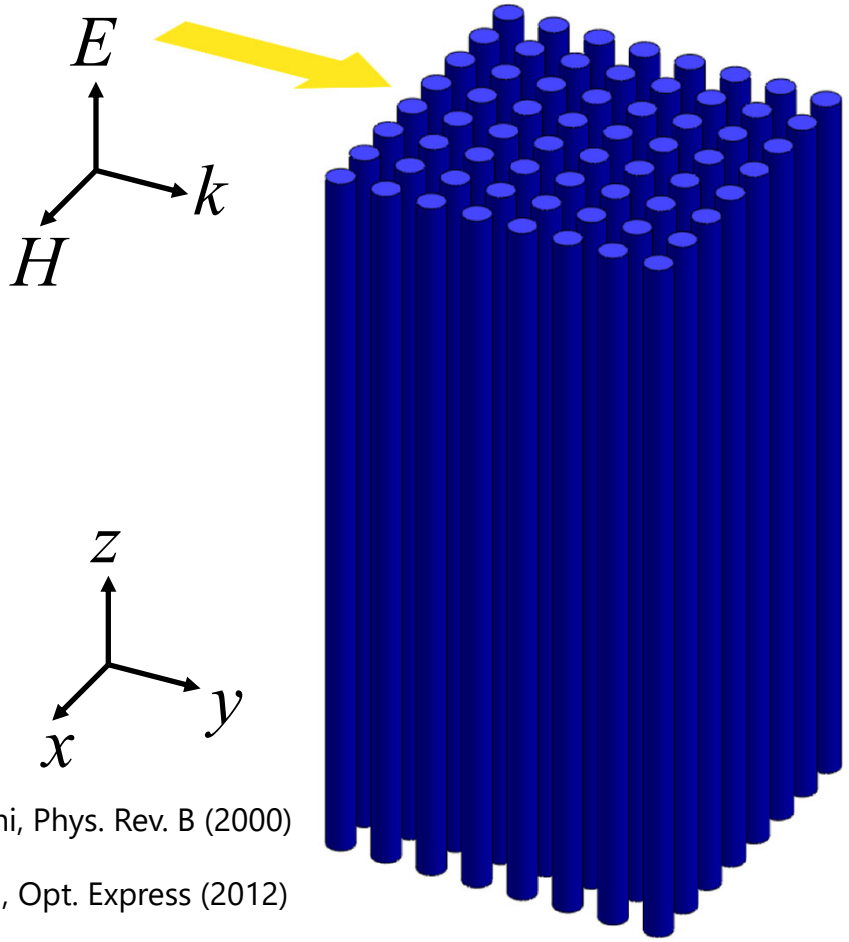
2 Design

$n > 0$

$n < 0$

$n = 0$

G. Dolling, *et al.*, *Opt. Express* (2006)




M. Notomi, Phys. Rev. B (2000)

K. Sakoda, Opt. Express (2012)

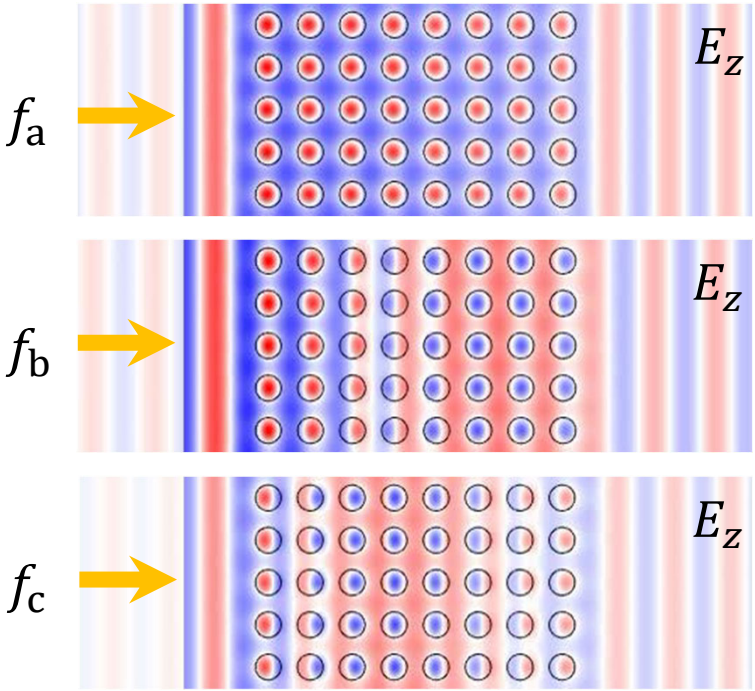
X. Q. Huang, *et al.*, Nature Mater. (2011)

P. Moitra, *et al.*, Nature Photon. (2013)

**1 Zero index**

**2 Design**

# What is the $n_{\mathrm{eff}}$ at $f_{\mathrm{a}}$, $f_{\mathrm{b}}$ and $f_{\mathrm{c}}$?

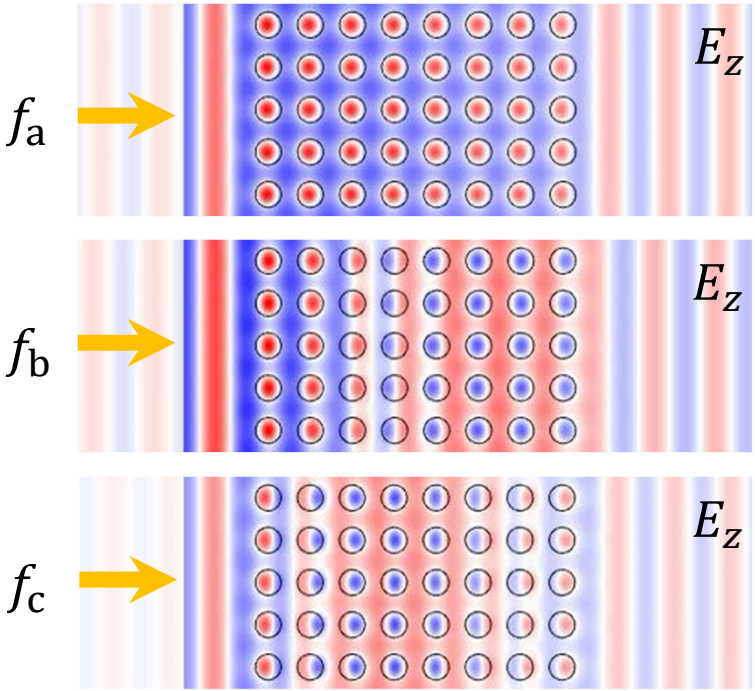



1. $n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} > 0$, respectively
2. $n_{\mathrm{eff}} = 0, n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} < 0$, respectively
3. $n_{\mathrm{eff}} = 0, n_{\mathrm{eff}} < 0, n_{\mathrm{eff}} > 0$, respectively
4. None of above

1 Zero index

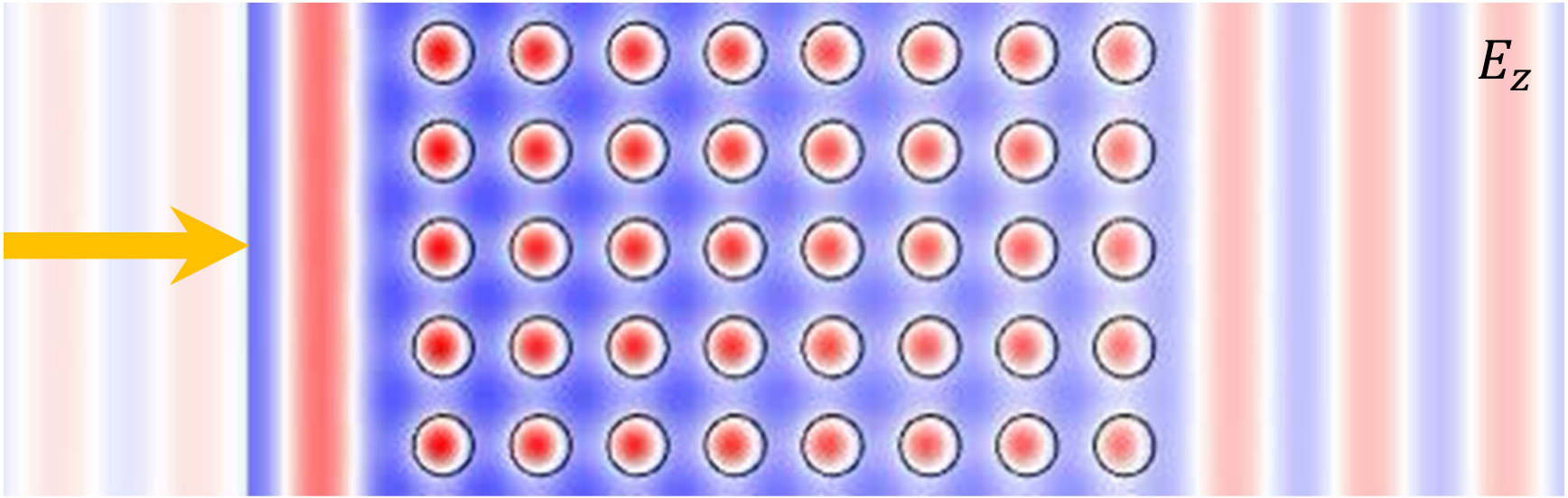
2 Design

# What is the $n_{\mathrm{eff}}$ at $f_{\mathrm{a}}$, $f_{\mathrm{b}}$ and $f_{\mathrm{c}}$?




1. $n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} > 0$, respectively
2. $n_{\mathrm{eff}} = 0, n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} < 0$, respectively
3. $n_{\mathrm{eff}} = 0, n_{\mathrm{eff}} < 0, n_{\mathrm{eff}} > 0$, respectively ✔
4. None of above

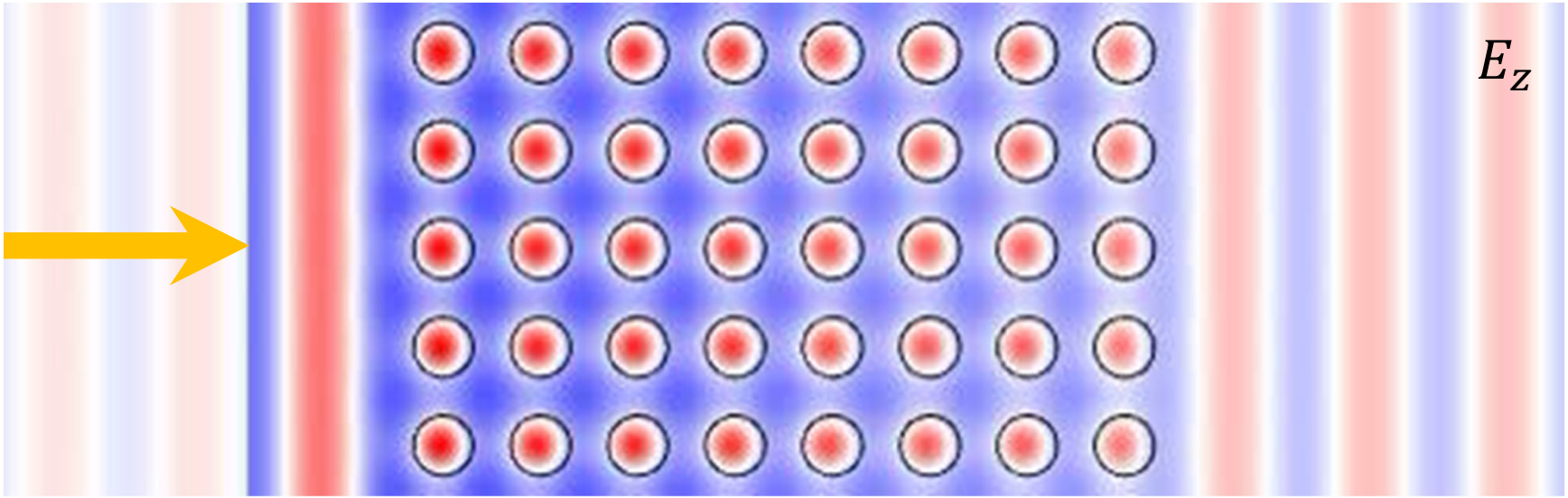
# At $f_a$



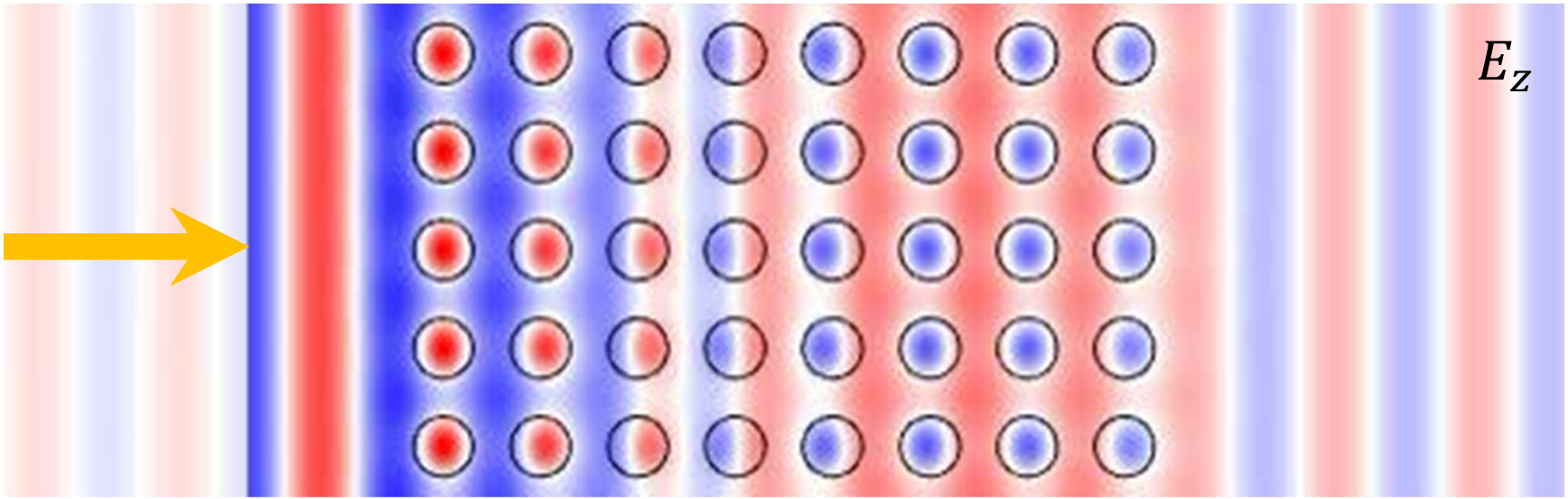

1 Zero index

2 Design

# At $f_a$: $n_{eff} = 0$



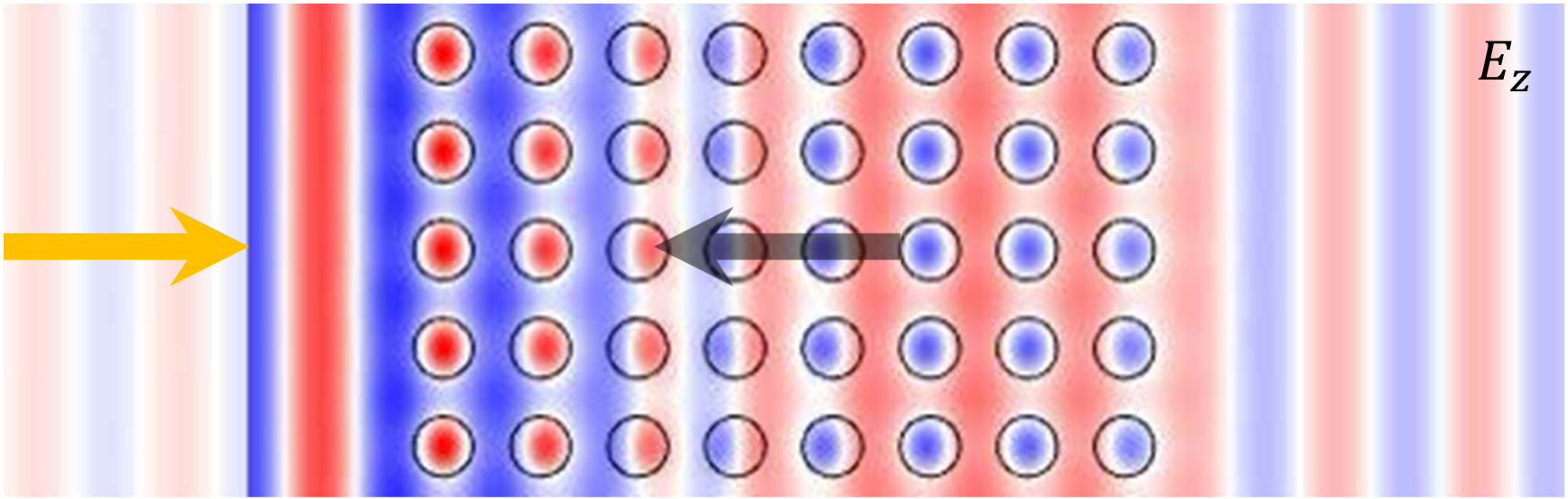
# At $f_b$



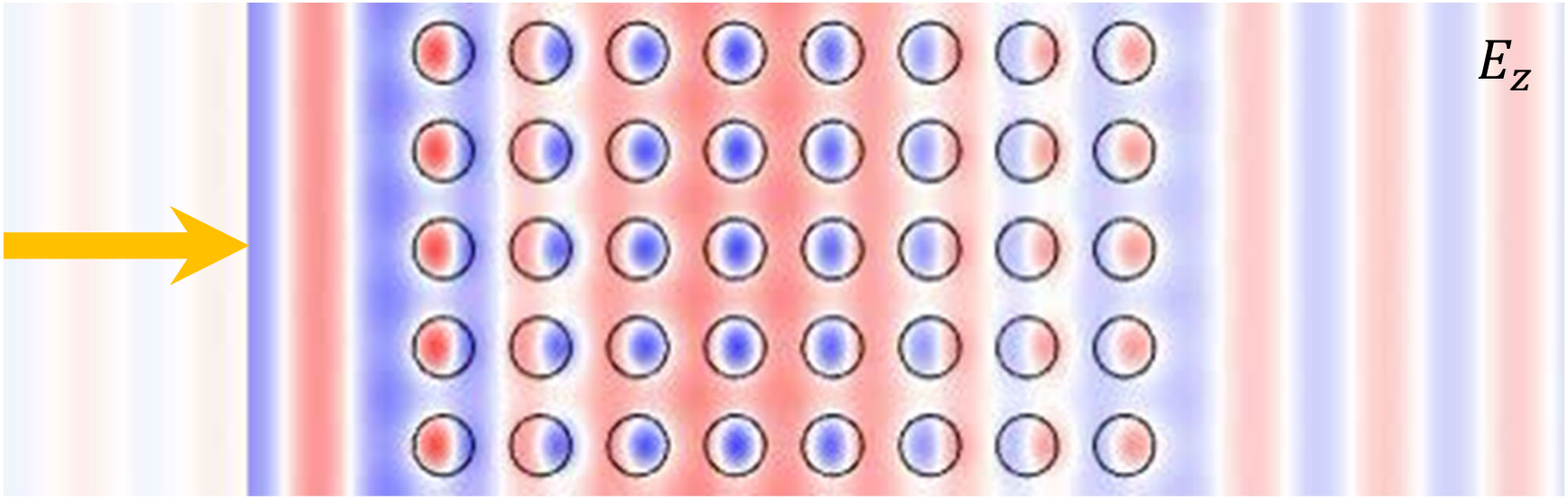

1 Zero index

2 Design

# At $f_b$: $n_{eff} < 0$



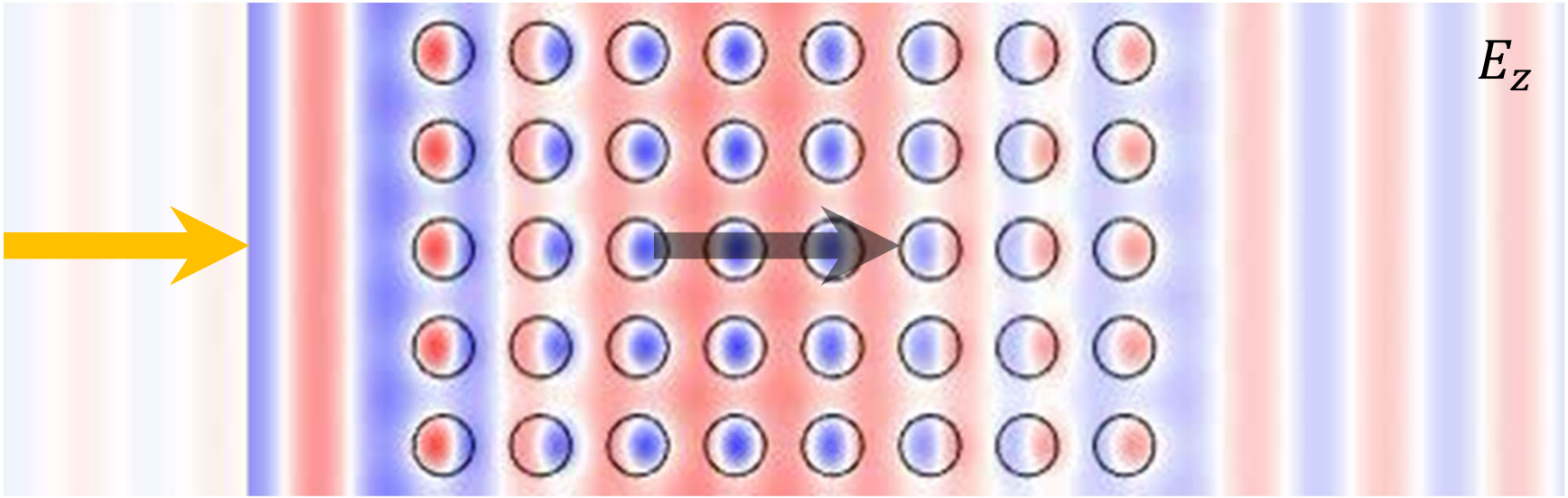
# At $f_c$



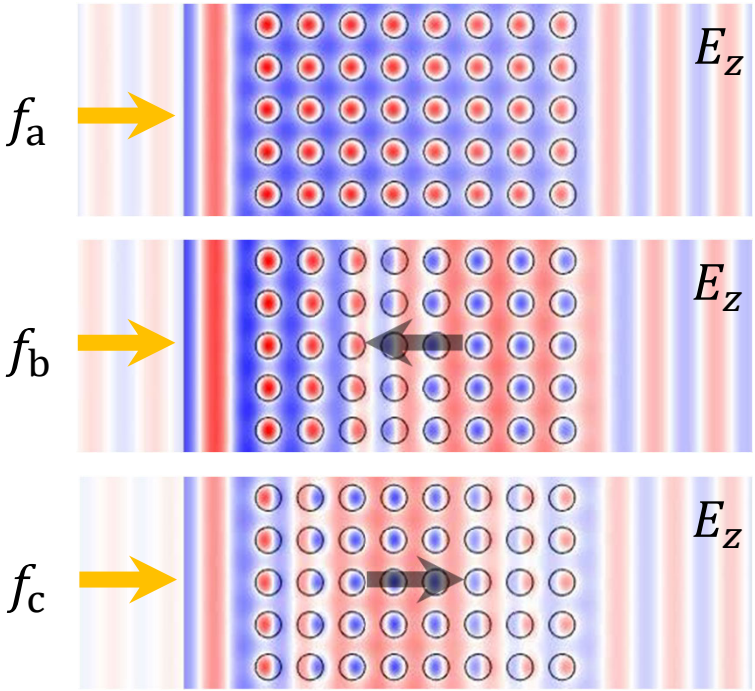

1 Zero index

2 Design

# At $f_c$: $n_{\mathrm{eff}} > 0$



# What is the $n_{\mathrm{eff}}$ at $f_{\mathrm{a}}$, $f_{\mathrm{b}}$ and $f_{\mathrm{c}}$?




1. $n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} > 0$, respectively
2. $n_{\mathrm{eff}} = 0, n_{\mathrm{eff}} > 0, n_{\mathrm{eff}} < 0$, respectively
3. $n_{\mathrm{eff}} = 0, n_{\mathrm{eff}} < 0, n_{\mathrm{eff}} > 0$, respectively ✔
4. None of above

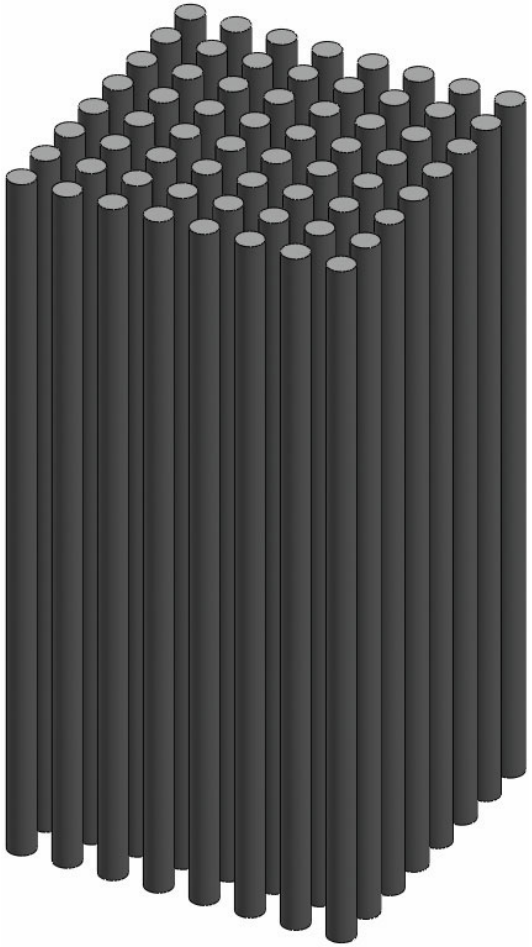
Can we make an on-chip Dirac-cone metamaterial with impedance-matched zero index?

Can we make an on-chip Dirac-cone metamaterial with impedance-matched zero index?

- Fabrication using standard planar processes over a large area in arbitrary shapes

Can we make an on-chip Dirac-cone metamaterial with impedance-matched zero index?

- Fabrication using standard planar processes over a large area in arbitrary shapes
- Efficient couple to photonic integrated circuits and other optical elements

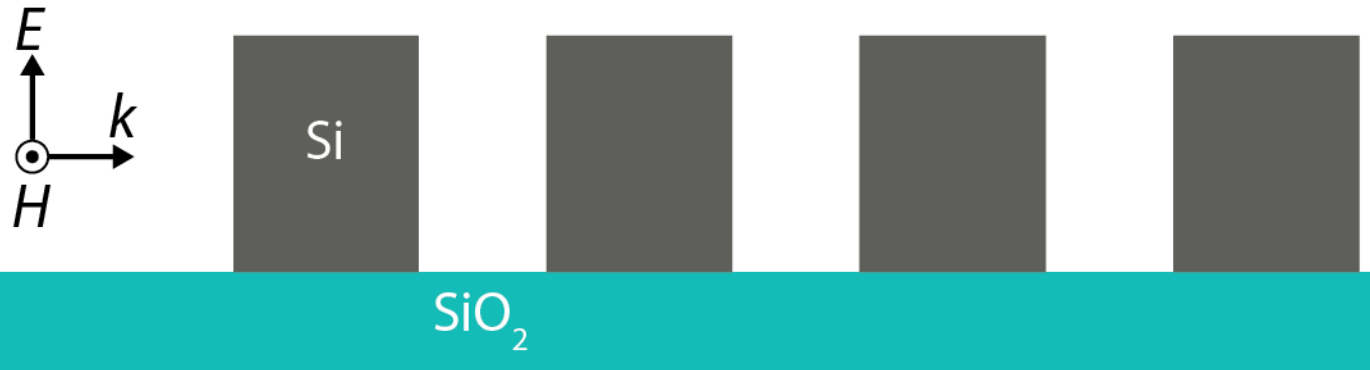


1 Zero index

2 Design

1 Zero index

2 Design

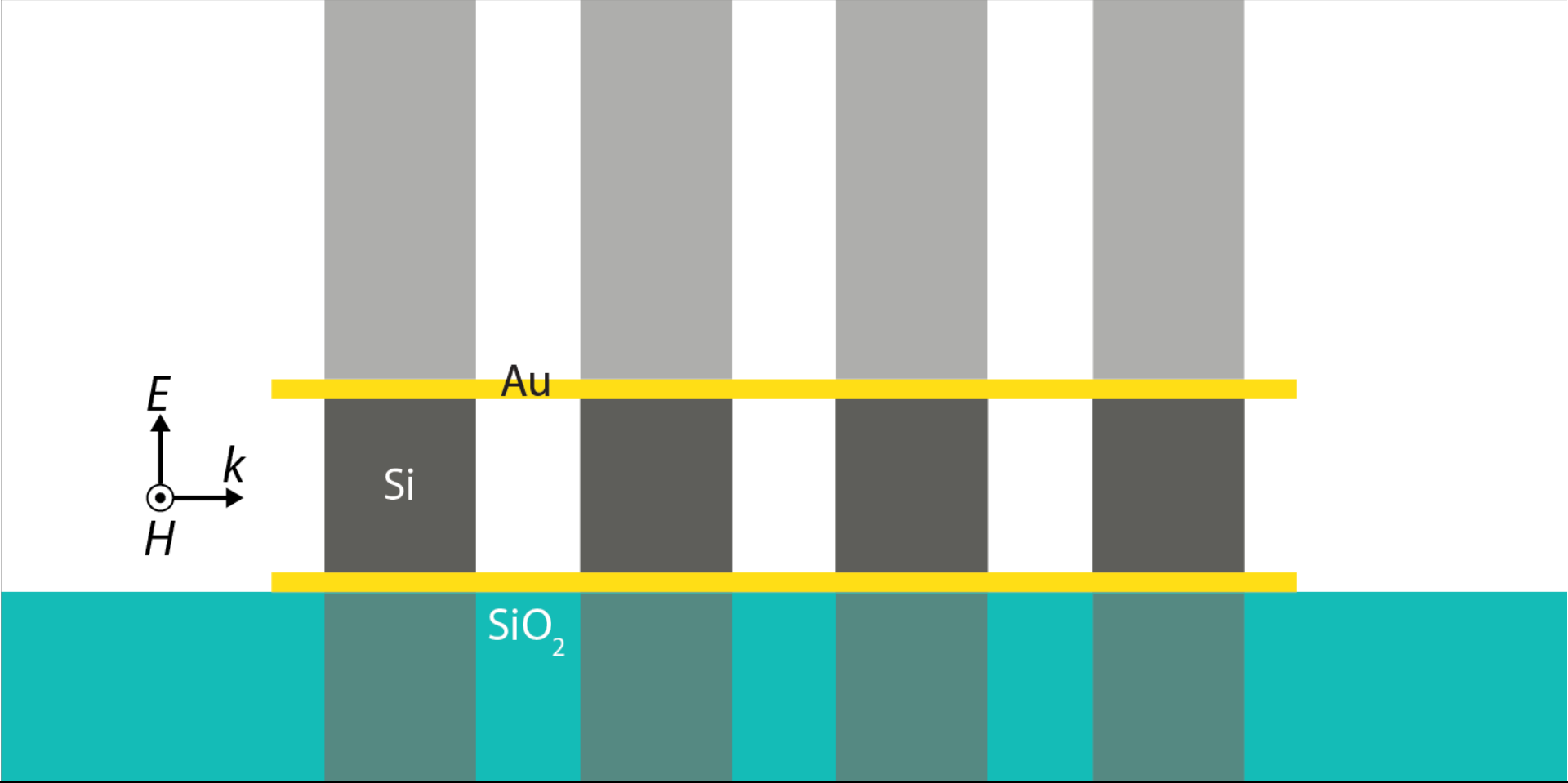



1 Zero index

2 Design

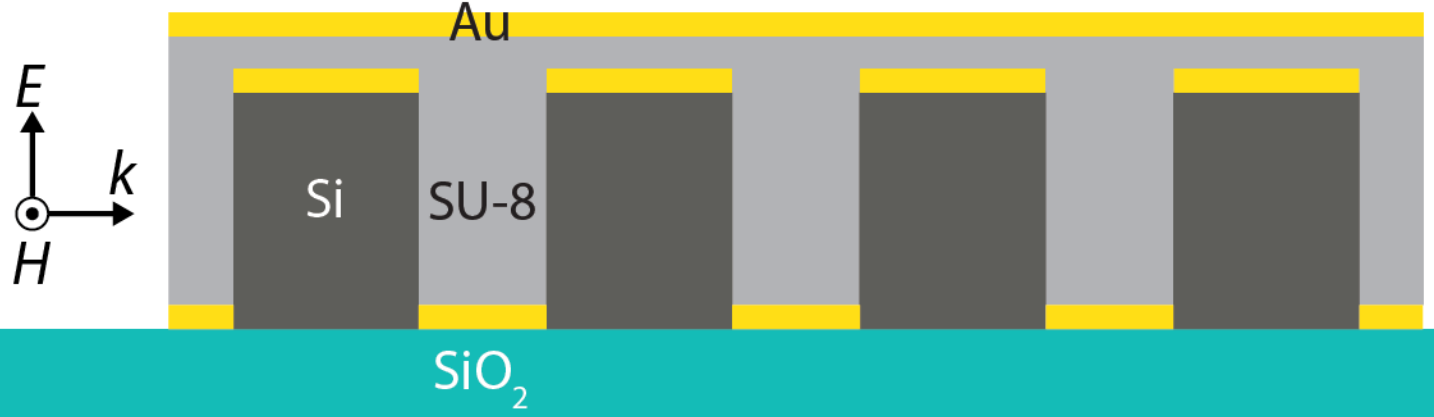
1 Zero index

2 Design



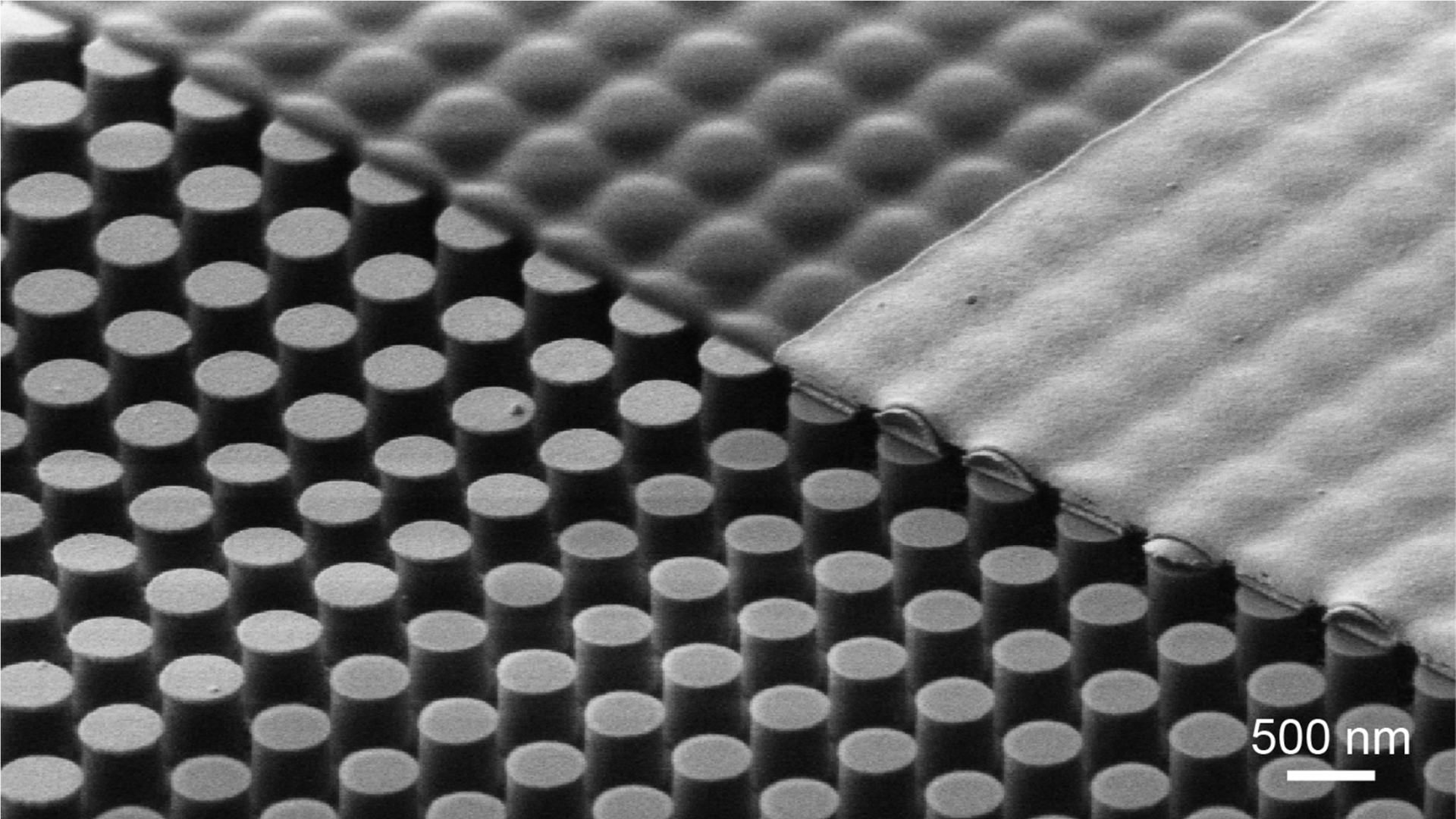

1 Zero index

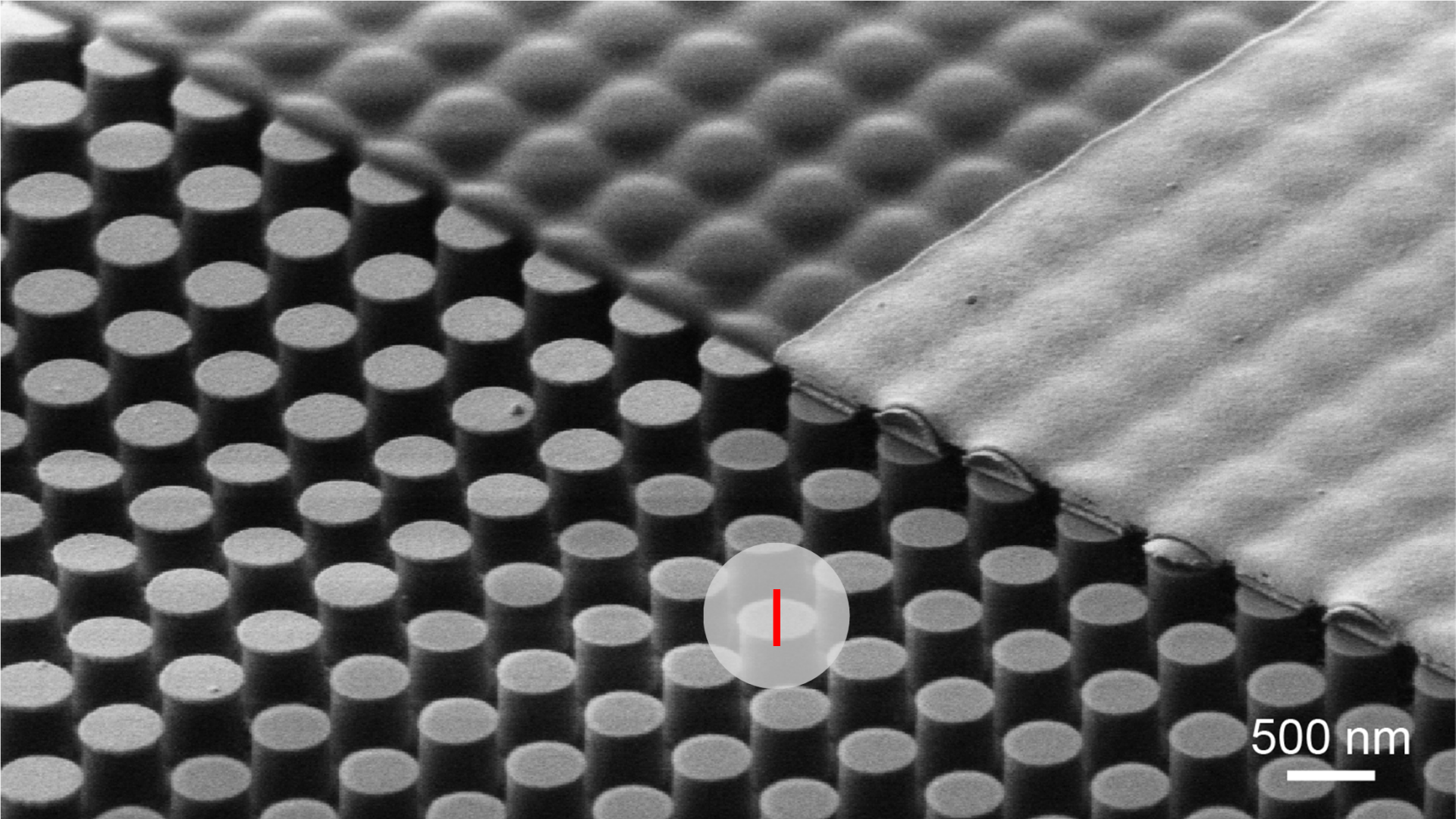
2 Design

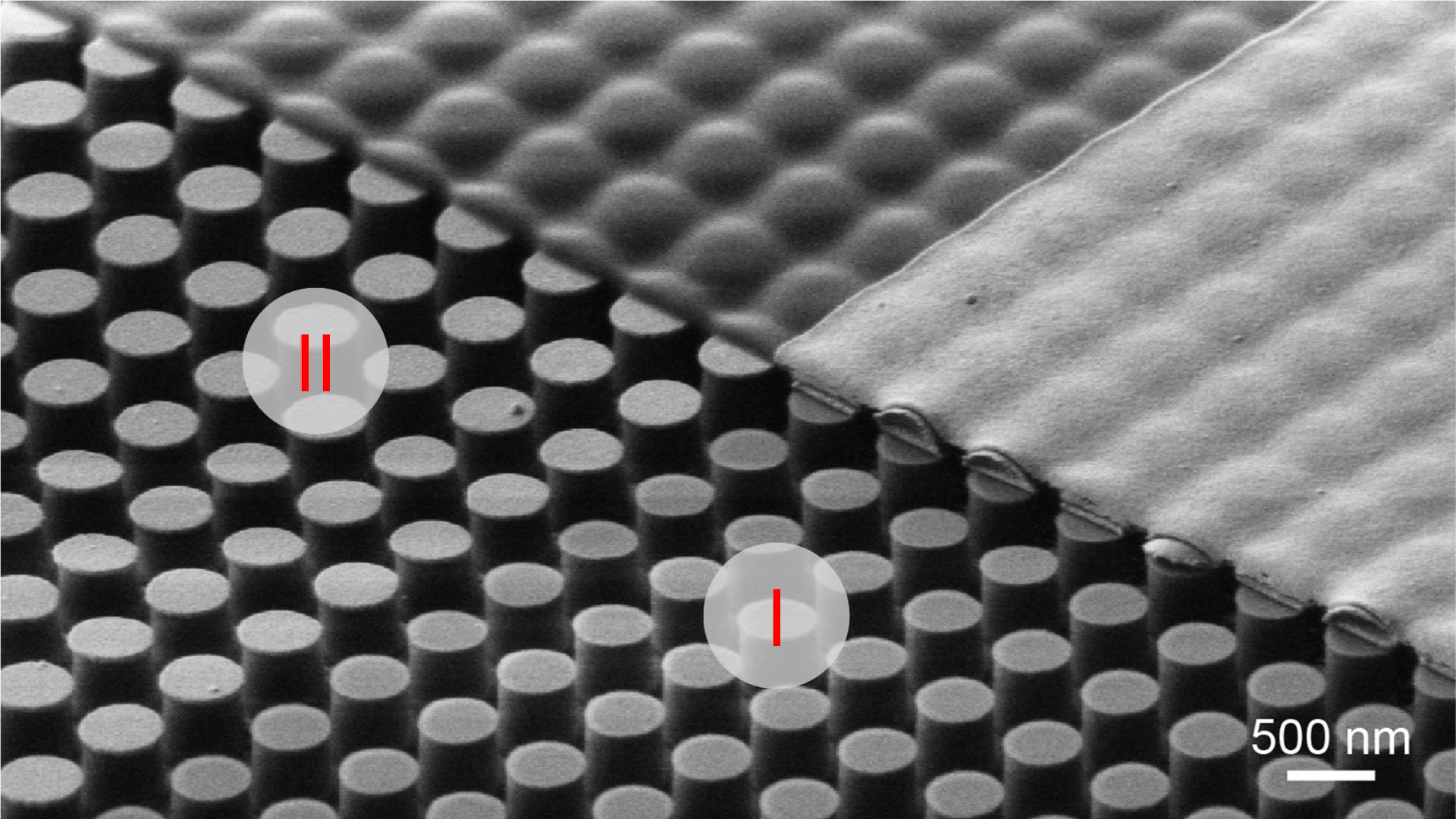


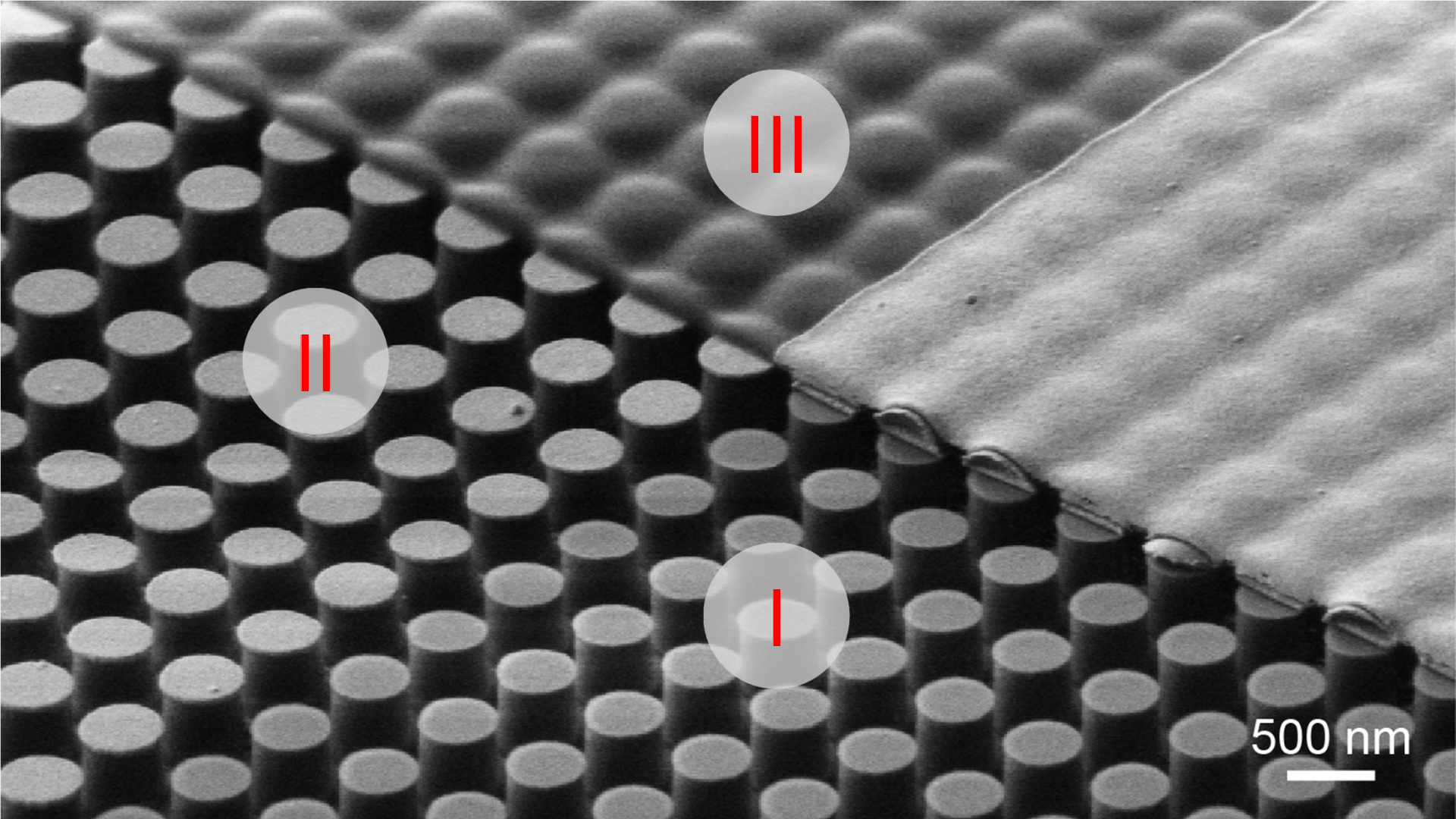

1 Zero index

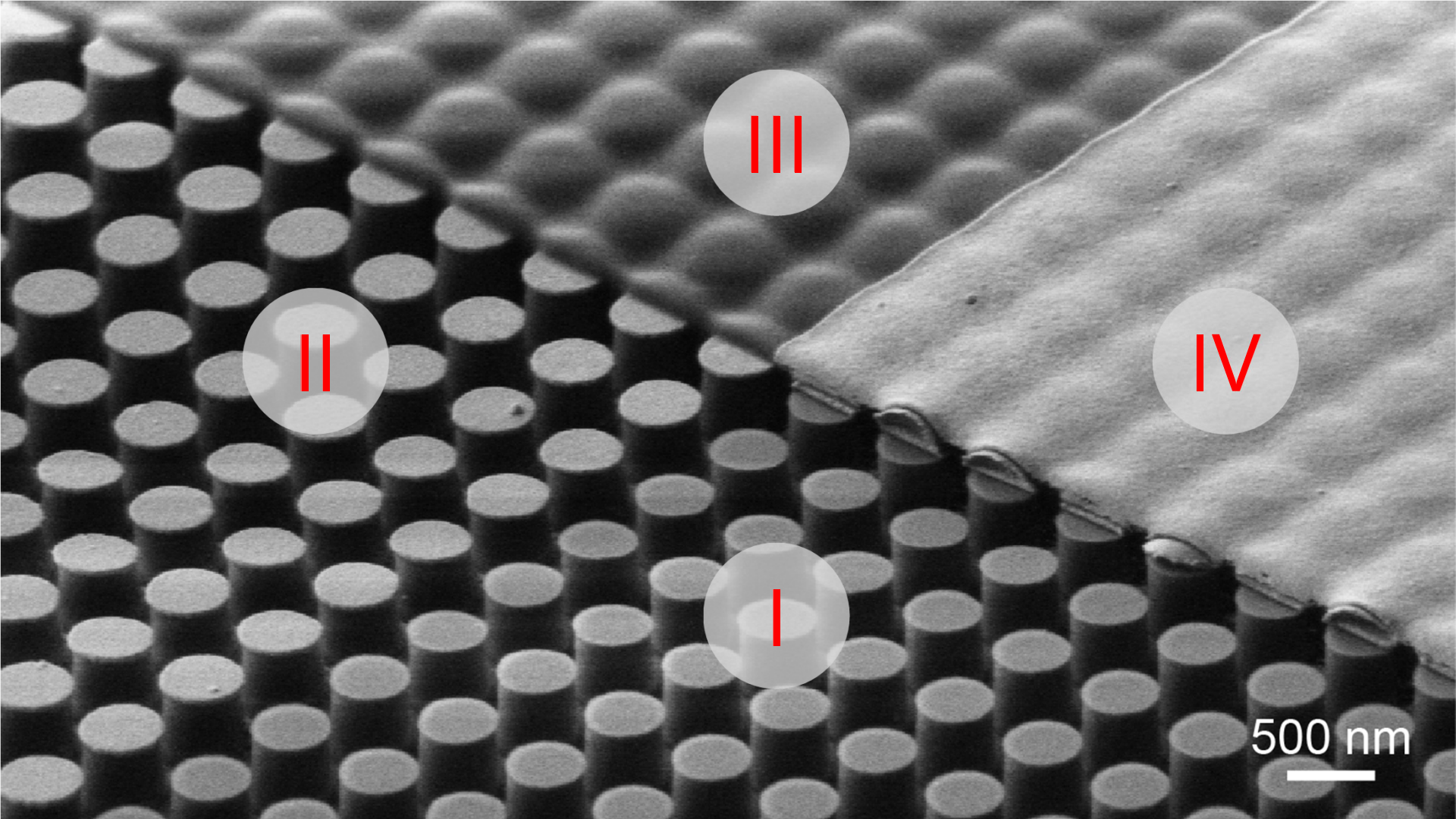
2 Design

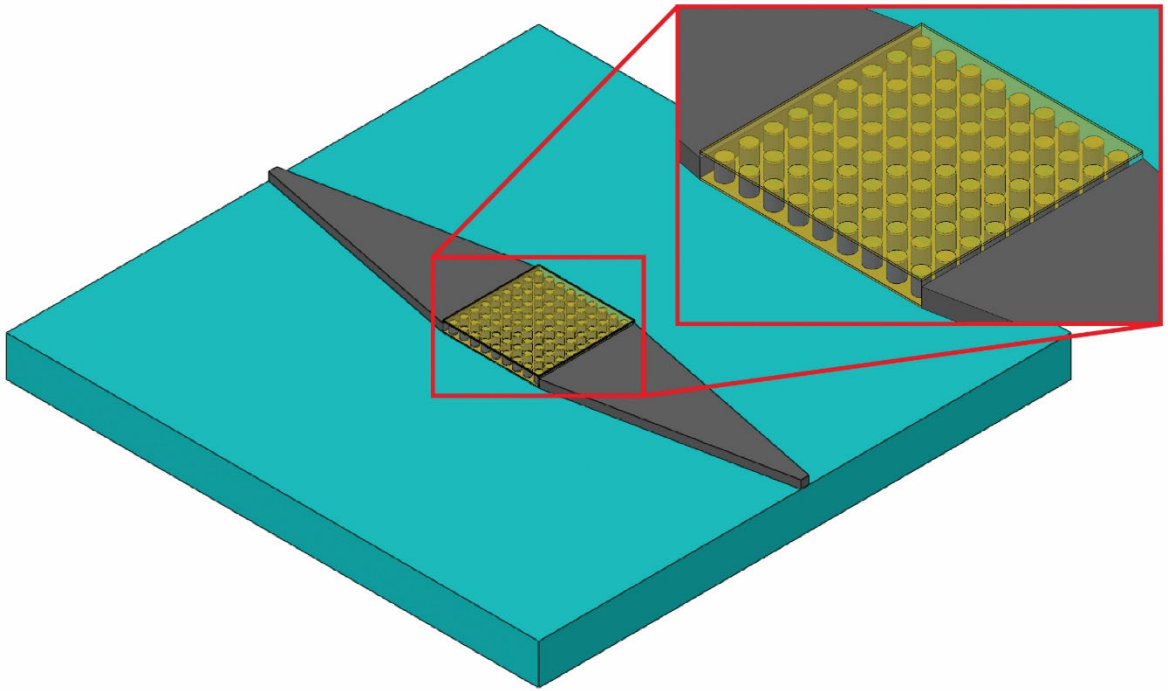

500 nm


500 nm


II
I
500 nm

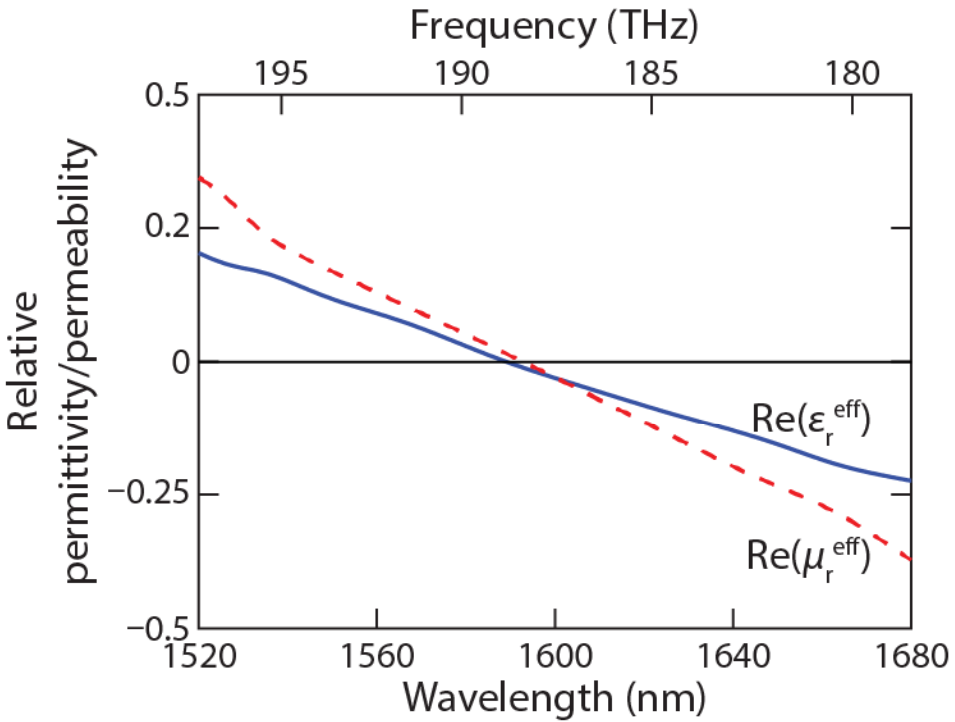

III
II
I
500 nm


III
II
IV
I
500 nm



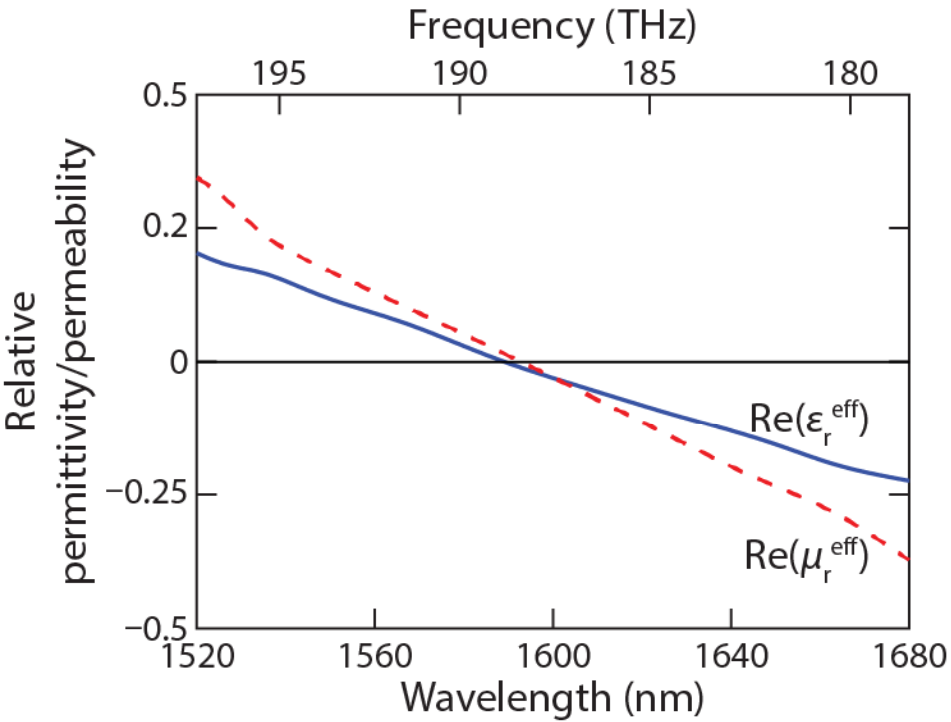
1 Zero index

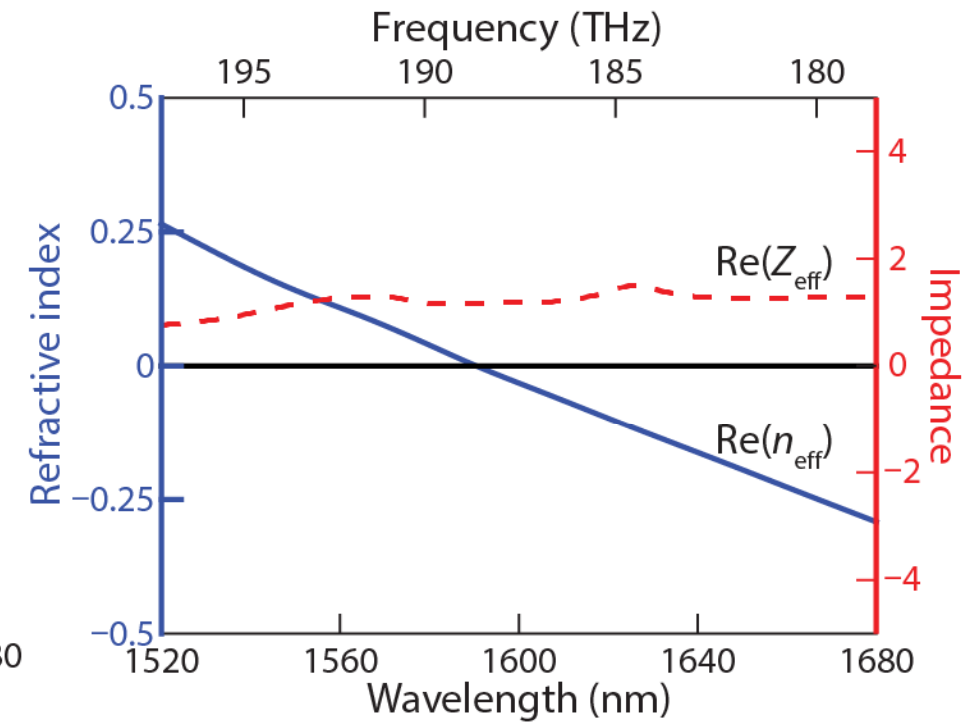
2 Design




1 Zero index

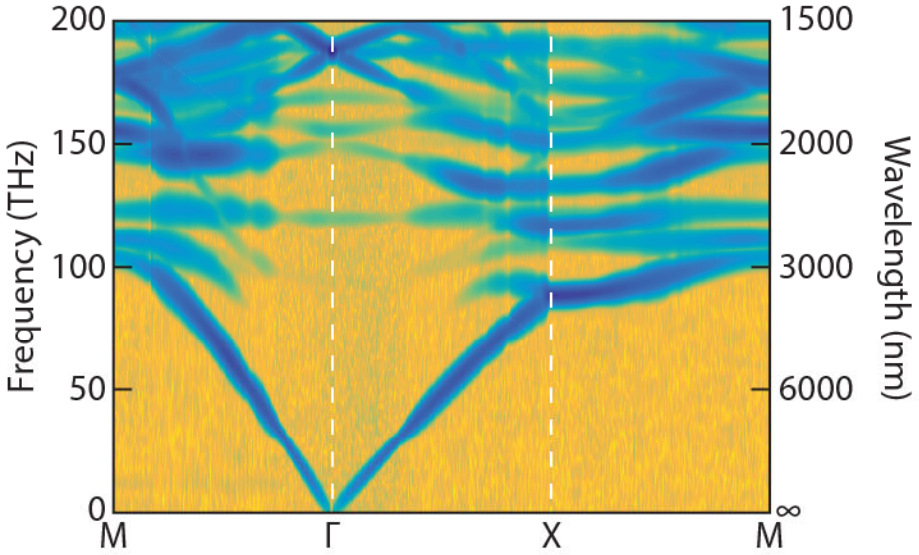
2 Design



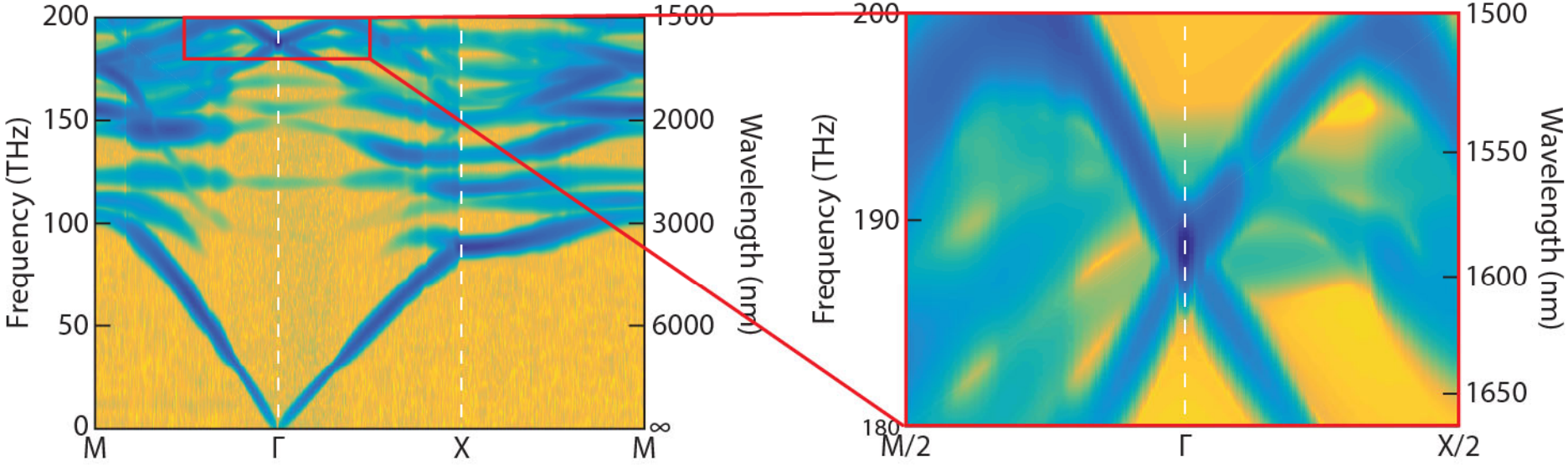

1 Zero index

2 Design



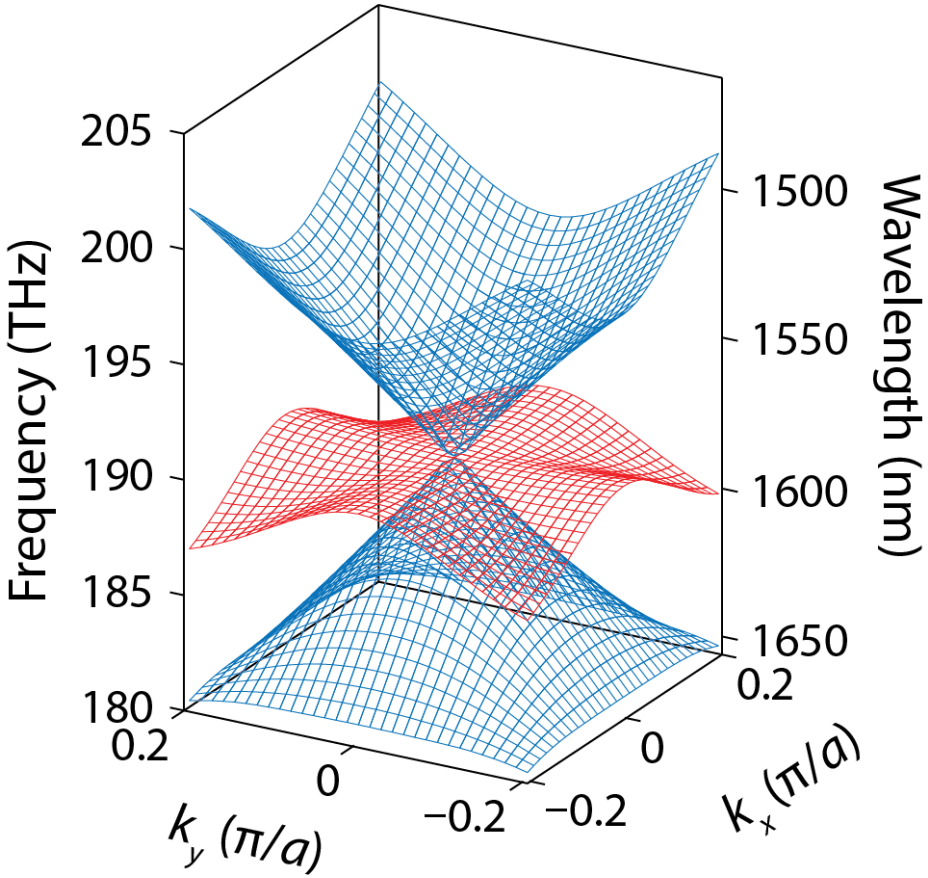

1 Zero index

2 Design




1 Zero index

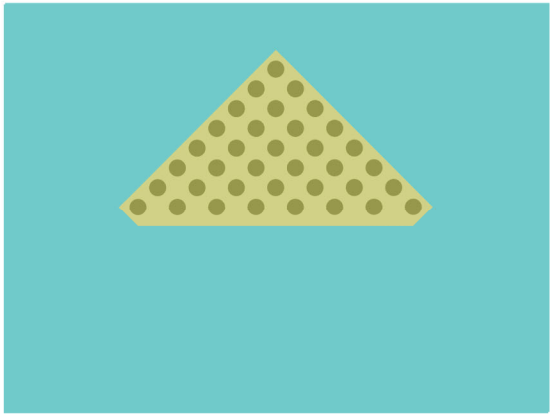
2 Design

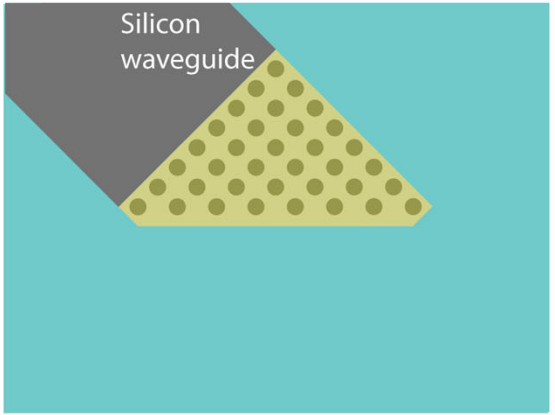


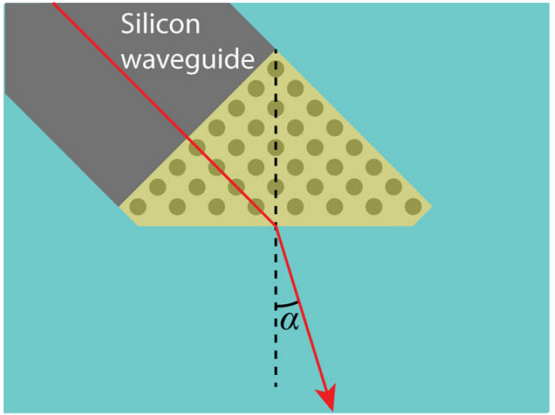

1 Zero index

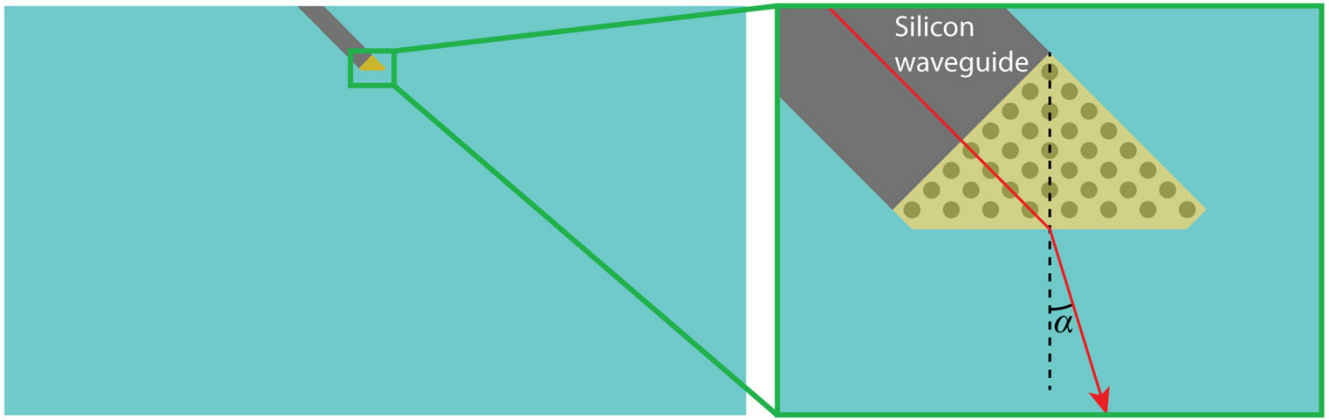
2 Design

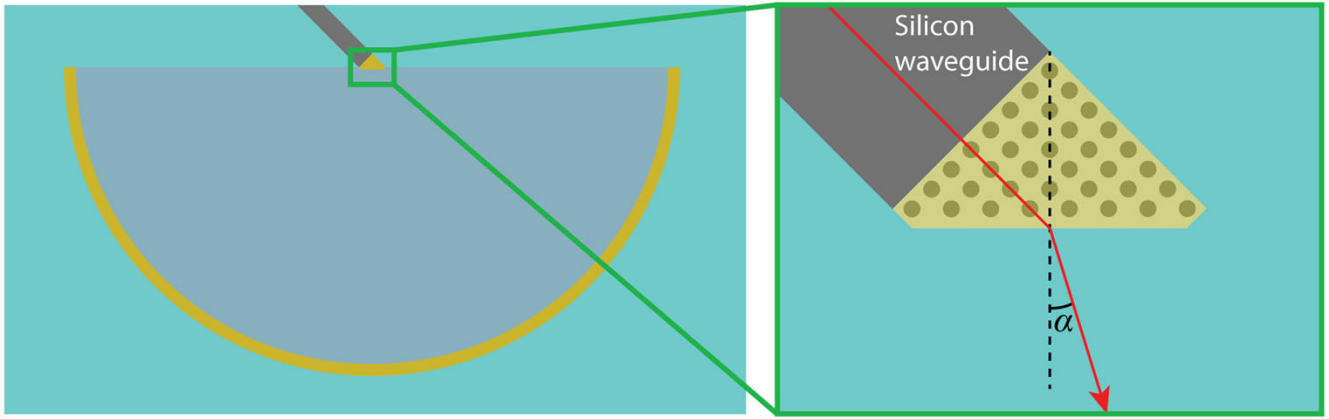
We have designed an on-chip Dirac-cone metamaterial with impedance-matched zero index at $1590\ \mathrm{nm}$

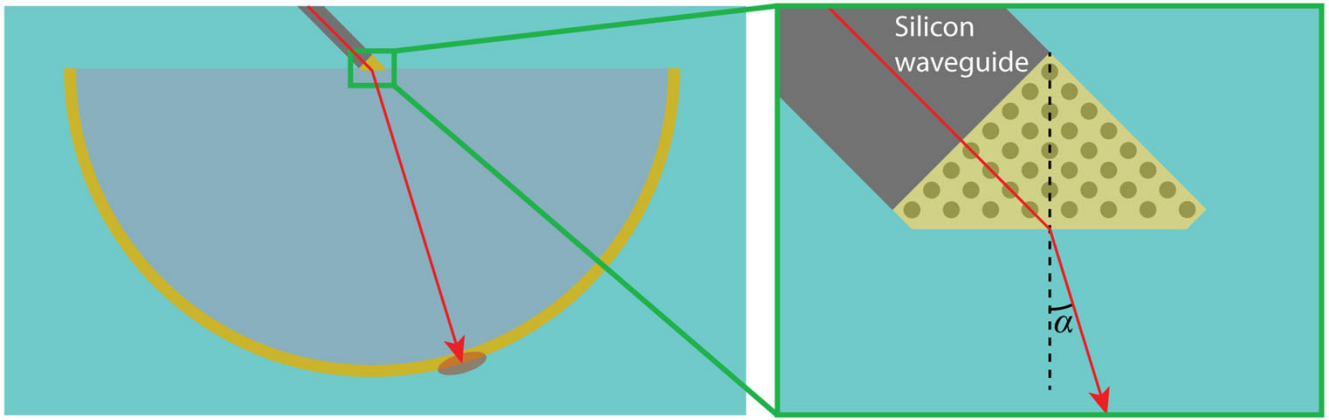


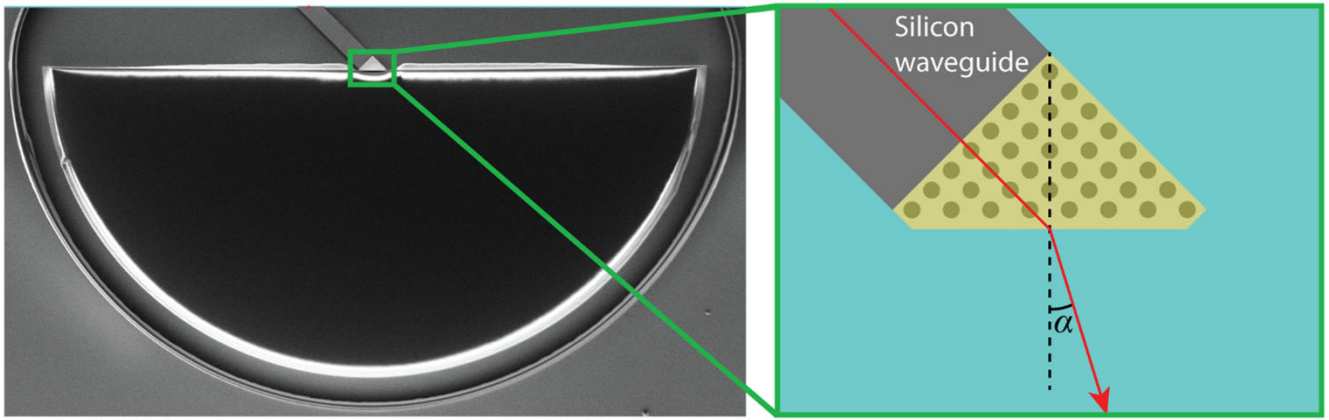

Silicon
waveguide


Silicon
waveguide
α


Silicon
waveguide
α


Silicon
waveguide
α

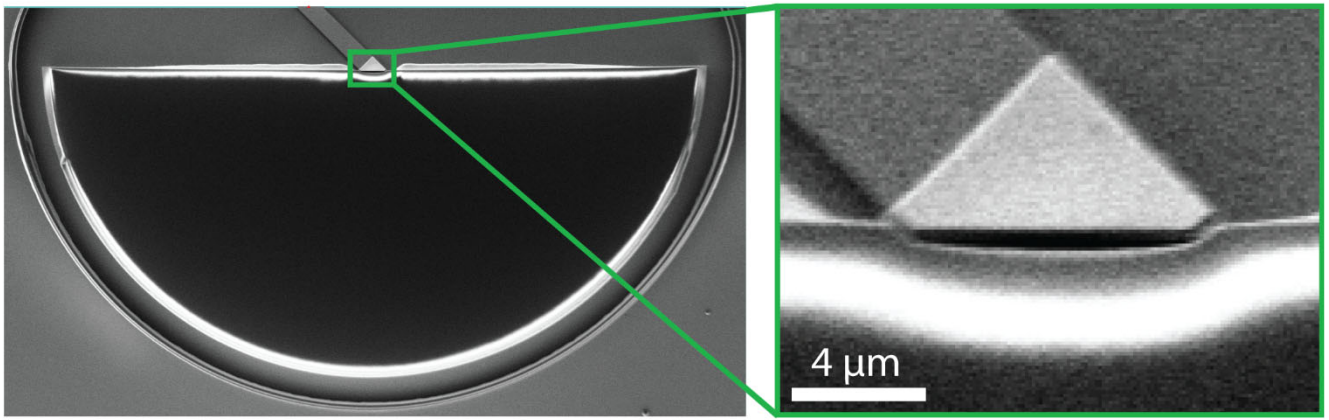

Silicon
waveguide
α

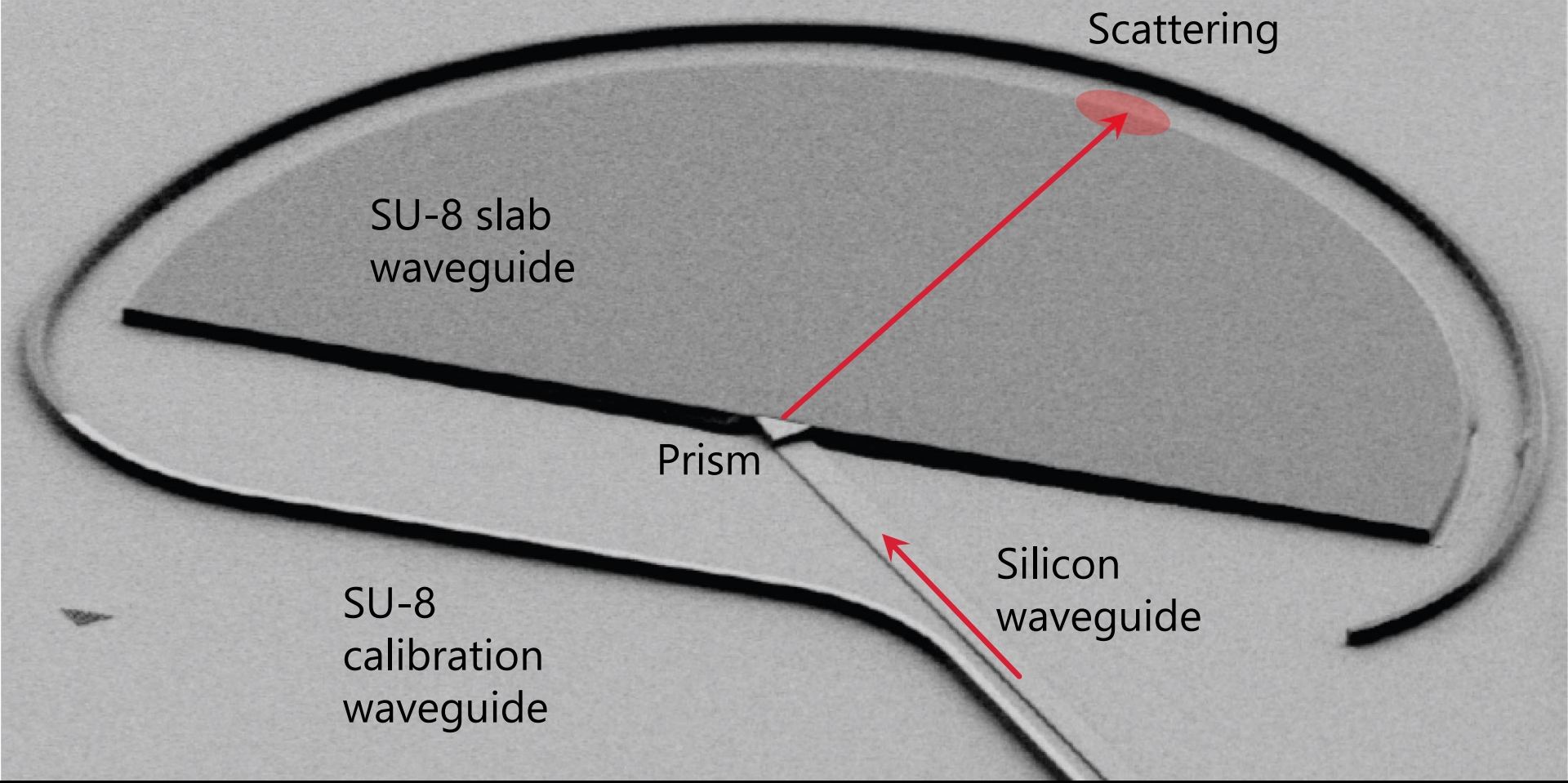


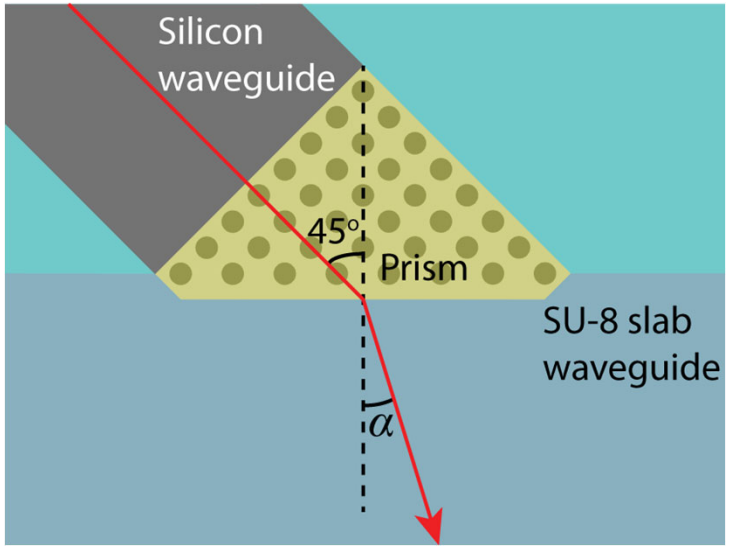

1 Zero index

2 Design

3 Experiment

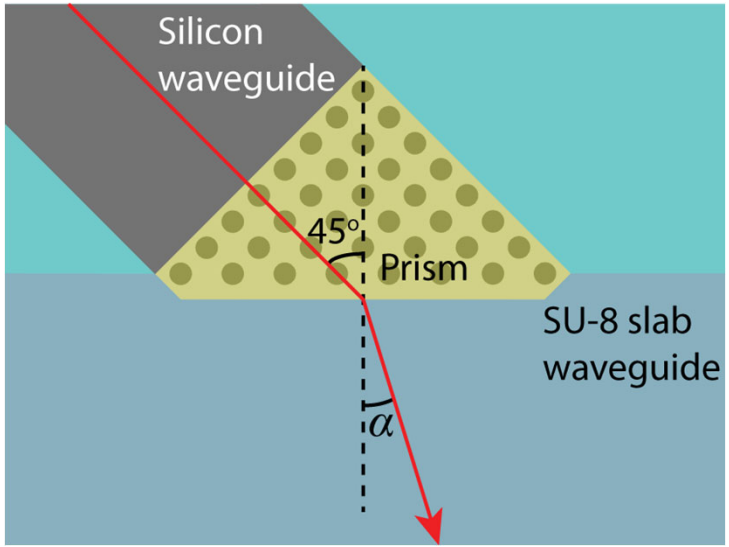

4 μm


Scattering
SU-8 slab
waveguide
Prism
Silicon
waveguide
SU-8
calibration
waveguide




Snell's law:

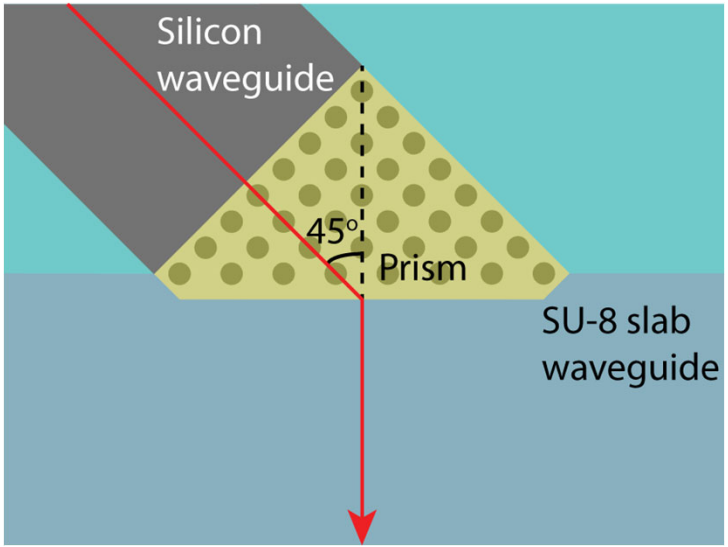
$$\frac{\sin 45^{o}}{\sin \alpha} = \frac{n_{\mathrm{slab}}}{n_{\mathrm{prism}}}$$




Snell's law:

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

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



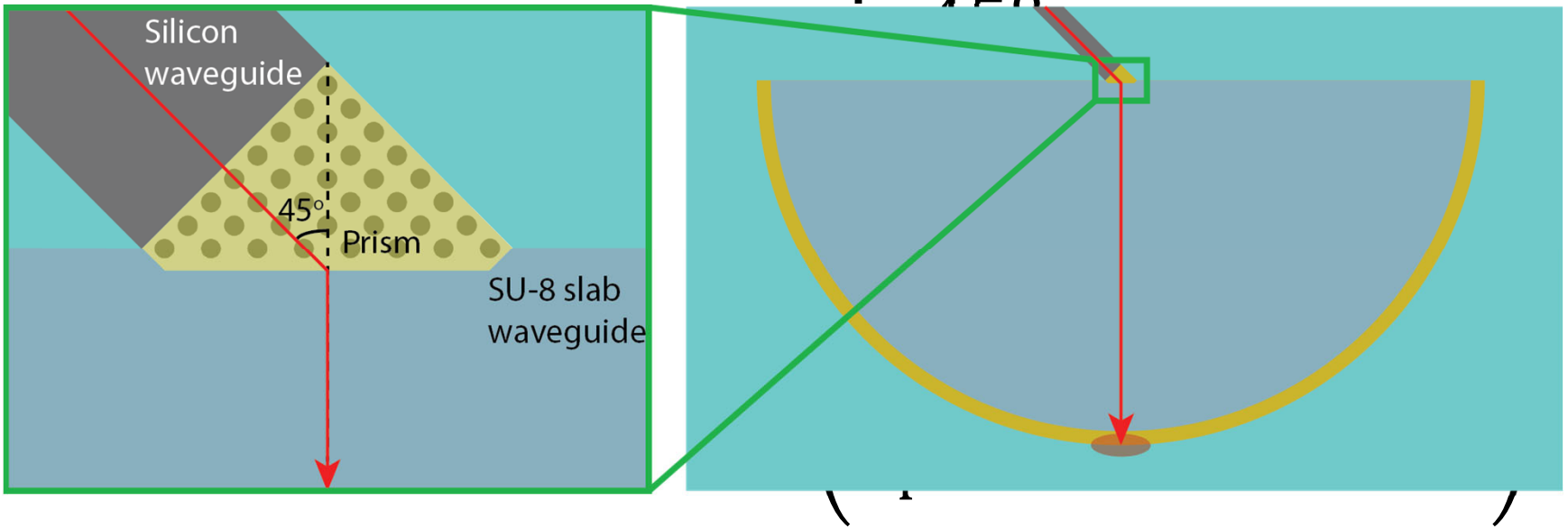

Snell's law:

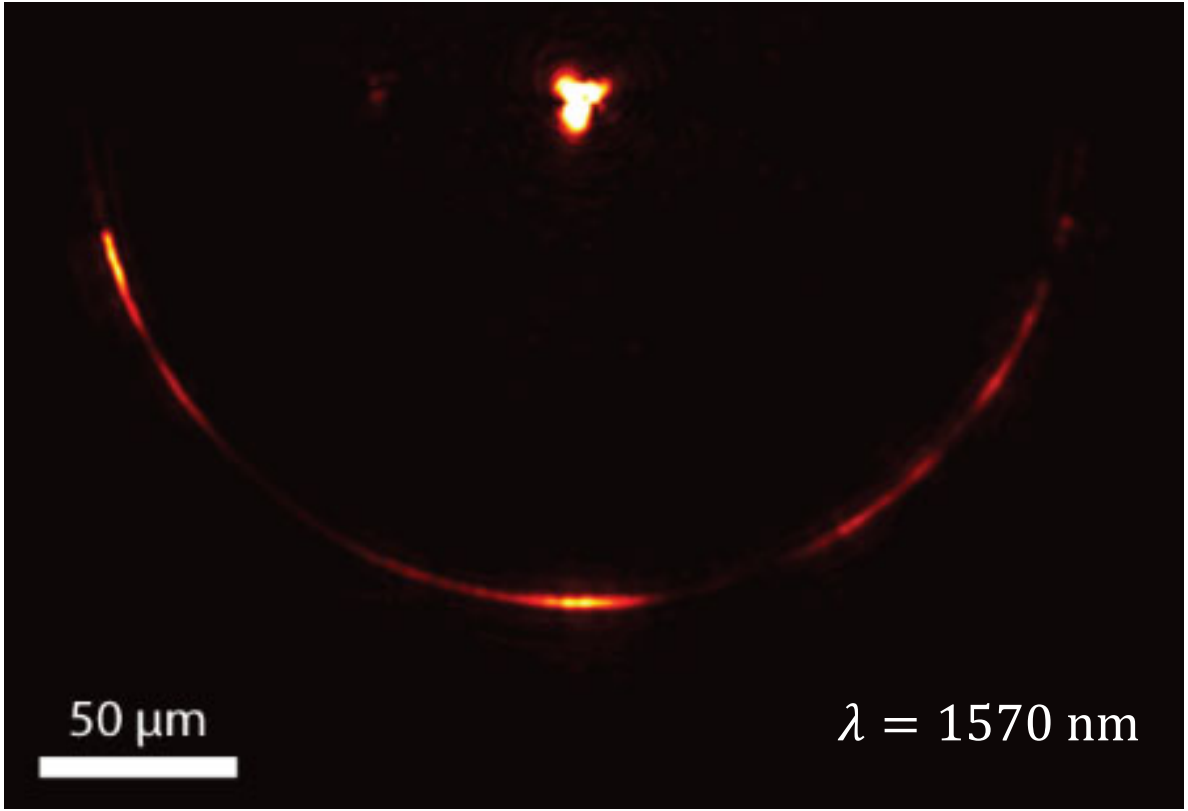
$$\frac{\sin 45^{\circ}}{\sin \alpha} = \frac{n_{\mathrm{slab}}}{n_{\mathrm{prism}}}$$

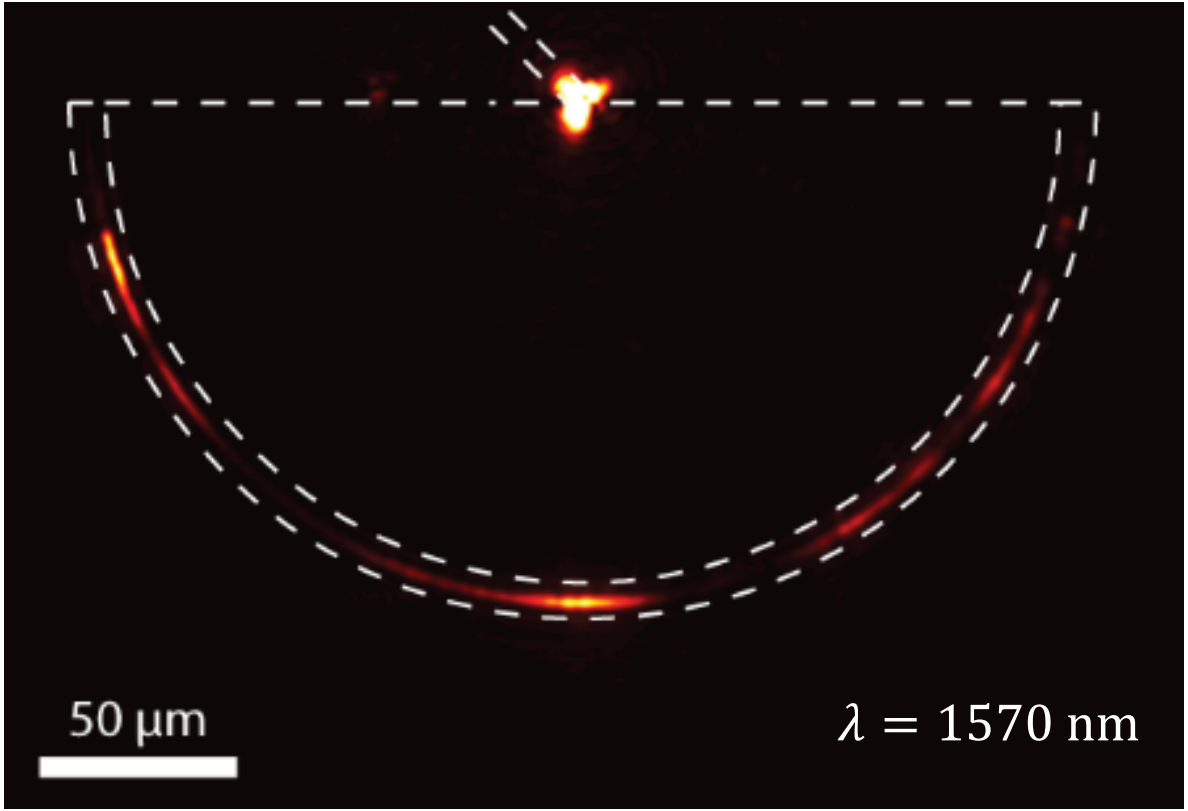
$$n_{\mathrm{prism}} = n_{\mathrm{slab}} \frac{\sin \alpha}{\sin 45^{\circ}}$$

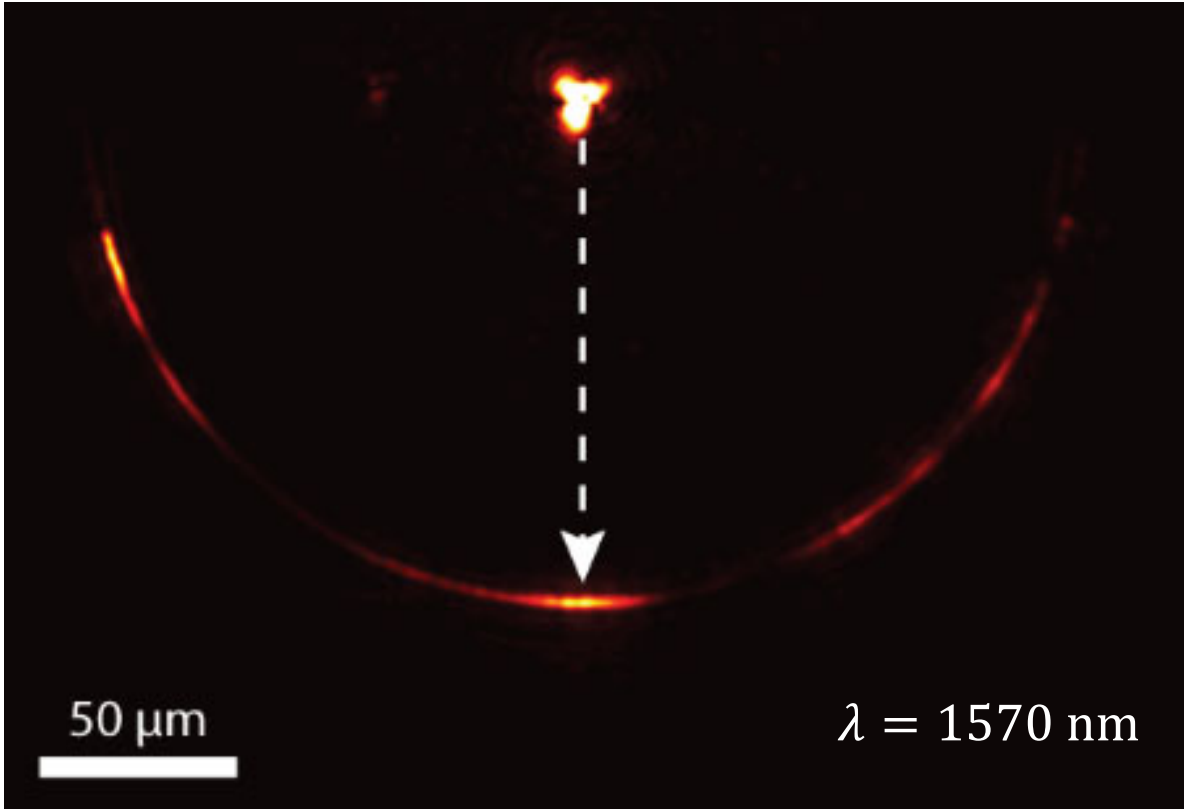
$$\left( n_{\mathrm{prism}} = 0 \leftrightarrow \alpha = 0 \right)$$

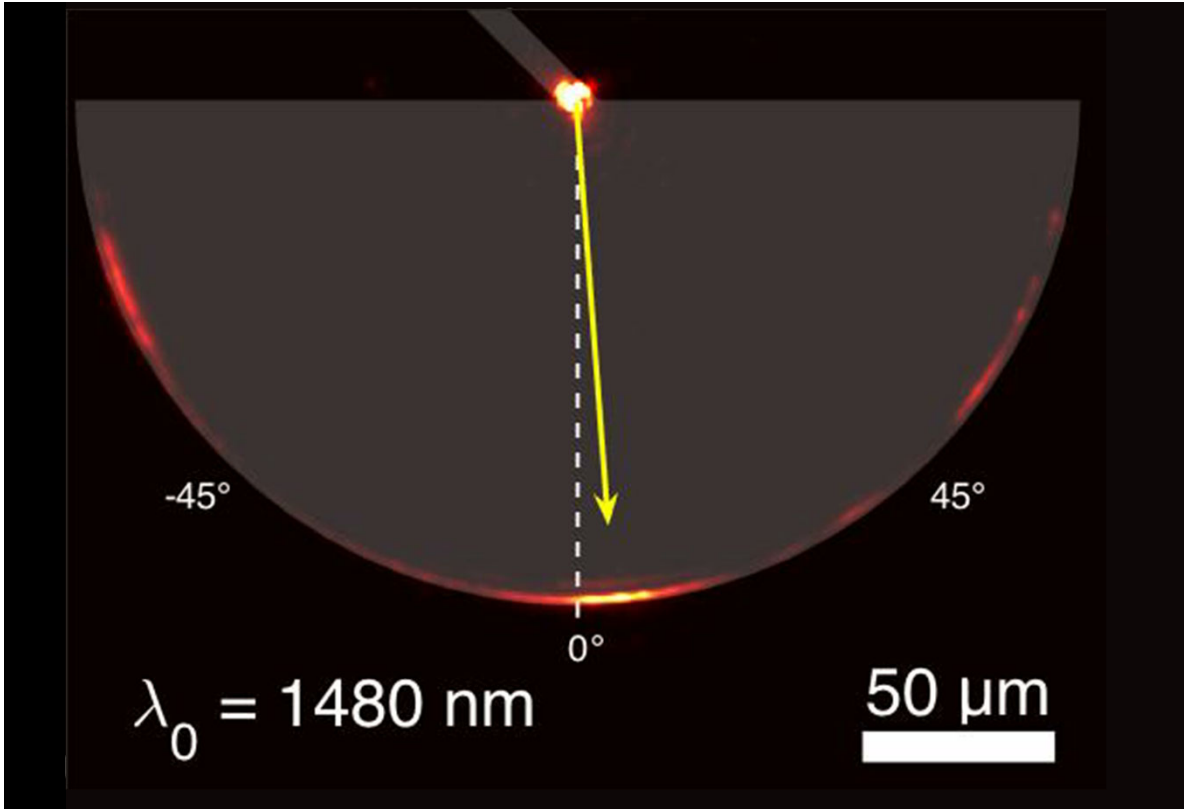
Snell's law:




50 μm
$\lambda = 1570$ nm


50 μm
$\lambda = 1570$ nm

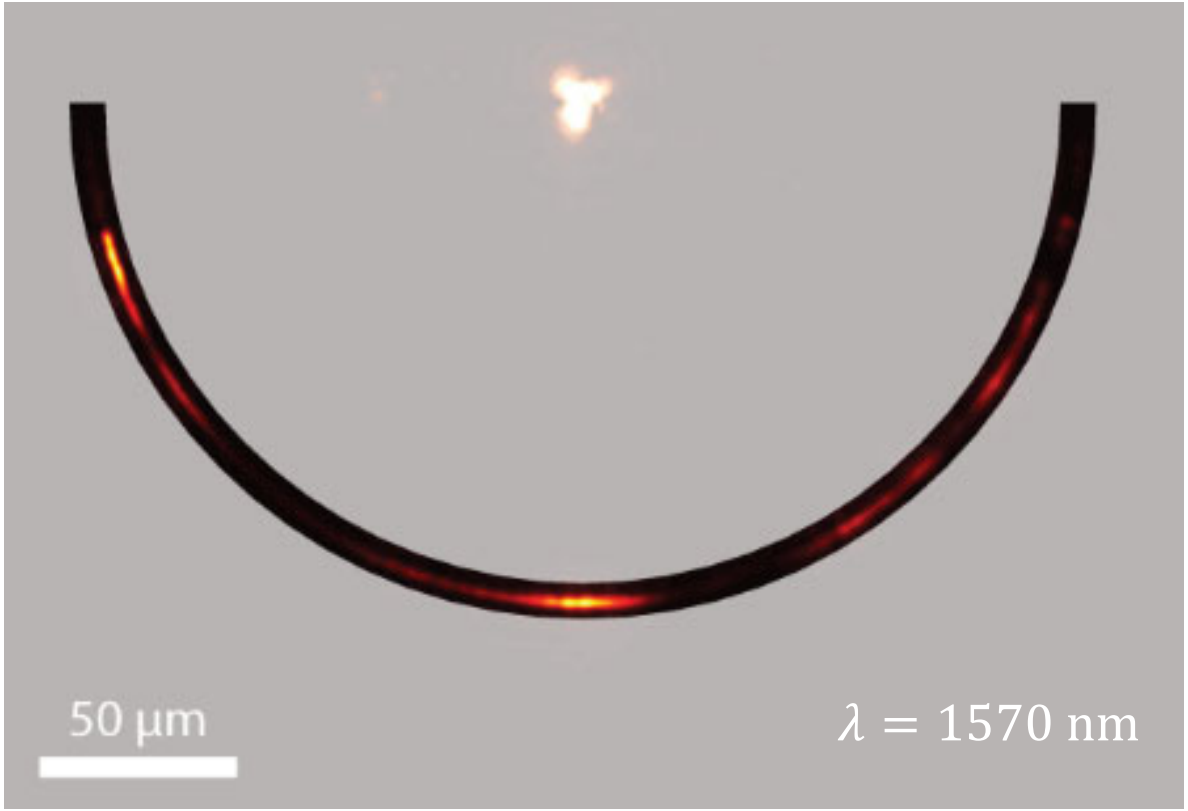

50 μm
$\lambda = 1570$ nm




1 Zero index

2 Design

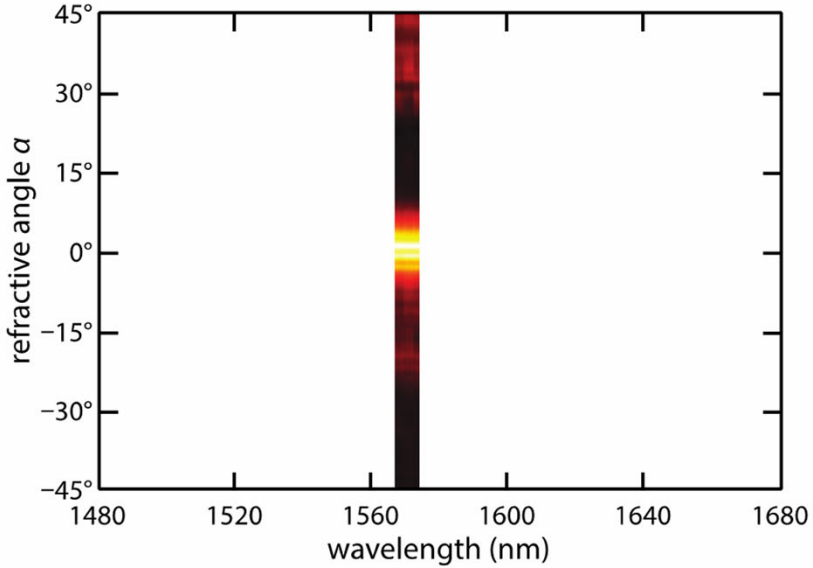
3 Experiment

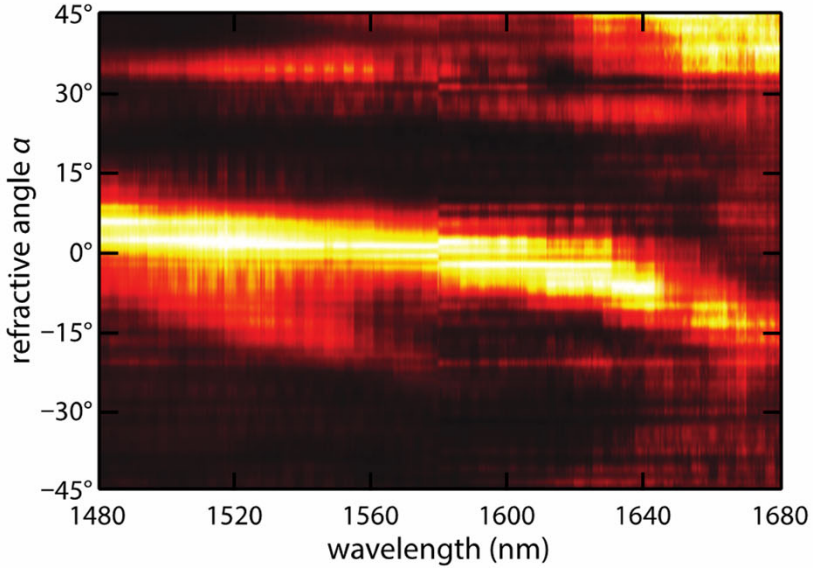



1 Zero index

2 Design

3 Experiment


45°
30°
15°
0°
−15°
−30°
−45°
refractive angle α
1480
1520
1560
1600
1640
1680
wavelength (nm)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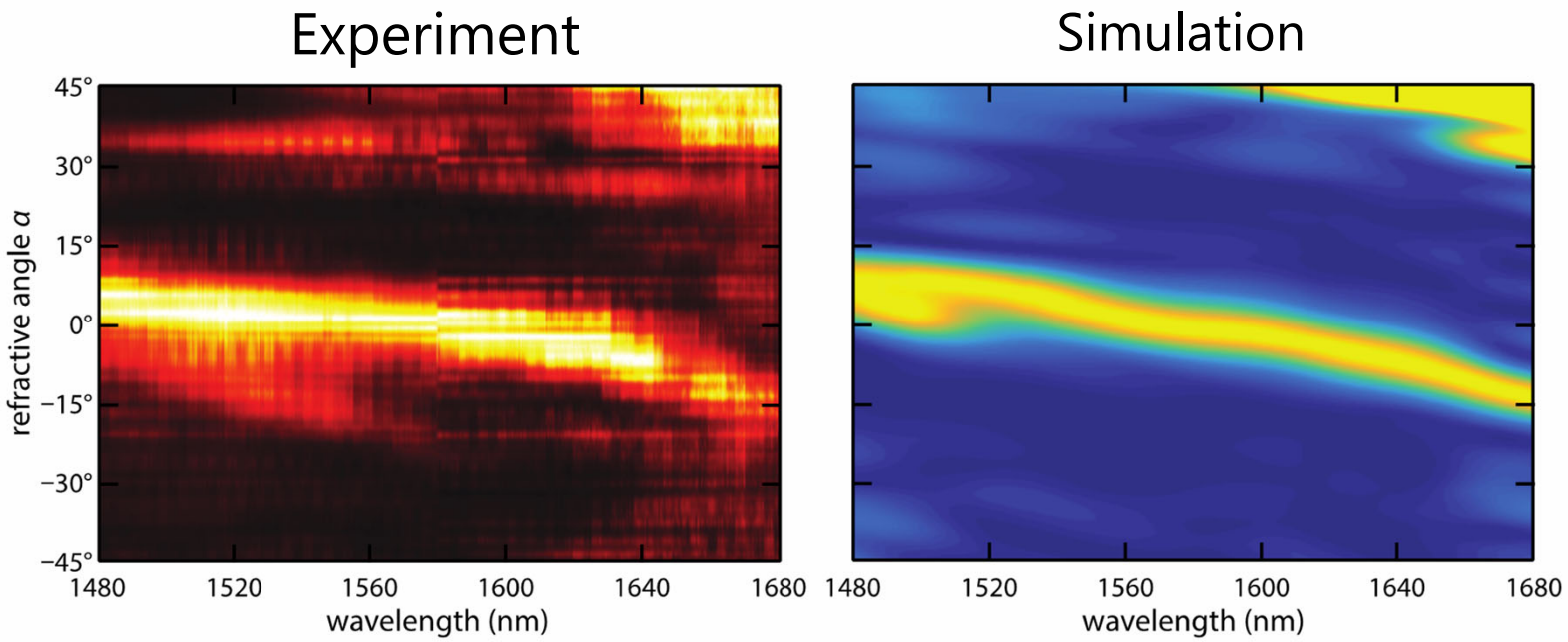


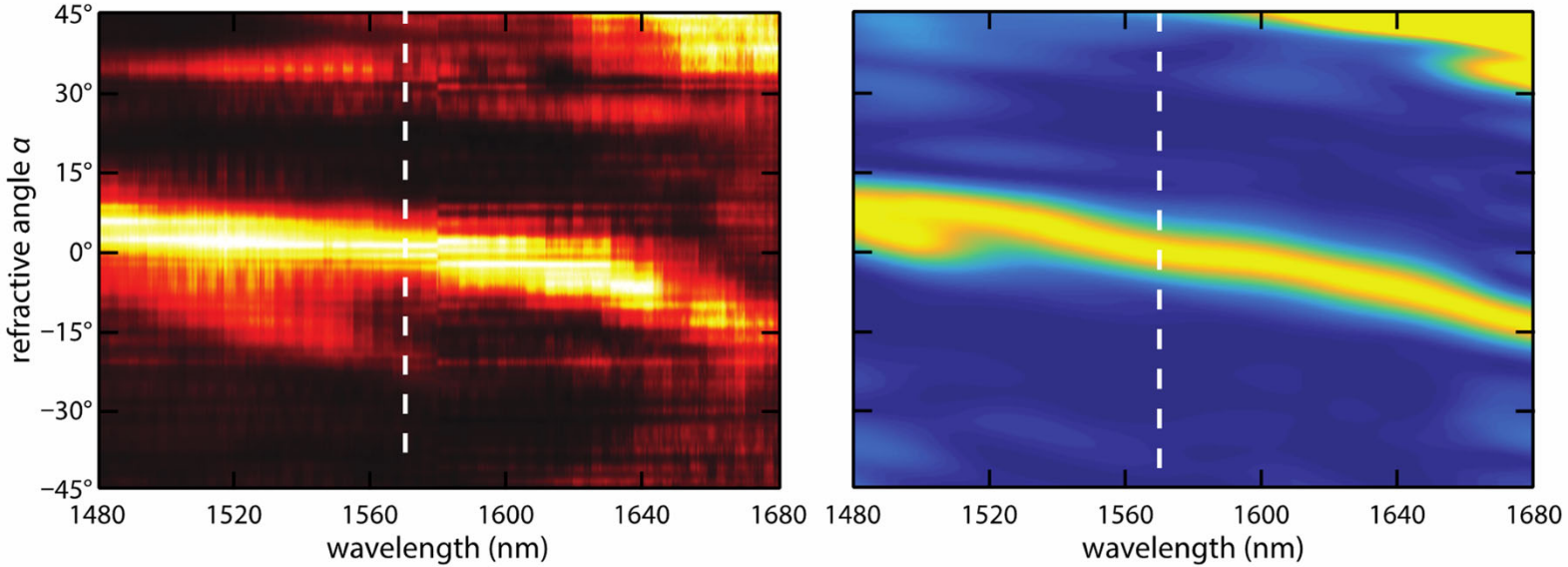

1 Zero index

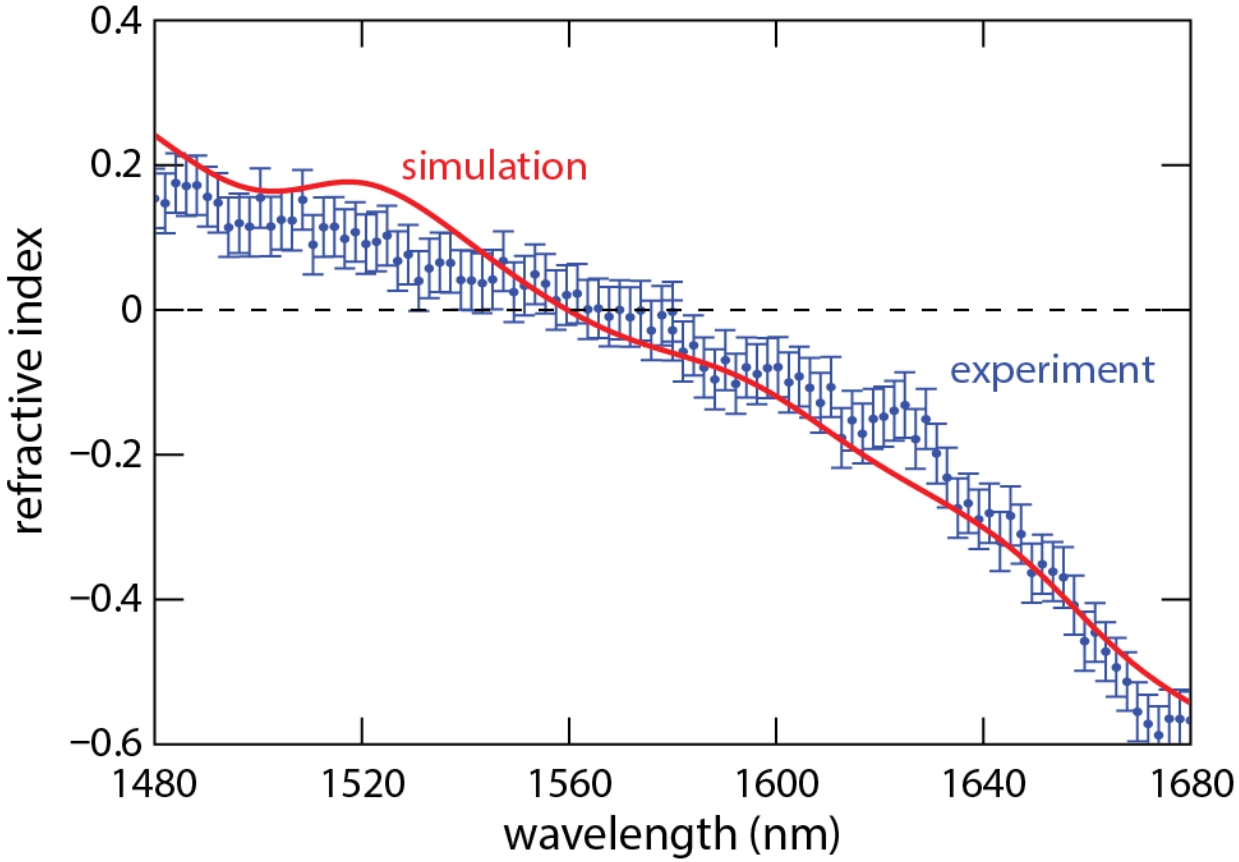
2 Design

3 Experiment

Experiment

Simulation






1 Zero index

2 Design

3 Experiment

We directly measured the zero index of a Dirac-cone metamaterial at $1570\ \mathrm{nm}$

# Conclusion

1. Zero index

   Physics and applications of zero index

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   Physics and applications of zero index

2. Design

   On-chip Dirac-cone metamaterial with impedance-matched zero index at $1590\ \mathrm{nm}$

# Conclusion

1. Zero index

   Physics and applications of zero index

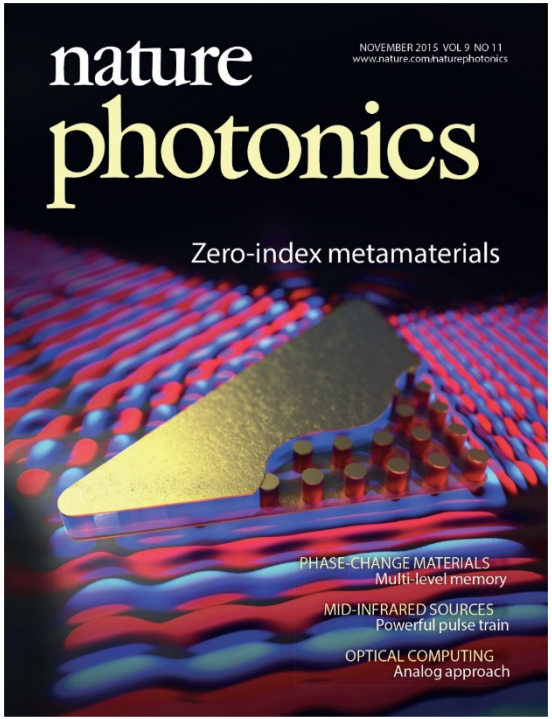
2. Design

   On-chip Dirac-cone metamaterial with impedance-matched zero index at $1590\ \mathrm{nm}$

3. Experiment

   Directly measure a zero index at $1570\ \mathrm{nm}$

For the first time, we unambiguously demonstrate an on-chip
Dirac-cone metamaterial with impedance-matched zero index




**Y. Li**, S. Kita, P. Muñoz, O. Reshef, D. Vulis, M. Yin, M. Lončar, E. Mazur, On-chip zero-index metamaterials. *Nat. Photonics* **9**, 738-742 (2015).

BRAINIAC

# How the tiniest light could supercharge computers





Tech Talk | Computing | Hardware

## Zero-Index Metamaterials Open New Possibilities for Optical Chips



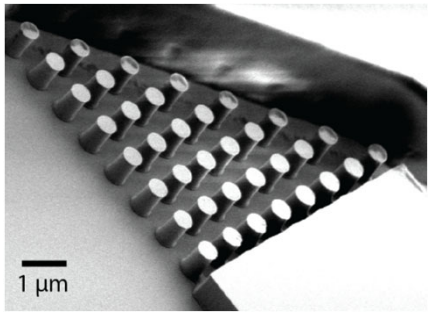
Posted by Tim De Chant on Tue, 27 Oct

Read Later Like Tweet

## New Gold-Plated Silicon Array Can Cleverly Control Light

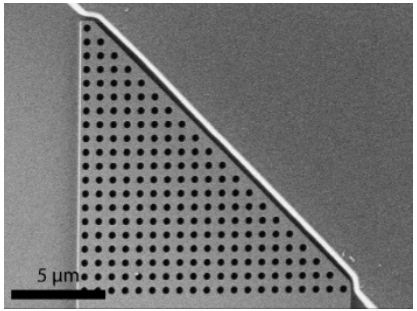
# On-chip zero-index metamaterials (ZIMs)

All-dielectric fabrication-tolerant ZIM



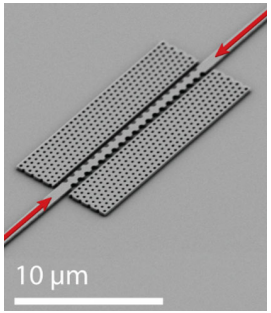

*Opt. Express*, 25, 8326 (2017)

Monolithic CMOS-compatible ZIM



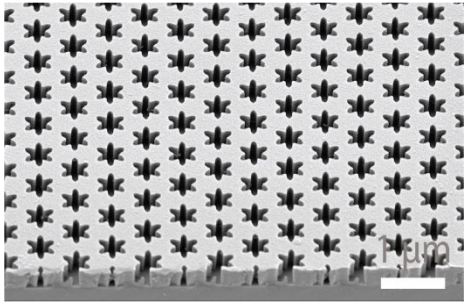

*Opt. Express*, 25, 12381 (2017)

1D zero-index waveguide



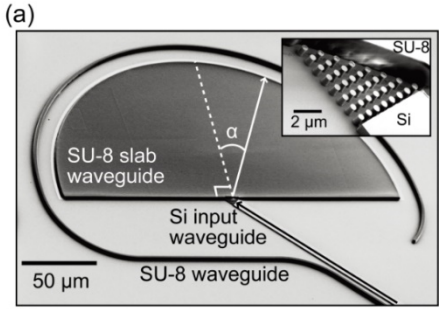

*ACS Photonics*, 4, 2385 (2017)

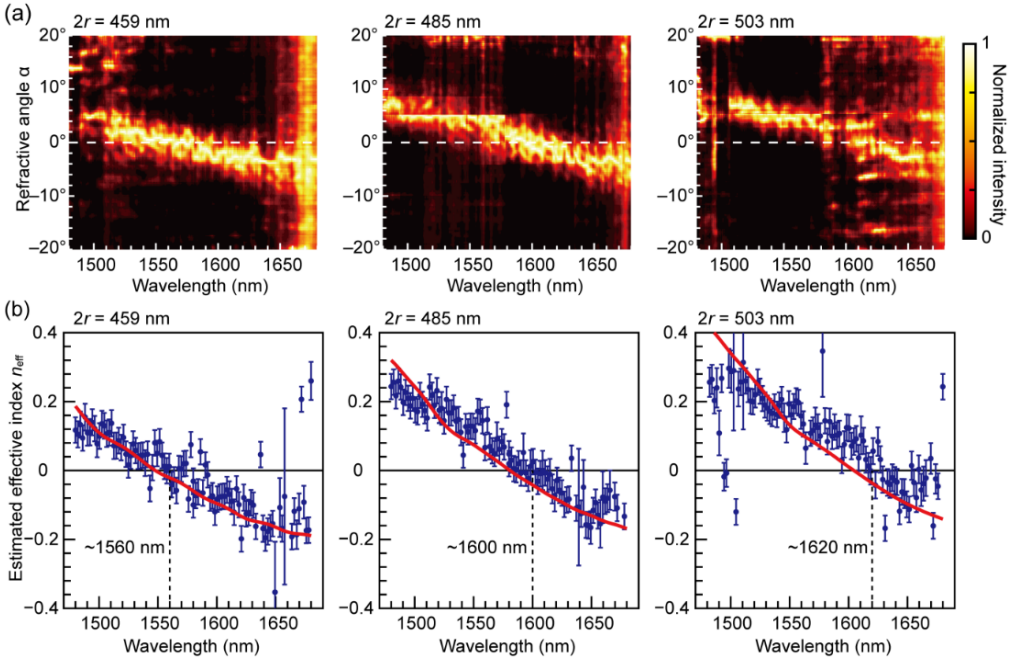
Ultra-low-loss ZIM



arXiv:2004.01818

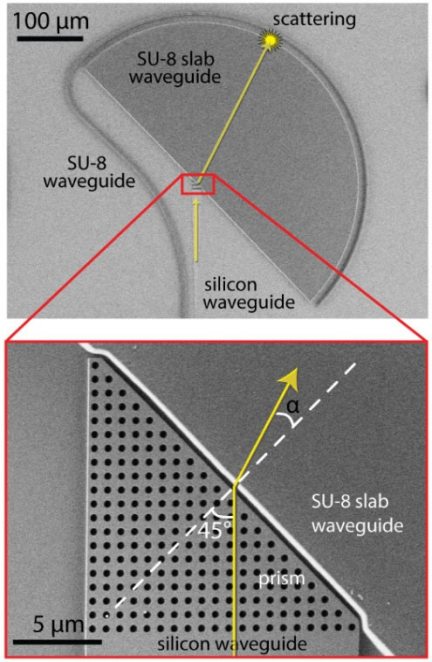
# All-dielectric fabrication-tolerant zero-index metamaterials

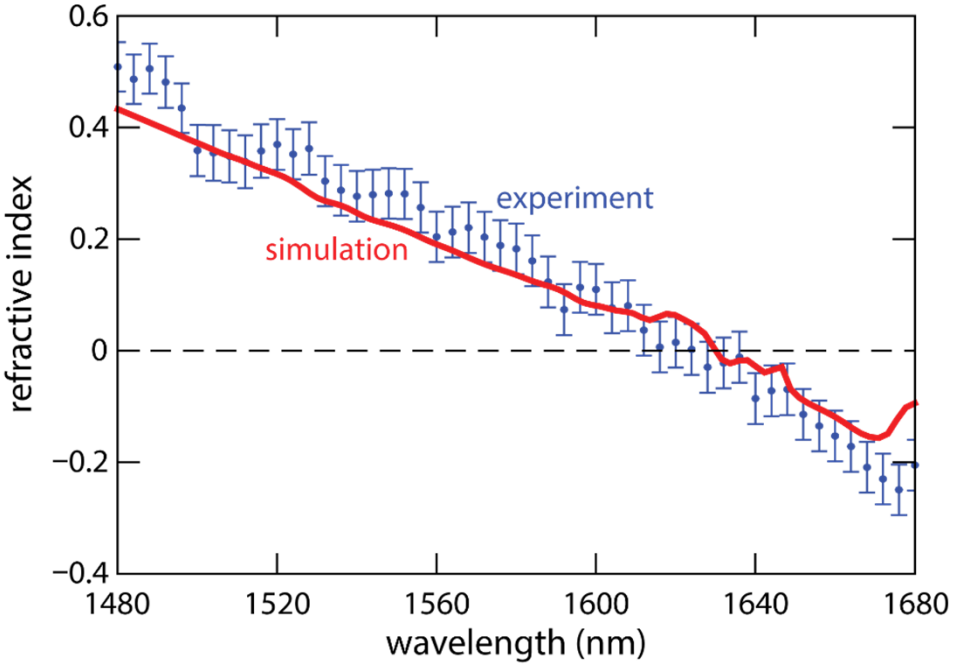



*Opt. Express*, 25, 8326 (2017)

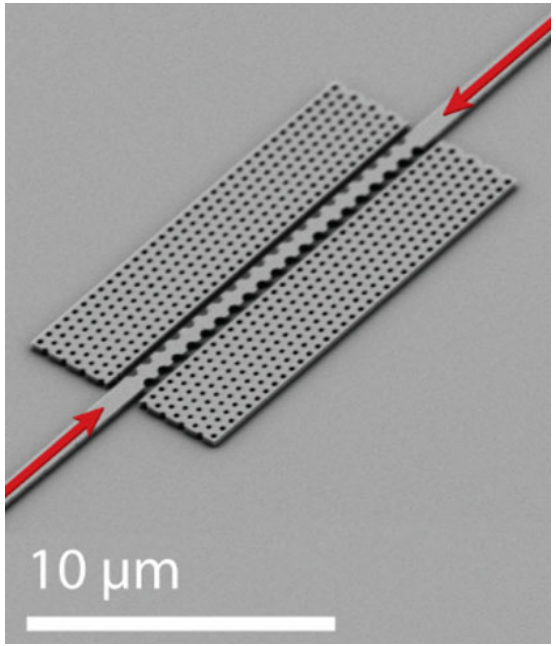
# Monolithic CMOS-compatible zero-index metamaterials

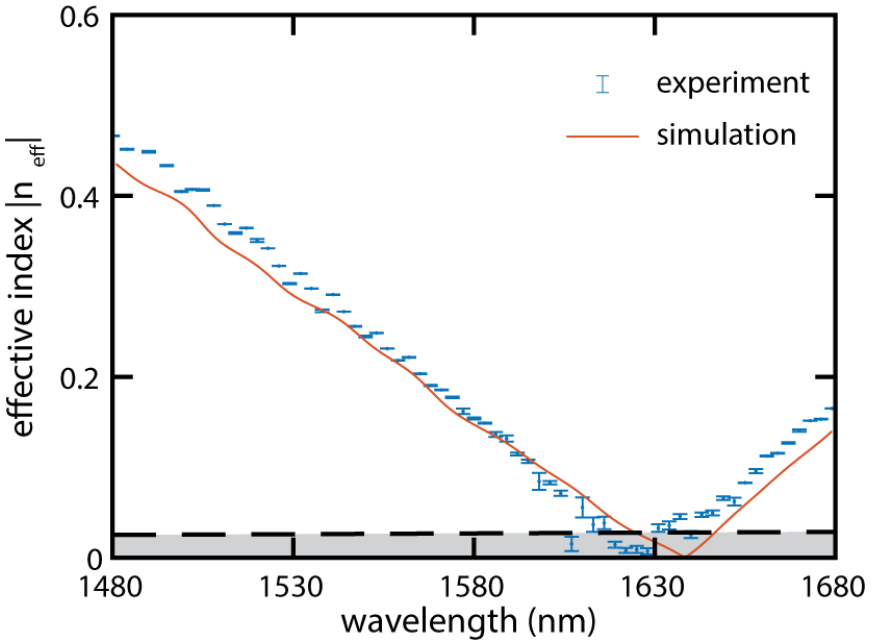



*Opt. Express*, 25, 12381 (2017)

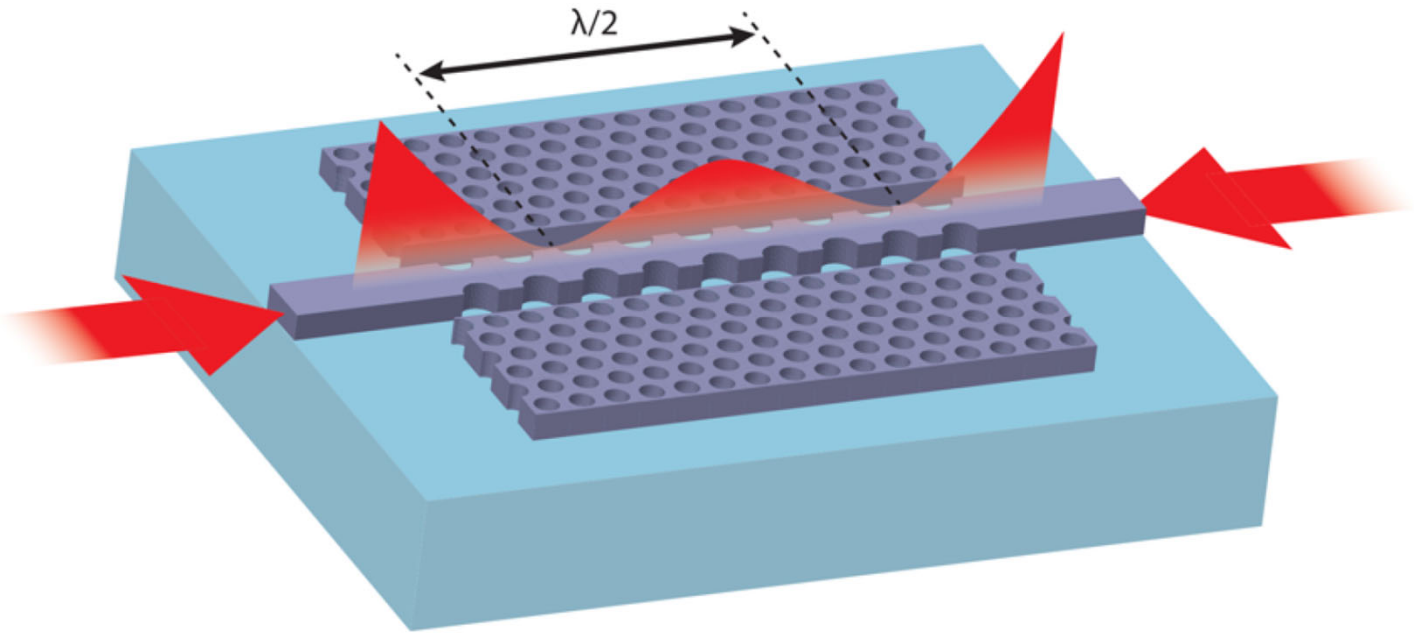
# 1D zero-index waveguide



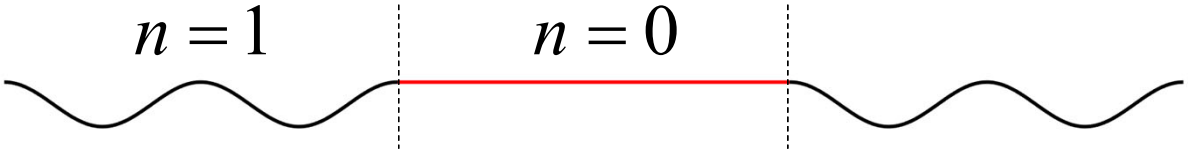

*ACS Photonics*, 4, 2385 (2017)

# 1D zero-index waveguide

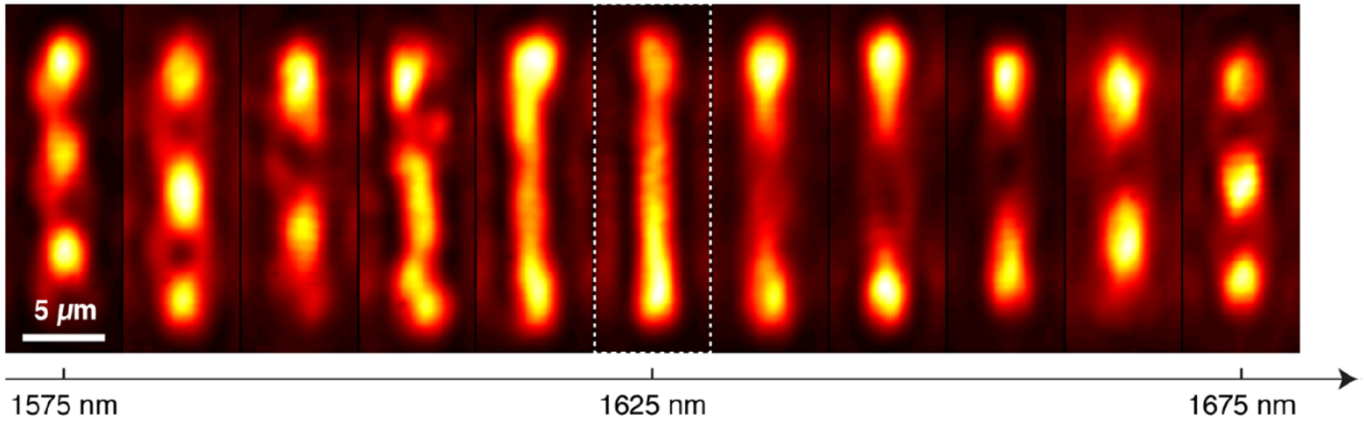



*ACS Photonics*, 4, 2385 (2017)

# 1D zero-index waveguide

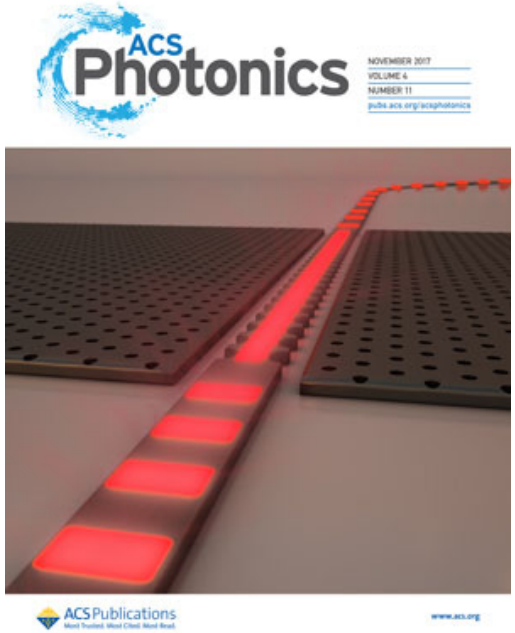



Measured interference pattern




*ACS Photonics*, 4, 2385 (2017)

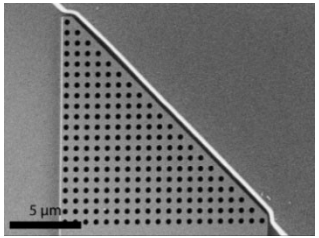
# 1D zero-index waveguide

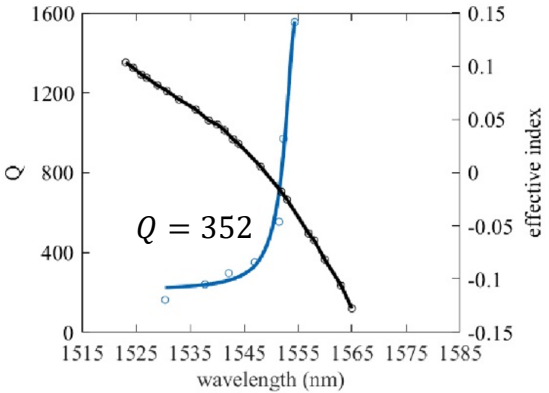



*ACS Photonics*, 4, 2385 (2017)

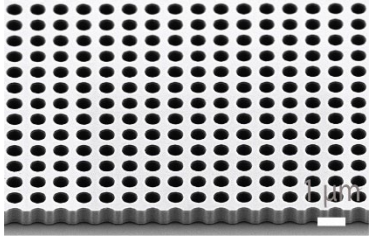
# Low-loss zero-index metamaterials

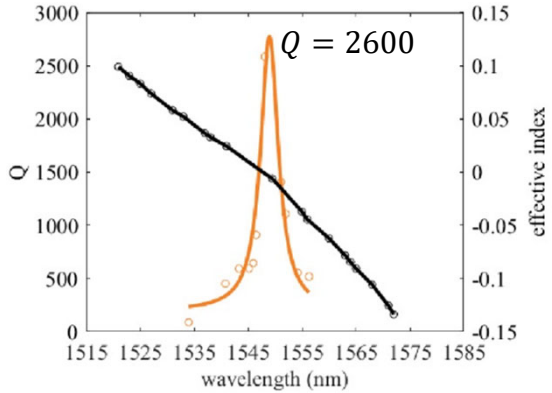
Regular ZIM



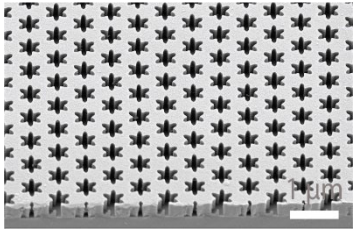



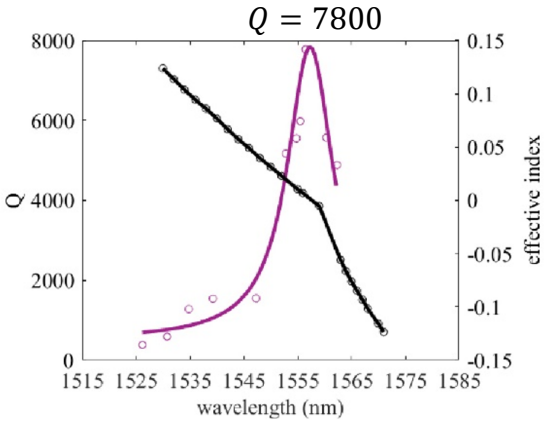

Resonance-trapped ZIM




Symmetry protected ZIM

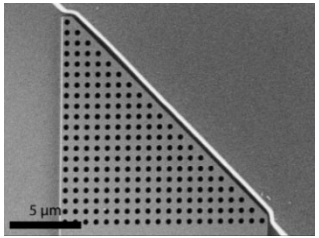


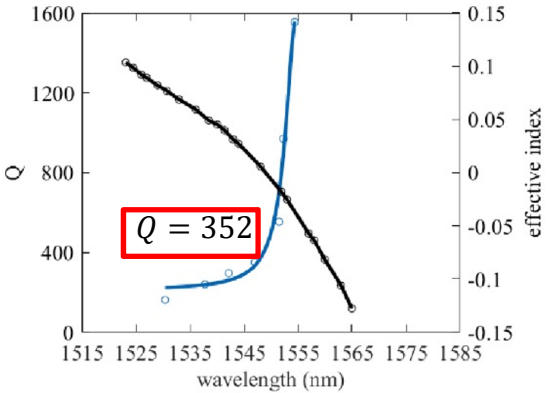




arXiv:2004.01818

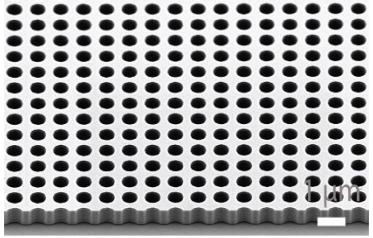
# Low-loss zero-index metamaterials

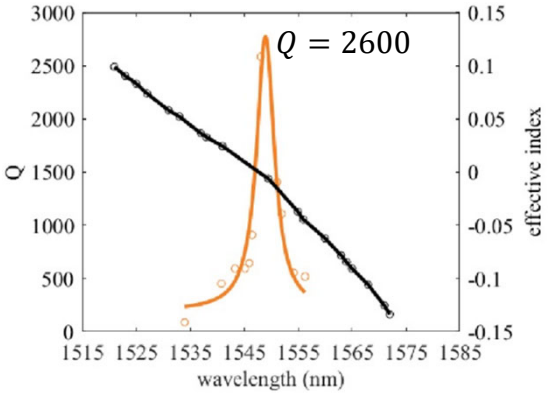
Regular ZIM



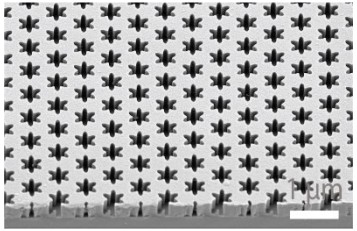



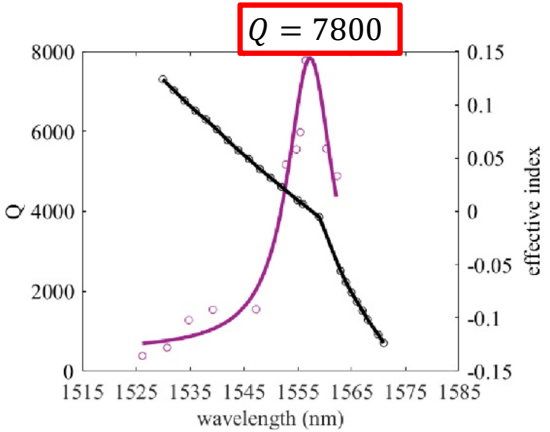

Resonance-trapped ZIM



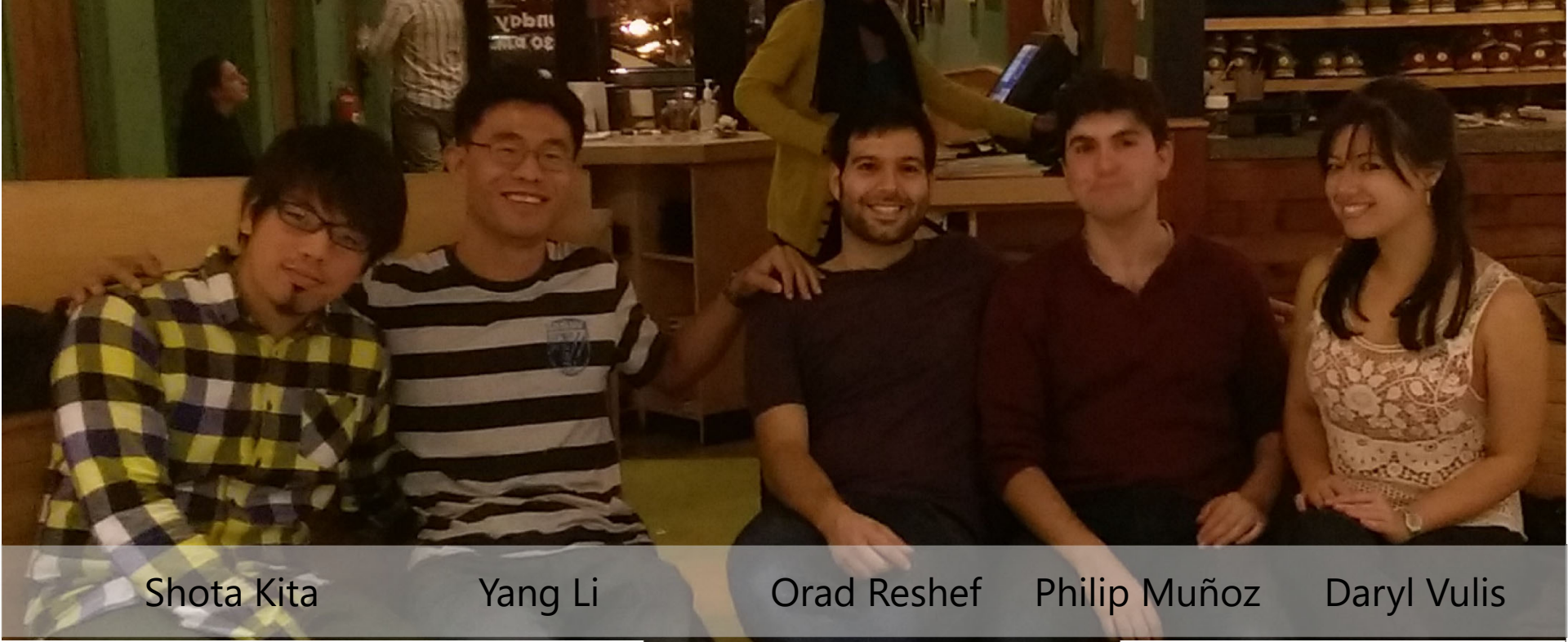



Symmetry protected ZIM

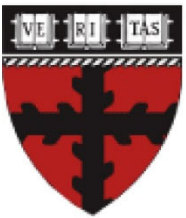





arXiv:2004.01818



Shota Kita Yang Li Orad Reshef Philip Muñoz Daryl Vulis




Laboratory for Nanoscale Optics

Prof. Marko Loncar

HARVARD School of Engineering and Applied Sciences

Center for Nanoscale Systems

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Federico Capasso
Robert L. Wallace Professor
of Applied Physics

Marko Loncar
Tiantsai Lin Professor of
Electrical Engineering

Eric Mazur
Balkanski Professor of
Physics and Applied Physics

NSF PHY-1720438

- PI: E. Mazur, Co-PI: M. Lončar
- Amount: $460,000
- Dates: 2017-08-01 to 2020-07-31

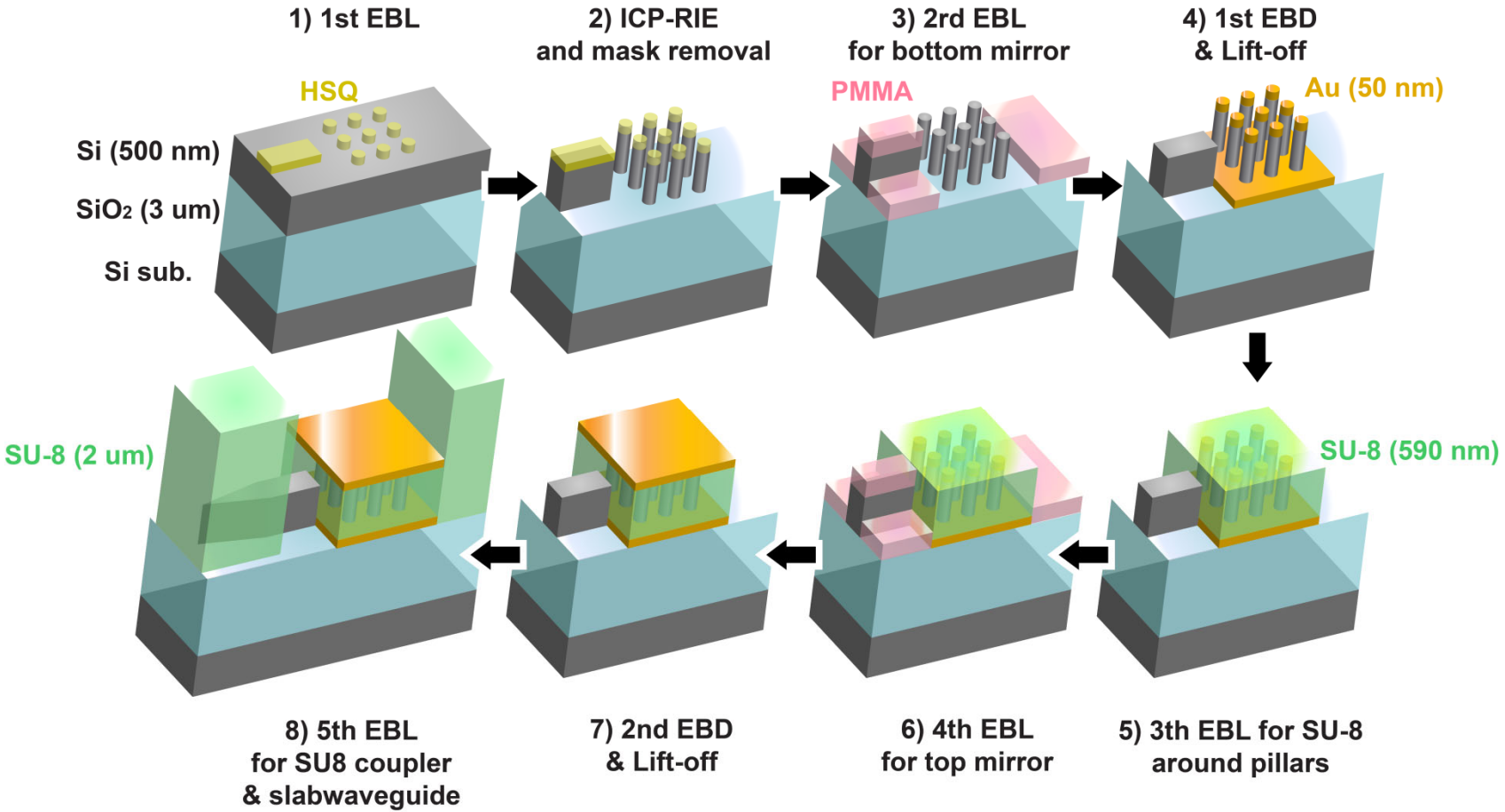
NSF DMR-1360889

- PI: E. Mazur, Co-PI: **Y. Li**
- Amount: $400,000
- Dates: 2014-07-01 to 2016-06-30

SAMSUNG Global Research Outreach (GRO) Program

- PI: E. Mazur, Co-PI: **Y. Li**
- Amount: $100,000
- Dates: 2016-11-14 to 2017-11-13

Thank you ☺


1) 1st EBL
2) ICP-RIE
and mask removal
3) 2rd EBL
for bottom mirror
4) 1st EBD
& Lift-off
HSQ
PMMA
Au (50 nm)
Si (500 nm)
SiO2 (3 um)
Si sub.
SU-8 (2 um)
SU-8 (590 nm)
8) 5th EBL
for SU8 coupler
& slabwaveguide
7) 2nd EBD
& Lift-off
6) 4th EBL
for top mirror
5) 3th EBL for SU-8
around pillars