Today's Webinar

Designing High Performance Devices in Silicon Using Subwavelength Structures

Prof. Robert Halir

University of Malaga (Spain)
Andalusian Institute for Nano-medicine and Biotechnology (Bionand)

You can find more information about subwavelength integrated photonics on the ***review*** *co-authored by Dr. Halir and recently published by* ***Nature****: P. Cheben, et al. "Subwavelength integrated photonics." Nature 560.7720 (2018)*

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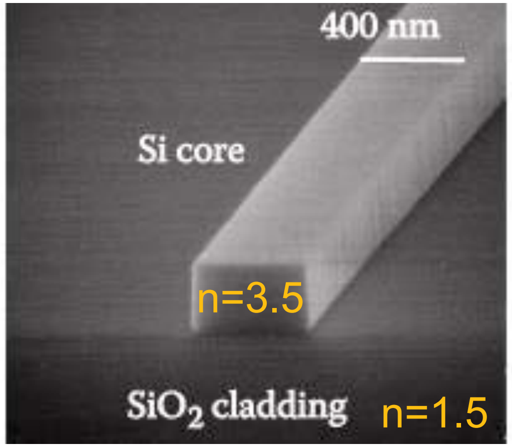
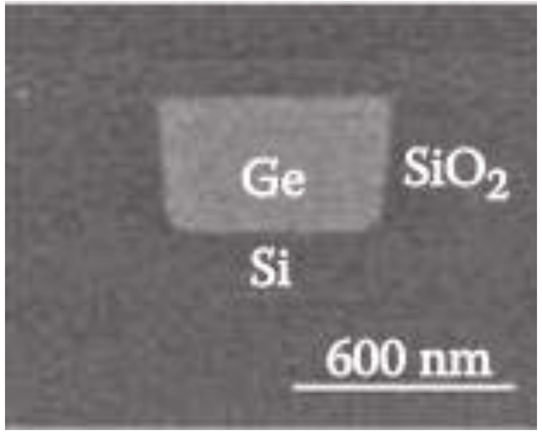
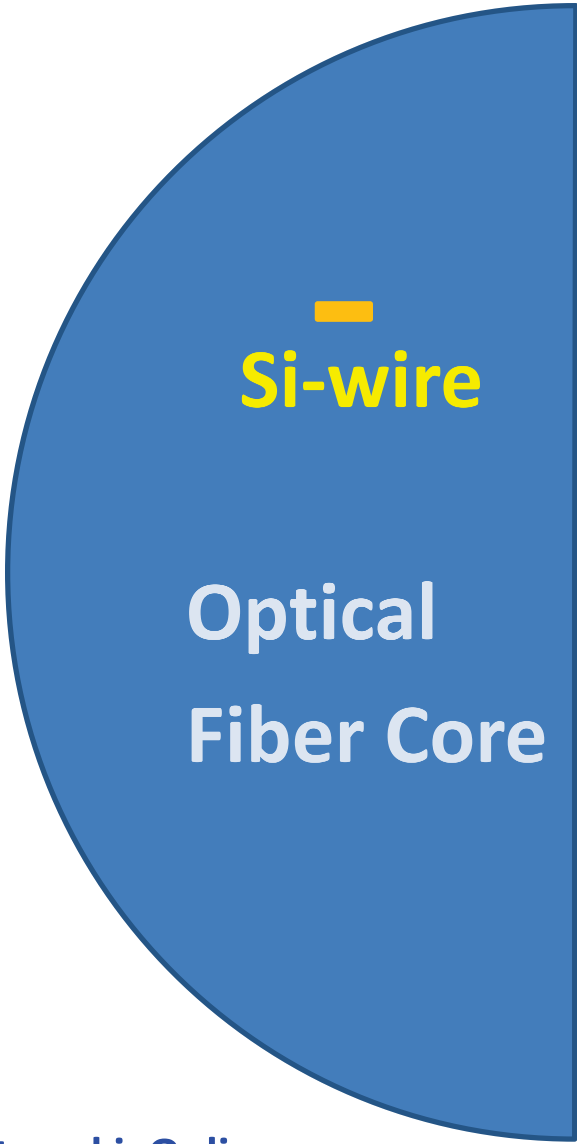




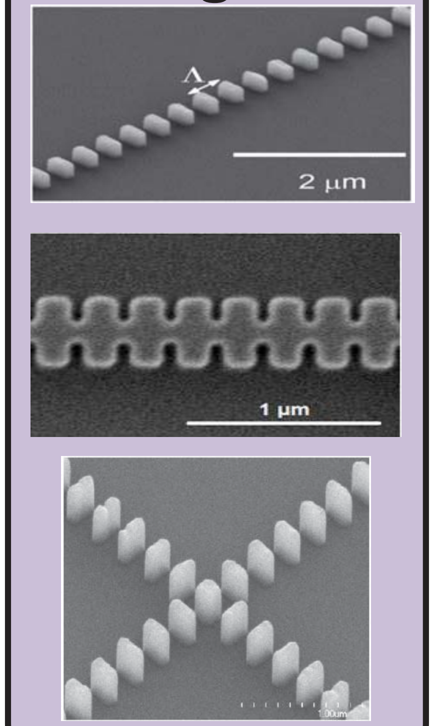


- Silicon microelectronics (the "age of silicon")
- High contrast ($\Delta n=2$), small features ($\approx$100nm)
- High speed photodetection and modulation
- Hybrid integration of III-V lasers
- Commercial use: Luxtera, Acacia, …
- Only a few CMOS compatible materials available.

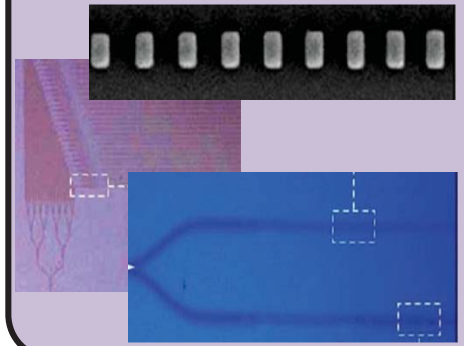
"Handbook of Silicon Photonics", Laurent Vivien, 2013 + "Silicon Photonics Design" Lukas Chrostowski, Online course
"Silicon photonics circuit design" Wim Bogaerts, Laser and Photonics Reviews 12, 2018

The right material for every device

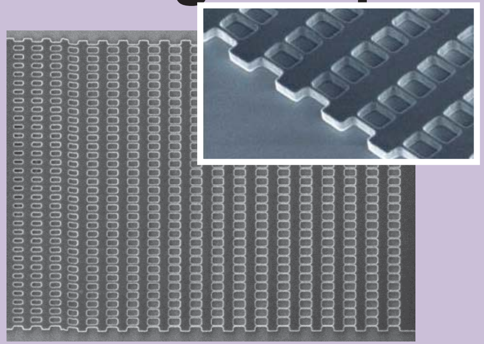
Waveguides



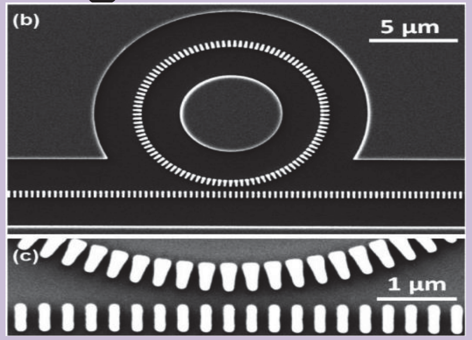
Spectrometers



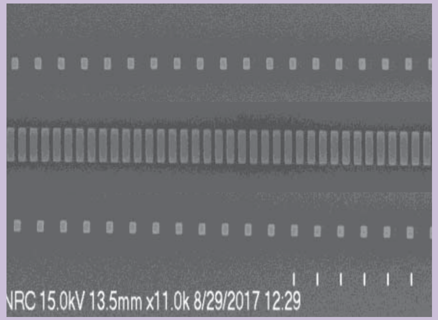
Grating Couplers



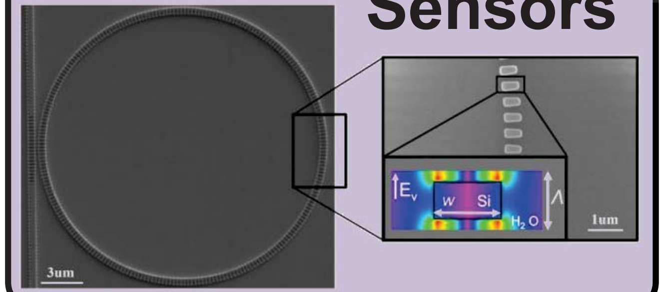
Ring Resonators



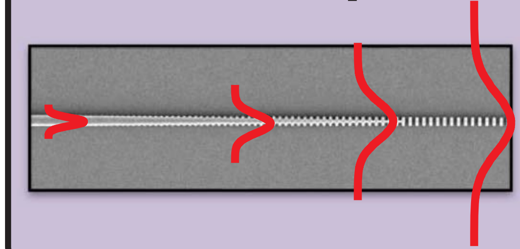
Spectral Filters



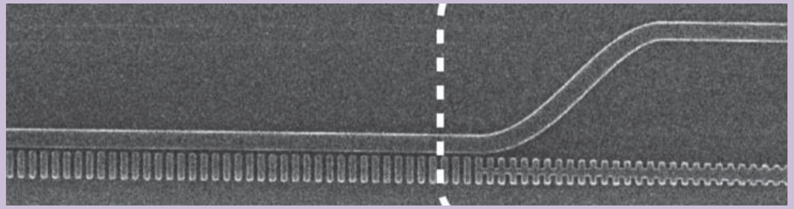
Sensors



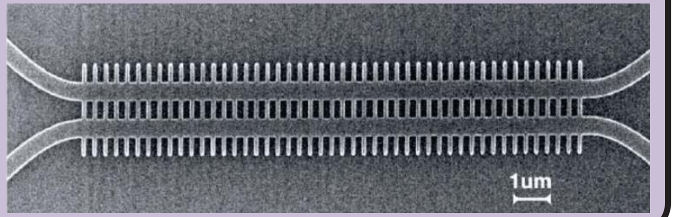
Facet Couplers



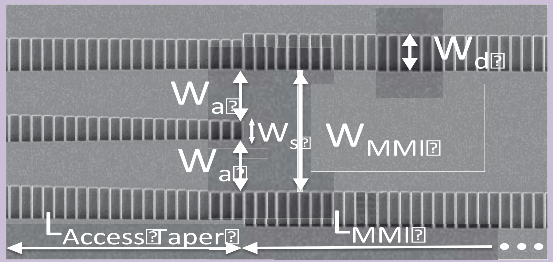
Polarization Management

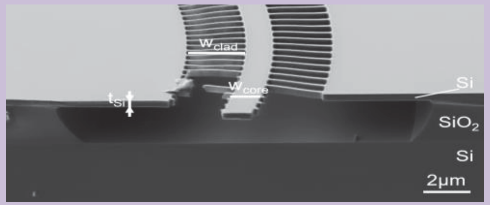


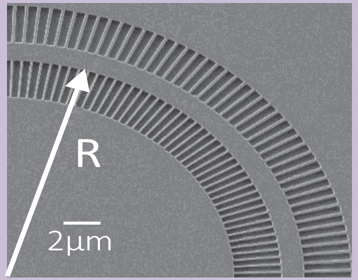
Broadband couplers



Mid-Infrared







Review paper: R. Halir *et al.*, Laser and Photonics Reviews 9, 2015 nature > review articles > article

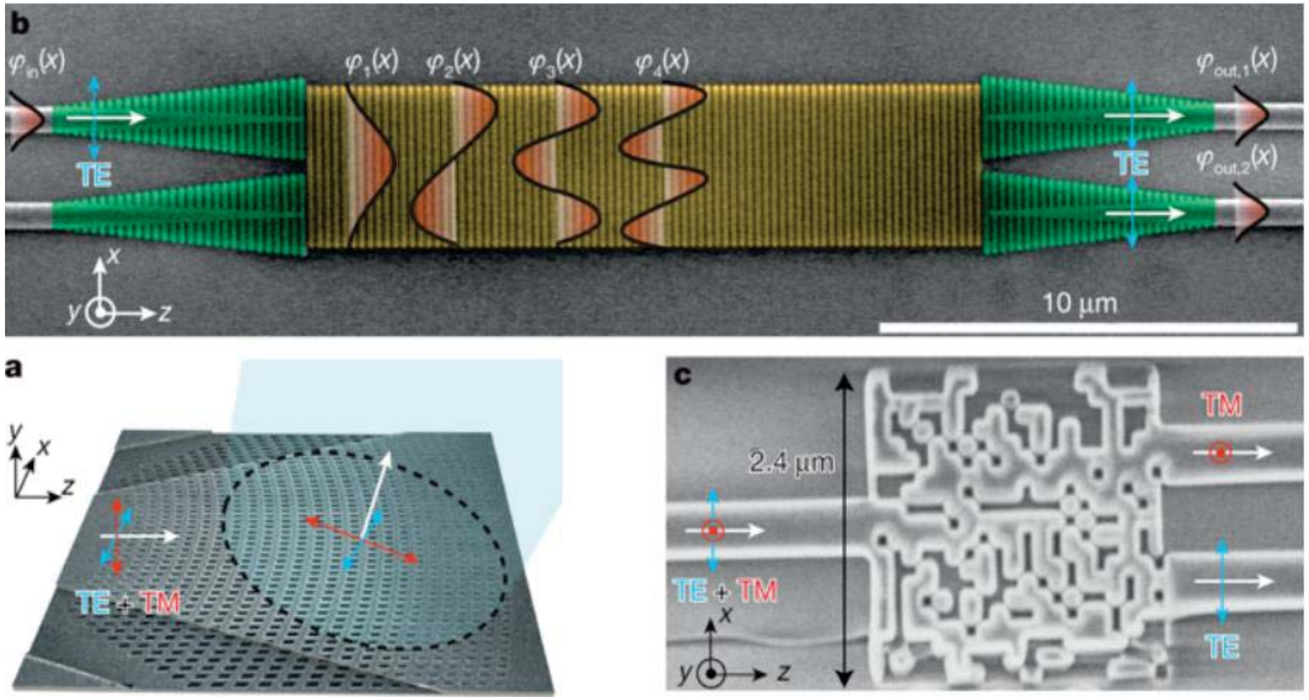
nature
International journal of science

Review Article | Published: 29 August 2018

Subwavelength integrated photonics

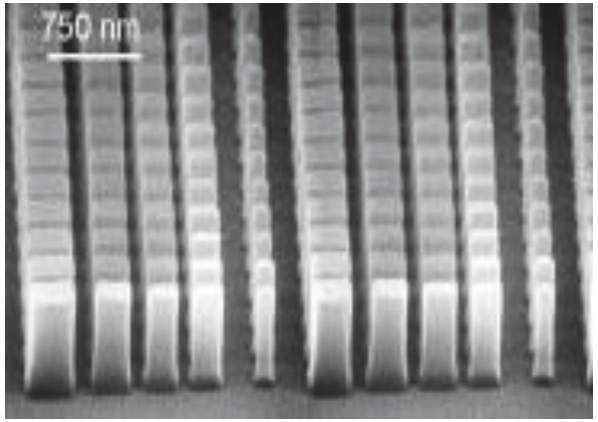
Pavel Cheben, Robert Halir, Jens H. Schmid, Harry A. Atwater & David R. Smith

Nature **560**, 565–572 (2018) | Download Citation



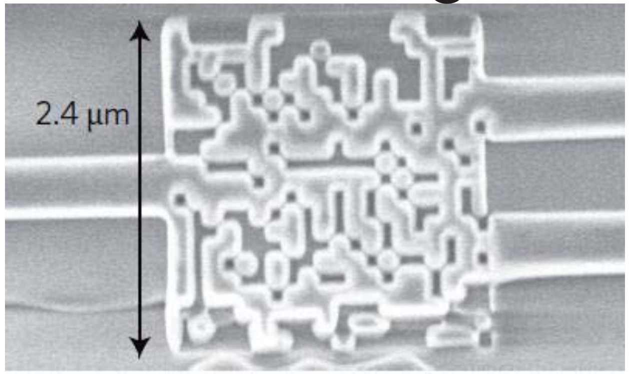
P. Cheben *et al.*, Nature 560, 2018

Metasurfaces

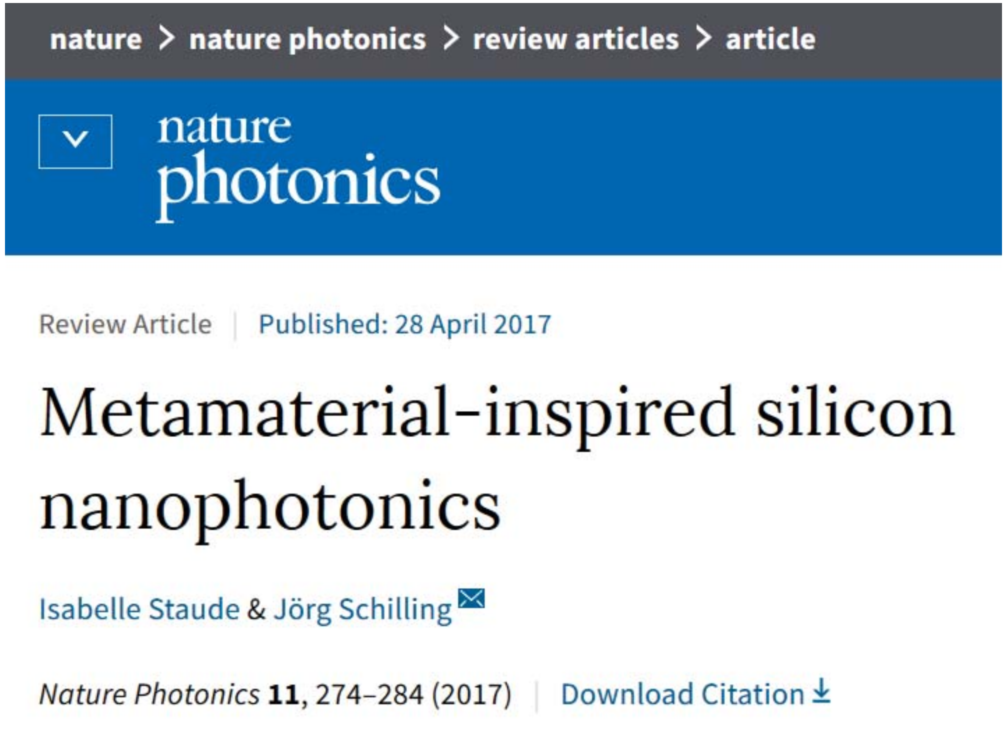


P. Lalanne, J. Opt. Soc. Am. A 16, 1999
M. Khorasaninejad, Nano Lett. 16, 2016

Inverse design



A. Y. Piggot, Nature Photonics 9, 2015
B. Shen, Nature Photonics 9, 2015


nature > nature photonics > review articles > article

nature photonics

Review Article | Published: 28 April 2017

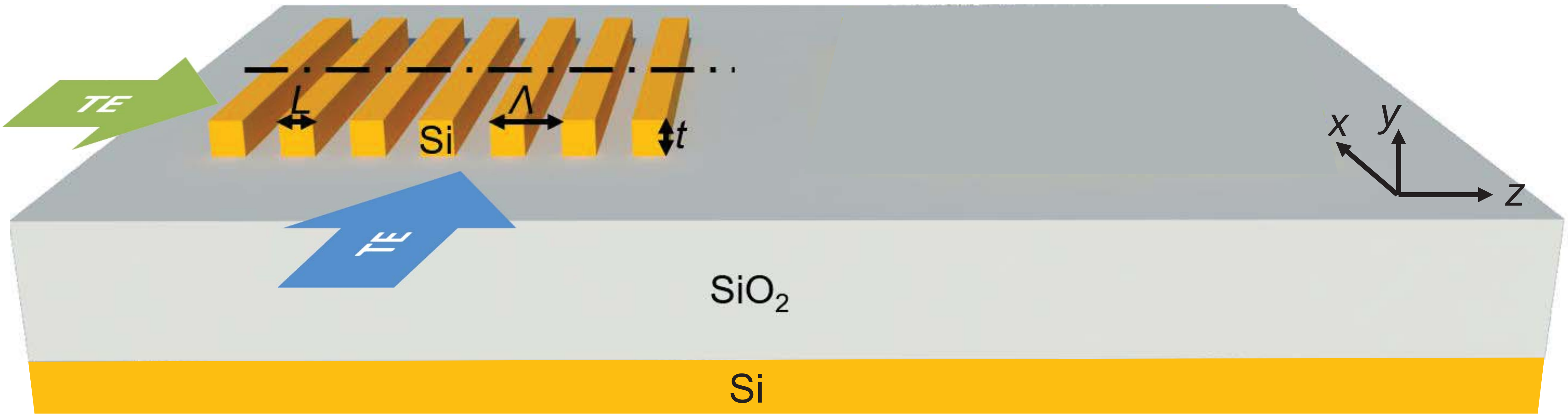
Metamaterial-inspired silicon nanophotonics

Isabelle Staude & Jörg Schilling

Nature Photonics **11**, 274–284 (2017) | Download Citation

I. Staude, Nature Photonics 11, 2017

Refractive Index	Dispersion & Anisotropy
Fundamentals	Fundamentals
Applications & Devices	Applications & Devices



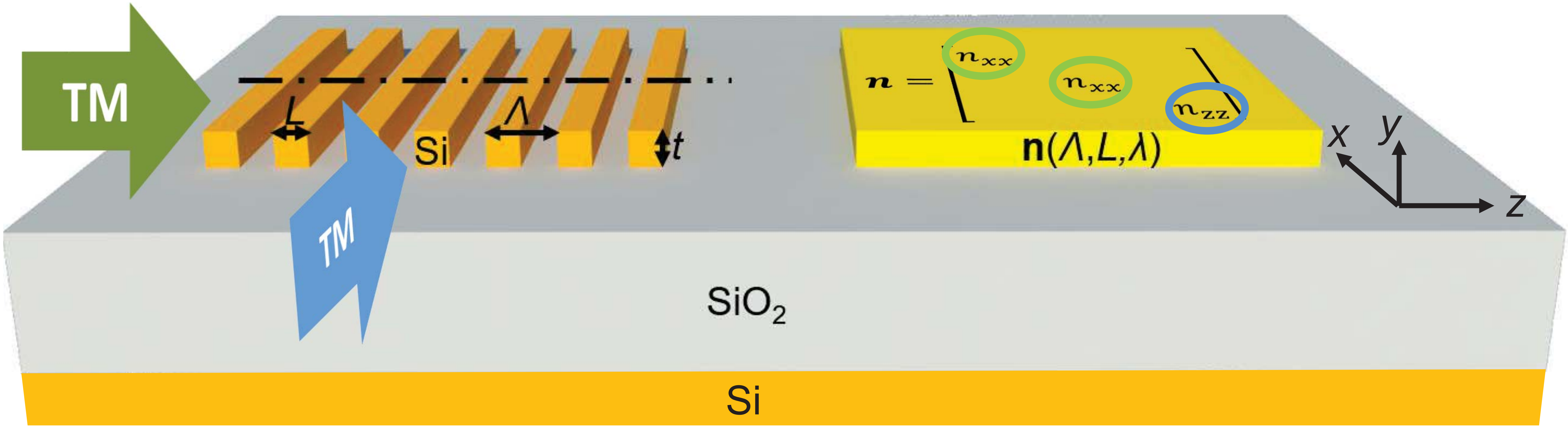
Small pitch [$\Lambda < \lambda/(2n_{\mathrm{eff}})$] avoids diffraction. Synthesizes an artificial material.

$$n_{xx}^2 \approx \frac{L}{\Lambda} n_{Si}^2 + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^2$$

$$n_{zz}^{-2} \approx \frac{L}{\Lambda} n_{Si}^{-2} + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^{-2}$$

S. M. Rytov, Sov. Phys. JETP 2, 1956

Rigorous formulas for n_{xx} and n_{zz}: Luque-González, Optics Letters 43, 2018



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$$n_{xx}^2 \approx \frac{L}{\Lambda} n_{Si}^2 + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^2$$

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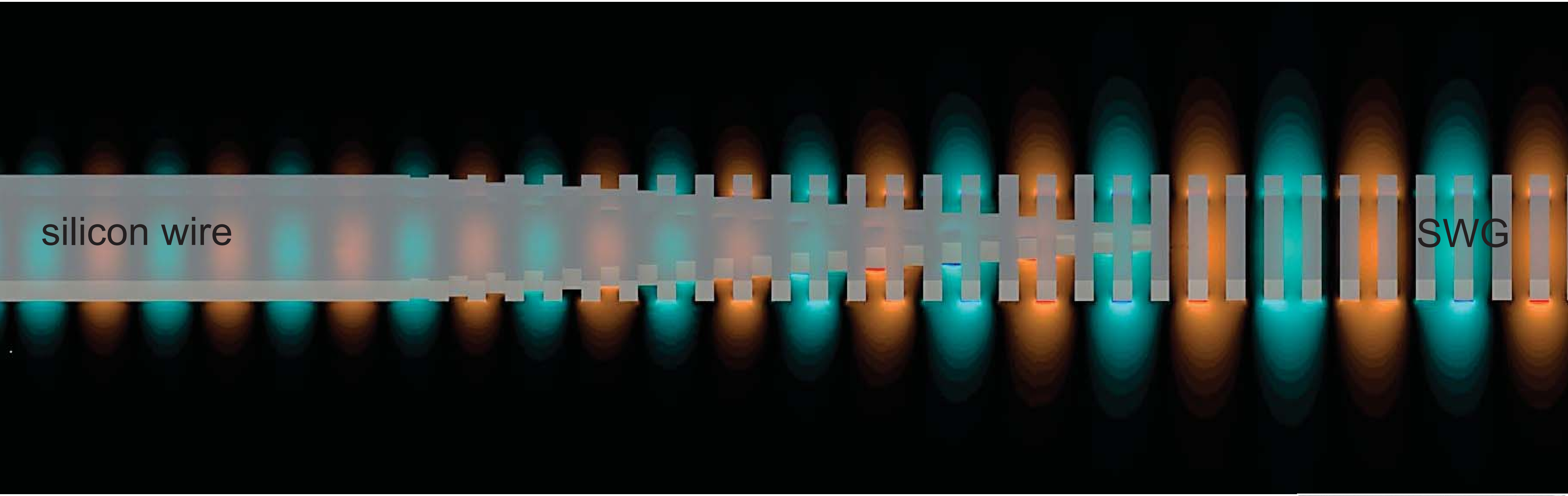
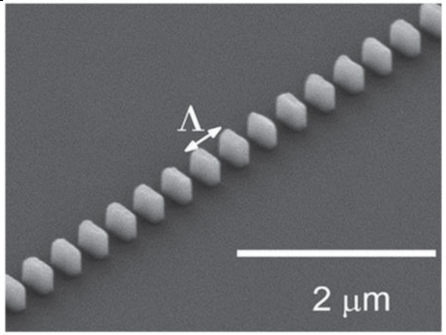
S. M. Rytov, Sov. Phys. JETP 2, 1956

Engineer the refractive index through duty-cycle.

Propagation example

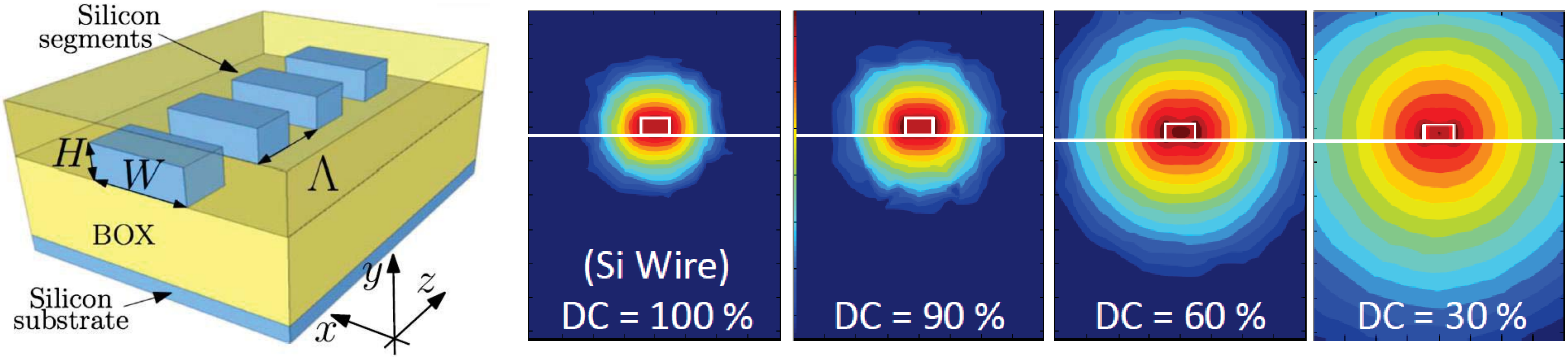




- SWG waveguide has lower effective index than the silicon wire.
- SWG waveguide supports loss-less Bloch-Floquet mode.
- Loss-less integration with silicon wire waveguides.

P. Cheben, Optics Letters 35, 2010

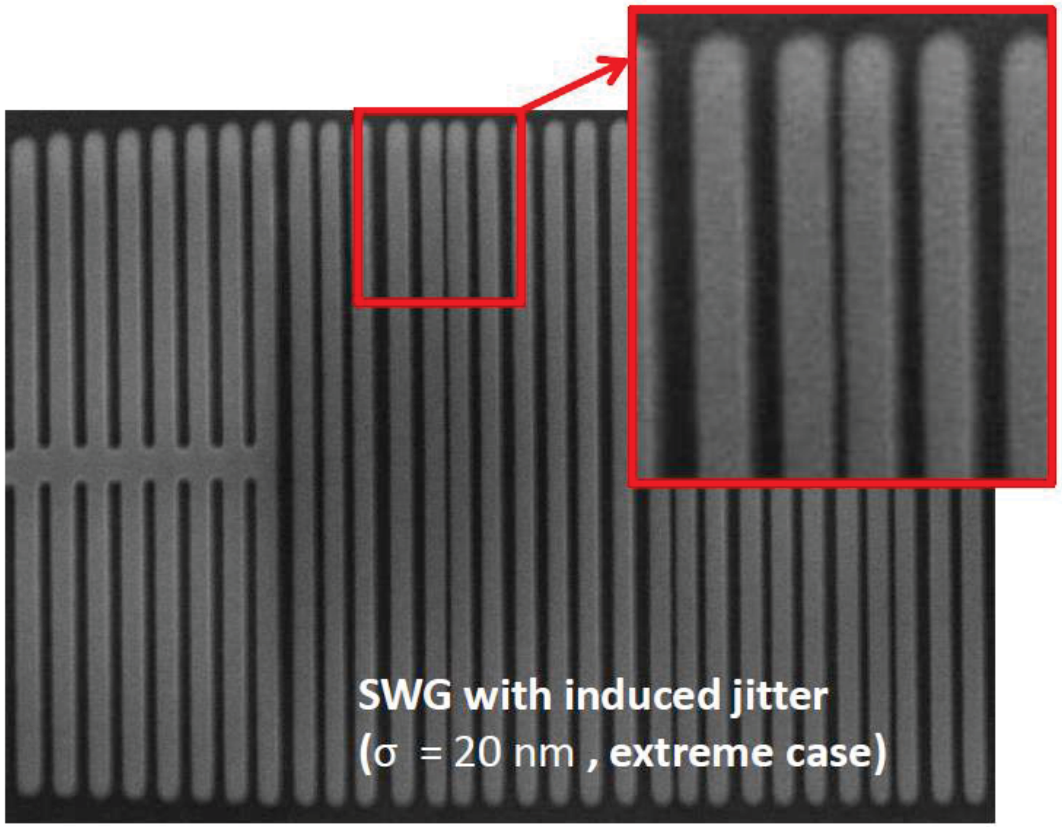
Precautions: leakage

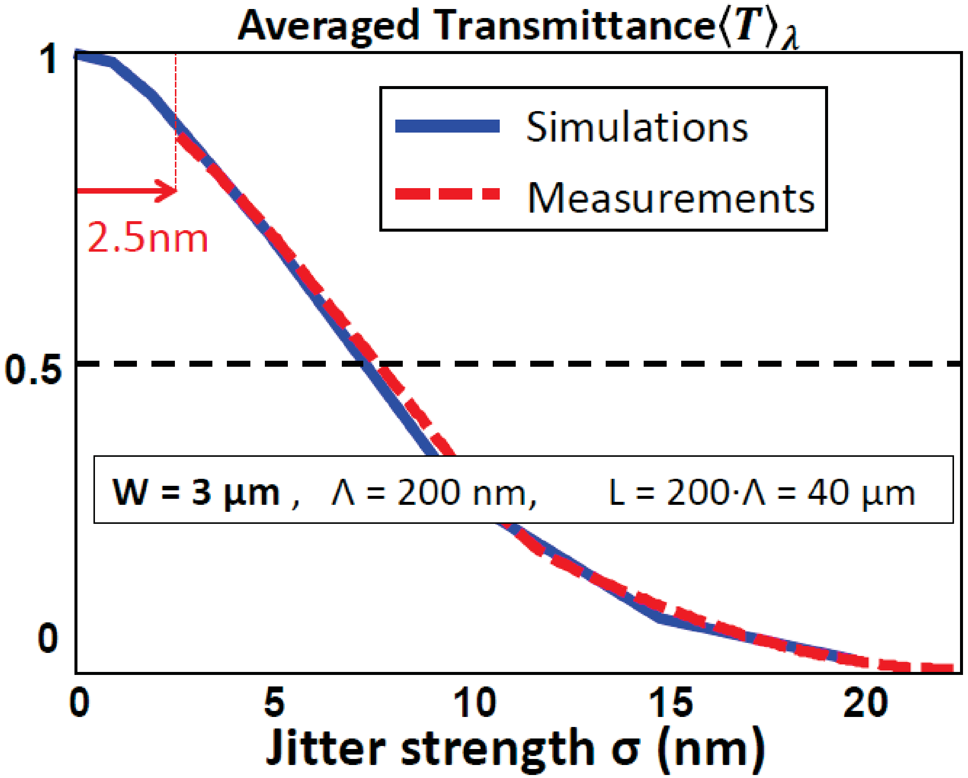


Reduced effective index: substrate leakage for $n_{\mathrm{eff}} < 1.6$

J. D. Sarmiento-Merenguel, Optics Letters 41, 2016

Precautions: jitter





Disorder (jitter) of ~5nm produces losses for wide (multimode) waveguides.

A. Ortega-Moñux, Optics Express 25, 2017

Refractive Index

Fundamentals

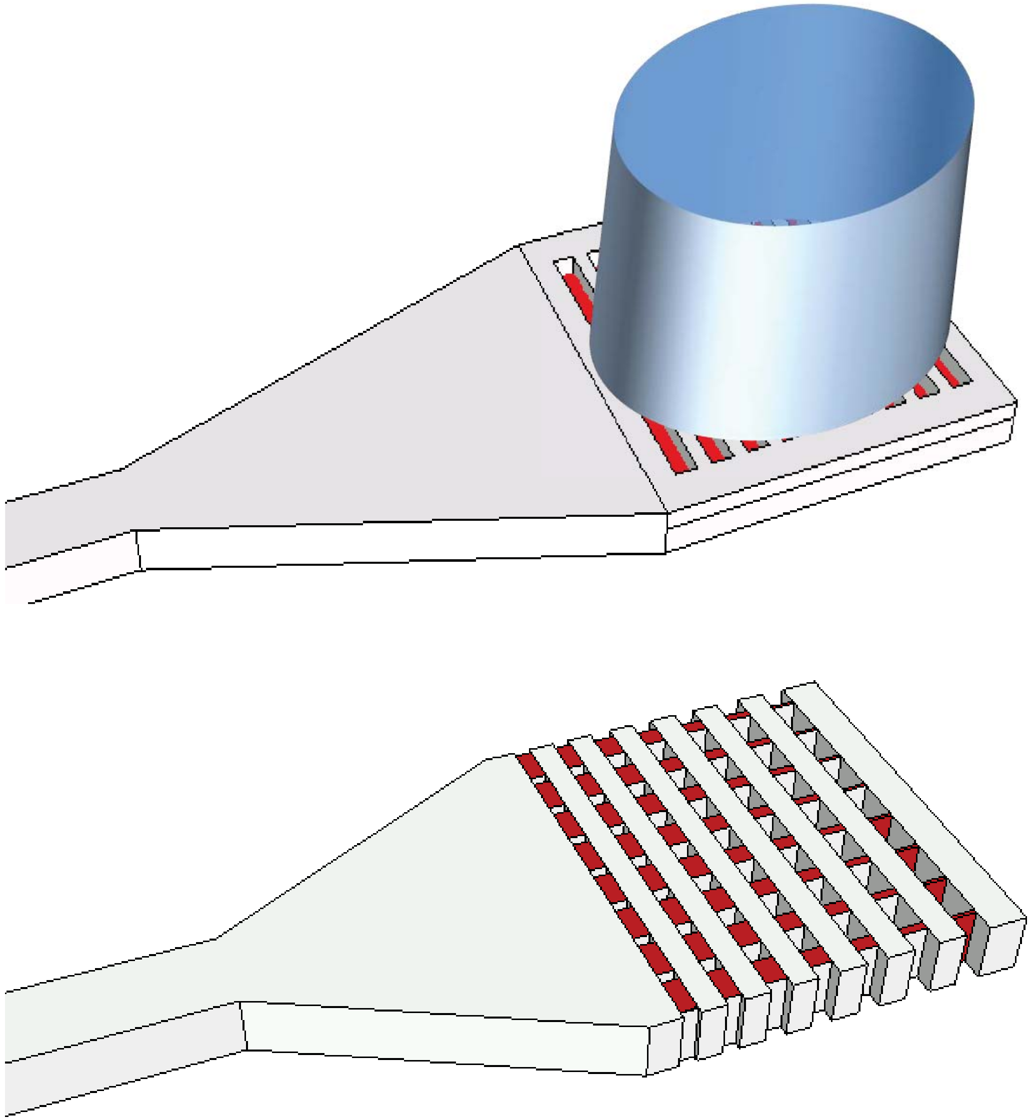
Applications & Devices

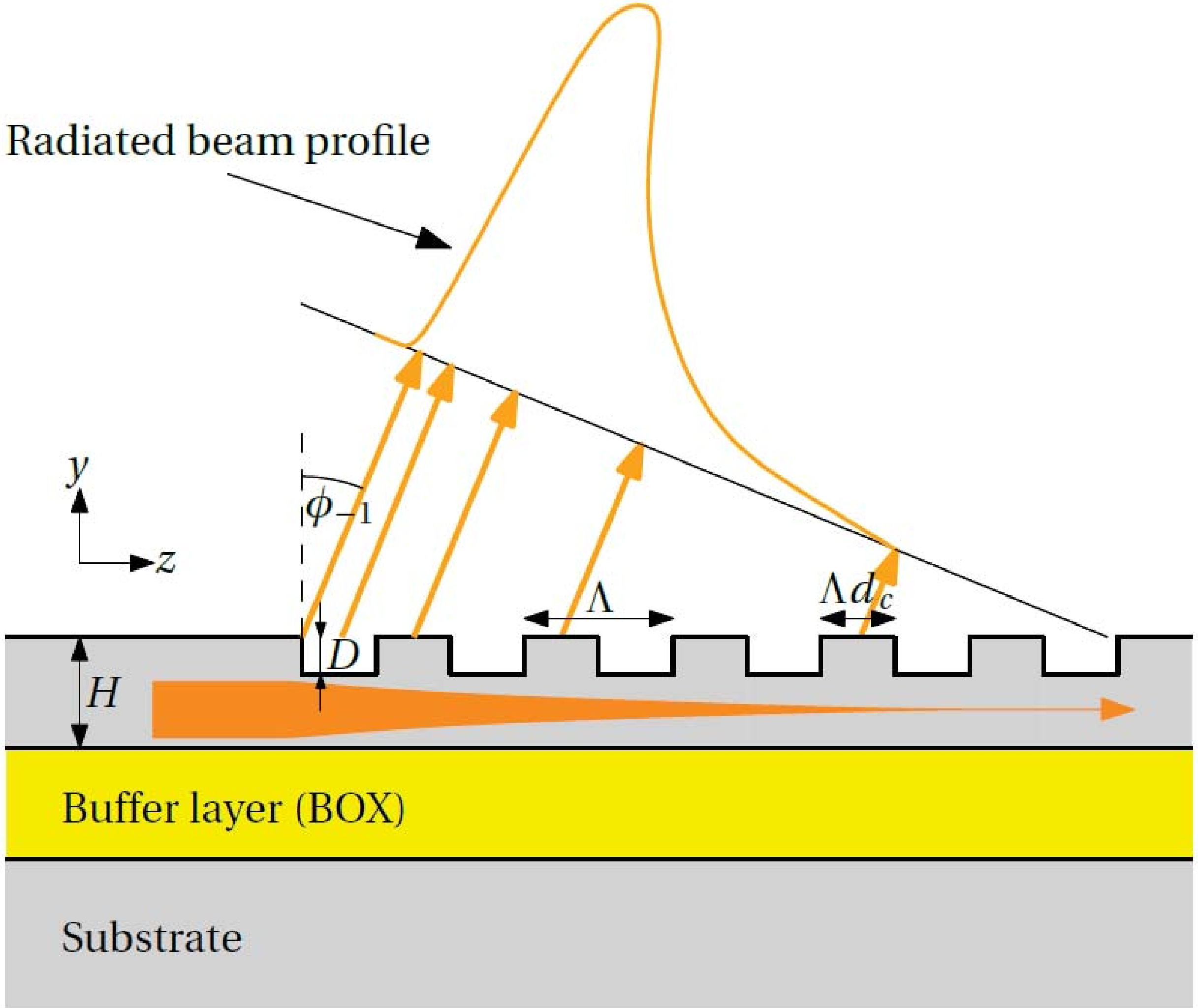
Dispersion & Anisotropy

Fundamentals

Applications & Devices

Grating couplers

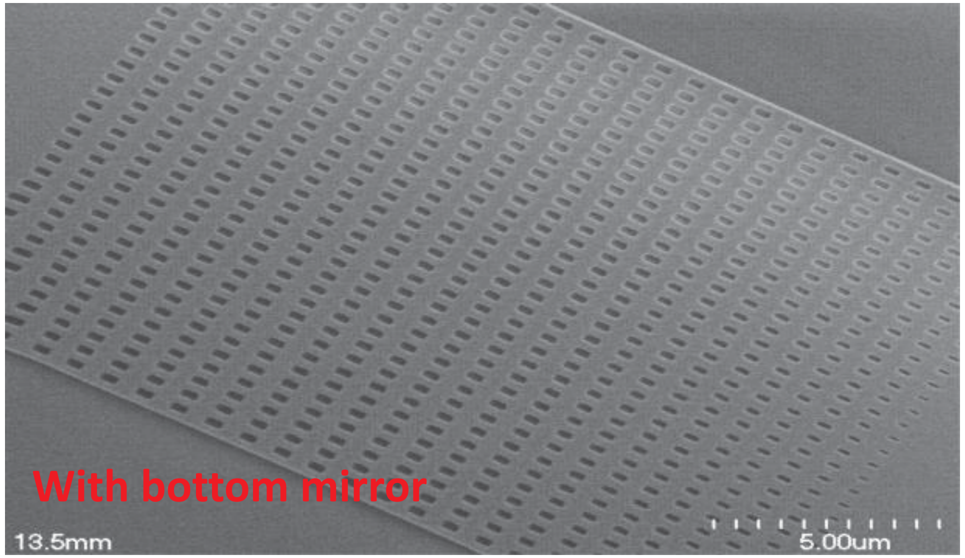


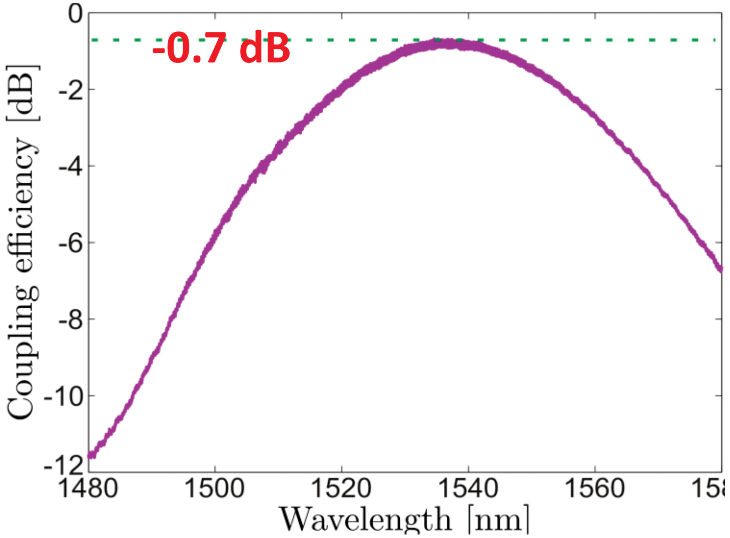


R. Halir, Optics Letters 34, 2009

Grating couplers

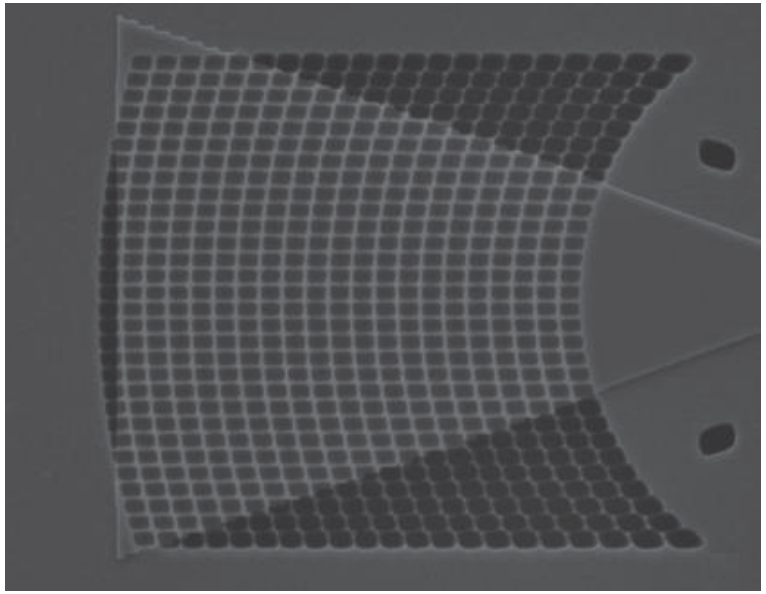
Silicon – near infrared

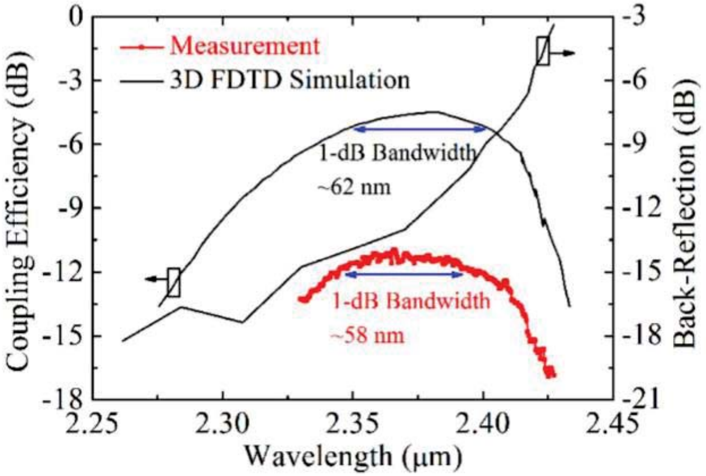




D. Benedikovic, Optics Express 23, 2015

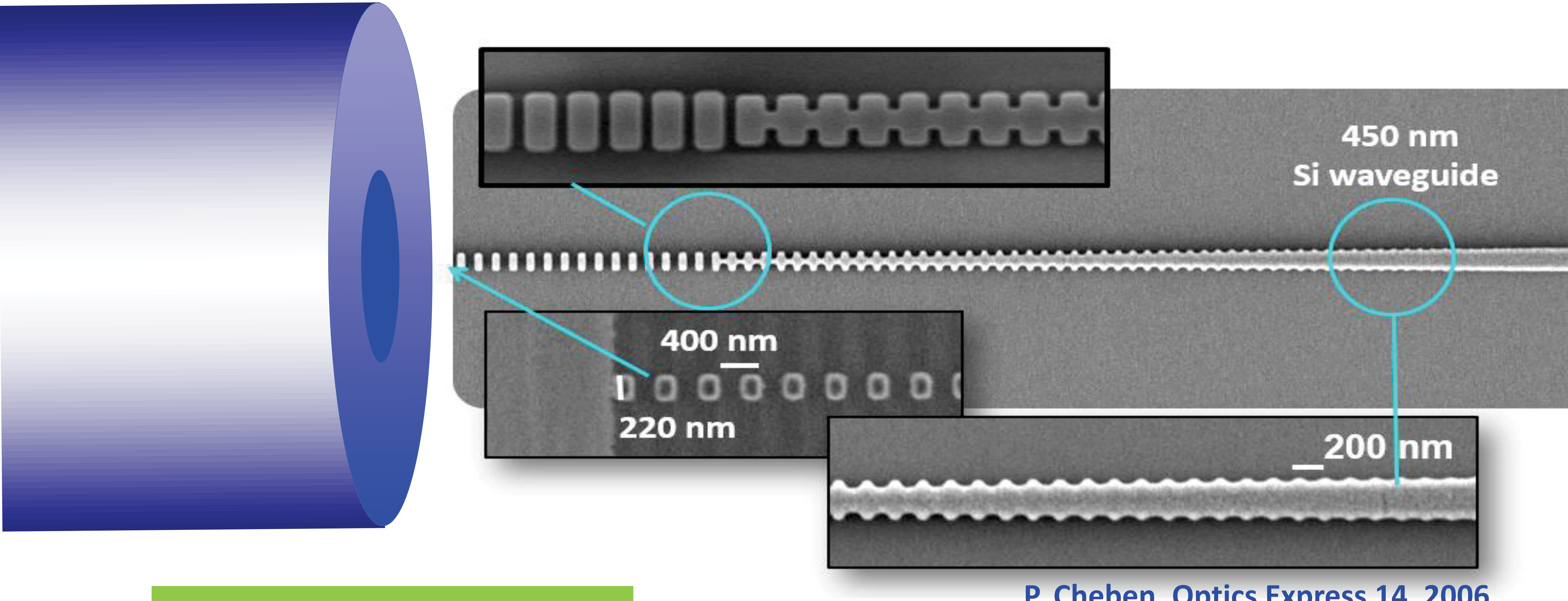
Germanium – mid infrared





J. Kang, Optics Letters 42, 2017

Edge couplers



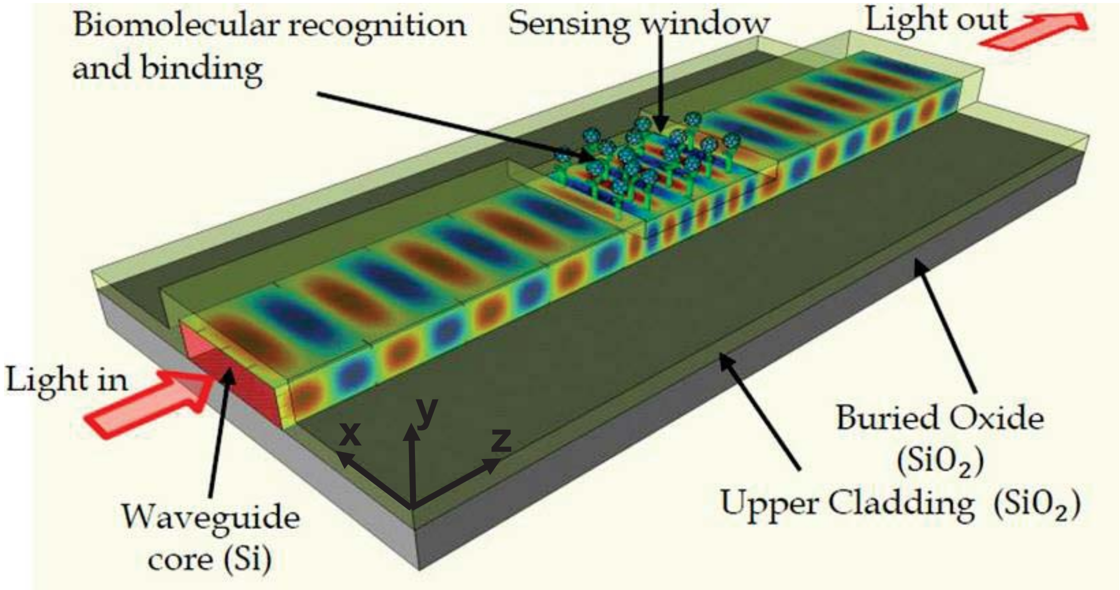
0.32dB Loss, PDL<0.05dB
BW>100nm, MFD=3.2um

P. Cheben, Optics Express 14, 2006

P. Cheben, Optics Express 23, 2015

P. Cheben, US Patent 7,680,371

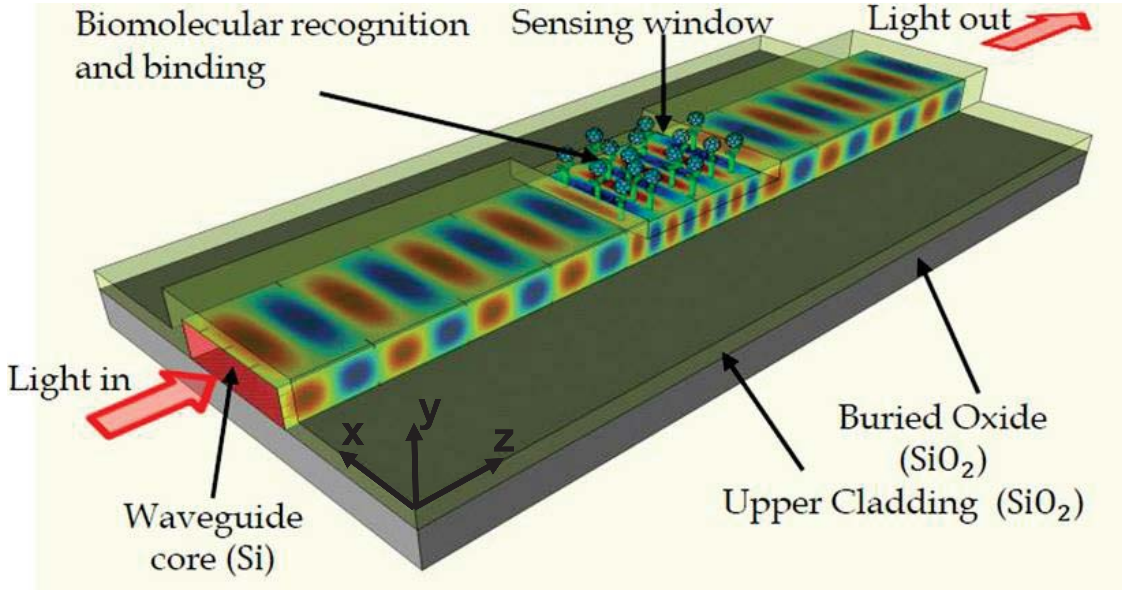
T. Barwicz, OFC 2016, M2I.3 (IBM)

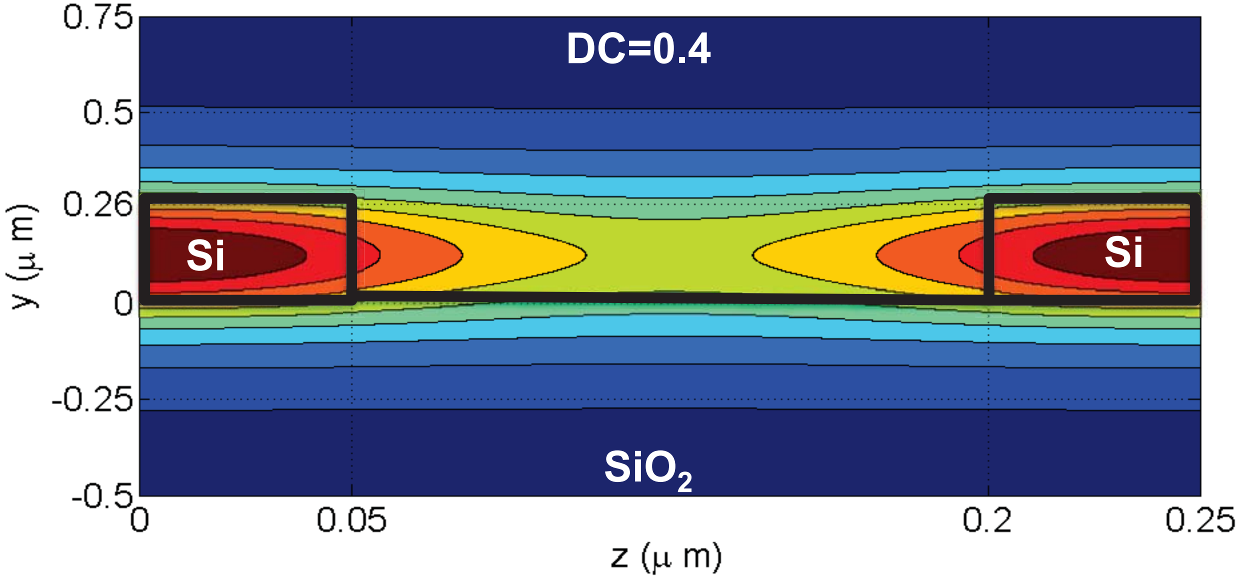


$$\Delta n_{eff} = c \int \Delta n(x,y)^2 \mid E(x,y) \mid^2 dxdy$$

Delocalize field

J. G. Wangüemert-Pérez, Optics Letters 39, 2014 + J. G. Wangüemert-Pérez,Optics Laser Technol. 109, 2019





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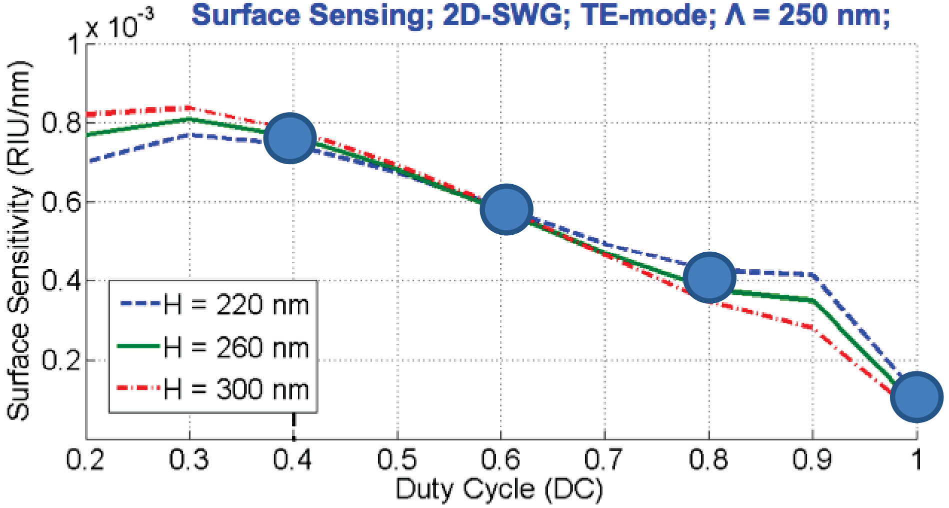
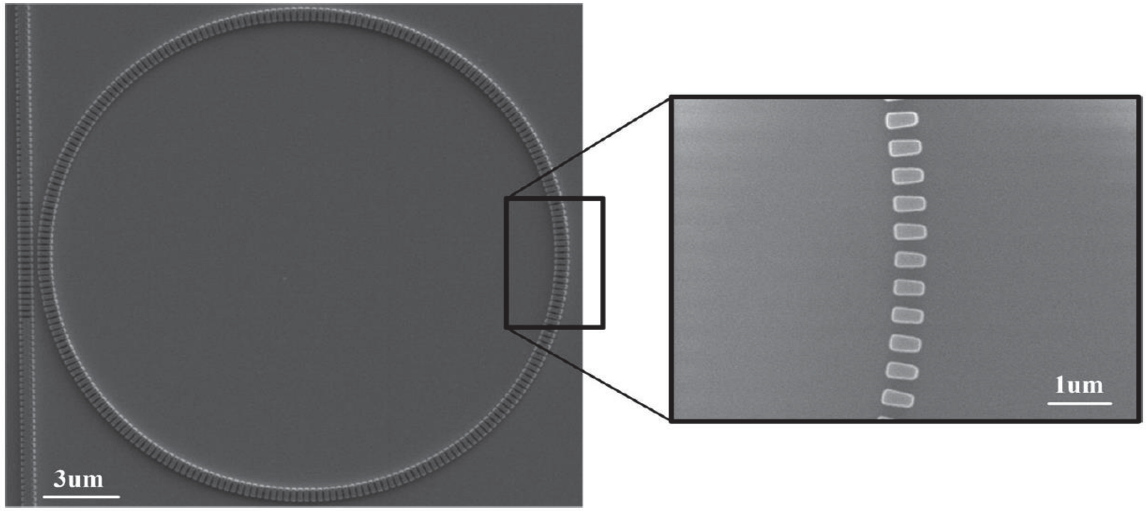
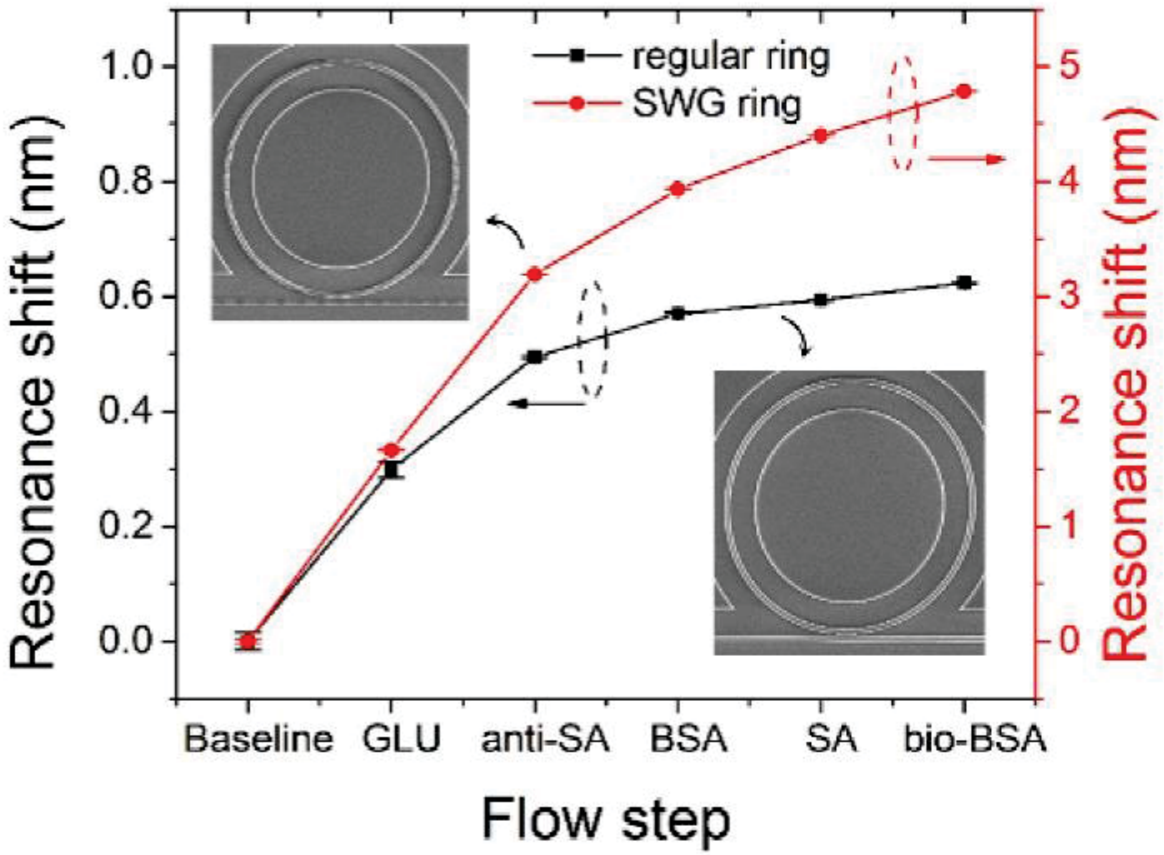
Delocalize field



J. G. Wangüemert-Pérez, Optics Letters 39, 2014 + J. G. Wangüemert-Pérez,Optics Laser Technol. 109, 2019



490nm / RIU

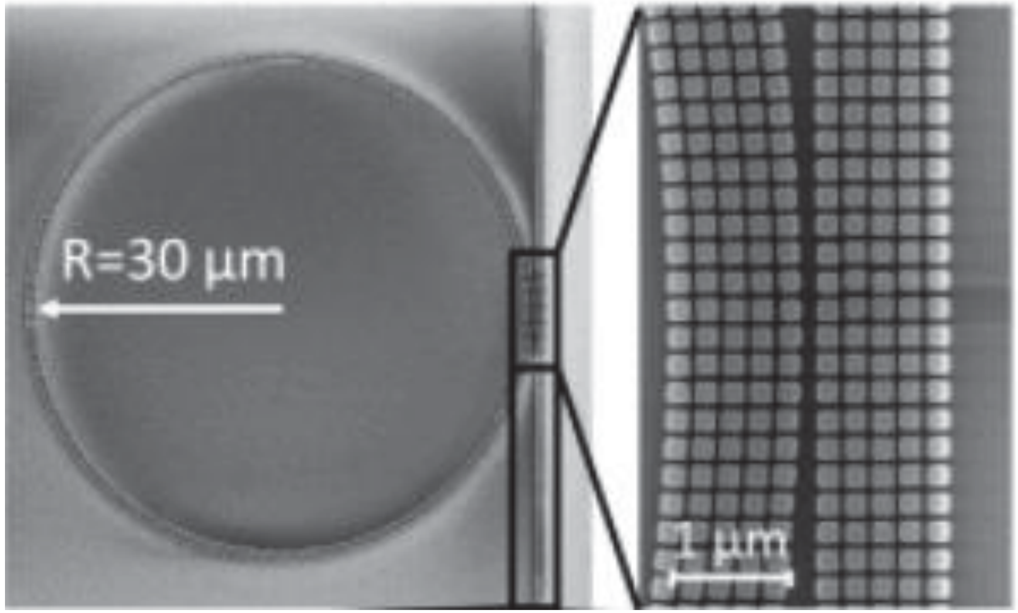


Demonstration of enhanced bulk sensing

Flueckiger, Optics Express 24, 2016

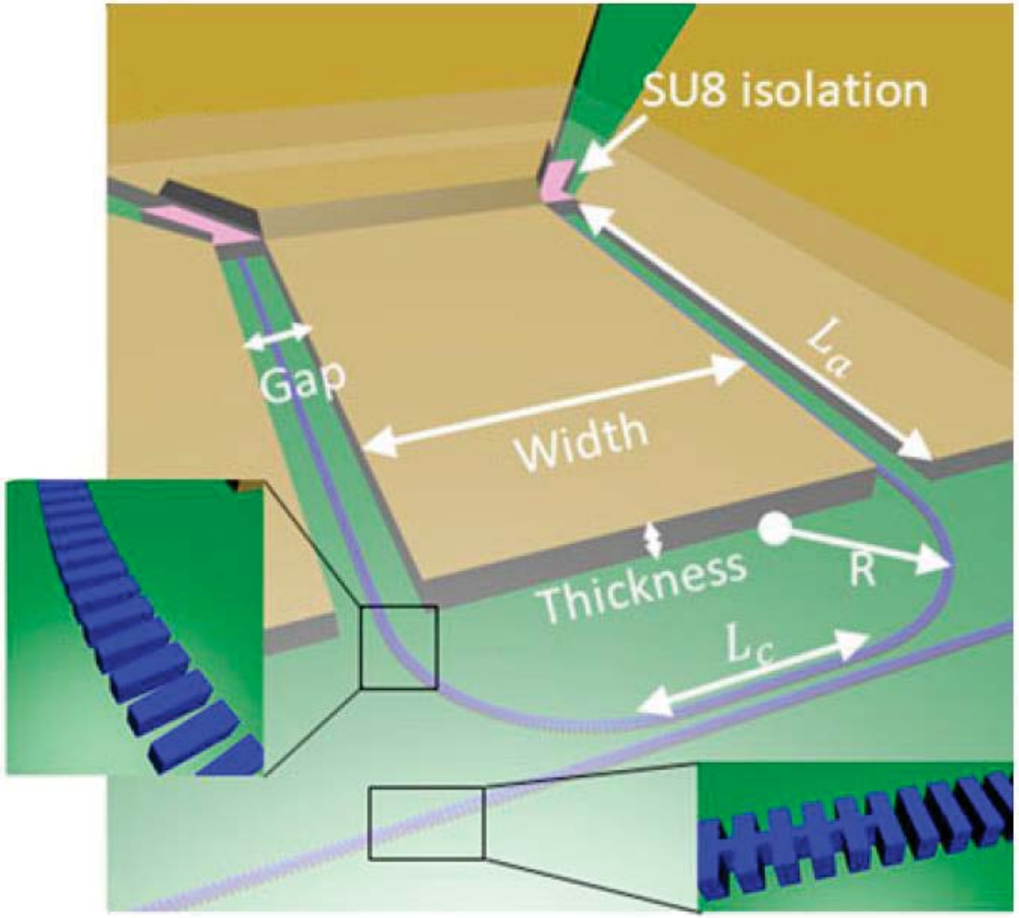
Demonstration of surface sensing

H. Yan, Optics Express 24, 2016



580nm / RIU

E. Luan, J. Selected Topics Quantum Eletronics 25, 2018

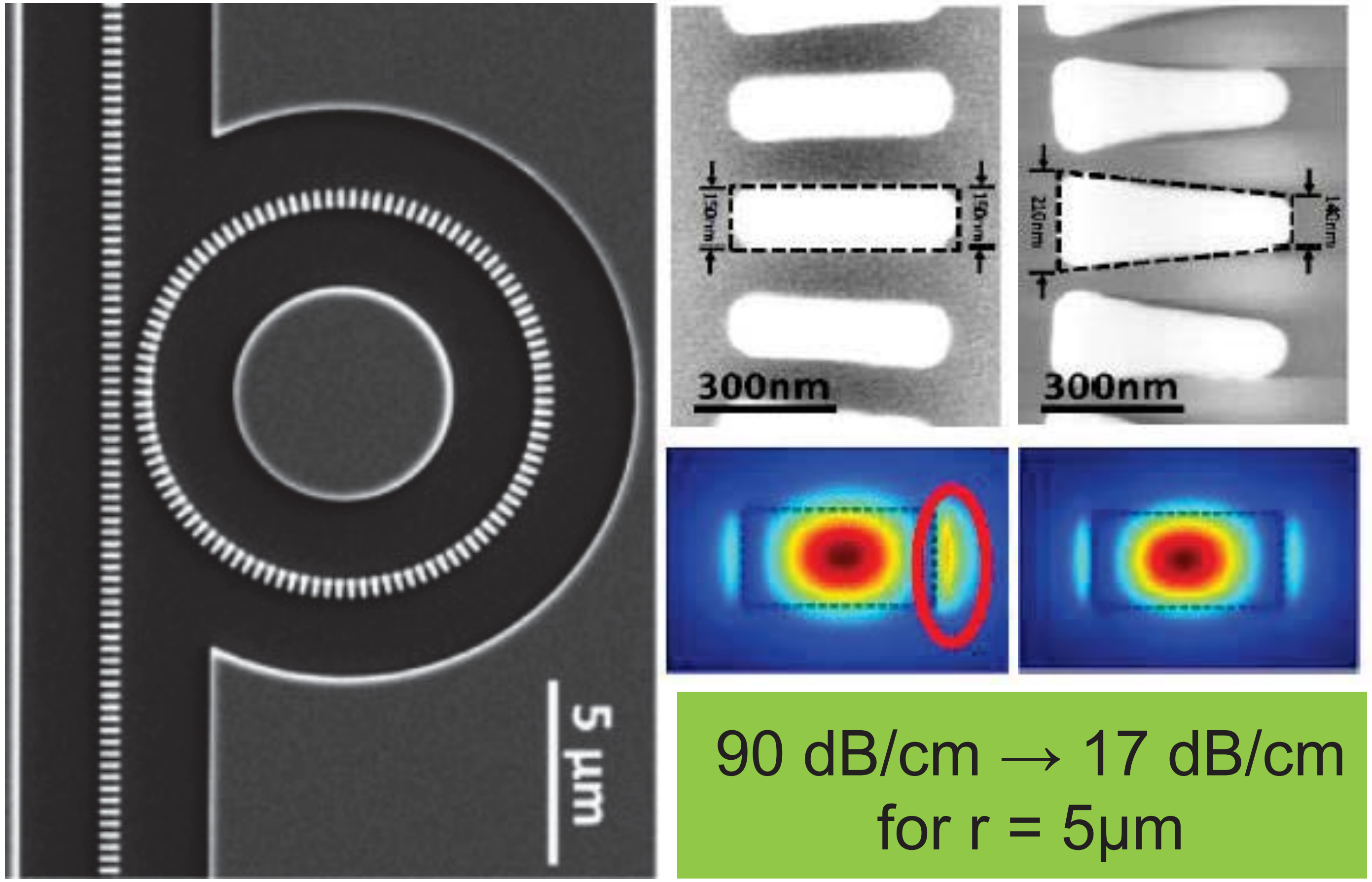


Electro-optic polymer
40GHz bandwidth

Z. Pan, Laser and Photonics Reviews 12, 2018

Intra-waveguide index engineering

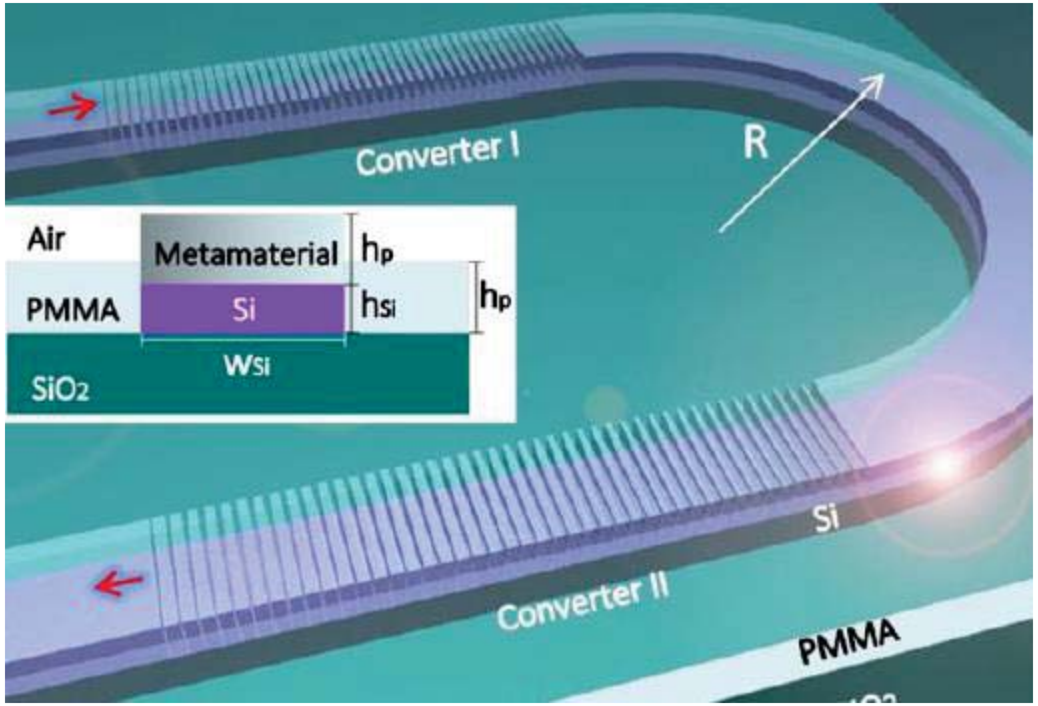
Single-mode waveguide bends



90 dB/cm → 17 dB/cm
for r = 5µm

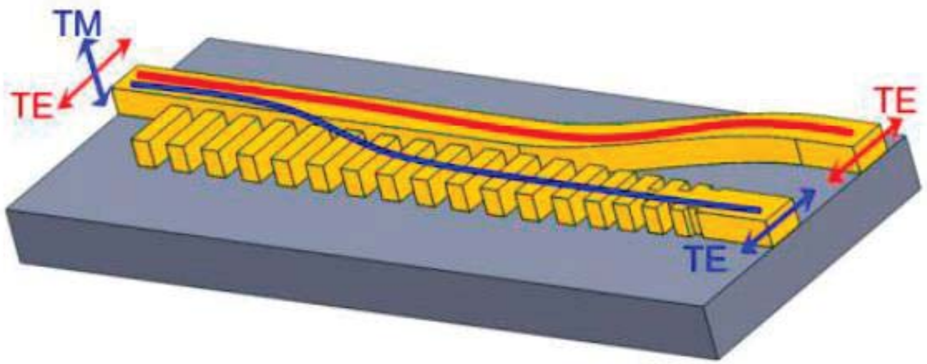
[Z. Wang, Optics Letters 41, 2016]

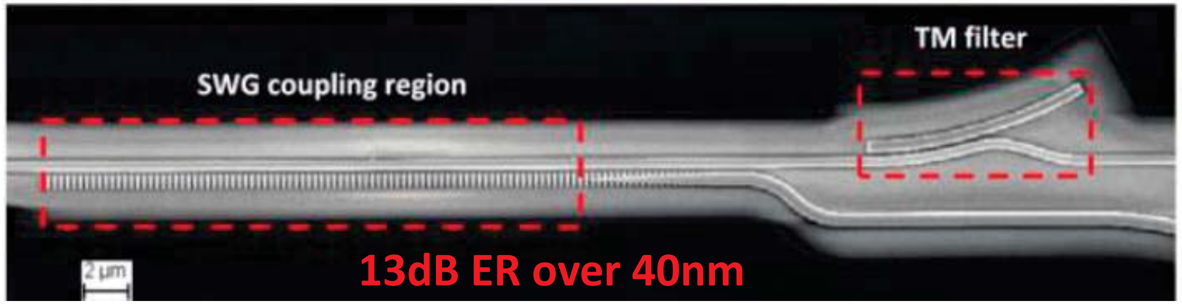
Multi-mode waveguide bends

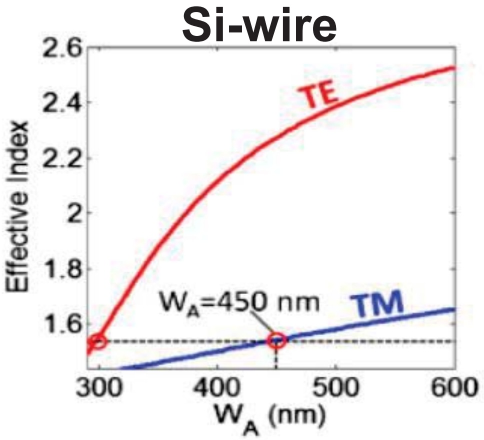


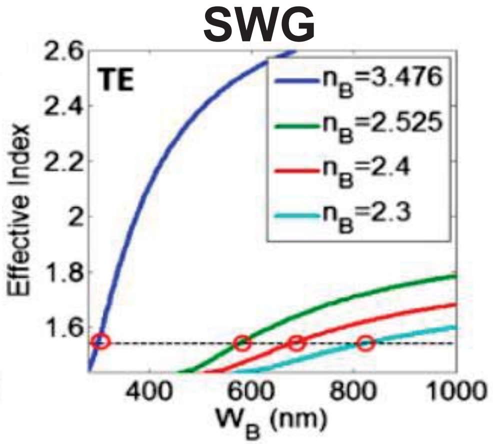
Intermodal crosstalk 5dB → 20dB
for r=30µm

[H. Xu, Laser and Photonics Reviews 12, 2018]

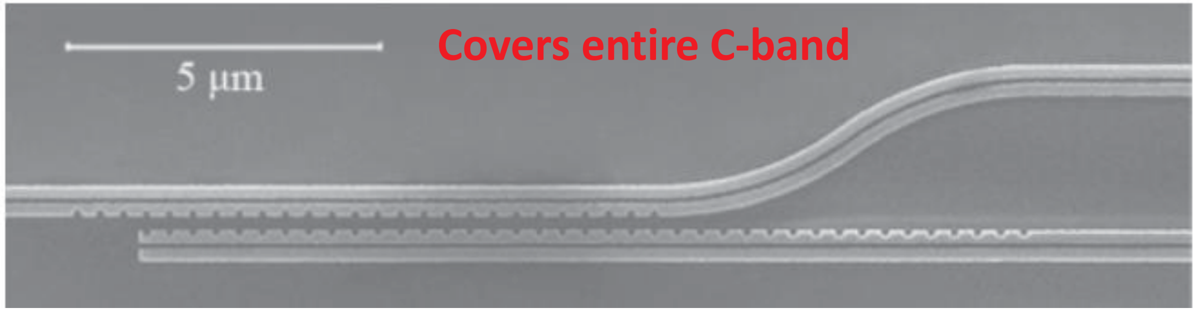


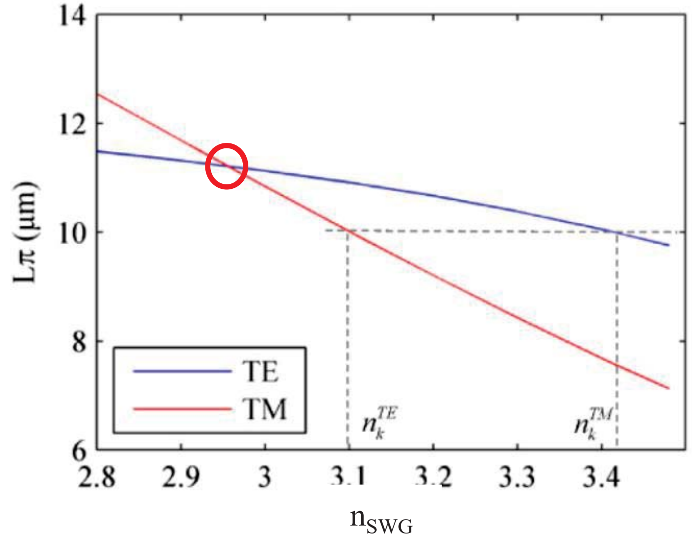






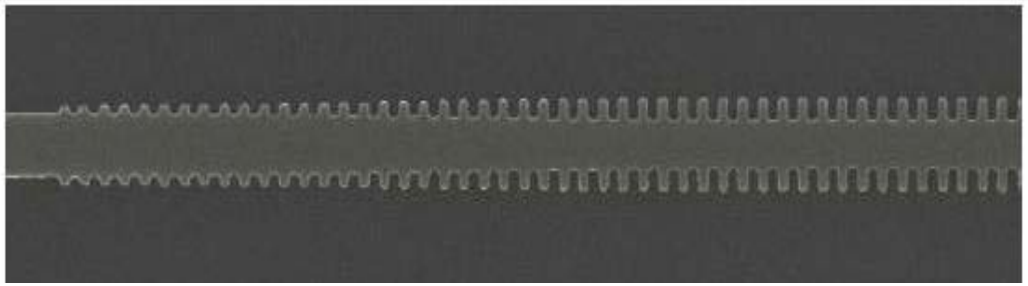
Polarization independent coupler

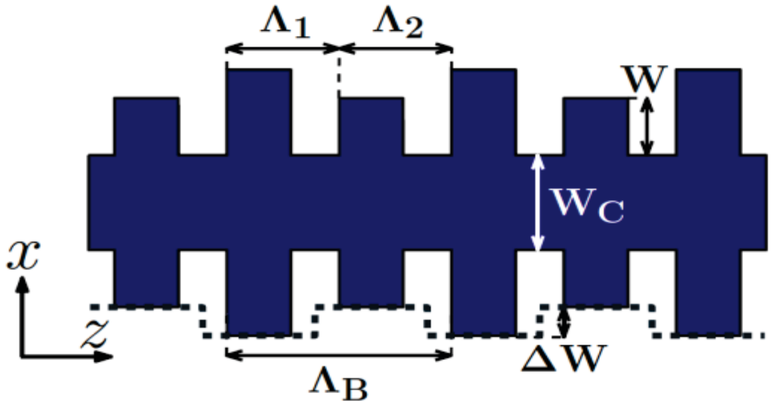


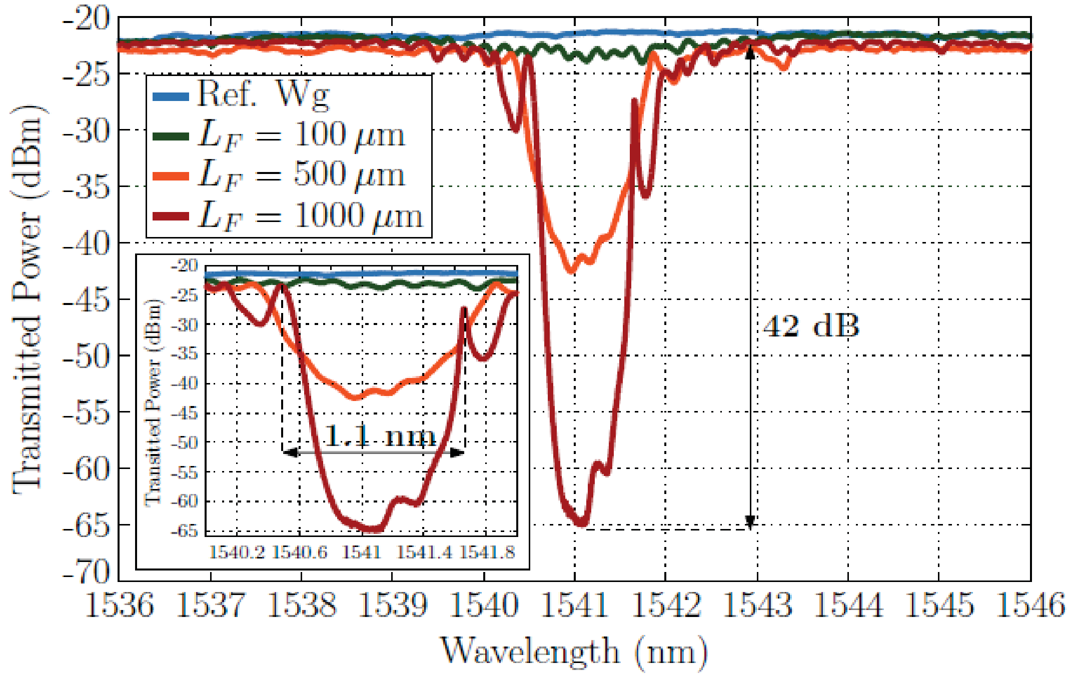


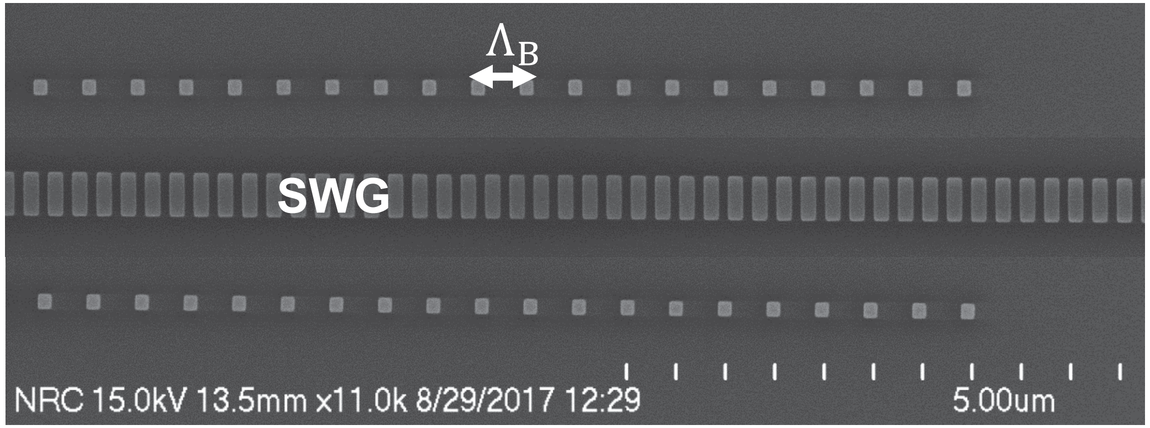
Y. Xiong, Optics Letters 39, 2014 + Y. He, OFC 2017, Th1G.6

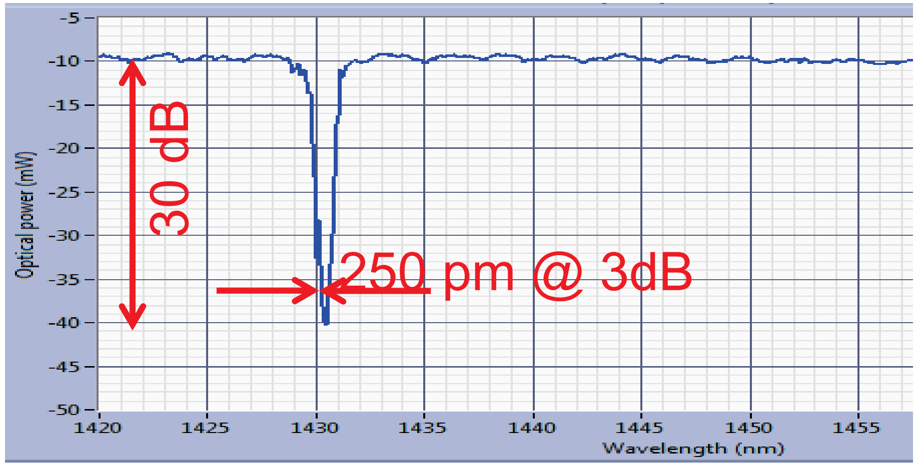
L. Liu, Optics Letters 41, 2016





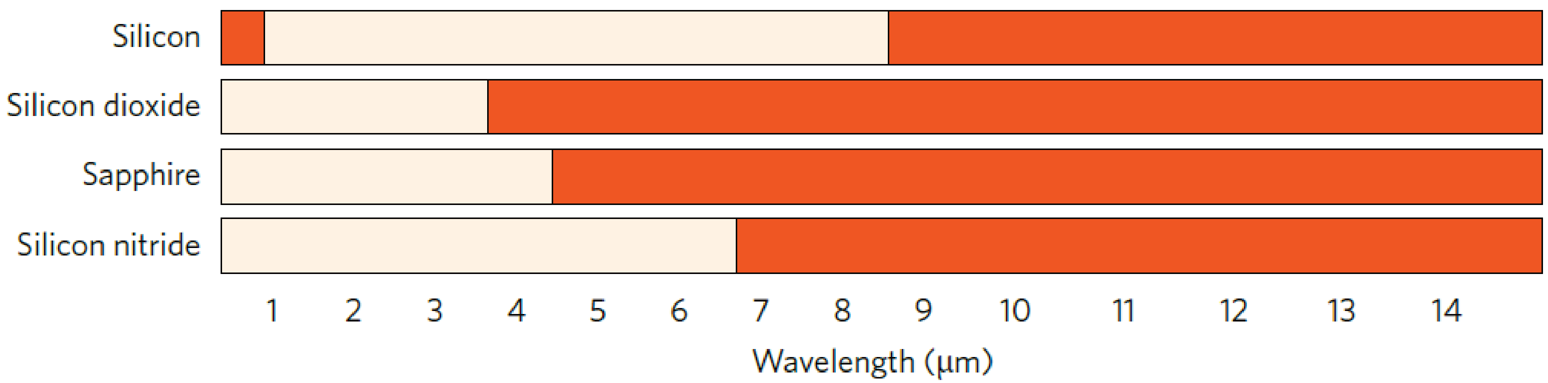




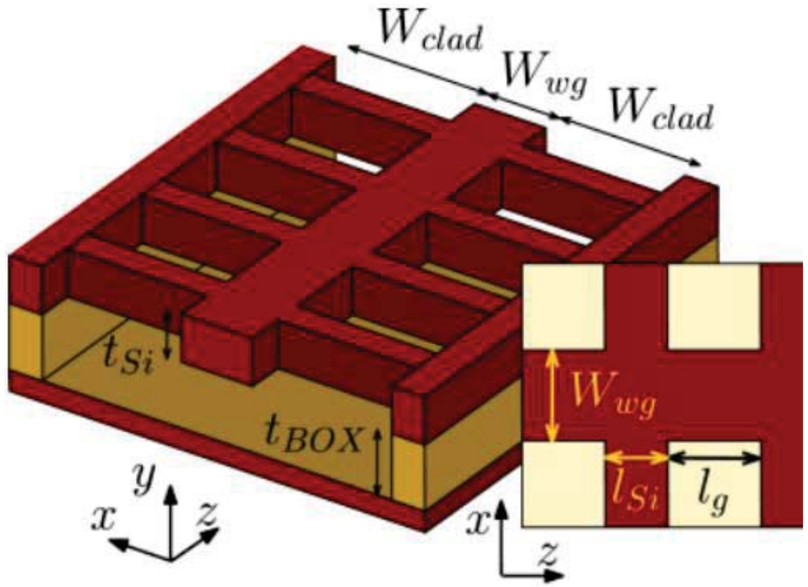


D. Pérez-Galacho, Optics Letters 42, 2017 + J. Ctyroky, Optics Express 26, 2018 + P. Cheben, ECOC 2018, Invited

Mid-IR suspended waveguides

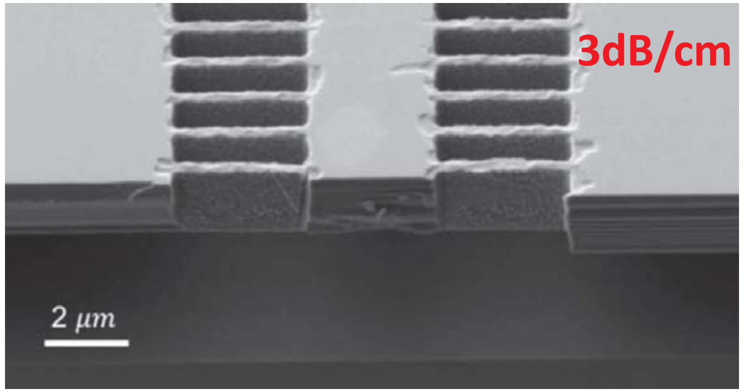


R. Soref, Nature Photonics 4, 2010



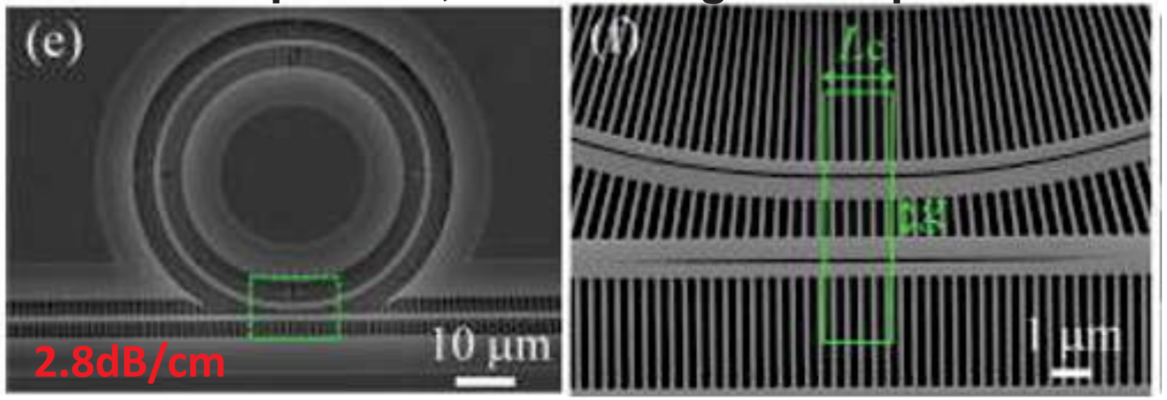
J. Soler Penadés, Optics Letters 39, 2014

Suspended waveguide at 7.7µm



J. Soler Penadés, Optics Letters 43, 2018

Suspended, slotted rings at 2.2µm



W. Zhou, J. Applied Physics 123, 2018

Refractive Index

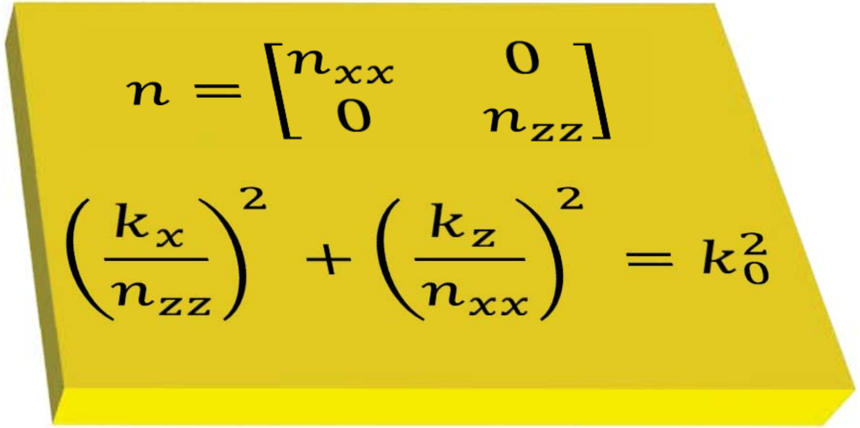
Fundamentals

Applications & Devices

Dispersion & Anisotropy

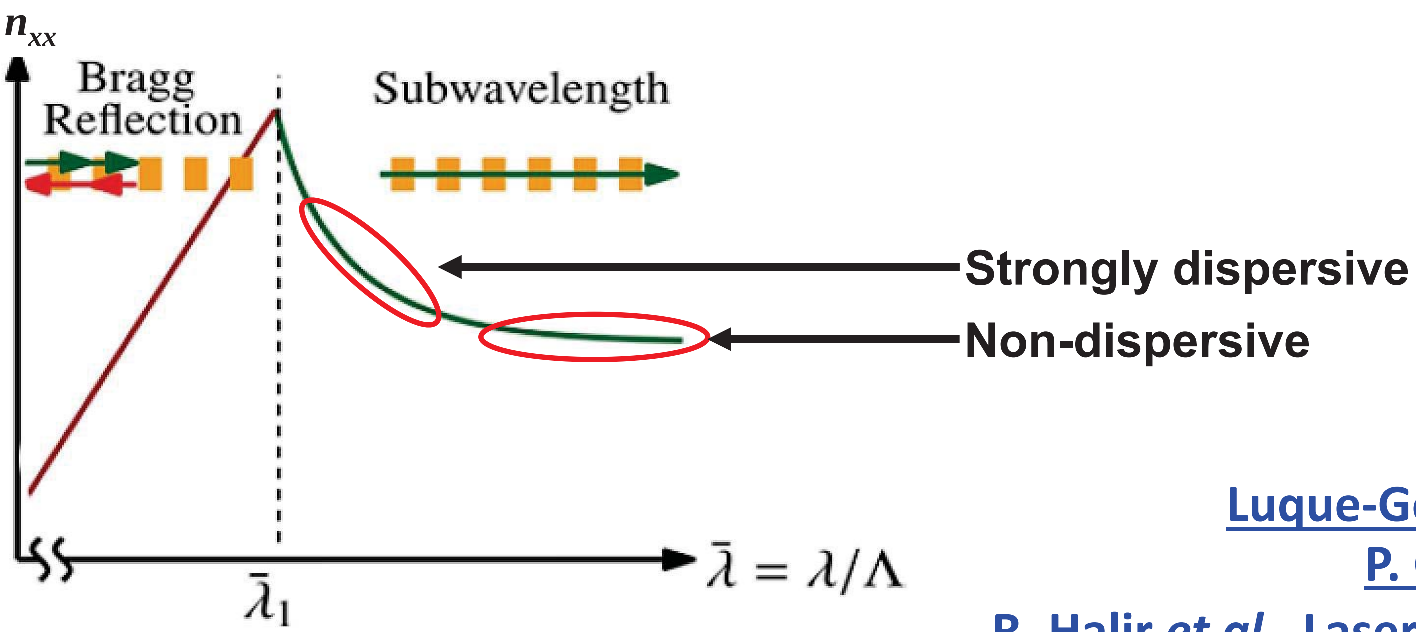
Fundamentals

Applications & Devices



$$n = \begin{bmatrix} n_{xx} & 0 \\ 0 & n_{zz} \end{bmatrix}$$

$$\left(\frac{k_x}{n_{zz}}\right)^2 + \left(\frac{k_z}{n_{xx}}\right)^2 = k_0^2$$



[Luque-González, Optics Letters 43, 2018](#)
P. Cheben *et al.*, Nature 560, 2018
R. Halir *et al.*, Laser and Photonics Reviews 9, 2015

Refractive Index

Fundamentals

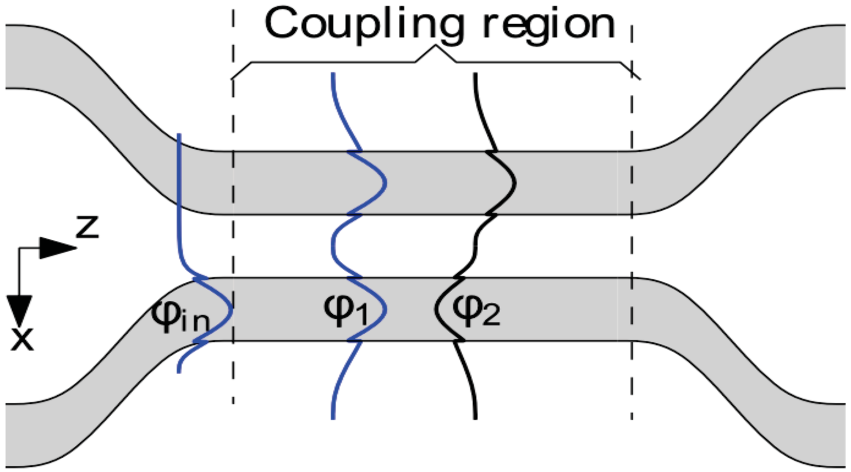
Applications & Devices

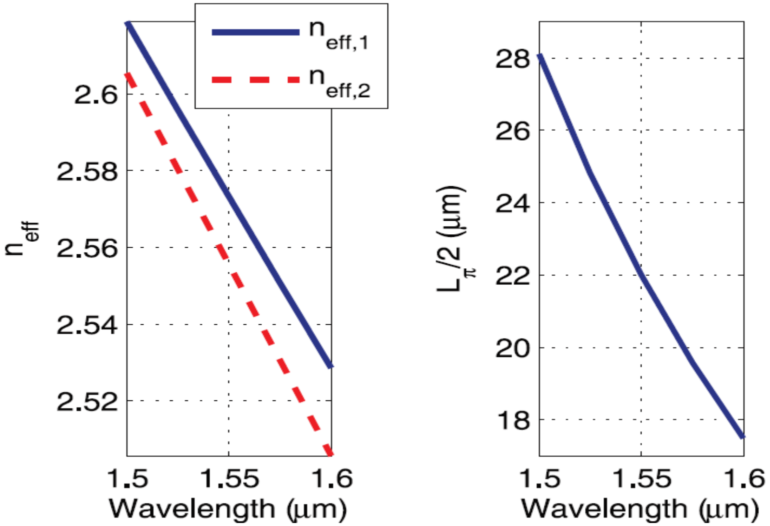
Dispersion & Anisotropy

Fundamentals

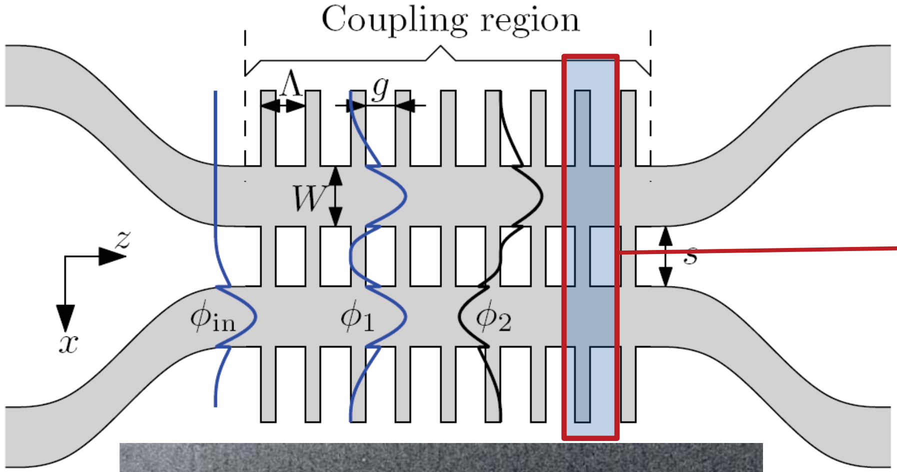
Applications & Devices

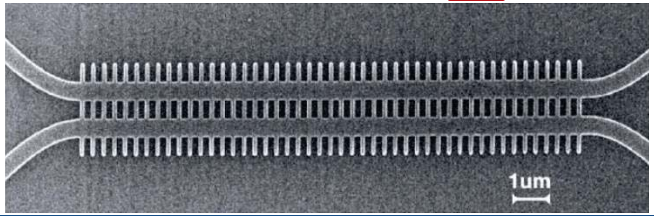
Broadband directional coupler

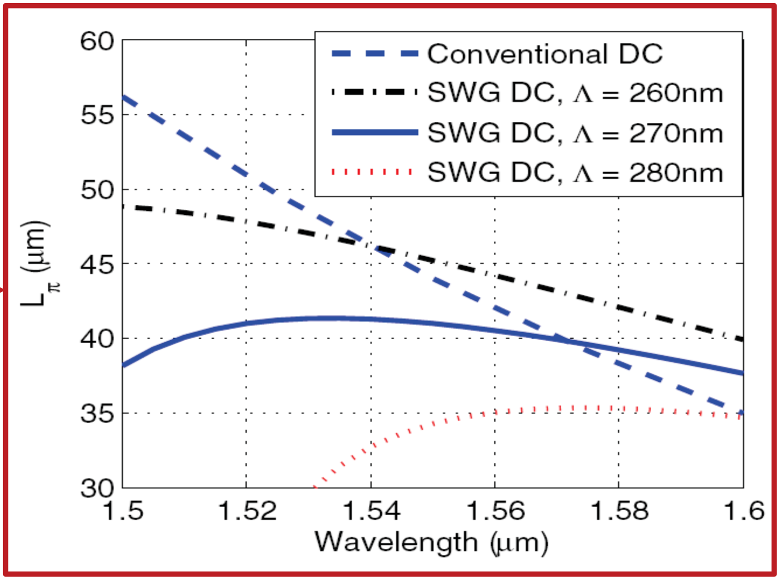




5x bandwidth enhancement

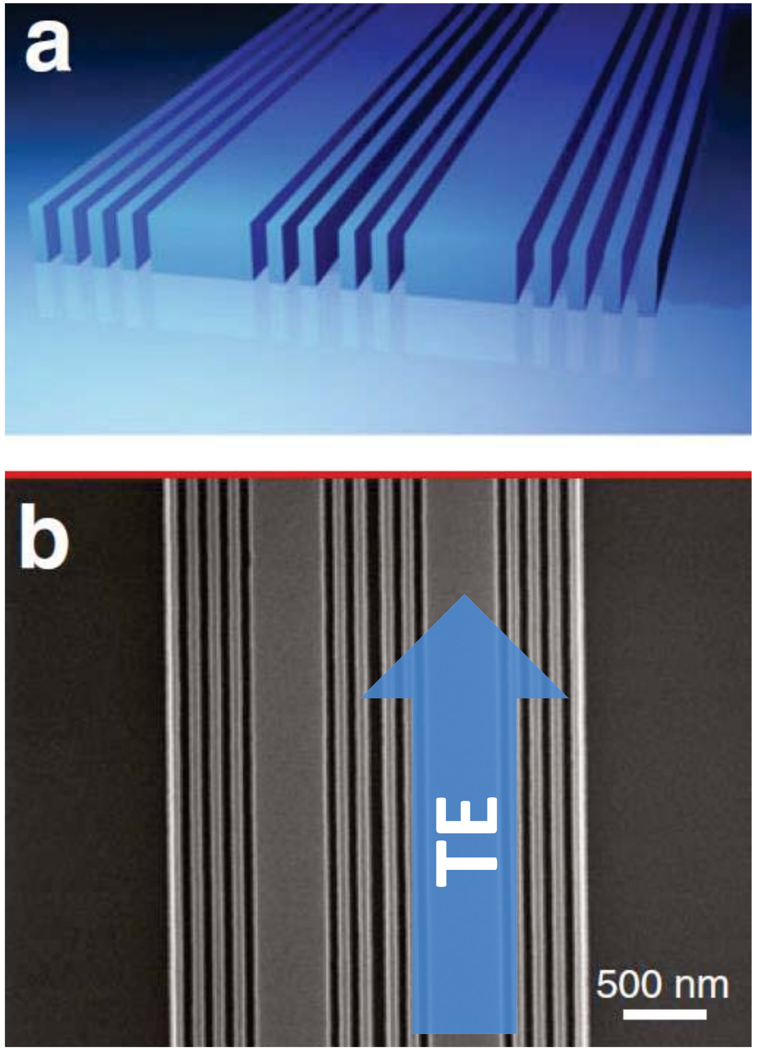


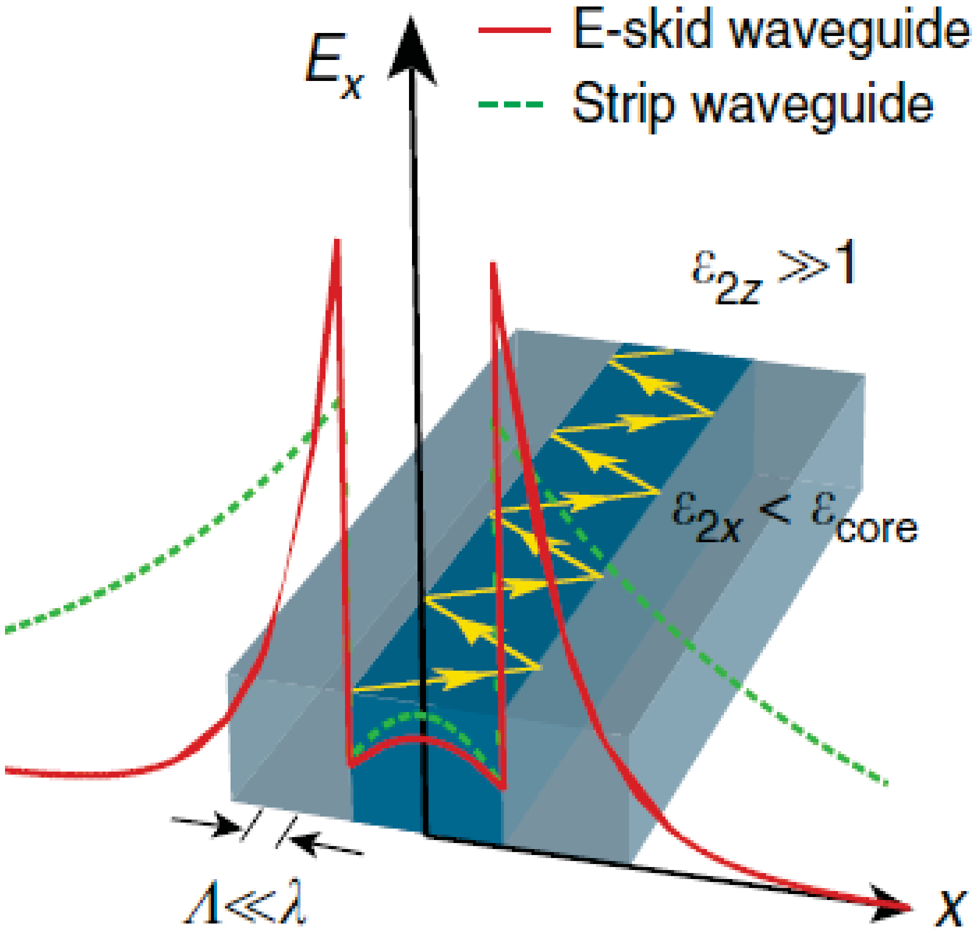




R. Halir, Optics Express 20, 2012 + Y. Wang, IEEE Photonics J. 8, 2016

Densely spaced waveguides





"Relaxed" TIR:

$n_{core} > n_{xx}$

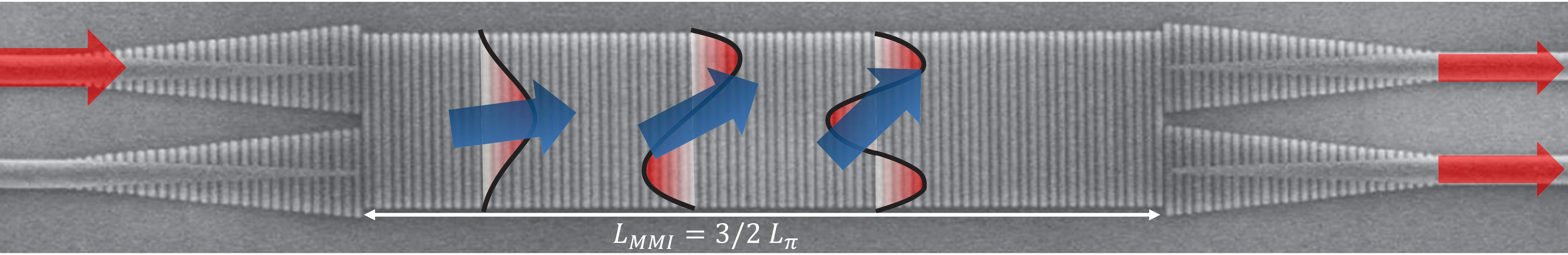
Evanescent decay:

$k_x \propto n_{zz}$

Crosstalk reduced by 30dB.

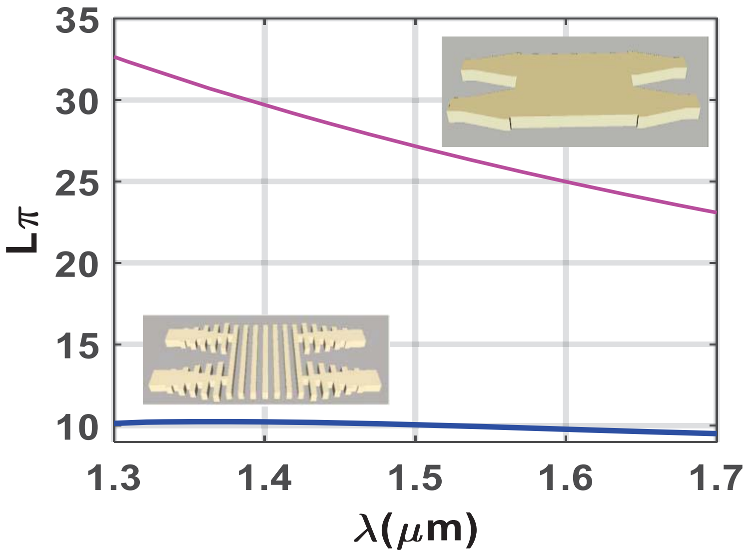
S. Jahani, Nature Communications 9, 2018 + A. Khavasi, Photonics Technol. Letters 28, 2016

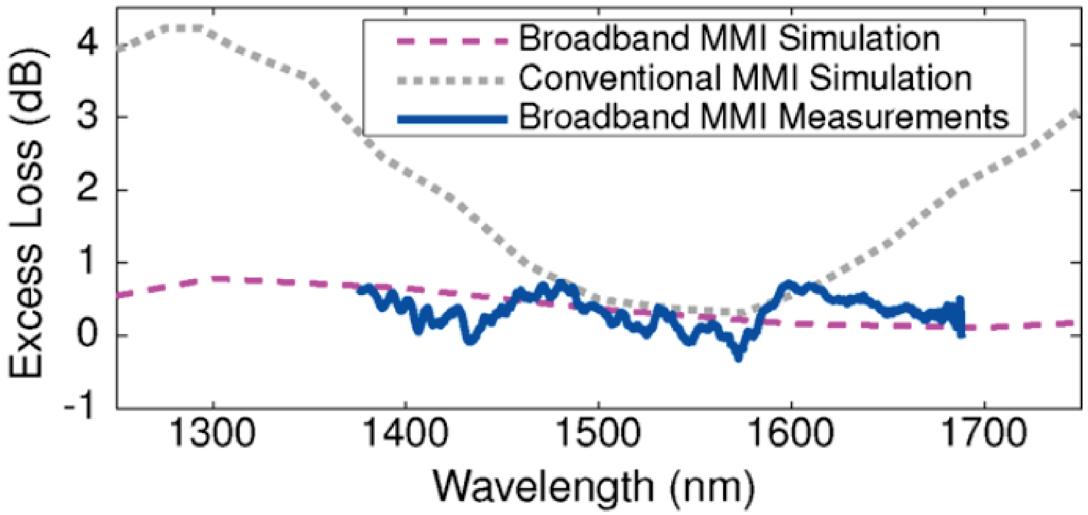
Broadband beam-splitter



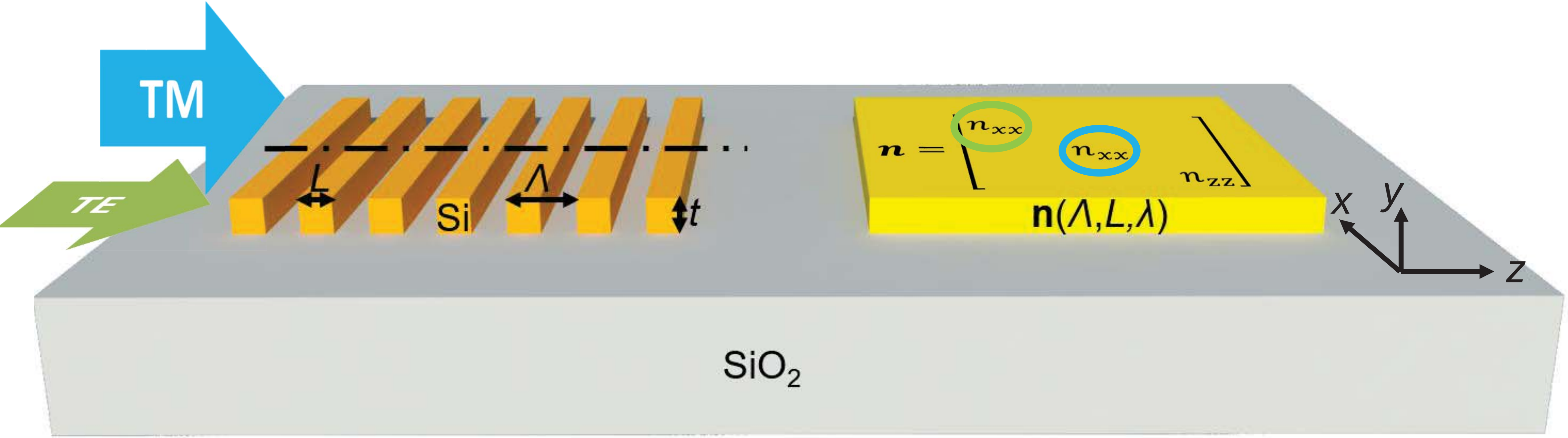
$$L_\pi^{conv} \approx \frac{4W^2}{3\lambda} n_{core}$$

$$L_\pi^{aniso} \approx \frac{4W^2}{3\lambda} \frac{n_{zz}^2}{n_{xx}}$$





R. Halir, Laser and Photonics Reviews, 2016

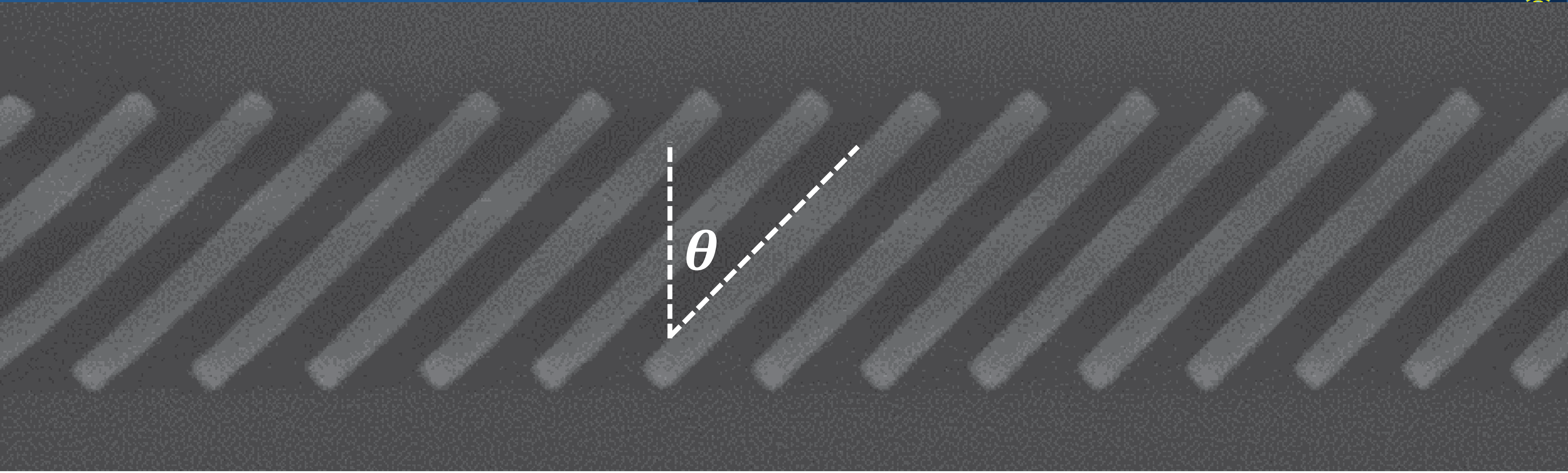


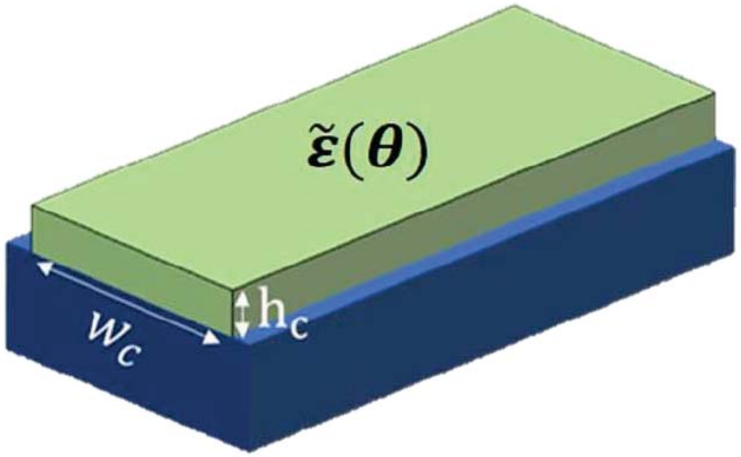
$$n_{xx}^2 \approx \frac{L}{\Lambda} n_{Si}^2 + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^2$$

Wide index range
Small feature sizes
Both polarizations affected equally

Tilted Sub-λ structures

Concept

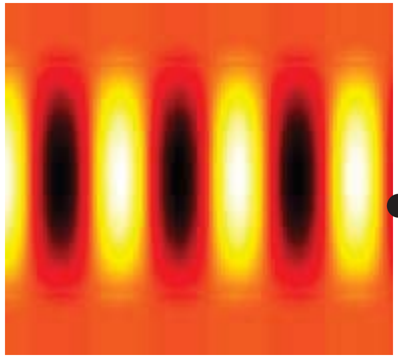




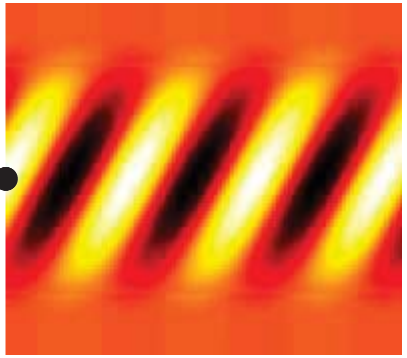
$$\tilde{\boldsymbol{\varepsilon}} = R^{-1}(\theta)\begin{bmatrix} n_{xx}^2 & 0 & 0 \\ 0 & n_{xx}^2 & 0 \\ 0 & 0 & n_{zz}^2 \end{bmatrix} R(\theta)$$

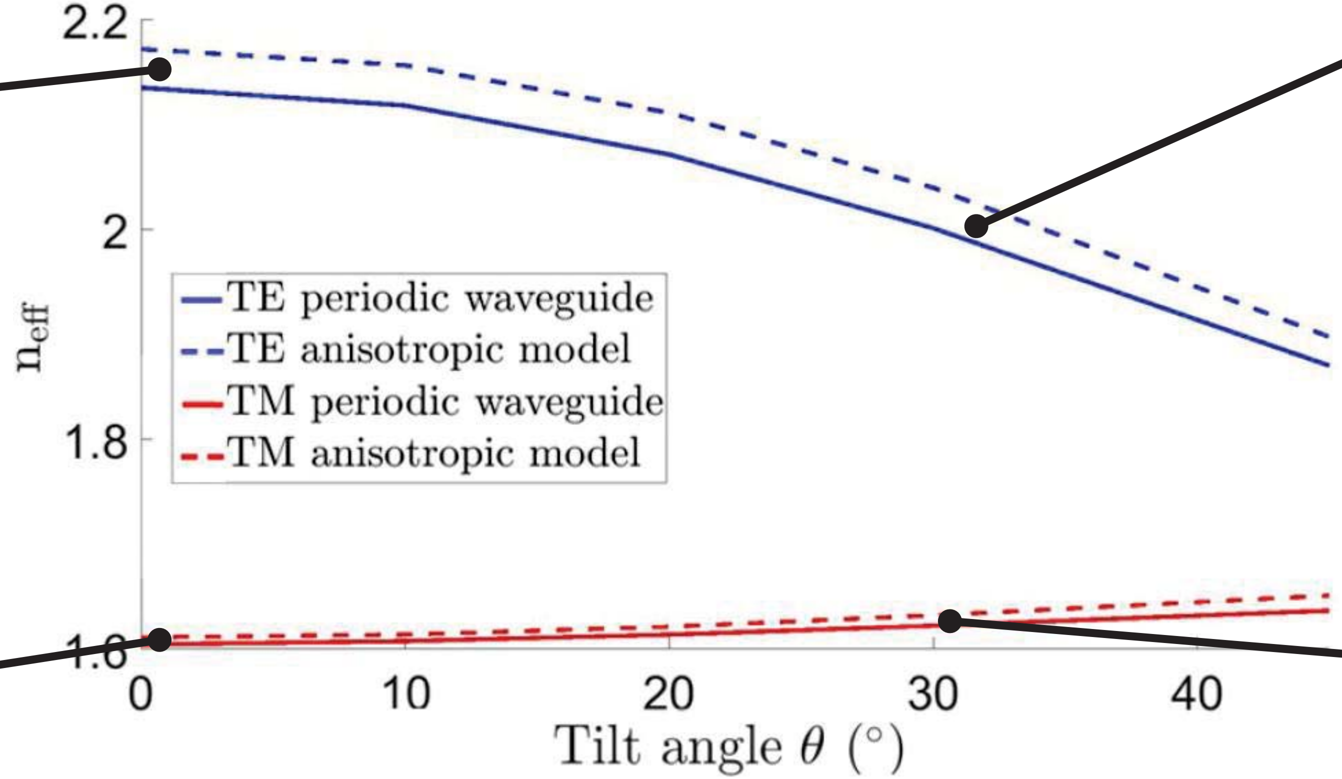
Luque-González, Optics Letters 43, 2018

TE 0º

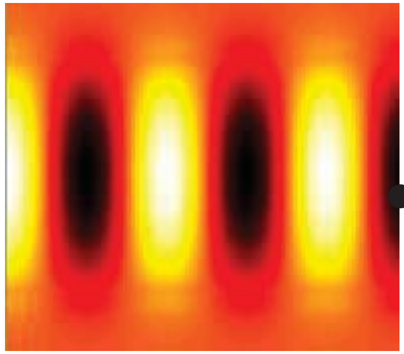


TE 30º

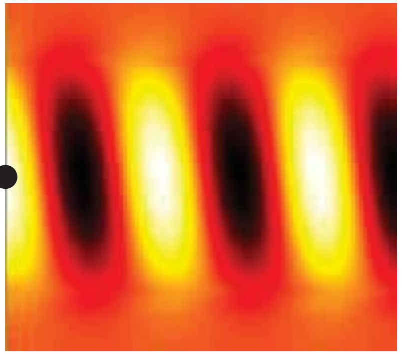




TM 0º



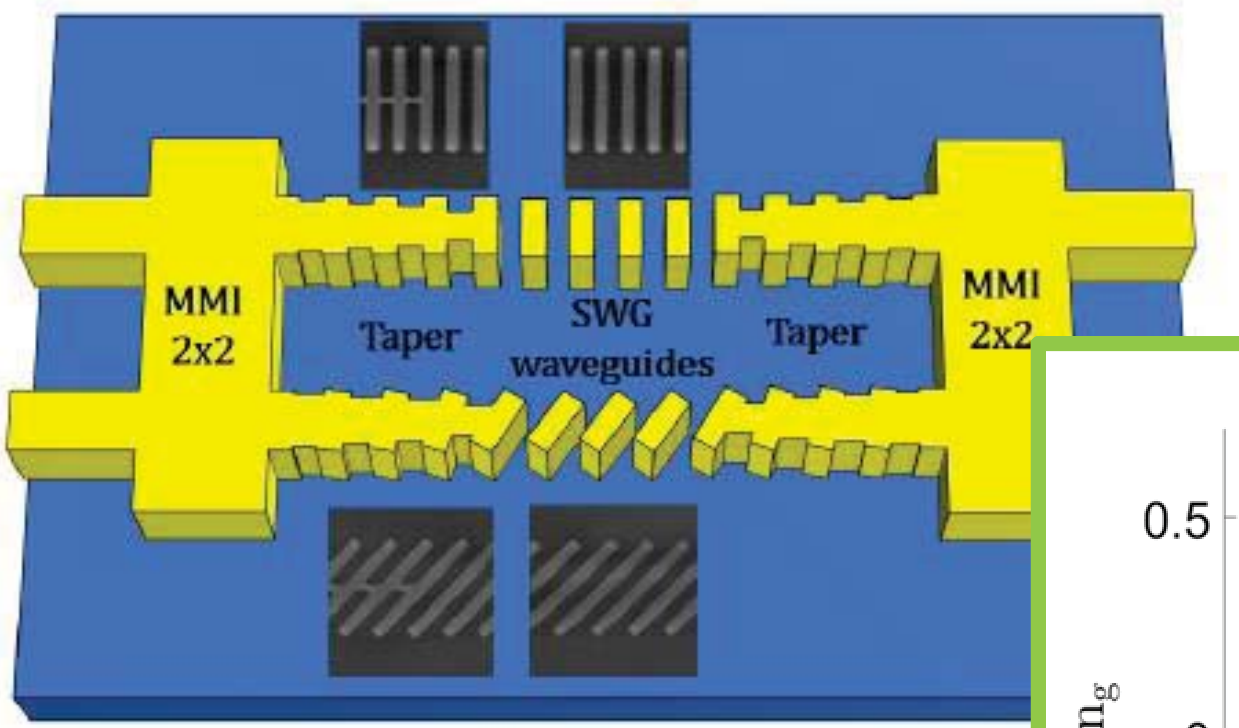
TM 30º

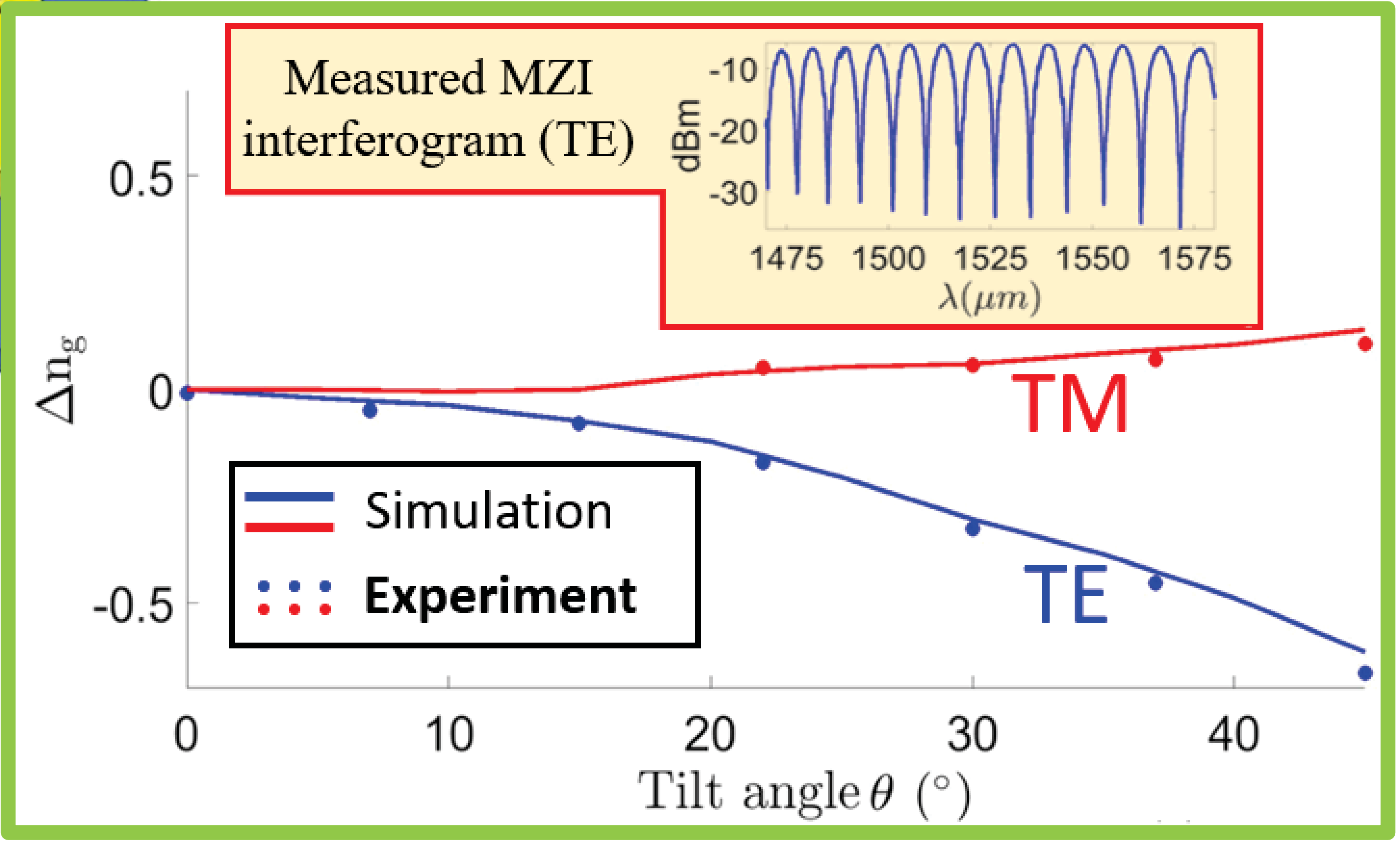


Engineer TE effective index with constant feature size!
TM unaffected!

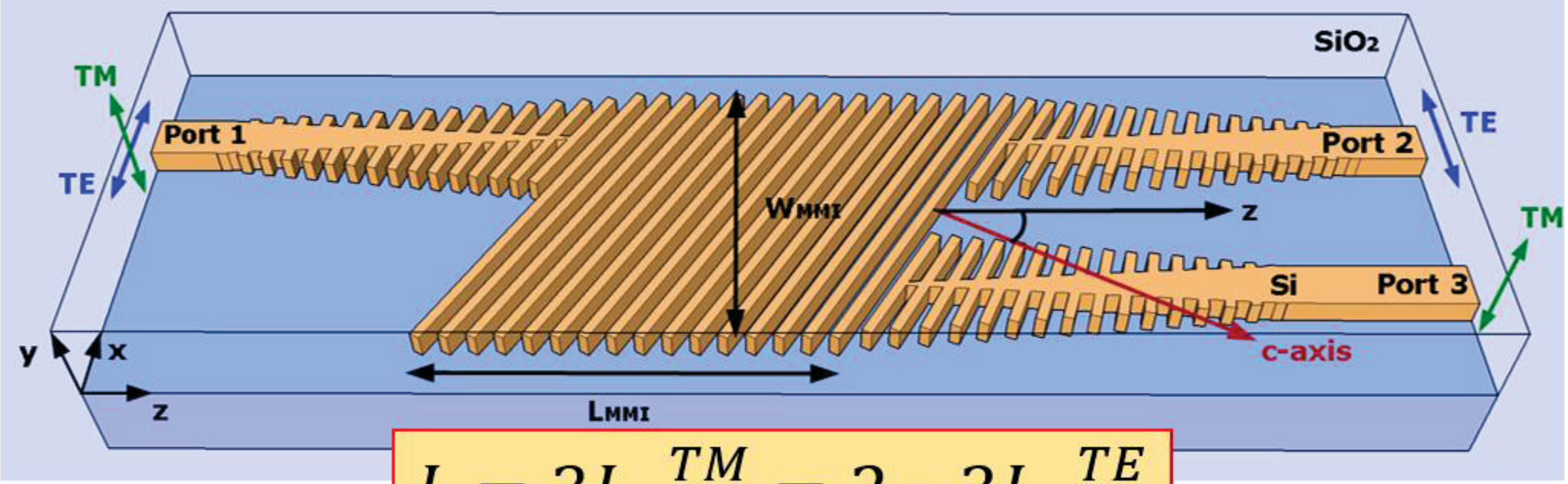
Luque-González, Optics Letters 43, 2018

Experiment

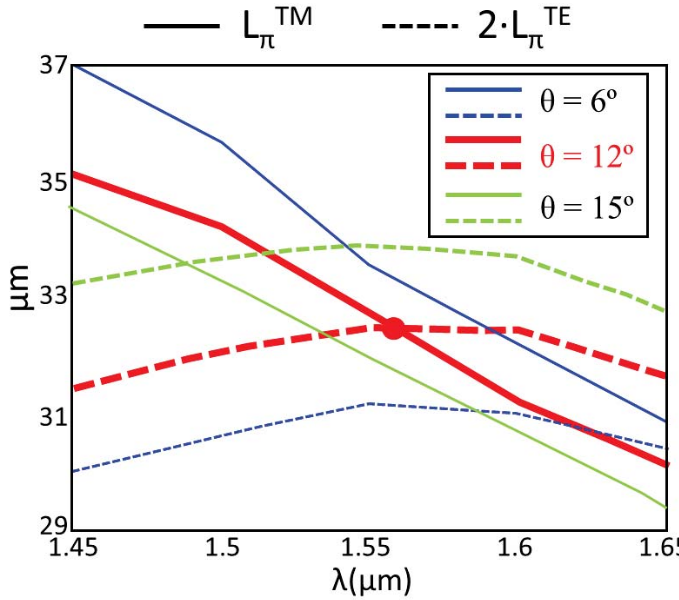


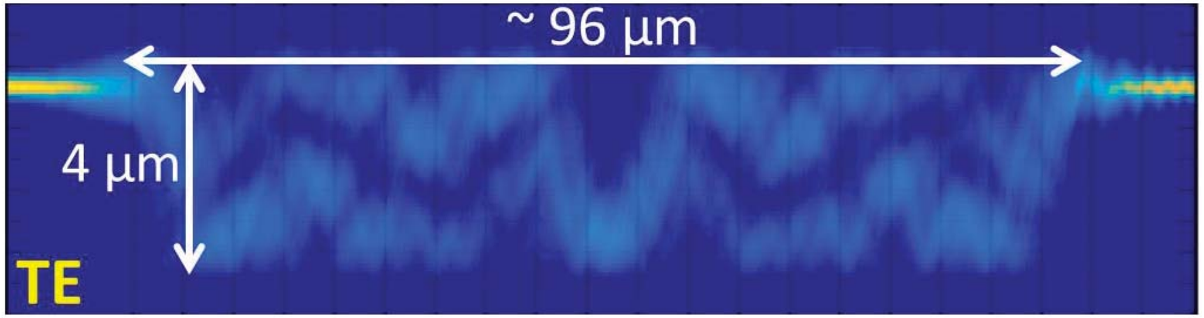


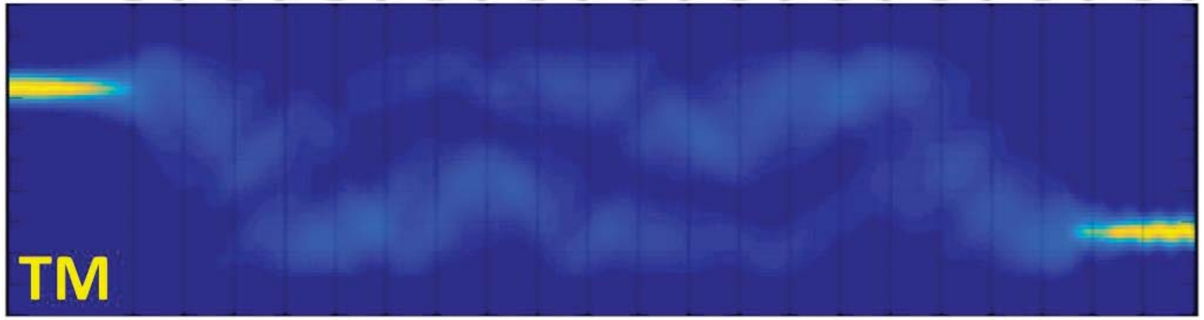
Luque-González, Optics Letters 43, 2018



$$L = 3L_{\pi}^{TM} = 2 \cdot 3L_{\pi}^{TE}$$





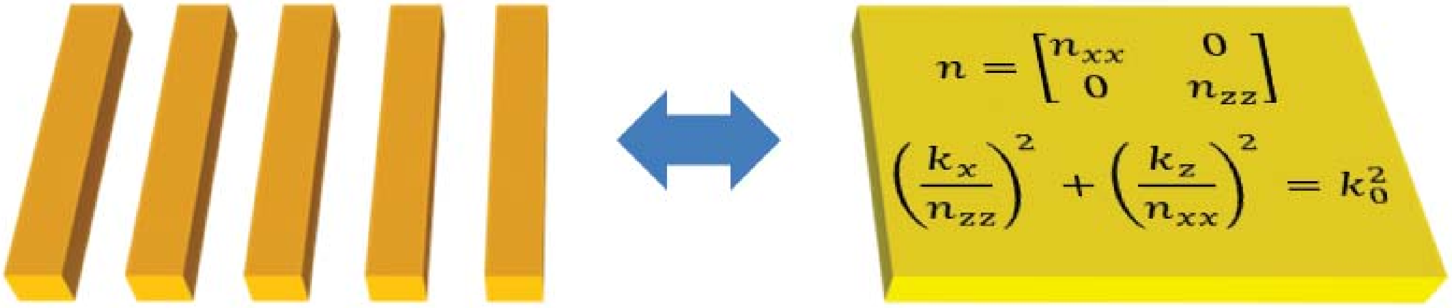


Extinction ratio > 20dB Insertion Losses < 1.5dB 120nm bandwidth (3D FDTD)

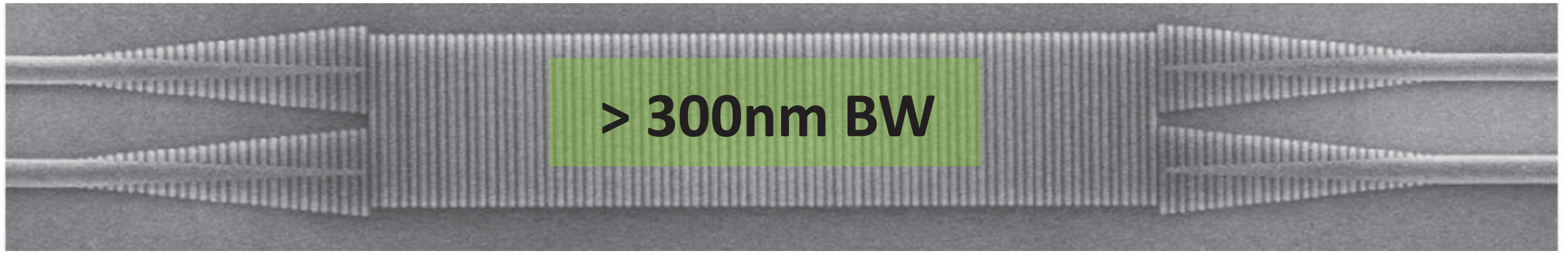
A. Herrero, Optics Letters, submitted

Conclusions

Thank you!



R. Halir, "Subwavelength-Grating Metamaterial Structures for Silicon Photonic Devices", Proceedings of the IEEE, in press



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QUESTIONS?

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