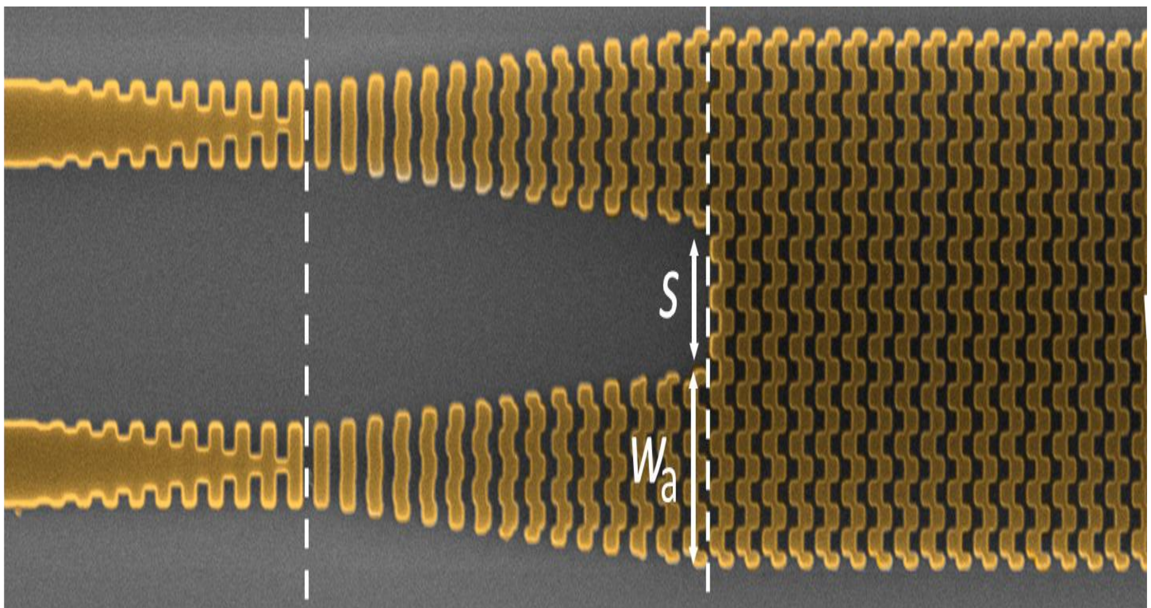
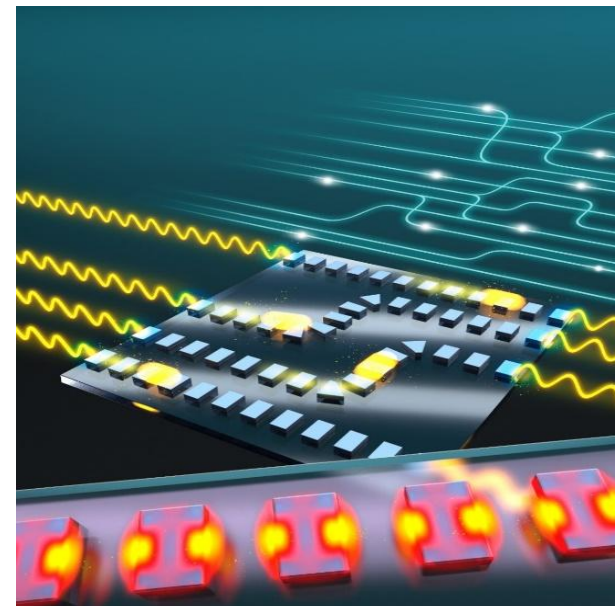
National Research Council Canada | Conseil national de recherches Canada

Metamaterial integrated photonics

Pavel Cheben

National Research Council Canada





VŠB, Ostrava, 21.7.2025

National Research Council, Canada
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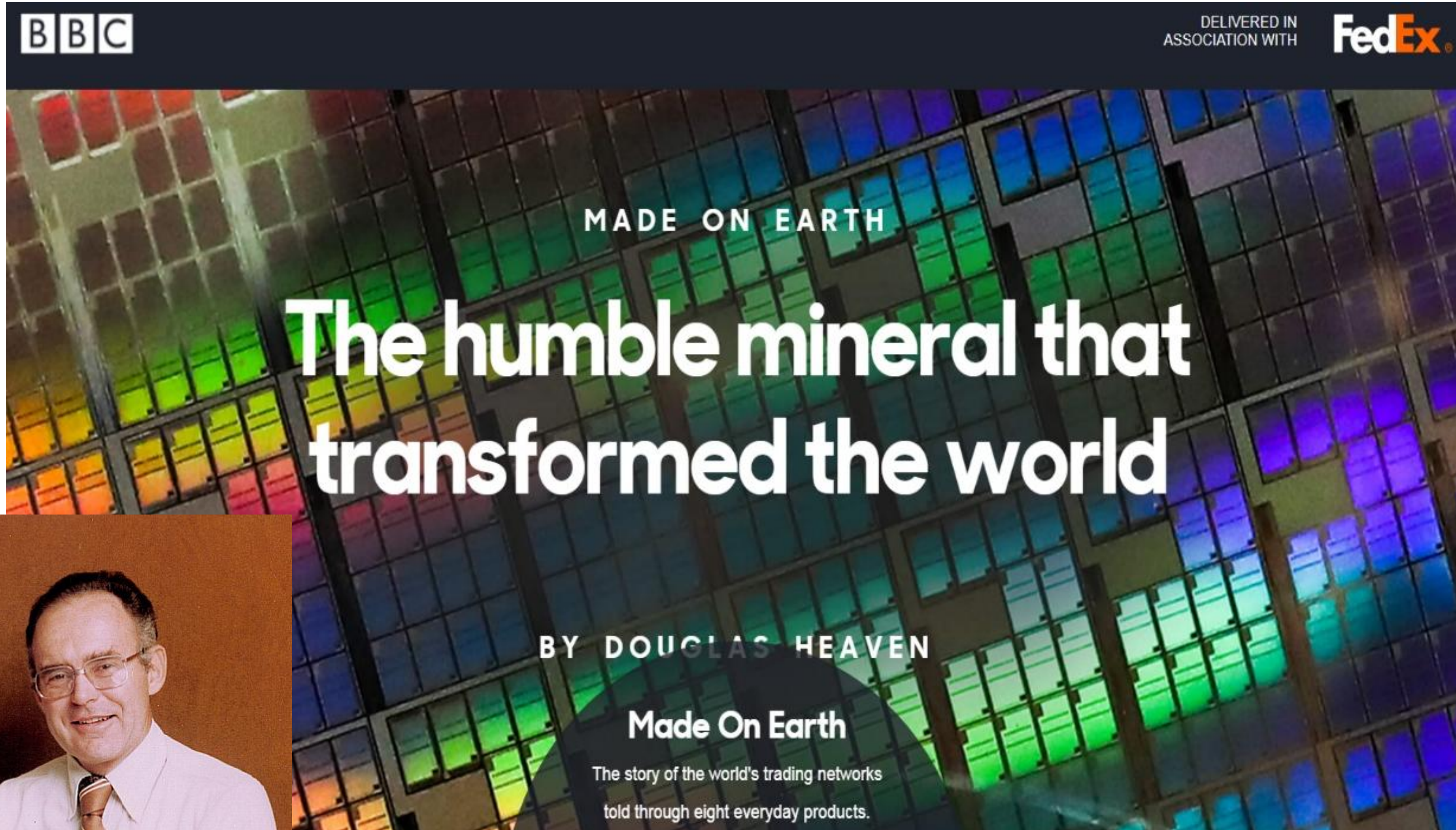
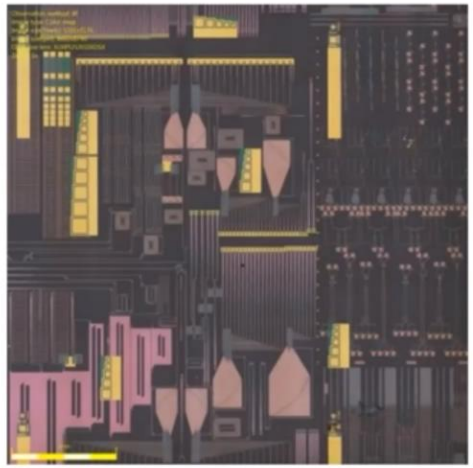


Gordon Earle Moore (1929 – 2023)
The co-founder and emeritus chairman of Intel Corporation.

Silicon photonics

WHAT IS SILICON PHOTONICS?

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab



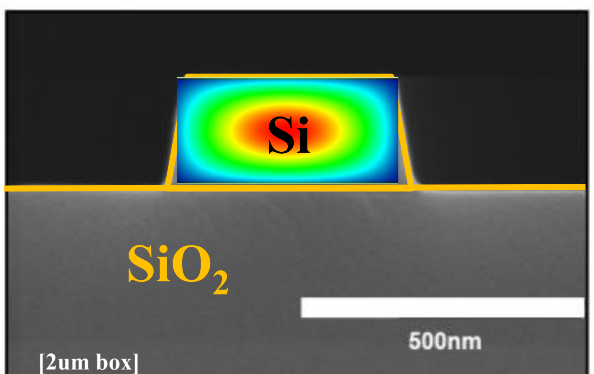
Pictures, courtesy of imec

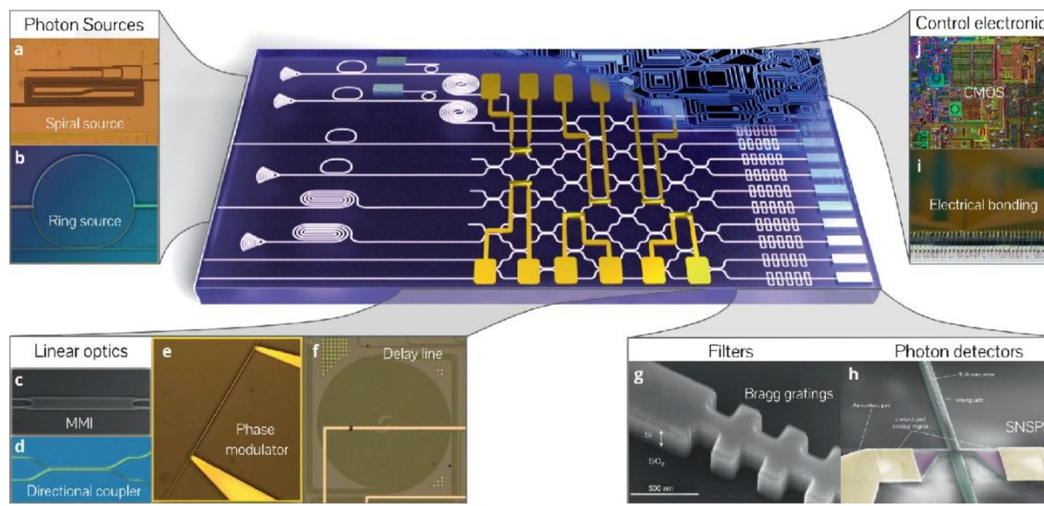
Enabling complex optical functionality on a compact chip at low cost

Courtesy Prof. Roel Baets

Silicon waveguides

- Starting from Silicon-on-Insulator wafers (SOI, from CMOS electronics), 200 mm or 300 mm
- Fabricated using 193 nm DUV or e-beam lithography and reactive ion etching (RIE).
- Standard waveguide: 450nm x 220nm
- Strongly confined mode (much smaller than in optical fibers)
- Bend radius ~2 μm

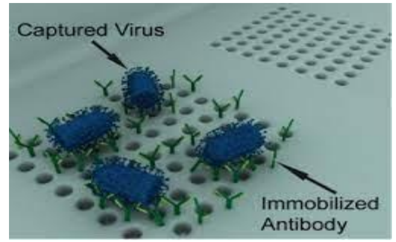




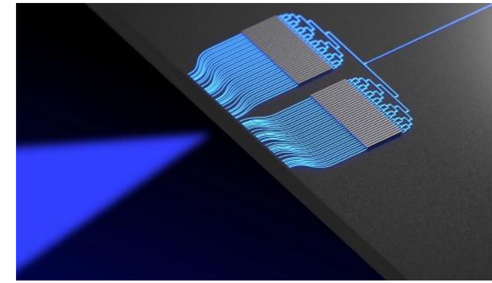
Silicon photonics

Telecom

Sensing



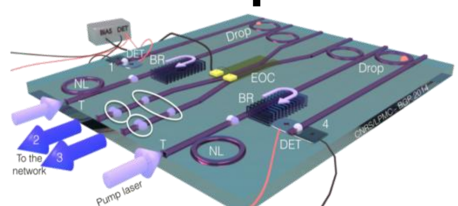
Antenna phased arrays



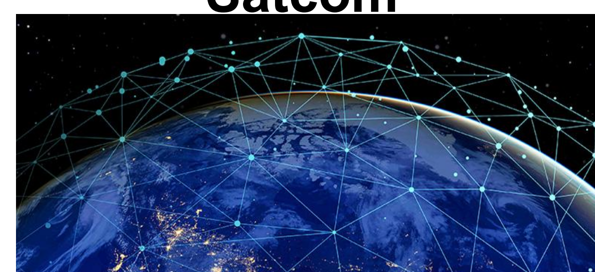
Lidars

Datacom

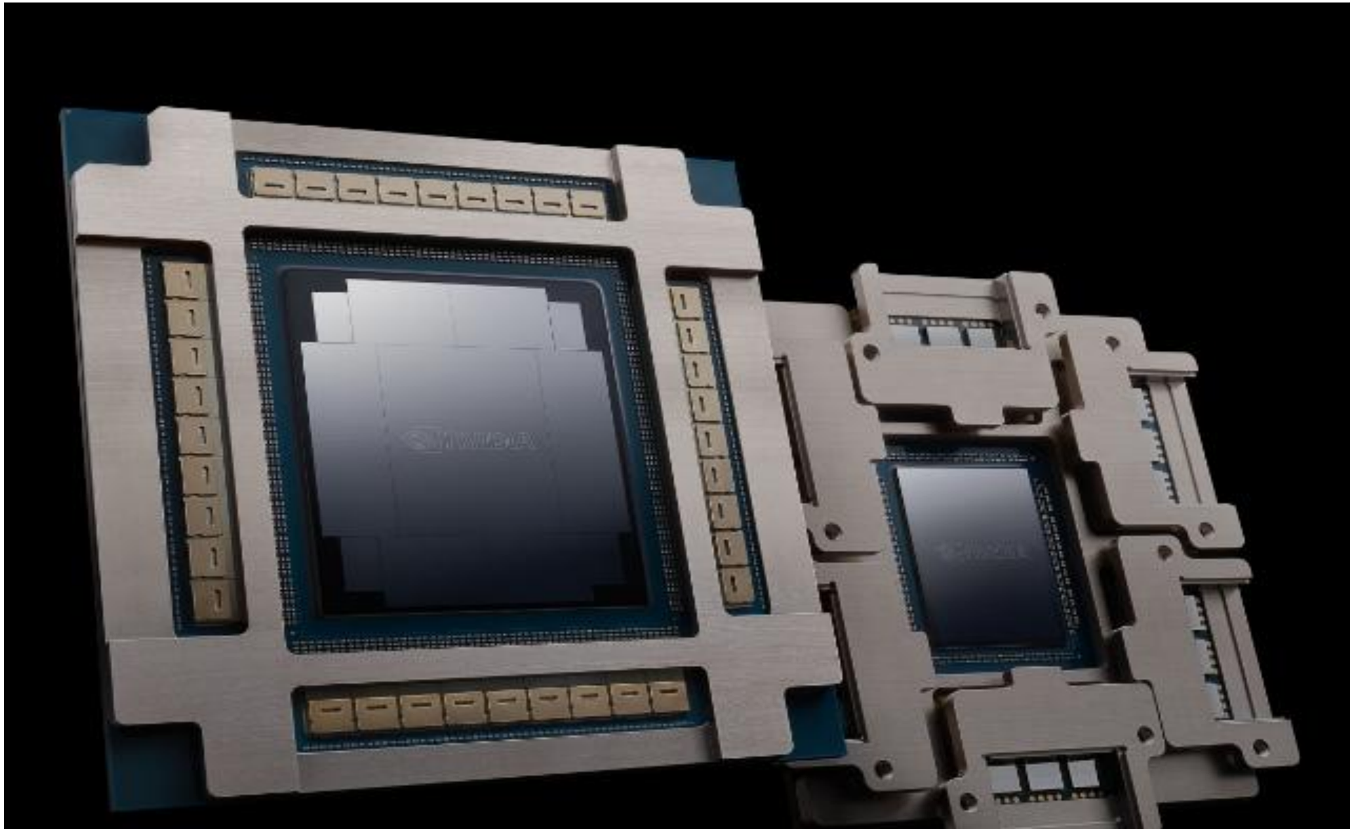
Quantum photonics



Satcom

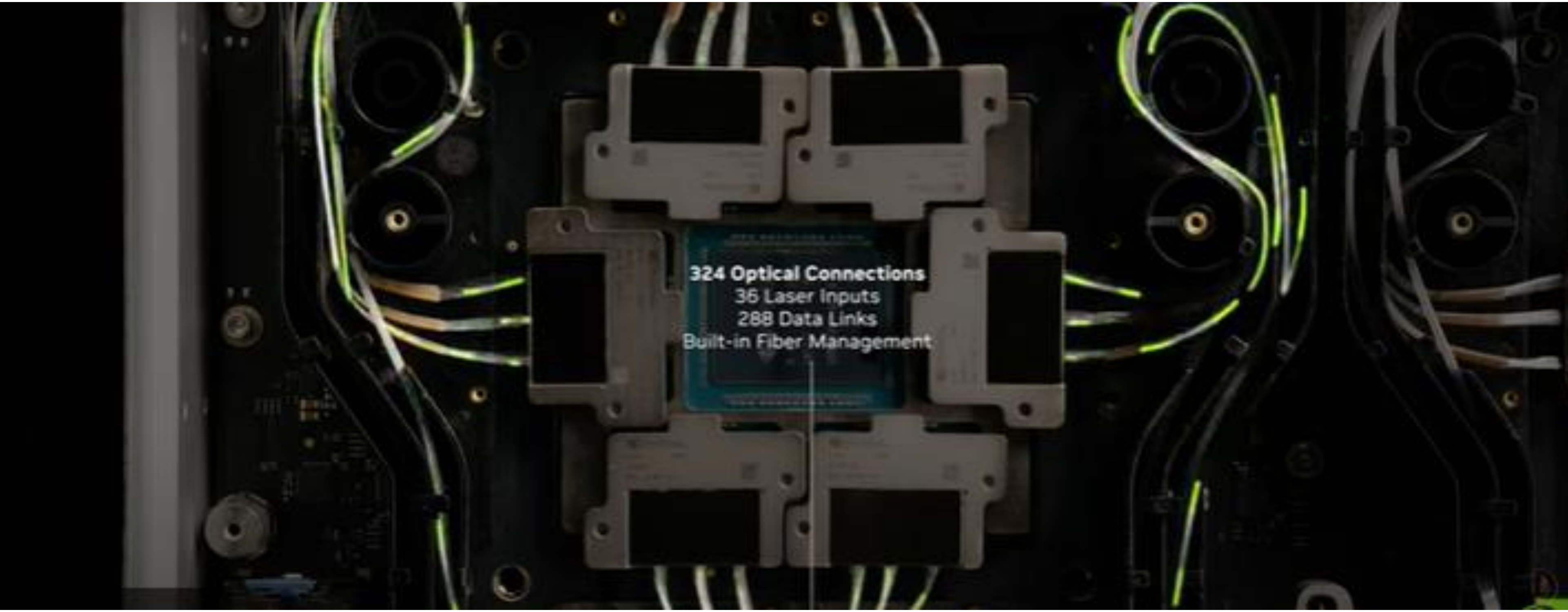


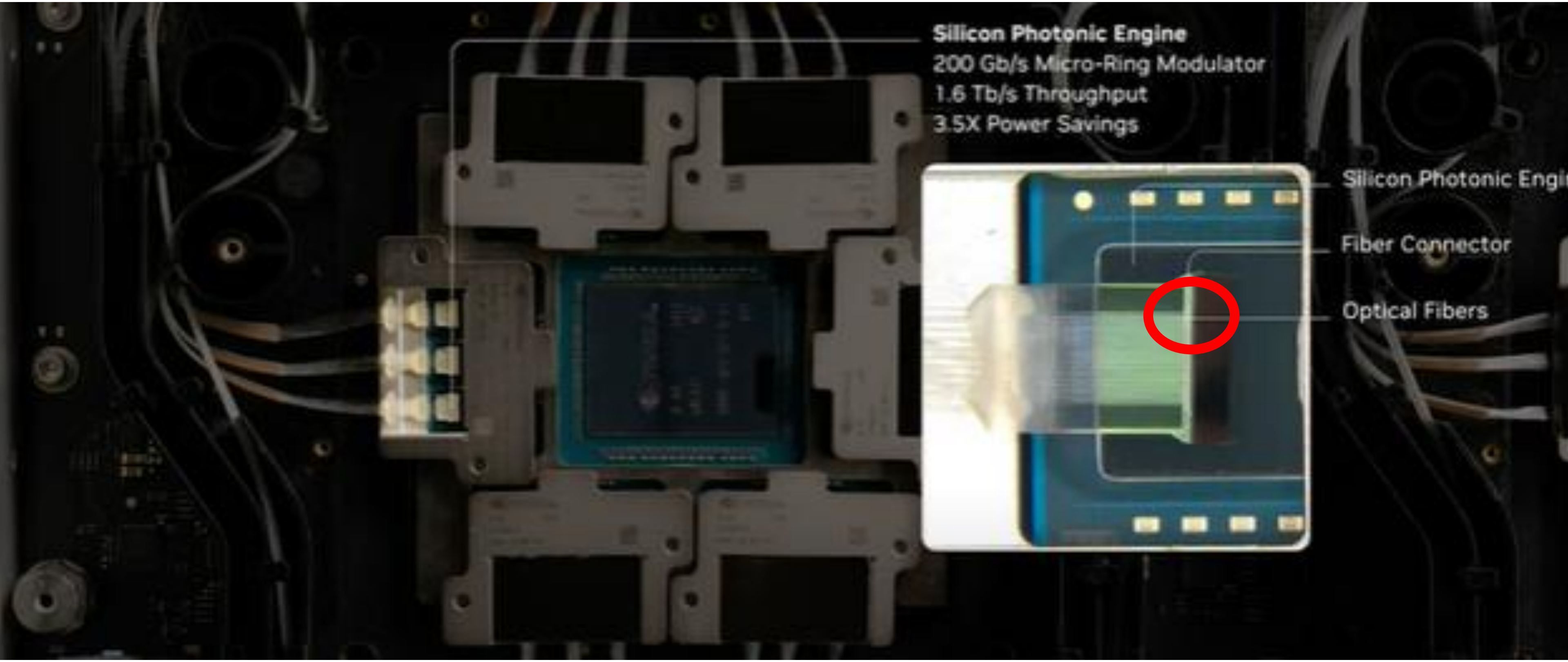
NVIDIA Co-Packaged Silicon Photonic Networking Switch



446 billion transistors

115 Tb/s throughput


324 Optical Connections
36 Laser Inputs
288 Data Links
Built-in Fiber Management

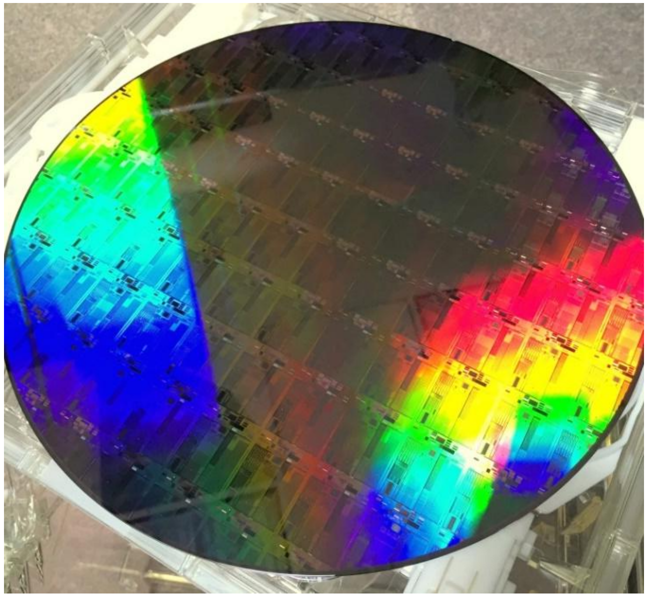

Silicon Photonic Engine
200 Gb/s Micro-Ring Modulator
1.6 Tb/s Throughput
3.5X Power Savings
Fiber Connector
Optical Fibers

Multiplane data optical connectors

1152 Single mode fibers

The scale needed for the future million-GPU AI facilities

Silicon photonics design space challenge



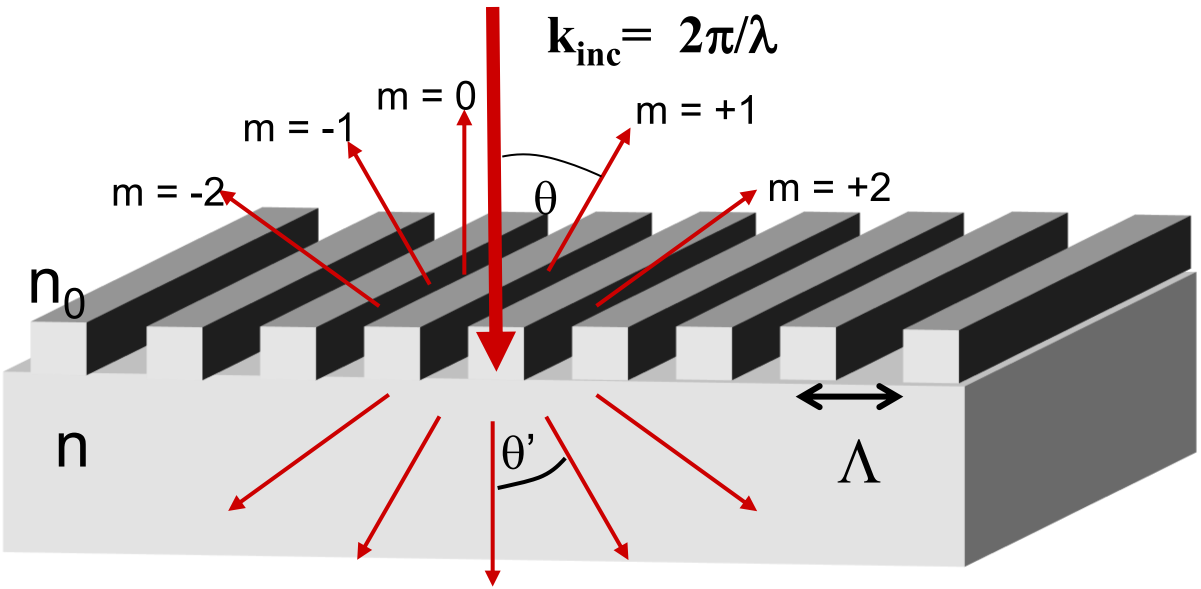
- Silicon fabrication provides two basic materials Si and SiO_2 (only two refractive indices n=3.47, n=1.44), unlike III-V semiconductor devices

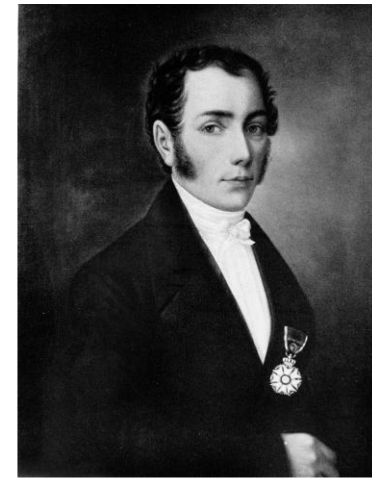
- Adding new materials to the mix moves manufacturing outside traditional silicon fab capabilities

Can the silicon design space be expanded without losing the advantages and simplicity of silicon?

Subwavelength optics

Diffraction grating





Joseph Ritter von Fraunhofer
*1787, +1826

Grating equation (normal incidence):

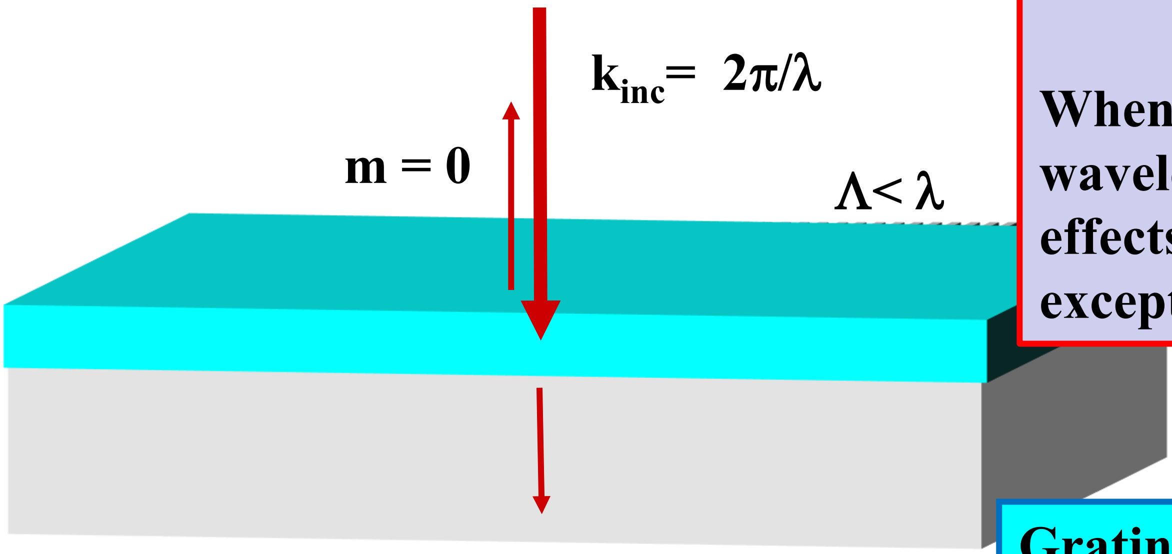
$$\sin\theta = \frac{m\lambda}{\Lambda} \qquad n\sin\theta' = \frac{m\lambda}{\Lambda}$$

(backward) (forward)

Diffraction grating:

$$\Lambda > \lambda \quad \text{and} \quad m < \frac{\Lambda}{\lambda}$$

Subwavelength grating



NO DIFFRACTION

When grating period Λ is less than wavelength of light λ, diffraction effects are supressed for all orders except m = 0.

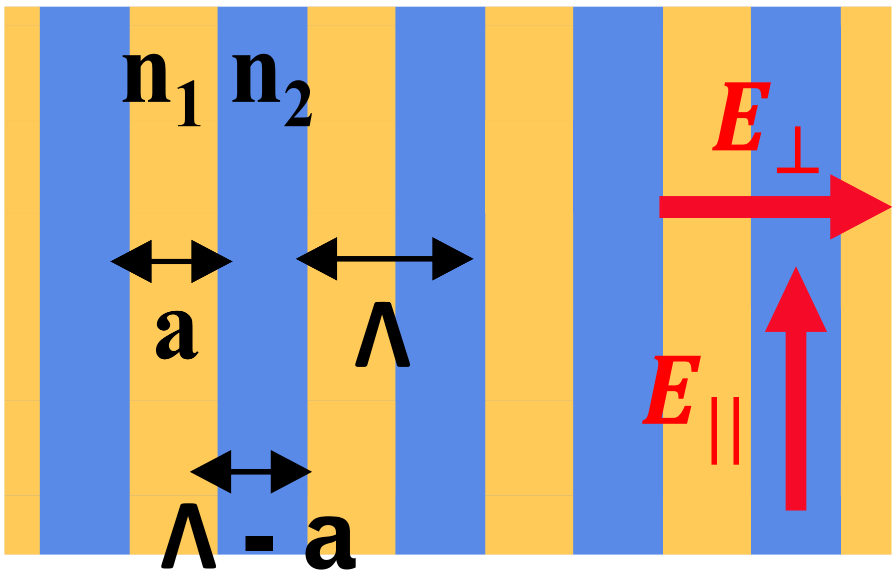
Grating region behaves like a <u>homogeneous anisotropic layer</u> with an equivalent dielectric permittivity tensor.

Subwavelength grating:

$$\Lambda < \lambda \;\rightarrow\; m\lambda / \Lambda > 1$$

$$\sin\theta = \frac{m\lambda}{\Lambda} \qquad n\sin\theta' = \frac{m\lambda}{\Lambda}$$

Rytov's formulas

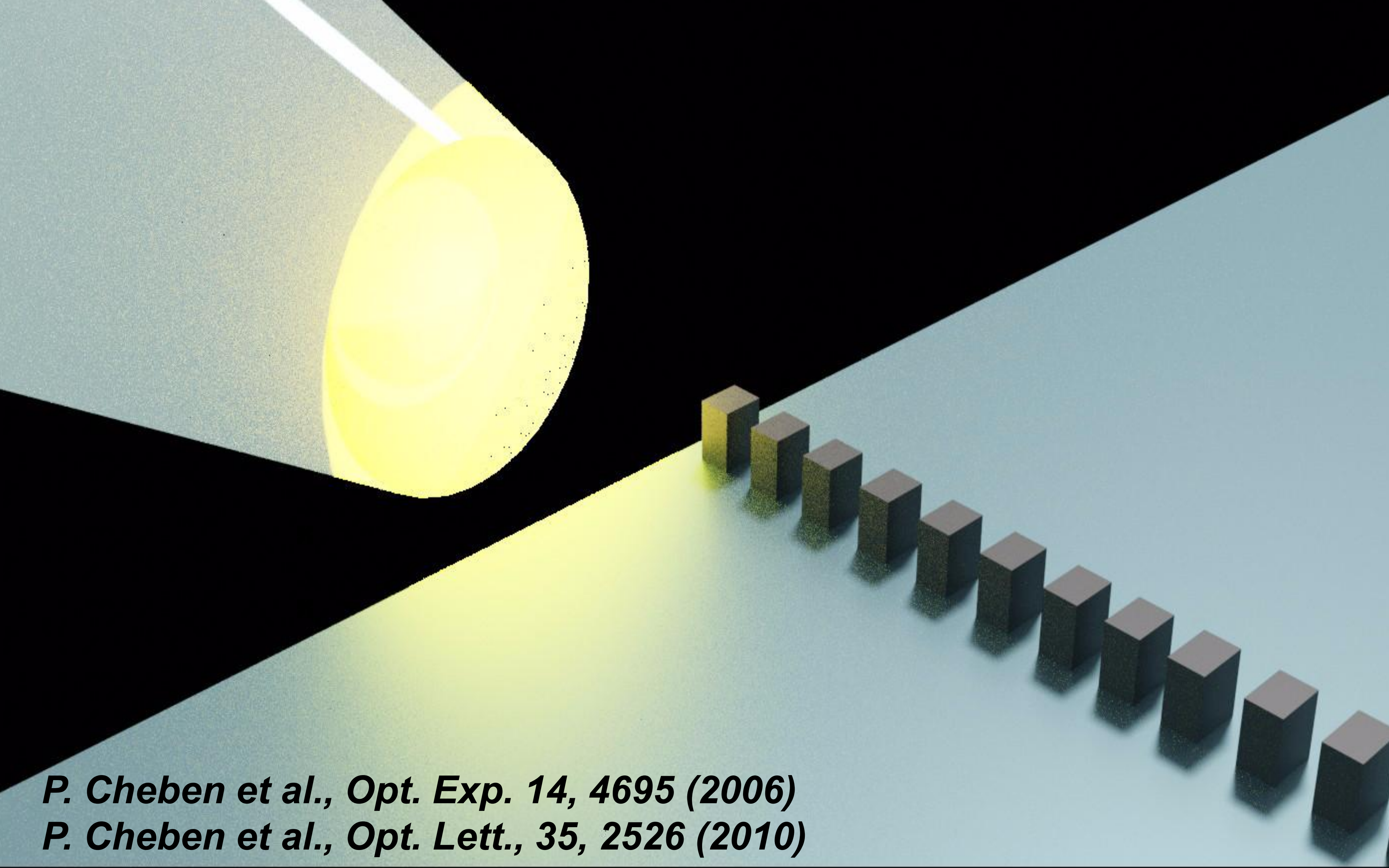


$$n_{\parallel}^2 = \frac{a}{\Lambda} n_1^2 + \left(1 - \frac{a}{\Lambda}\right) n_2^2$$

$$\frac{1}{n_{\perp}^2} = \frac{a}{\Lambda}\frac{1}{n_1^2} + \left(1 - \frac{a}{\Lambda}\right)\frac{1}{n_2^2}$$

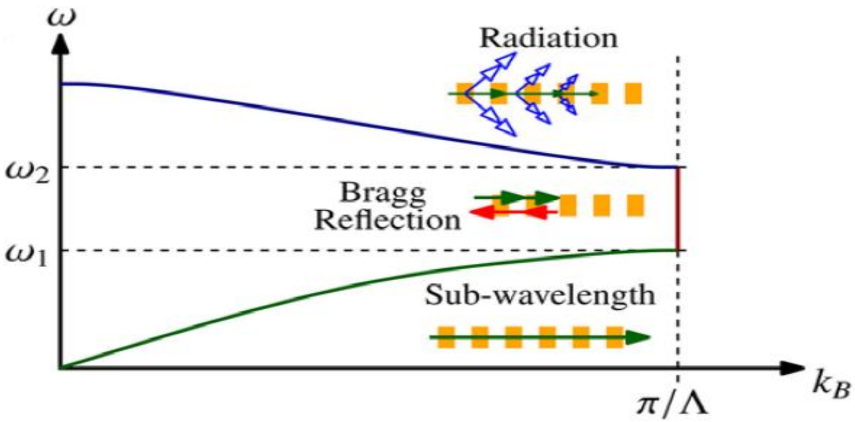
S. M. Rytov, Soviet Phys. JETP 2, 466-475 (1956)

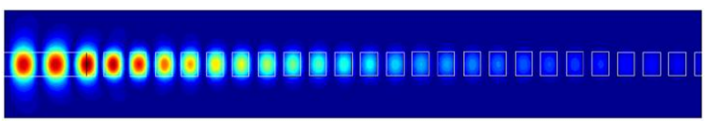
Sergei Mikhailovich Rytov (1908 –1996), a Soviet physicist.



P. Cheben et al., Opt. Exp. 14, 4695 (2006)
P. Cheben et al., Opt. Lett., 35, 2526 (2010)

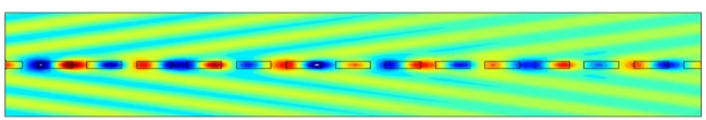
Periodic waveguides



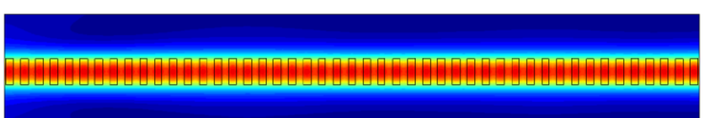


$\Lambda \sim \lambda_{eff}/2$: Bragg gratings, photon. crystals

Ken Hill, CRC Canada, 1976
Eli Yablonovitch and Sajeev John, 1987



$\Lambda > \lambda_{eff}/2$: Radiative gratings



$\Lambda < \lambda_{eff}/2$: SWG waveguides

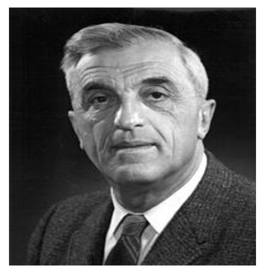
NRC Canada, 2006

Floquet-Bloch mode in a periodic waveguide

$$\frac{d^2\psi(z)}{dz^2} + P(z)\psi(z) = 0$$

(Gaston Floquet, 1883)
Second-order differential equation with periodic coefficients, $P(z \pm \Lambda) = P(z)$

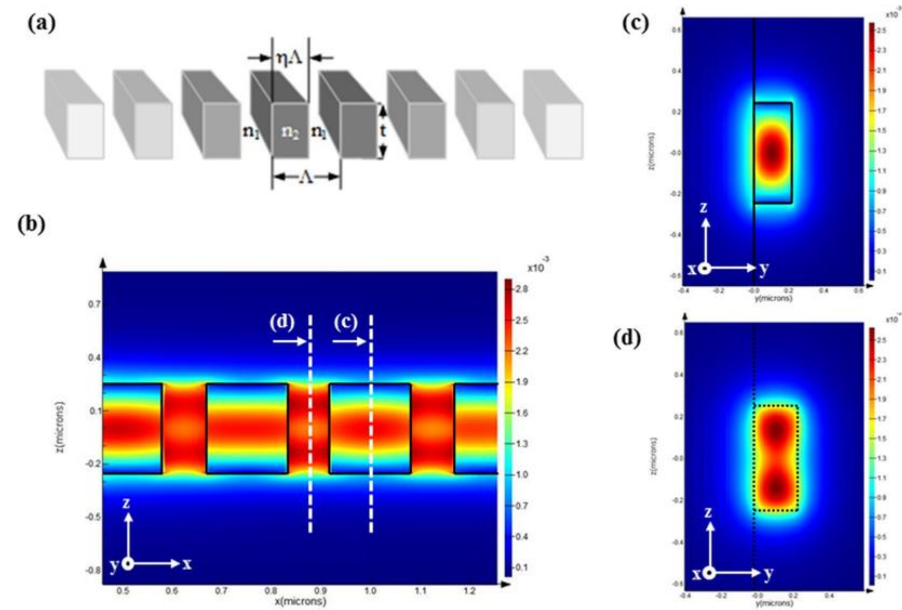
Felix Bloch

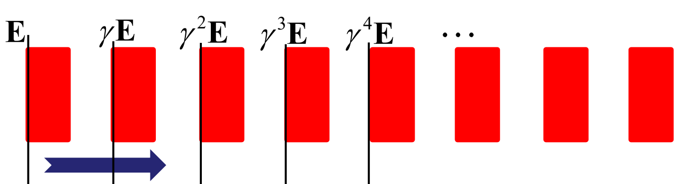


Solution is a periodic function:

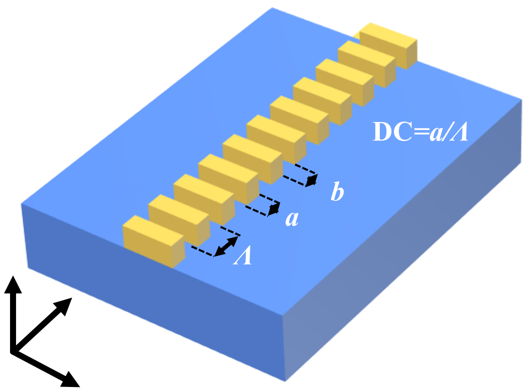
$$\psi(z) = e^{ikz}u(z)$$

Where $u(z \pm \Lambda) = u(z)$

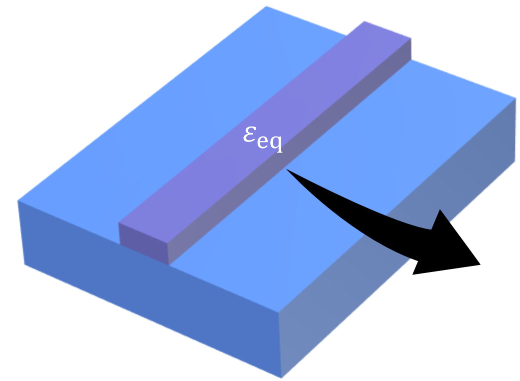


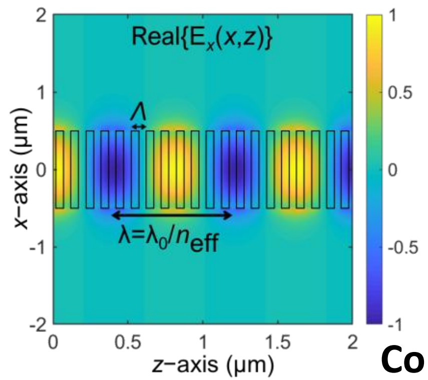


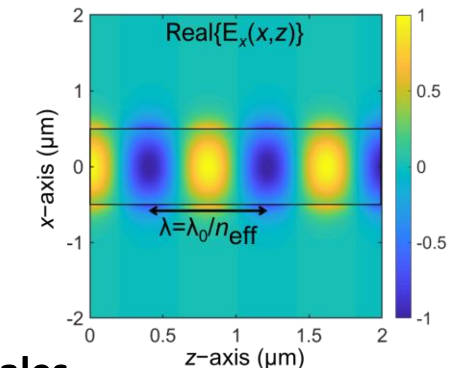
SWG metamaterial waveguide



$\Lambda << \lambda$



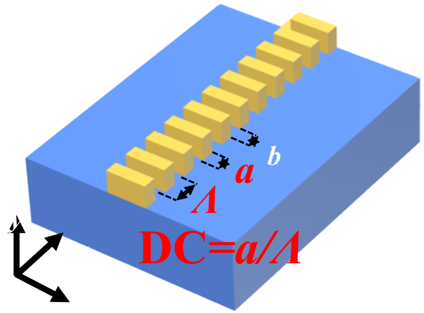




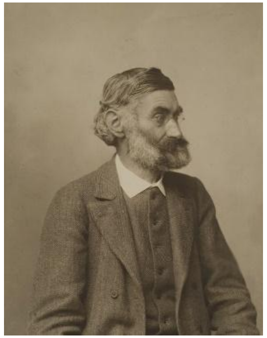
Courtesy - Jose Manuel Luque-Gonzales

Waveguide core equivalent refractive index controlled by "mixing" two dielectric materials by varying grating geometry

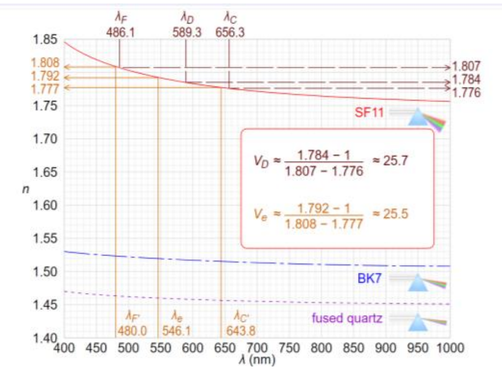
Engineering waveguide properties



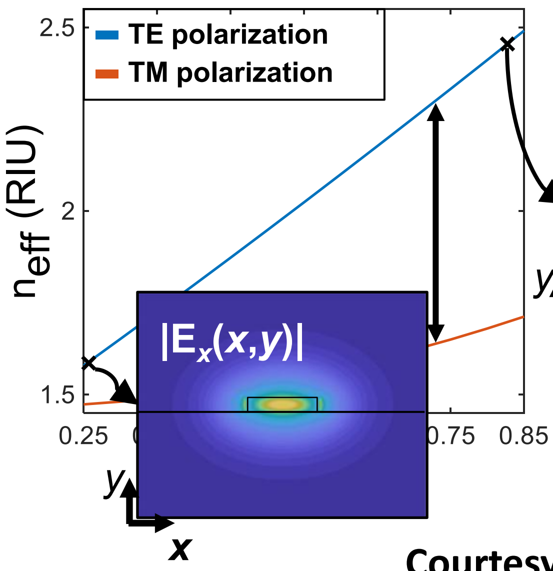
Ernst Abbe



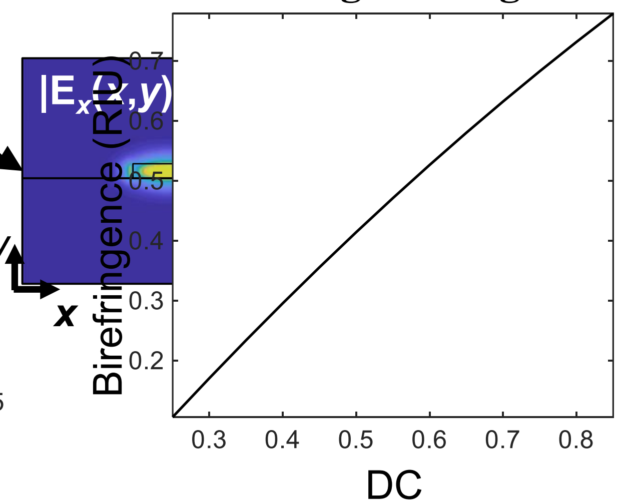
$$V_d = \frac{n_d - 1}{n_F - n_C}$$



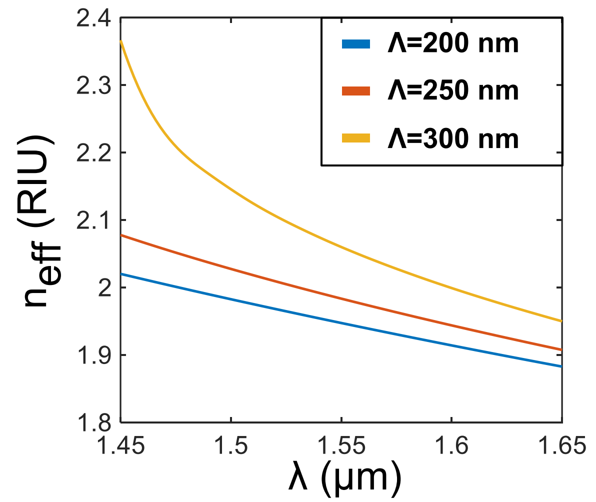
Refractive index engineering



Birefringence/Anisotropy engineering

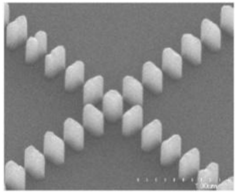


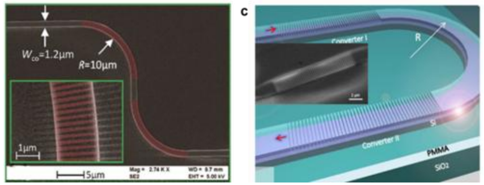
Dispersion engineering

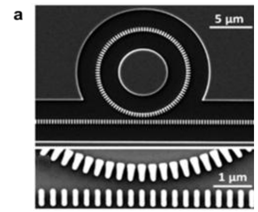


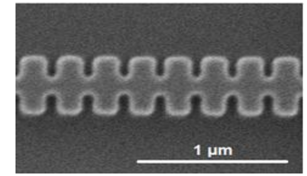
Courtesy - Jose Manuel Luque-Gonzales

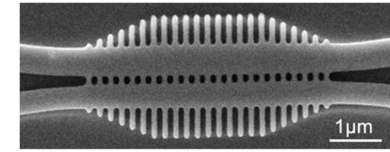
Surging field of research

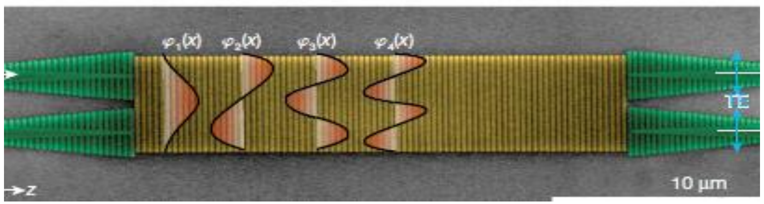


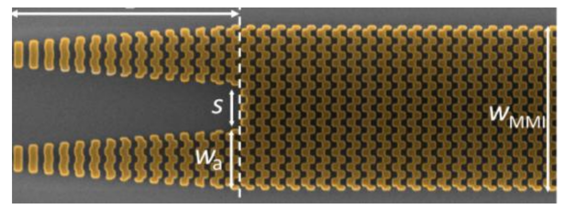


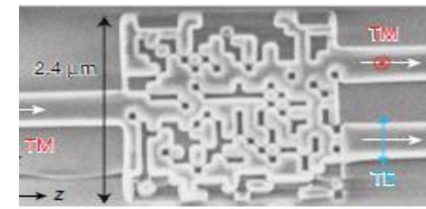


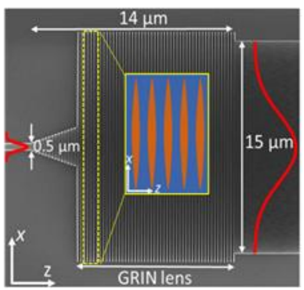


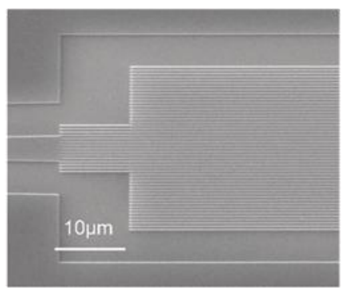


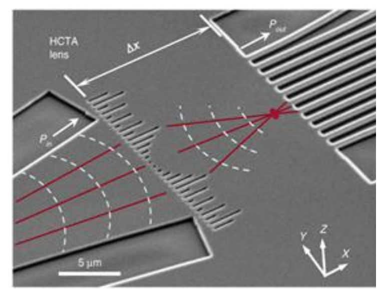


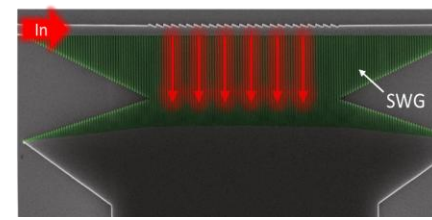


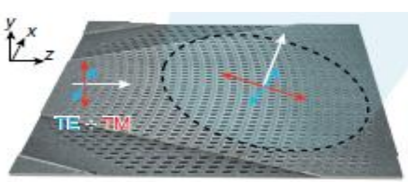


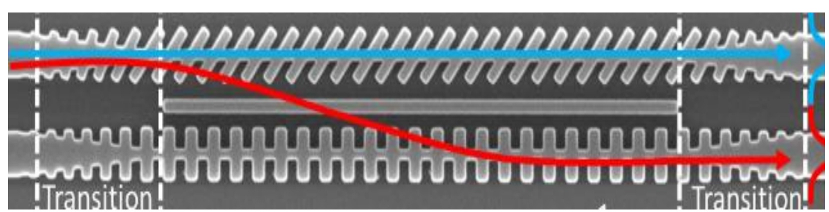


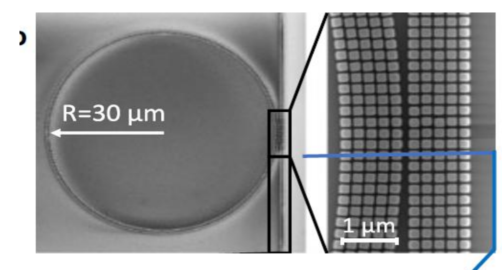










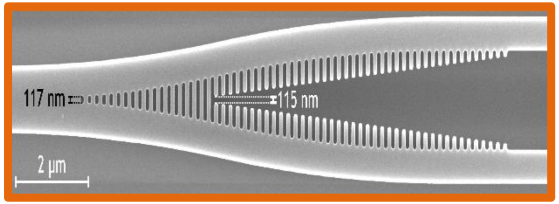


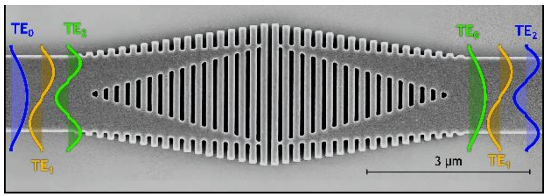
P. Cheben et al., Adv. Opt. Photon, vol. 15, no. 4, 2023

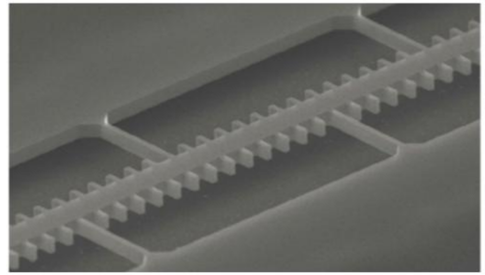
P. Cheben et al., Nature, vol. 560, no. 7720, 2018

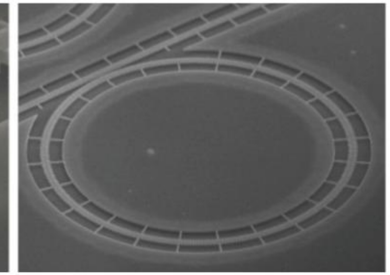
Halir et al., Proceedings of the IEEE, vol. 106, no. 12, 2018

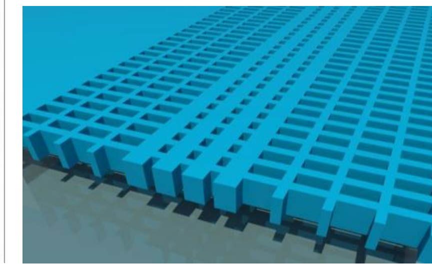
Surging field of research

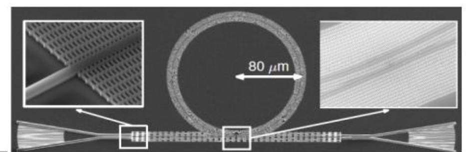


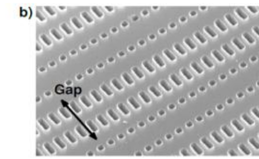


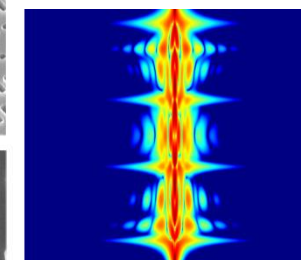


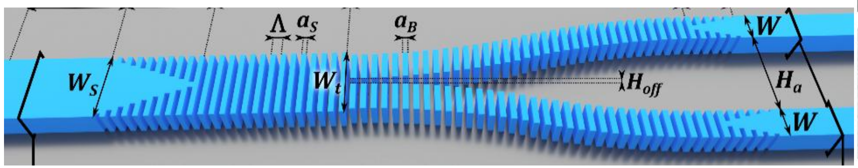


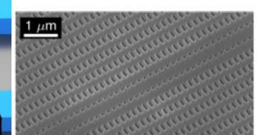


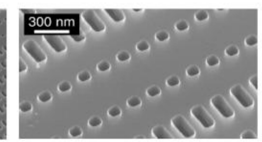


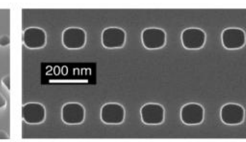


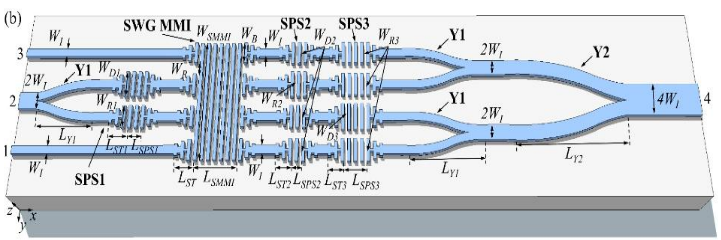


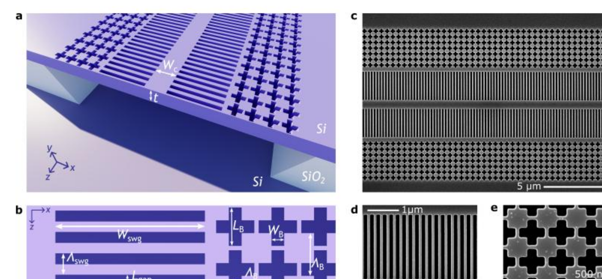






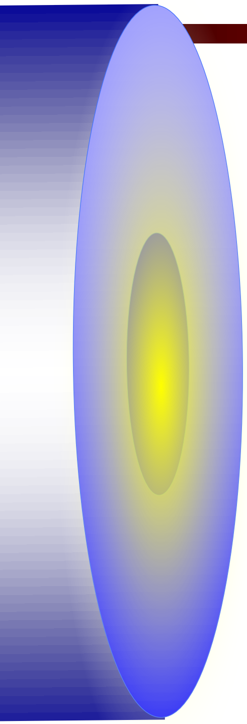


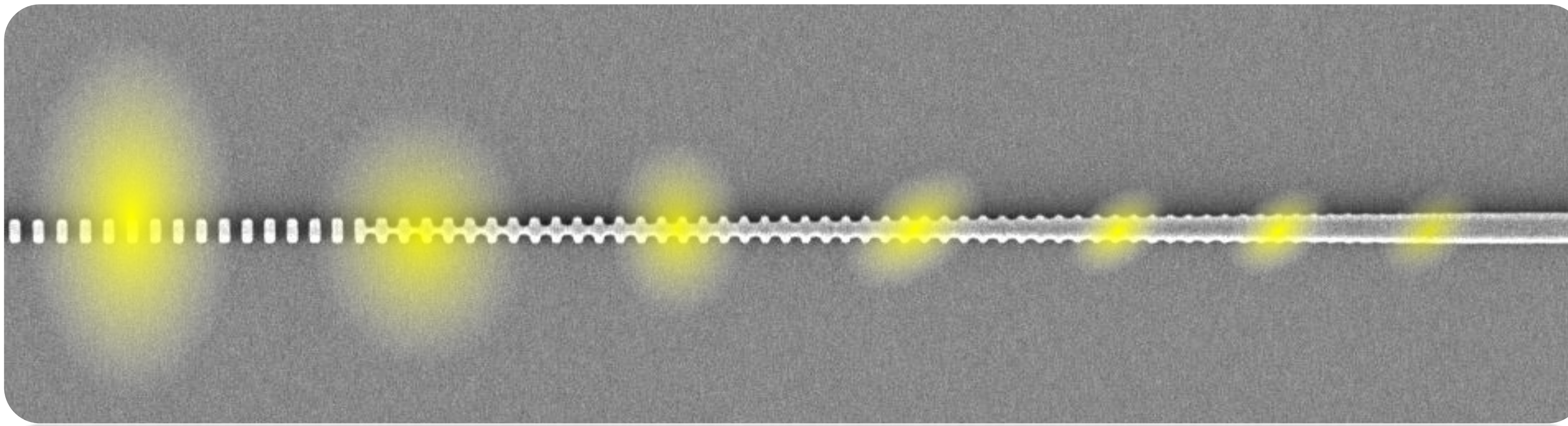




P. Cheben et al., Adv. Opt. Photon, vol. 15, no. 4, 2023
P. Cheben et al., Nature, vol. 560, no. 7720, 2018
R. Halir et al., Proceedings of the IEEE, vol. 106, no. 12, 2018

SWG metamaterial fiber-chip coupler





P. Cheben et al., US Patent 7,680,371
P. Cheben et al., Opt. Express, vol. 14, p. 4695 (2006)
P. Cheben et al., Opt. Lett., vol. 35, p. 2526 (2010)
P. Cheben et al., Opt. Express, vol. 23, p. 22554 (2015)

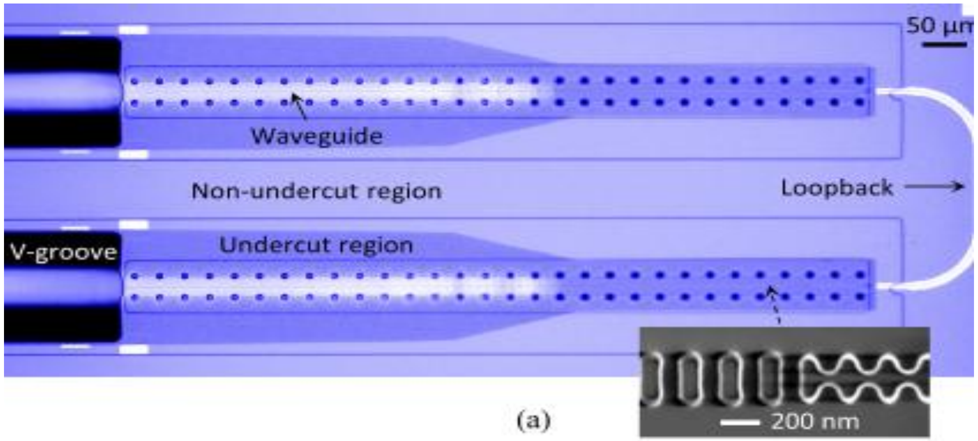
Loss 0.32dB (93%), BW > 100nm
PDL<0.05dB, MFD=3.2um

NRC with Teraxion, Ciena

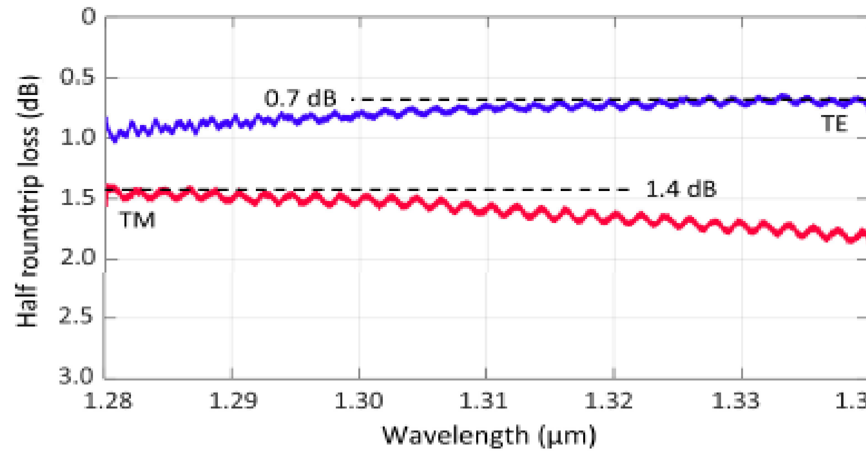
Minimum feature size 100 nm
E-beam, but compatible with deep-up

IBM metamaterial coupler

T. Barwicz et al., OFC 2015, Paper Th3F
T. Barwicz et al., OFC 2016, Paper M2I.3
T. Barwicz et al., OFC 2017, Paper Th2A.39



(a)

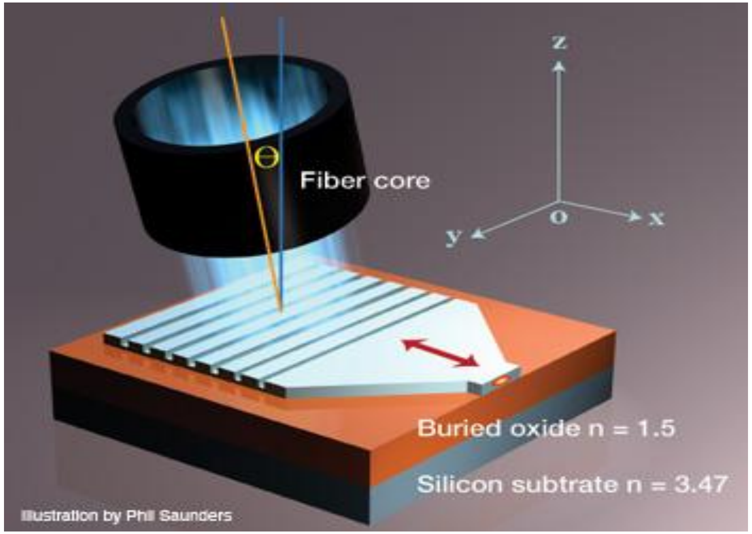


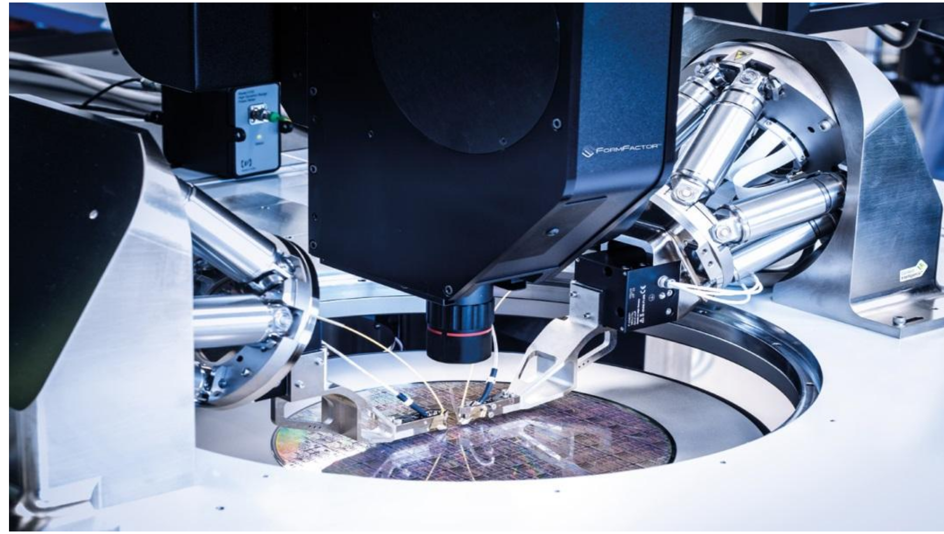
- 0.7 dB transmission loss from SMF-28 optical fiber to Si waveguide
- Localized substrate removal for large mode size
- Reflection -36 dB (TE) and -43 dB (TM)
- Available through a commercial product design kit

T. Barwicz et al., IEEE JSTQE, Vol. 25, No. 3 (2019)

GLOBAL FOUNDRIES

Surface grating couplers





High-throughput optical probing of on-wafer silicon photonic devices (Formfactor)

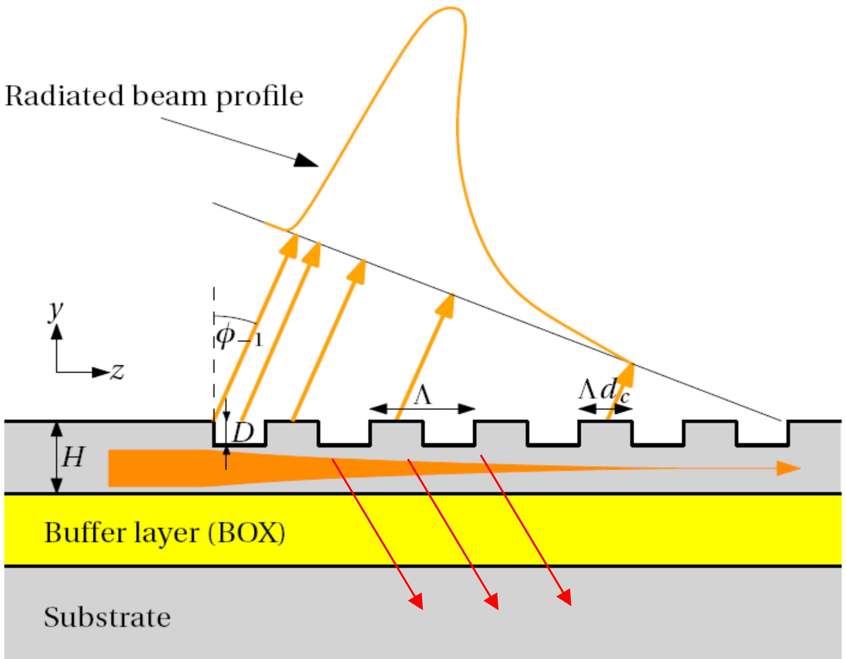
Pros:

- **Easier alignment**
- **No facet preparation**
- **Wafer level testing**

Cons:

- **Achieving sub-1dB efficiency is a challenge**
- **Limited wavelength range**

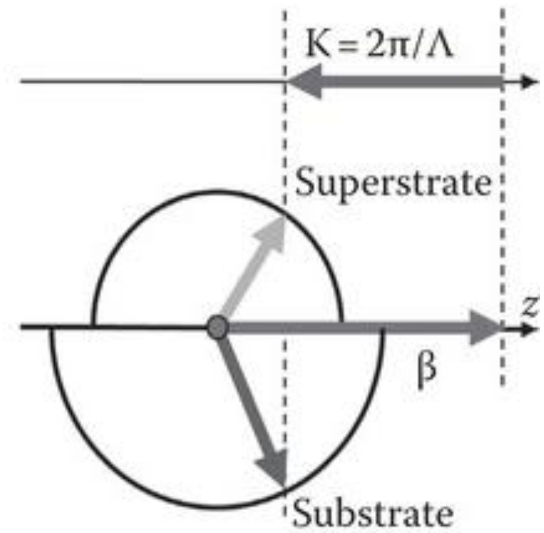
Surface grating couplers



$$k_0 n_{eff} = k_0 n_c \sin \phi + mK$$

$k_0 = 2\pi/\lambda_0$

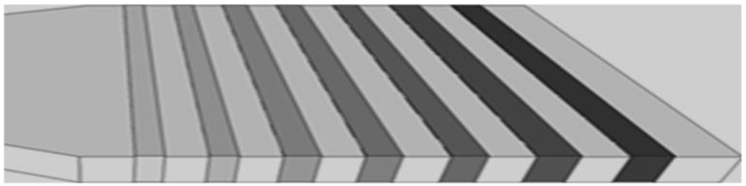
$K = 2\pi/\Lambda$

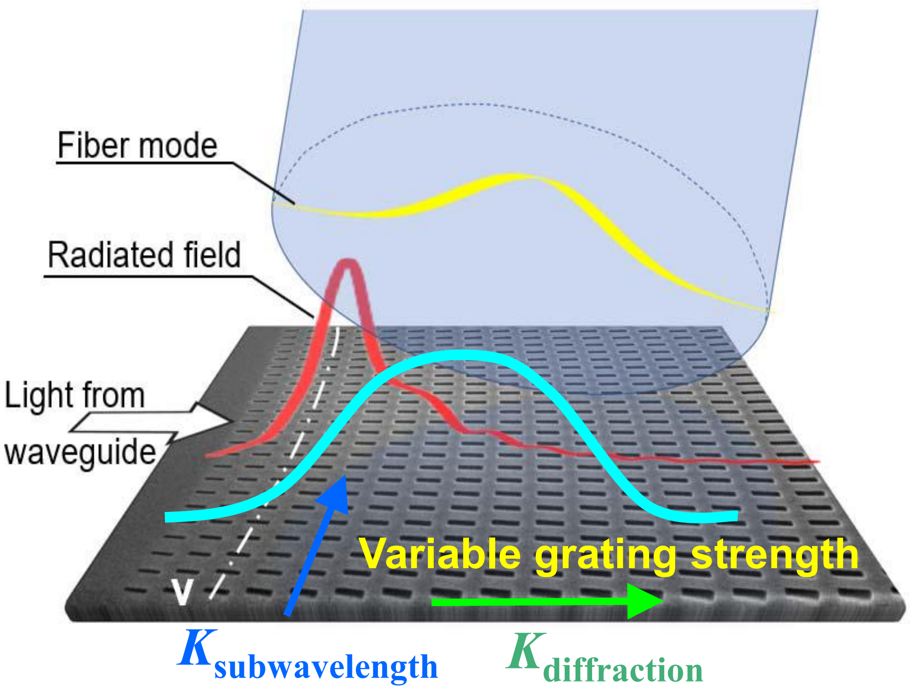


- Exponential near field, max. 80% overlap with a Gaussian beam (SMF-28)
- For field matching with an optical fiber, grating apodization is required
- Radiation loss to substrate

SWG surface grating couplers

Apodized grating



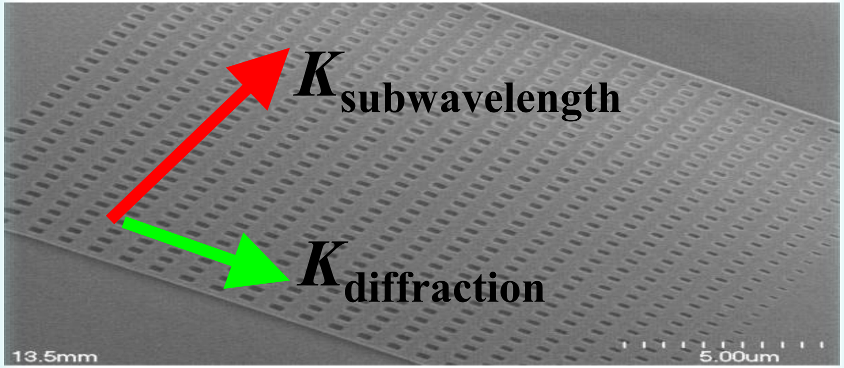


- Diffractive grating along longitudinal direction
- Non-diffractive SWG along transverse direction emulates shallow etch / apodization
- Surface grating strength can be defined and continuously varied across chip
- Apodization in one lithography / etch ste along with waveguide.

R. Halir et al., Opt. Lett., 34, 1408, 2009
X. Chen et al., IEEE Photon. J. 1, 184, 2009
R. Halir et al., Opt. Lett., 35, 3243, 2010

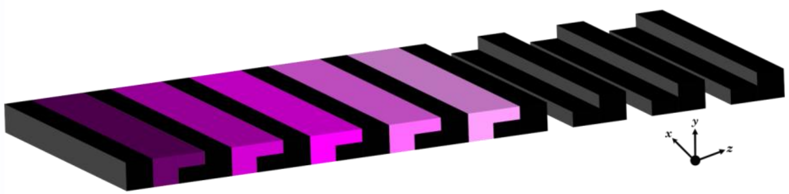
High-efficiency grating couplers

E-beam



D. Benedikovic *et al.*, Opt. Expr. 23 (2015)

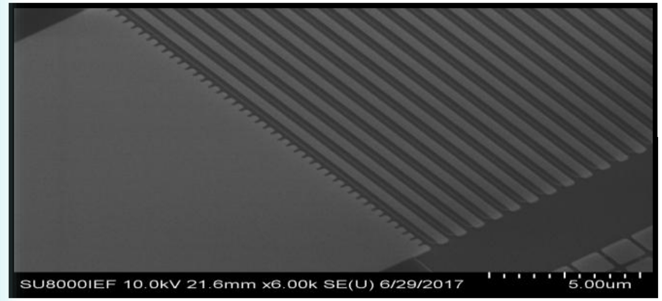
-0.7 dB (experiment)



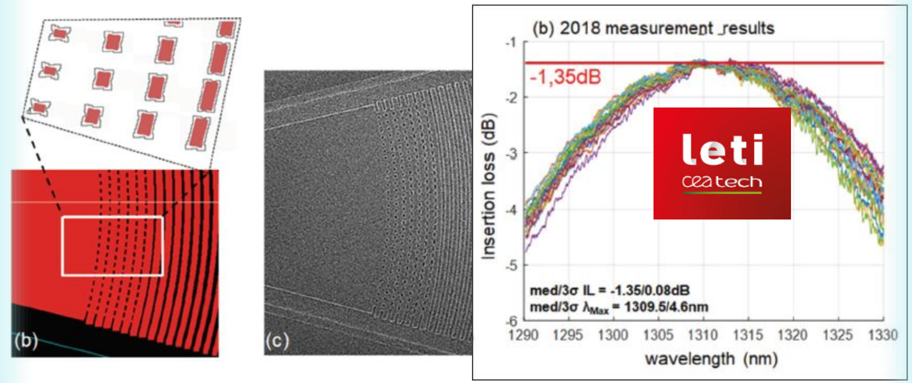
D. Benedikovic *et al.*, Opt. Expr. 2019

-0.25 dB (3D FDTD)

Deep-uv



D. Benedikovic *et al.*, Opt. Letters 42 (2017)



D. Fowler *et al.*, CEA LETI (2018)

-1.35 dB (experiment)

Engineering waveguide anisotropy

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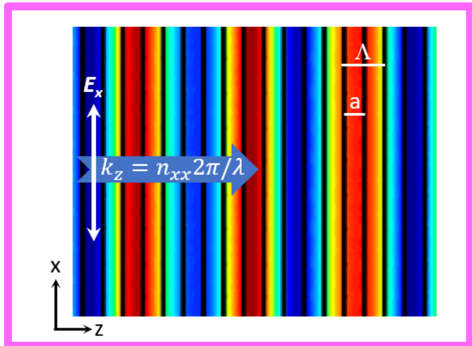
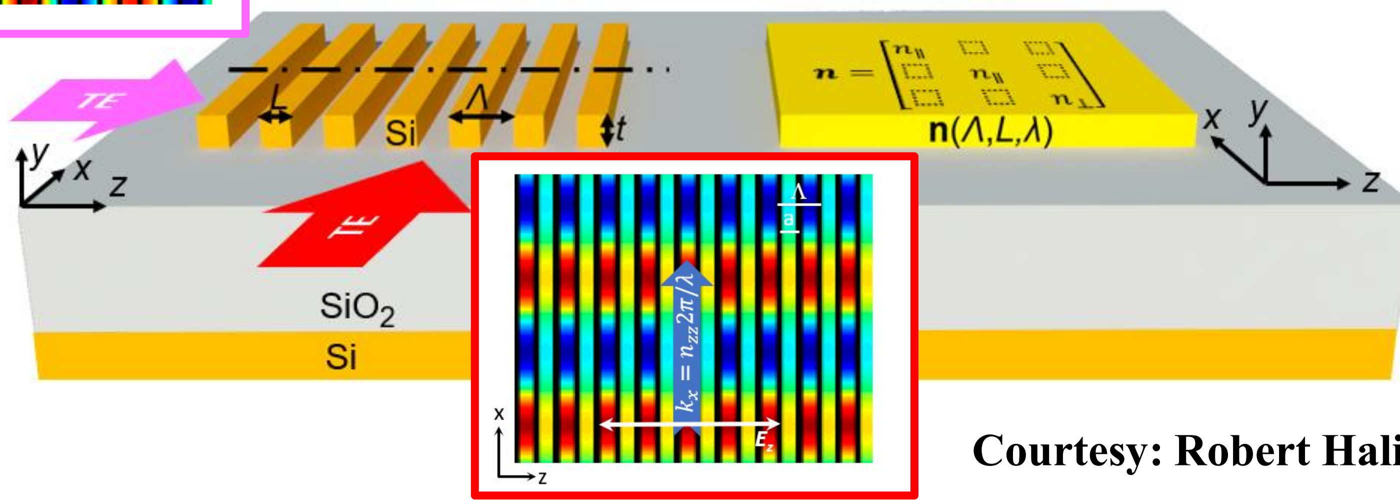


$$n_{\parallel}^2 \approx \frac{L}{\Lambda} n_{Si}^2 + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^2$$

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

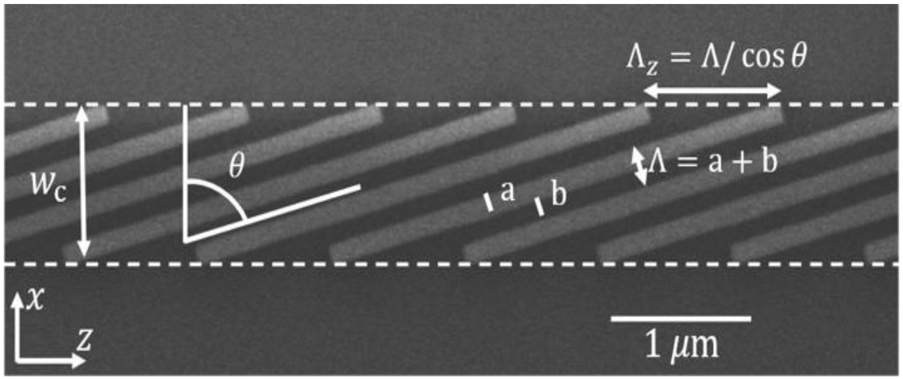


Courtesy: Robert Halir, UMalaga

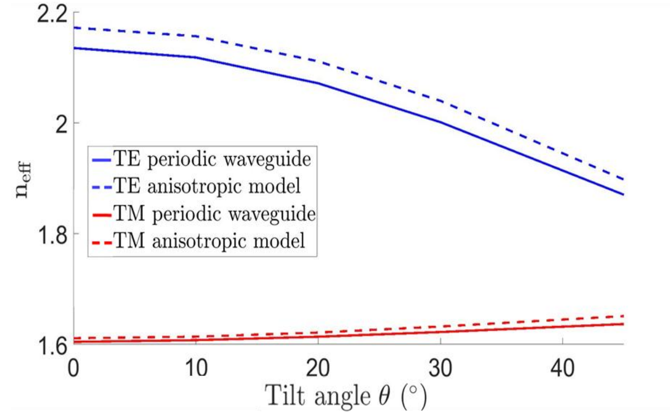
$$n_{\perp}^{-2} \approx \frac{L}{\Lambda} n_{Si}^{-2} + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^{-2}$$

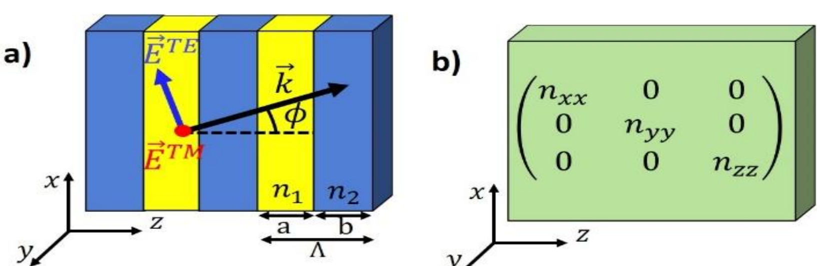
Luque-González et al., Optics Letters 43, 2018

Controlling anisotropy of Si-wires



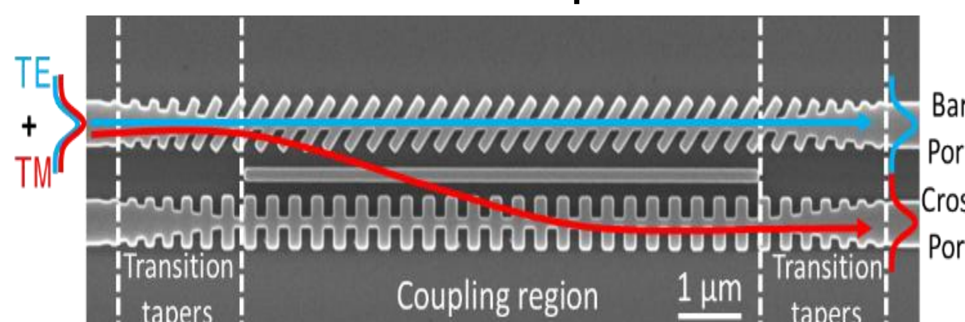
Tilted SWG waveguide. $w_c = 1\mu m$, $\Lambda = 0.25\mu m$, $DC = 0.5$, $\theta = 75°$. The SWG period $\Lambda_z = \Lambda/\cos(\theta)$.





J. M. Luque-González et al., Opt. Lett. vol. 43, 4691 (2018)

Polarization splitter



J. M. Luque-González *et al.*, Optics Letters (2020)

Ultra-broadband MMI coupler

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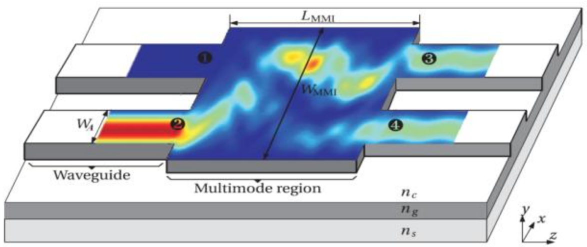
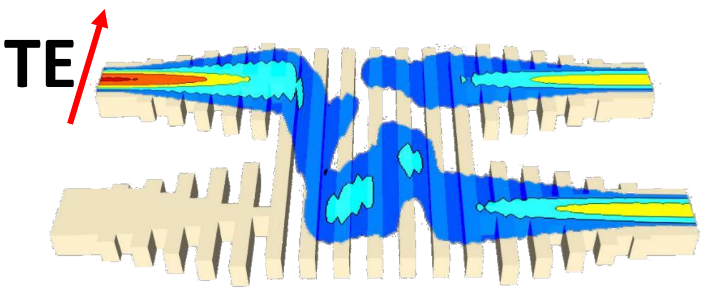


Talbot effect

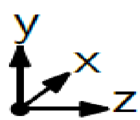
$$L_\pi = \frac{\lambda}{2(n_1 - n_2)} \approx \frac{4 n_c W^2}{3\lambda}$$

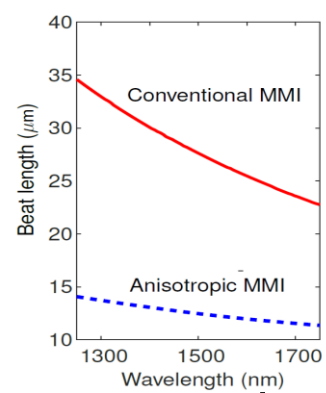
Uniaxial crystal

$$n_{core} = \begin{pmatrix} n_{xx} & 0 \\ 0 & n_{zz} \end{pmatrix}$$



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





William Henry Fox Talbot, 1800 – 1877, an English scientist and photography pioneer.

R. Halir, et al., Laser Photonics Rev., vol. 10, 1039 (2016)

500 nm design bandwidth exceeding all optical communication bands combined

Ultra-broadband MMI (experiment)

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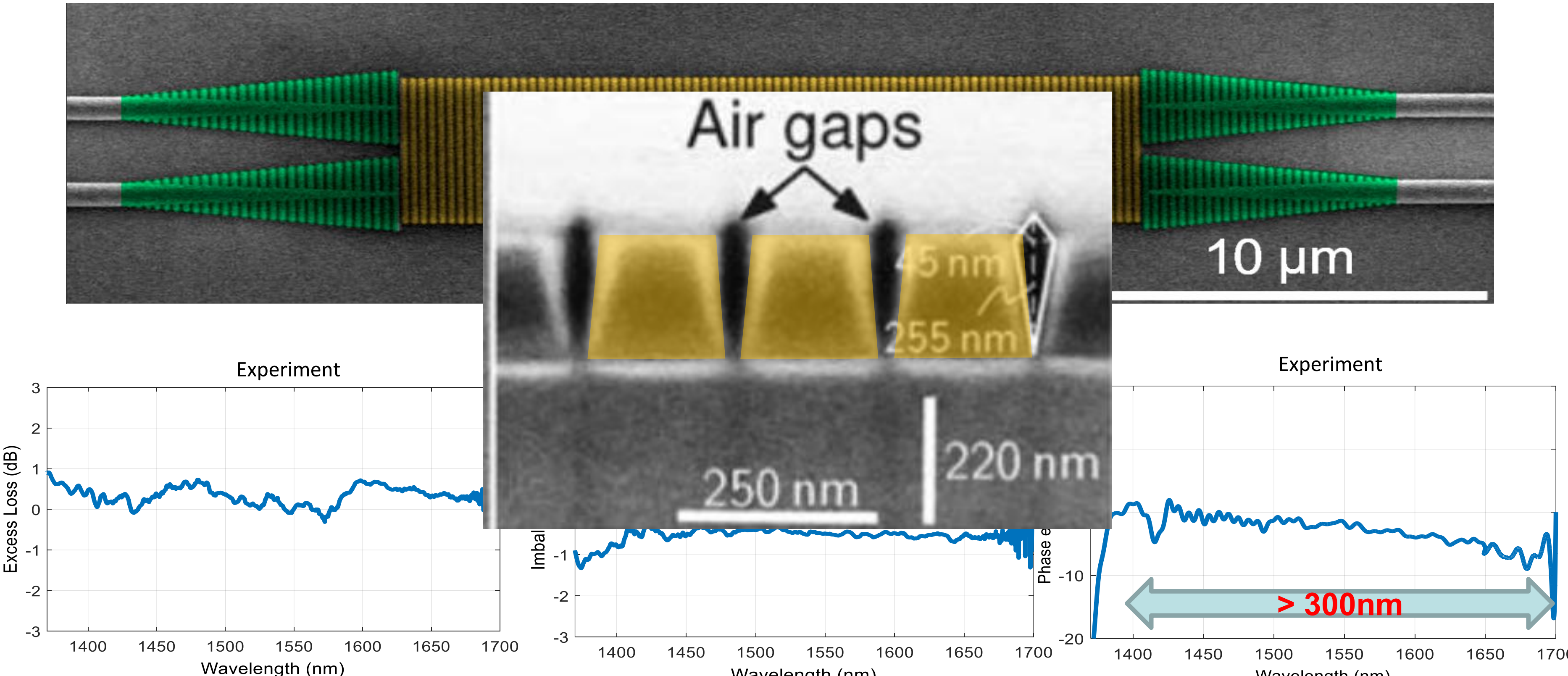
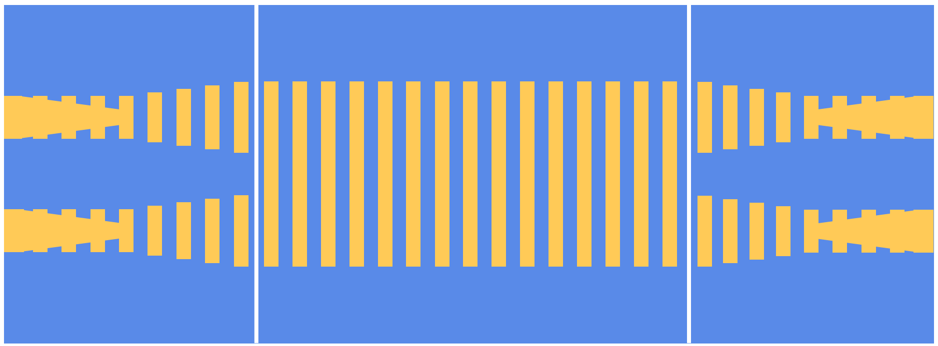


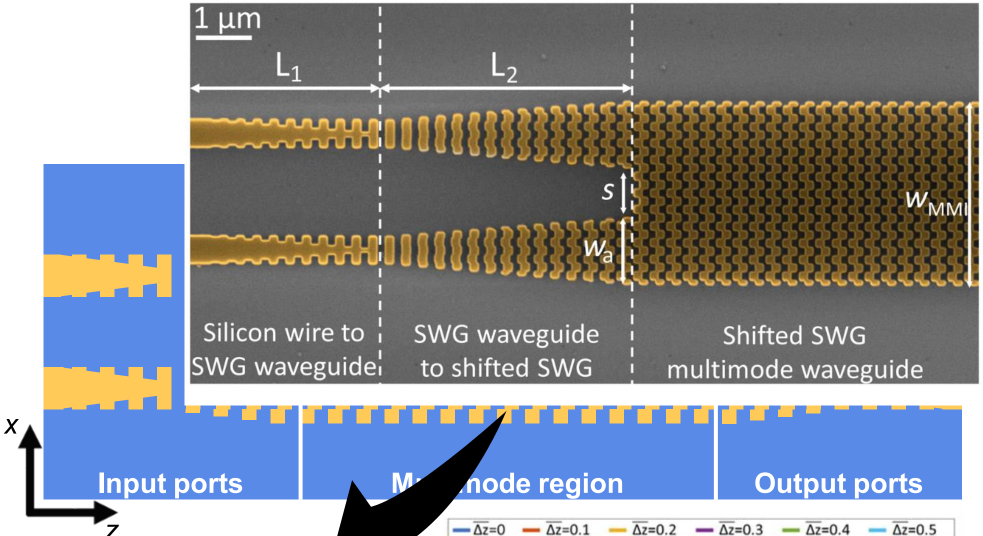
Over 300 nm bandwidth

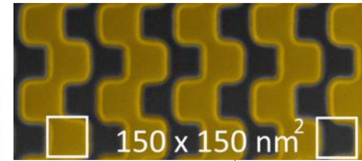
R. Halir, et al, Laser Photonics Rev., vol. 10, 1039 (2016)

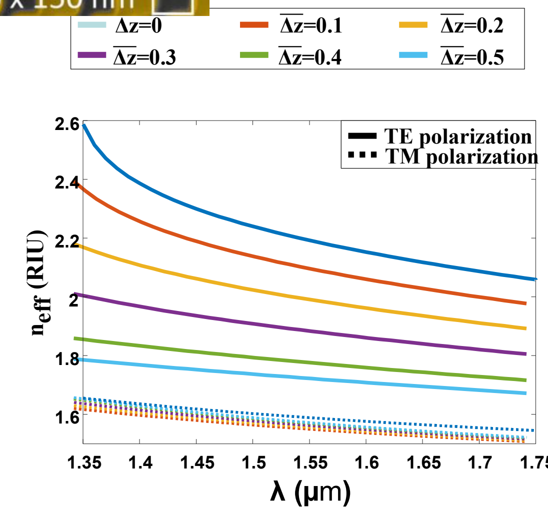
Ultra-broadband MMI – Uniaxial SWG



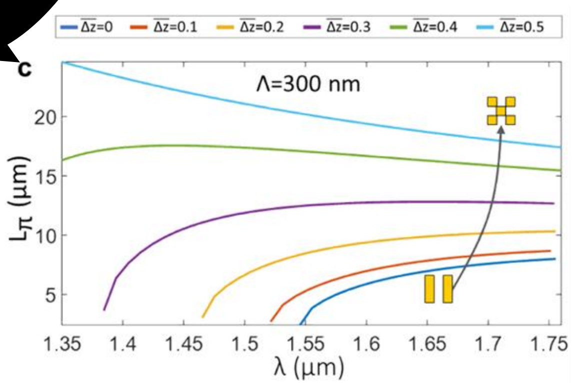
Ultra-broadband MMI - Biaxial SWG

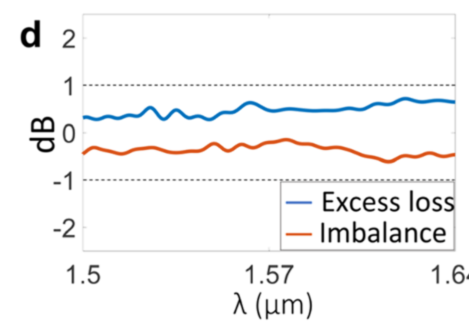






$$\begin{bmatrix} n_{xx}^2 & 0 & 0 \\ 0 & n_{yy}^2 & 0 \\ 0 & 0 & n_{zz}^2 \end{bmatrix}$$

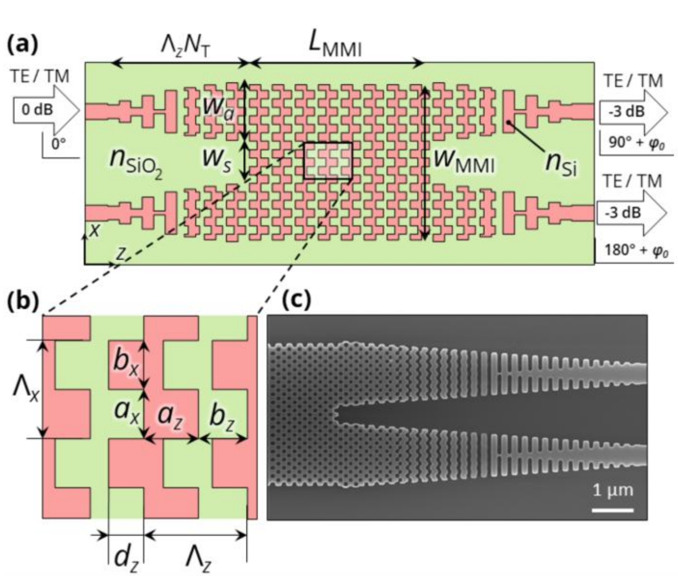


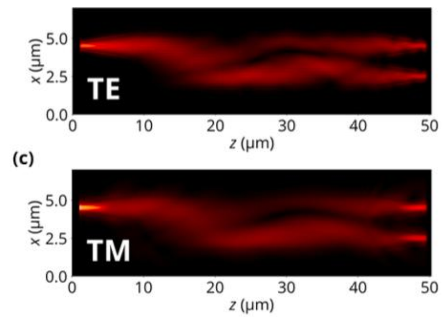


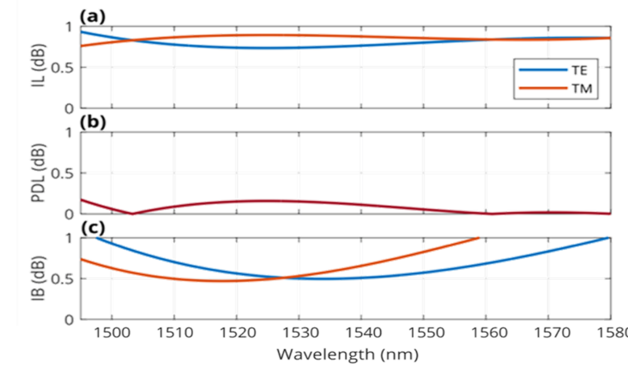
$$L_{\mathrm{mmi}} \propto \frac{W^2}{\lambda}\frac{n_{zz}^2(\lambda)}{n_{xx}(\lambda)}$$

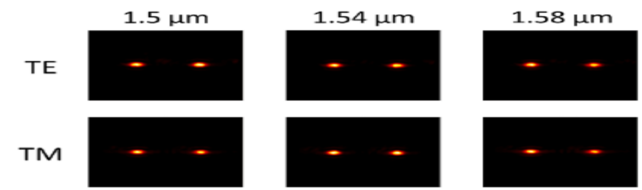
J.M.Luque-González et al., *Laser & Photonics Rev.* 2021, 15, 2000478

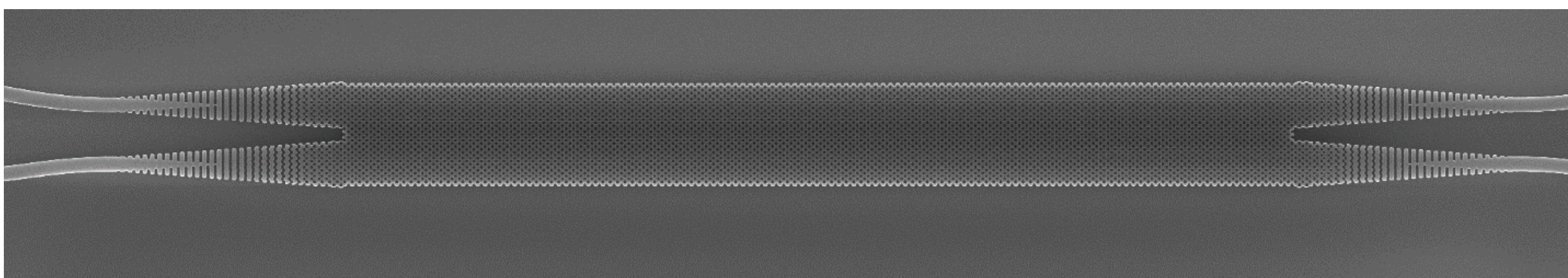
Polarization independent MMI











C. Pérez-Armenta, et al., "Polarization insensitive metamaterial engineered multimode interference coupler in a 220 nm silicon-on-insulator platform" 2023

Graded index metamaterial Expanding the beam

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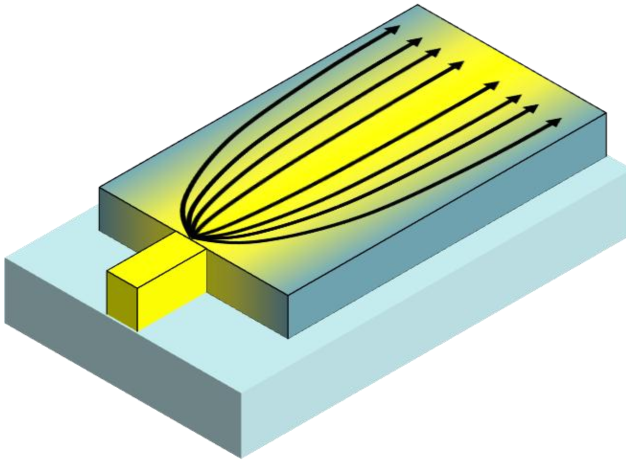
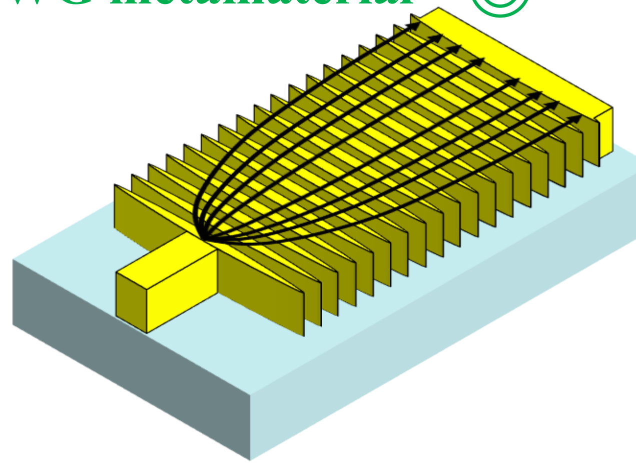
GRIN lens
Beam collimator ☹



SWG metamaterial ☺



An Ultracompact GRIN-Lens-Based Spot Size Converter using Subwavelength Grating Metamaterials

José Manuel Luque-González, Robert Halir, Juan Gonzalo Wangüemert-Pérez, José de-Oliva-Rubio, Jens H. Schmid, Pavel Cheben, Íñigo Molina-Fernández, and Alejandro Ortega-Moñux*

Beam expansion 0.5 µm → 15 µm in 14 µm

< 0.6 dB losses

Same losses & BW as 150 µm long taper

Courtesy - Prof. Inigo Molina Fernandez

Bragg deflector   Ultra-compact beam expansion

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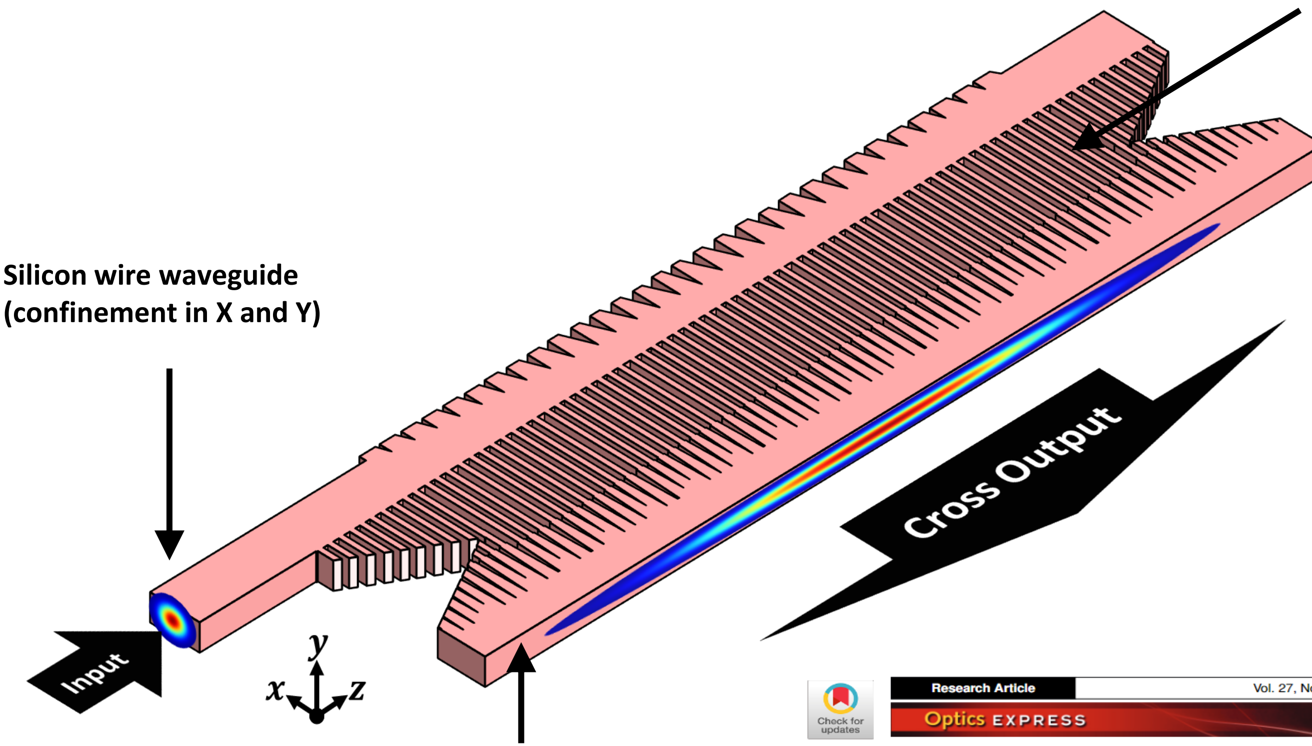


Research Article Vol. 27, No. 23 / 11 November 2019 / Optics Express 33180
Optics EXPRESS

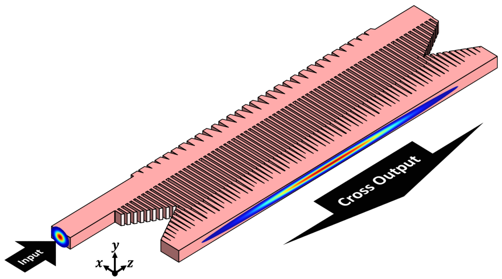
Distributed Bragg deflector coupler for on-chip shaping of optical beams

ABDELFETTAH HADIJ-ELHOUATI,[1,*] PAVEL CHEBEN,[3] ALEJANDRO ORTEGA-MOÑUX,[1] J. GONZALO WANGÜEMERT-PÉREZ,[1] ROBERT HALIR,[1,2] JENS H. SCHMID,[3] AND ÍÑIGO MOLINA-FERNÁNDEZ[1,2]

Courtesy - Prof. Inigo Molina Fernandez

Bragg deflector

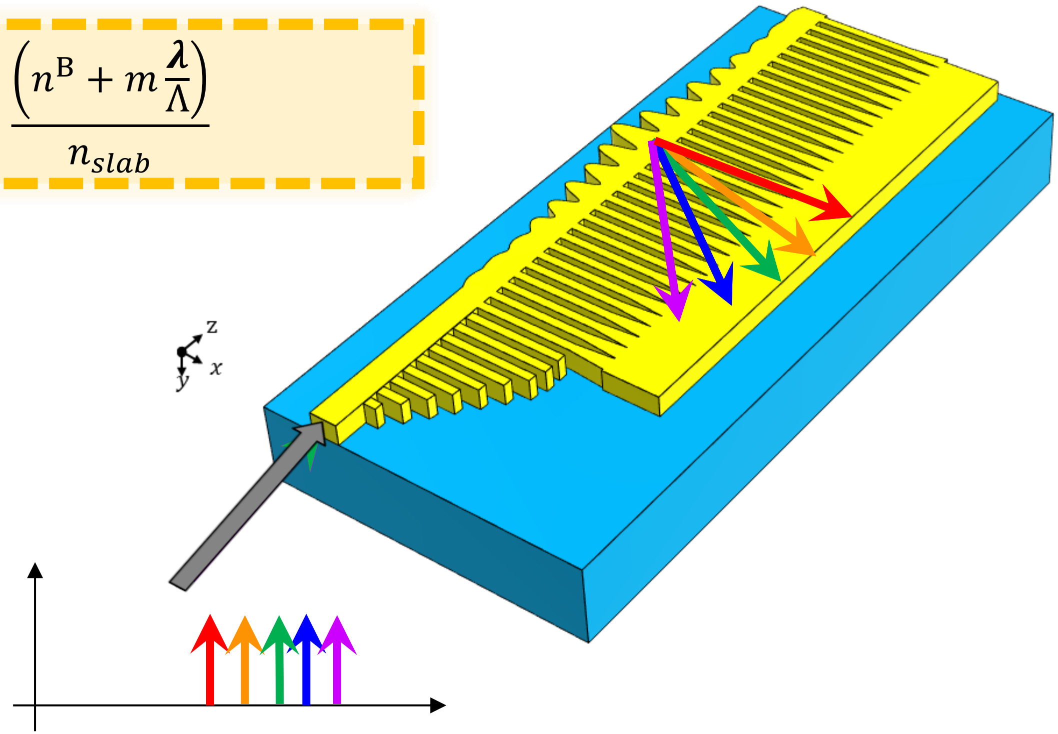
Ultra-compact beam expansion



Courtesy - Prof. Inigo Molina Fernandez

Wavelength steering

$$\sin(\boldsymbol{\theta}) = \frac{\left(n^{\mathrm{B}} + m\frac{\boldsymbol{\lambda}}{\Lambda}\right)}{n_{slab}}$$



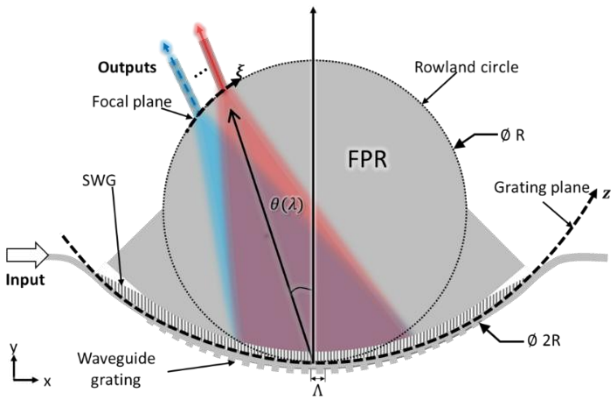
Courtesy - Prof. Inigo Molina Fernandez

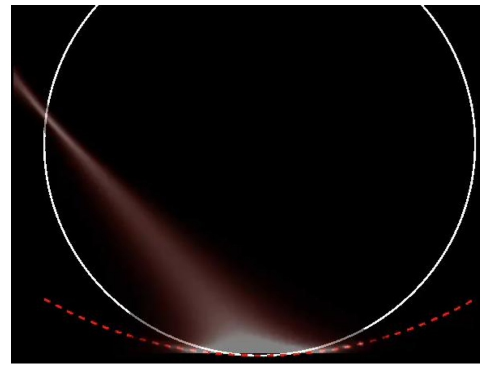
Low-loss wavelength demultiplexer

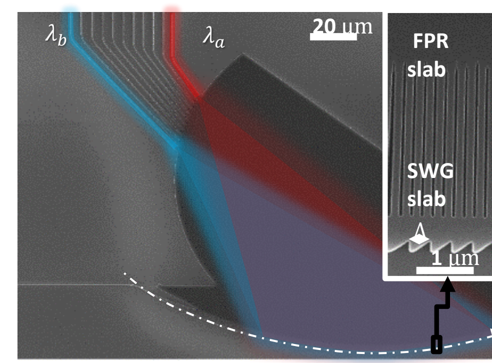
A.H. Elhouati, Opt. Lett. 46, 2409-2412 (2021)

TOP DOWNLOADS

EDITORS' PICK







Insertion Loss 1.1 dB
Crosstalk < -25 dB

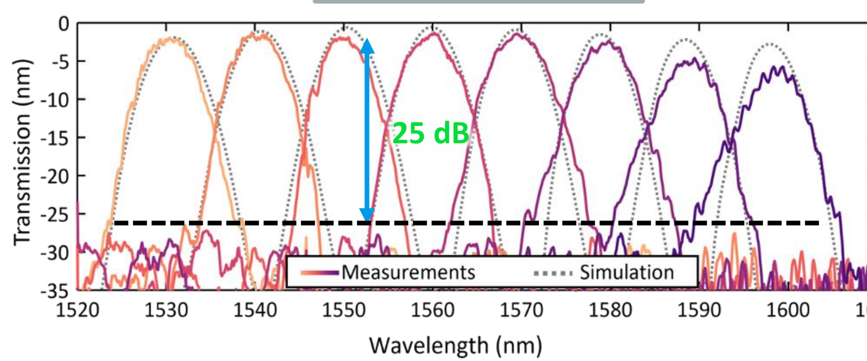
Letter

Vol. 46, No. 19 / 1 October 2021 / Optics Letters 4821

Optics Letters

Low-loss off-axis curved waveguide grating demultiplexer

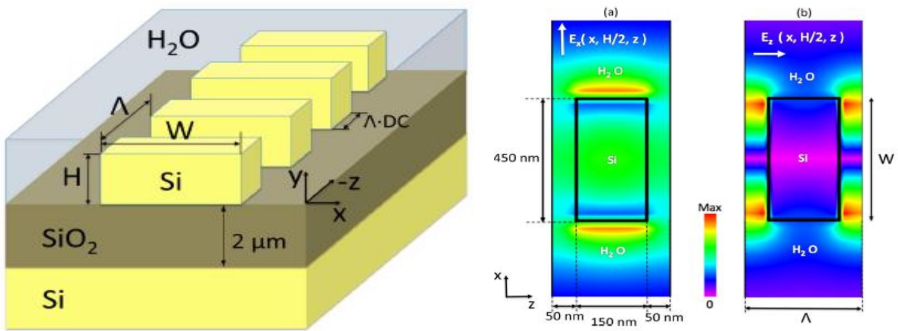
Abdelfettah Hadij-ElHouati,[1,*] Alejandro Ortega-Moñux,[1] J. Gonzalo Wangüemert-Pérez,[1] Robert Halir,[1] Shurui Wang,[2] Jens H. Schmid,[2] Pavel Cheben,[2] and I. Molina-Fernández[1]

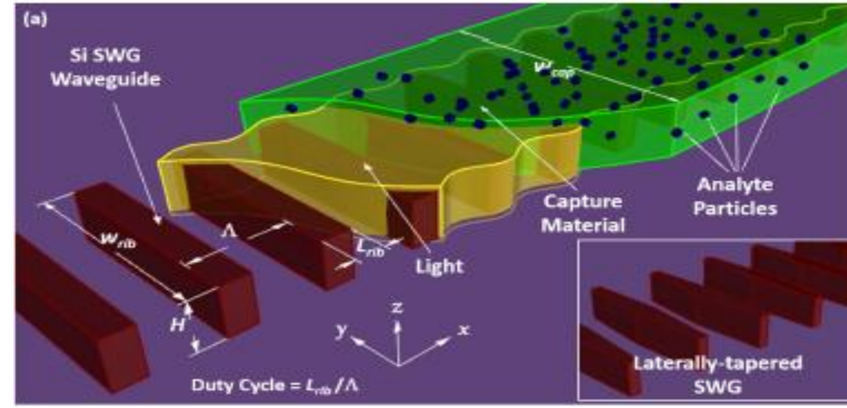


Courtesy - Prof. Inigo Molina Fernandez

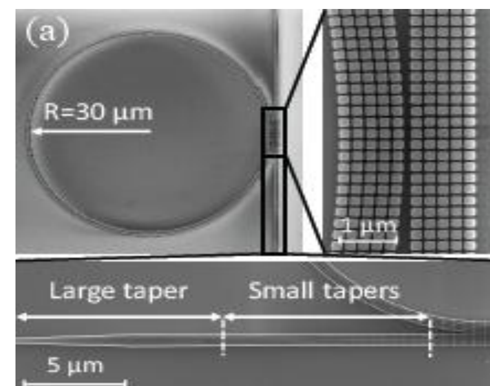
SWG waveguides for biochemical sensing

G. Wangüemert-Pérez *et al.*,
Opt. Lett. 39, 4442 (2014)





US Army Research Lab
J. Bickford *et al.*, JSTQE vol. 25, no. 3 (2019)

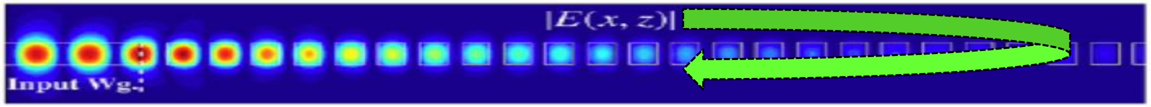


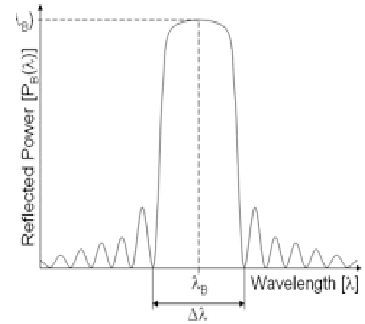
Univ. of British Columbia and Washington Univ.
J. Flueckiger *et al.*, Optics Express (2015)

Gaps allow increased interaction of analyte molecules with the waveguide mode

Waveguide Bragg gratings

$$\lambda_{Bragg} = 2\, n_{eff}\, \Lambda$$

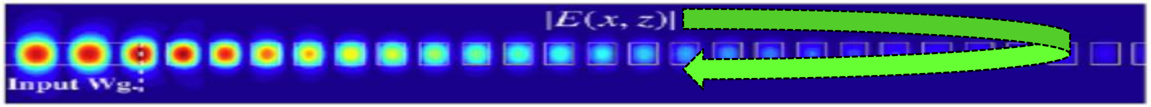


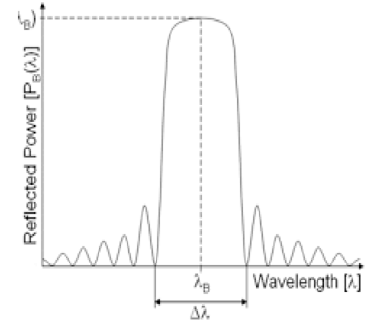


$$\Delta\lambda = \frac{\lambda_0^2}{\pi n_g}\sqrt{k^2 + \left(\frac{\pi}{L_F}\right)^2}$$

Waveguide Bragg gratings

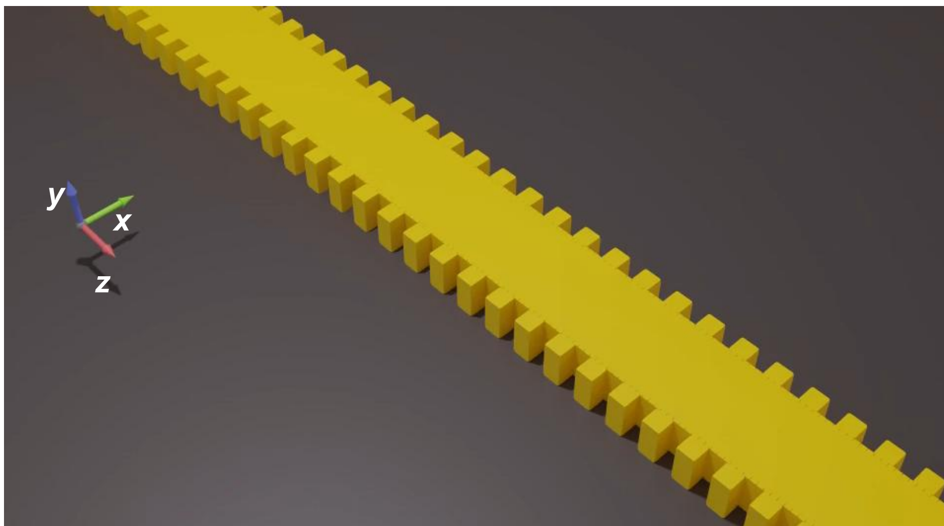
$\Lambda_B = \lambda_{eff} / 2$





$$\Delta\lambda = \frac{\lambda_0^2}{\pi n_g}\sqrt{k^2 + \left(\frac{\pi}{L_F}\right)^2}$$

- In silicon waveguides, high Δn makes it difficult to accurately control the grating strength and achieve narrow spectral bandwidths.



- SWG engineering can be used to control the bandwidth

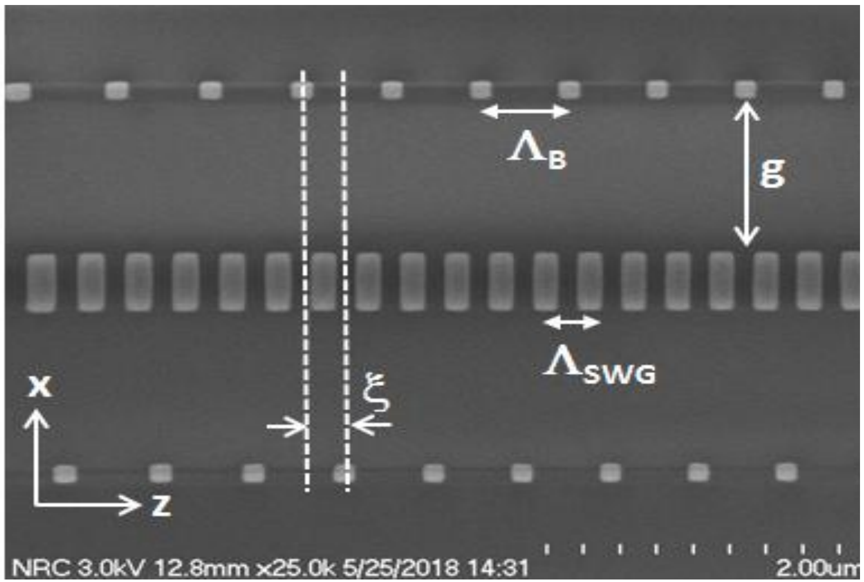
$$k \propto \int |E|^2 \cdot \Delta\varepsilon(x, y, z)\, dV$$

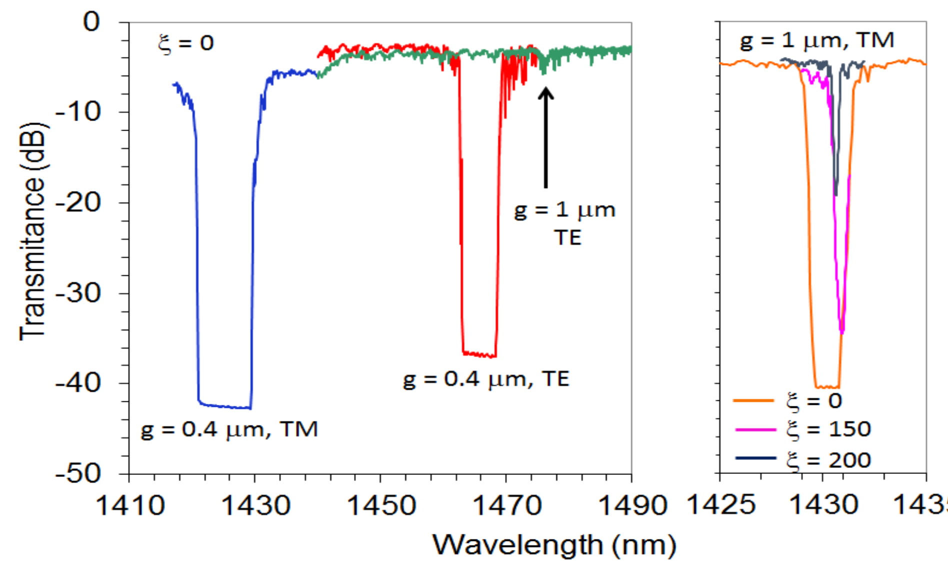
J. Wang et al., Opt. Express 22, 5335 (2014)

D. Oser et al., Opt. Lett. 43, 3208 (2018)

SWG Bragg filters

Grating strength controlled by adjusting the gap and the lateral shift

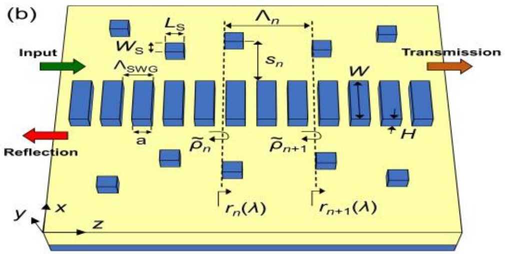


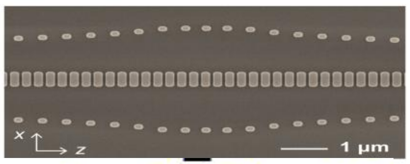


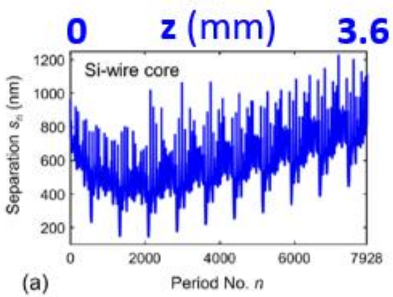
J. Ctyroky et al., Opt. Express 26 (2018)
P. Cheben et al., Optics Letters 44 (2019)

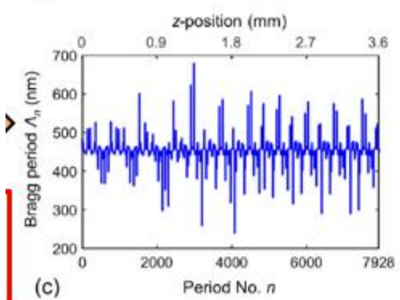
Filter bandwidth tuned from 8 nm to 150 pm

Complex spectral filters









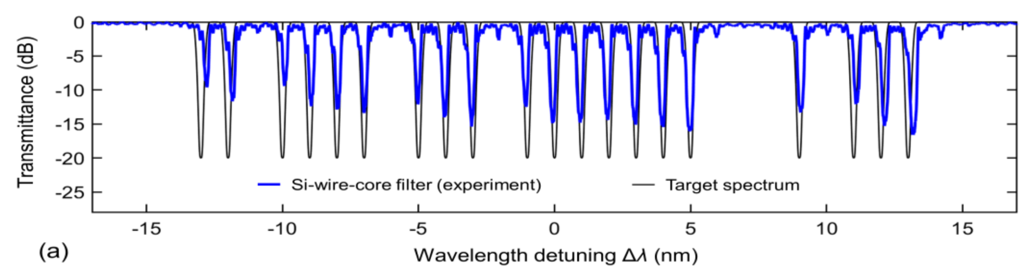
Research Article Vol. 29, No. 11 / 24 May 2021 / *Optics Express* 15867

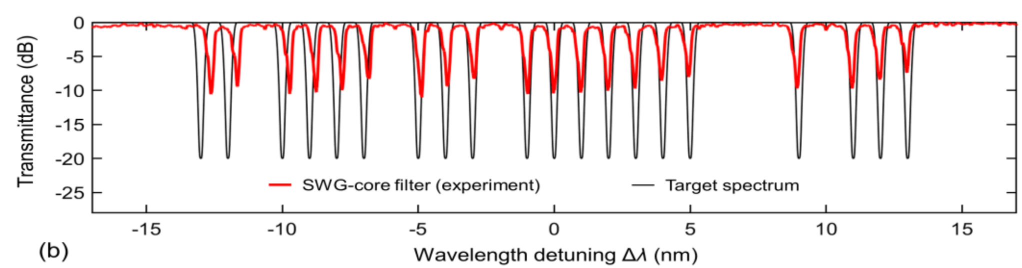
Optics EXPRESS

Complex spectral filters in silicon waveguides based on cladding-modulated Bragg gratings

DANIEL PEREIRA-MARTÍN,[1,*] JOSÉ MANUEL LUQUE-GONZÁLEZ,[1] J. GONZALO WANGÜEMERT-PÉREZ,[1] ABDELFETTAH HADIJ-ELHOUATI,[1] ÍÑIGO MOLINA-FERNÁNDEZ,[1] PAVEL CHEBEN,[2] JENS H. SCHMID,[2]

Layer peeling, J. Skaar et al., IEEE JQE 37 (2001)





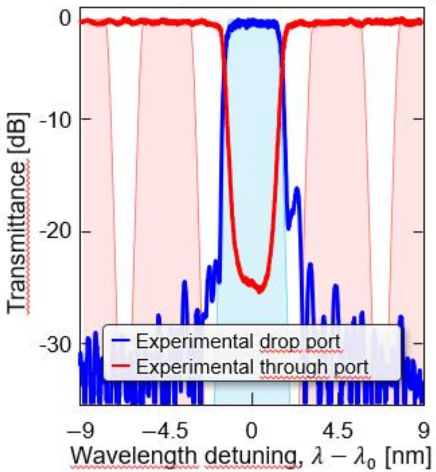
Add-drop filter for LAN-WDM

O-band, 1300 nm
Channel spacing 4.5 nm
3dB bandwidth 3 nm
Silicon nitride

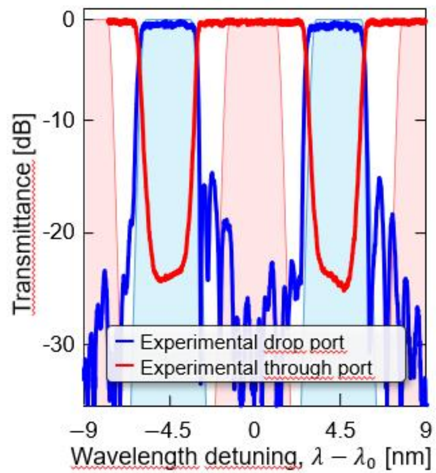
UNIVERSIDAD DE MÁLAGA

Experimental results

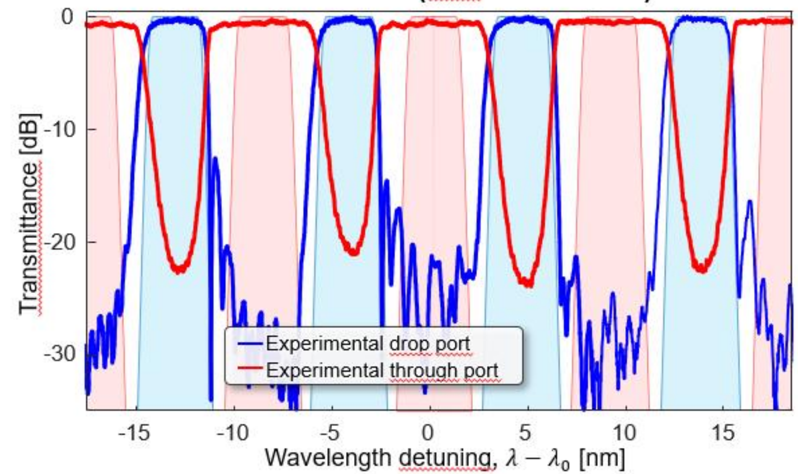
1-band (Wc = 1060 nm)

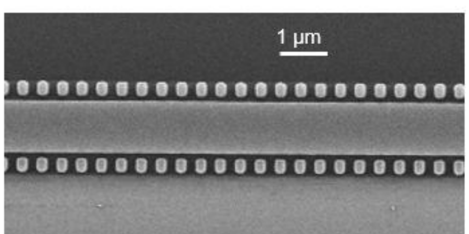


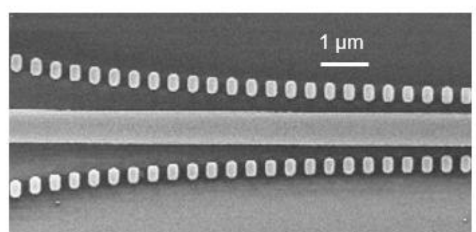
2-bands (Wc = 790 nm)

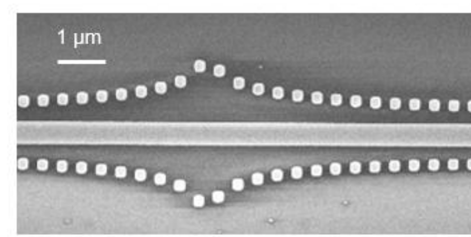


4-bands (Wc = 570 nm)



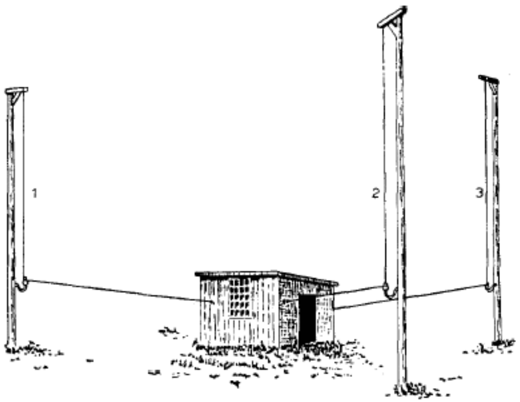




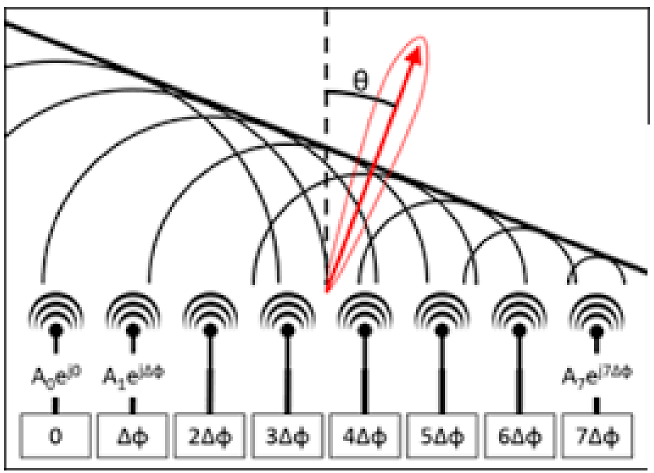


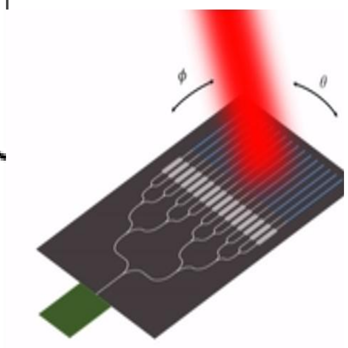
Courtesy: Prof. Alejandro Ortega Moñux, UMalaga

Optical Phased Arrays (OPAs)

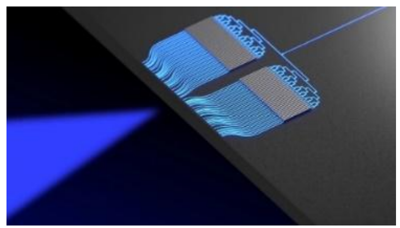


Phased array transmission was originally shown in 1905 by Nobel laureate Karl Ferdinand Braun who demonstrated enhanced transmission of radio waves in one direction.

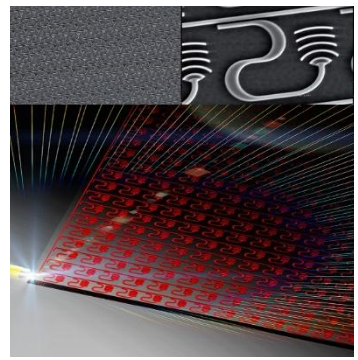




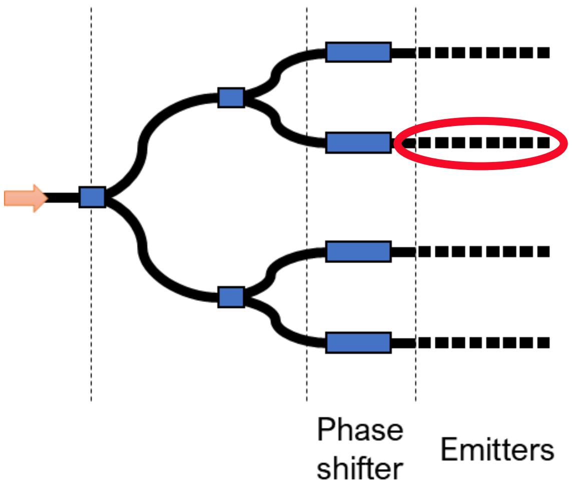
1D OPA

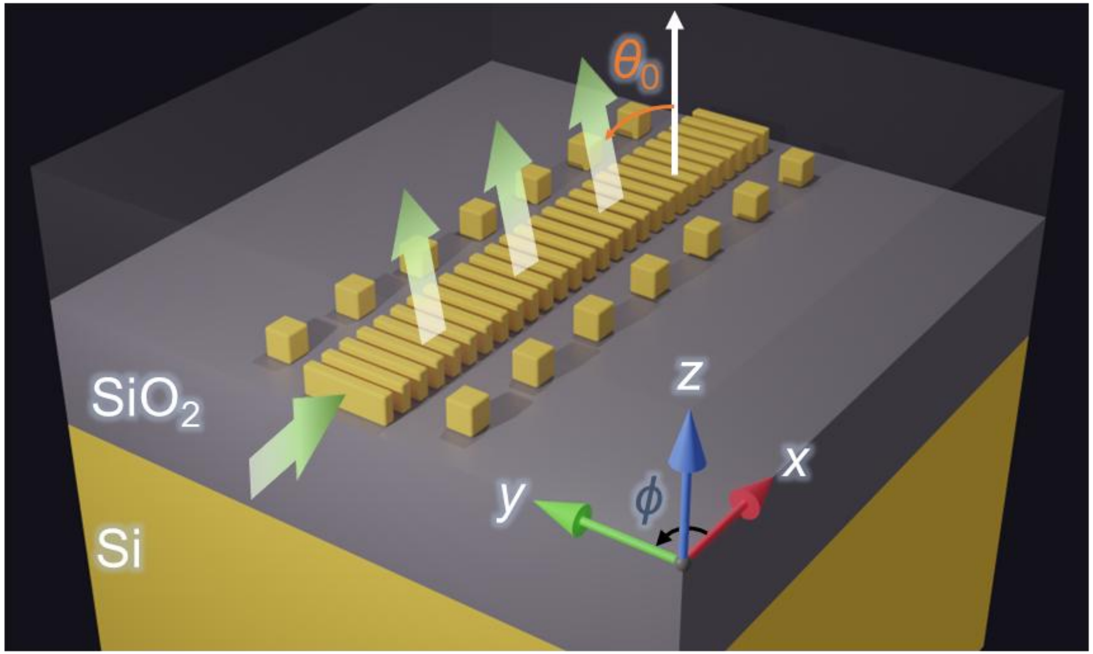


2D OPA



Long waveguide antennas for 1D OPAs





Long waveguide antennas for 1D OPAs

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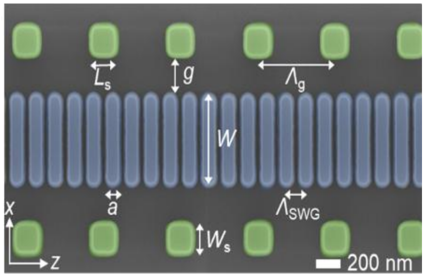
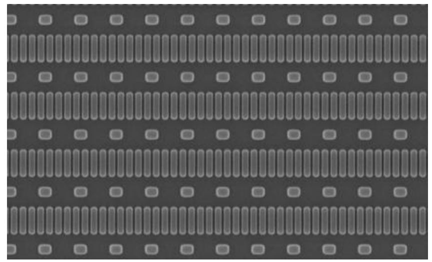
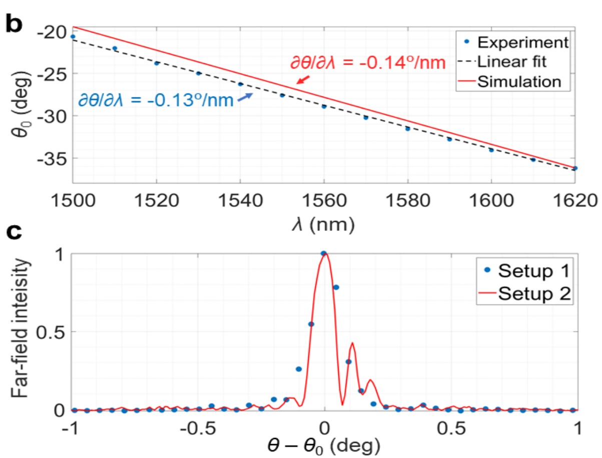
Experimental results







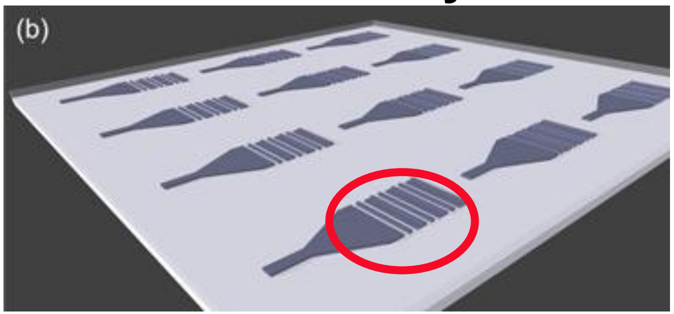
Technology	MFS [nm]	Beam width [deg]	∂θ/∂λ [deg/nm]	Ref.
SOI-220nm	80	0.10	0.15	Our work
SOI-220nm	8	0.08	0.26	[1]
SOI-220nm	7	0.15	0.15	[2]
SOI-220nm	7	0.18	0.19	[3]
SOI-500nm	238	0.58	0.14	[4]
Si-SiN	500	0.20	0.07	[5]
Si-SiN	315	0.07	0.17	[6]
Si-SiN	70	0.02	-	[7]

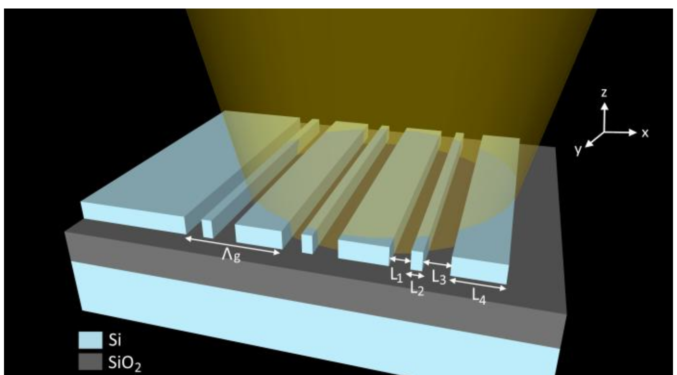
P. Ginel-Moreno et al., Opt. Lett., 2021

P. Ginel-Moreno, Laser Photon. Rev. 16, 2022

Compact grating couplers for 2D OPAs

M x N array





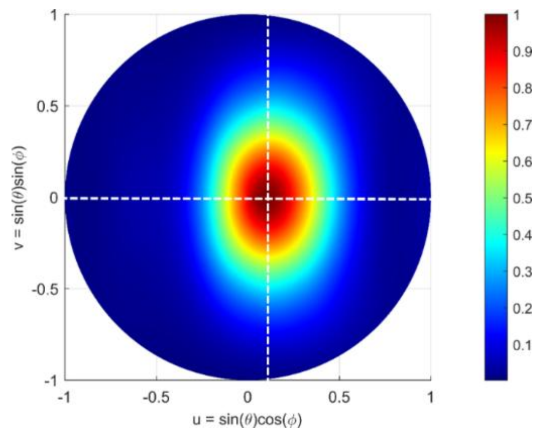
Angular width of far field inversely related to grating aperture size - Fraunhofer transformation.

Angular width determines the maximum steering range of OPA.

So we need short gratings for large steering range, 3-4 periods, but then the efficiency drops

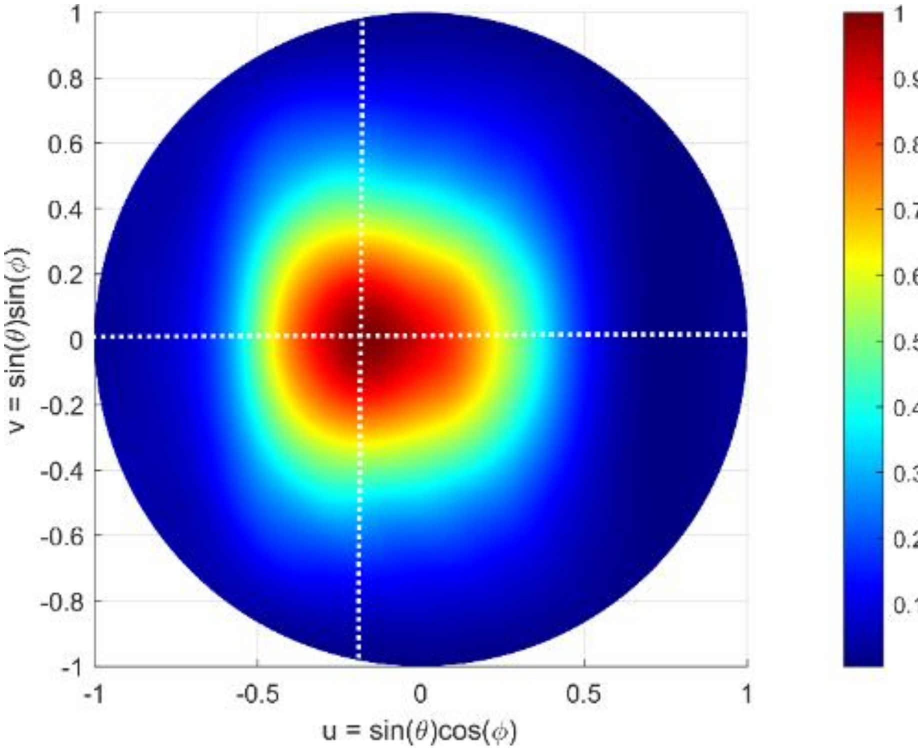
Can we broaden the far field without reducing aperture size? Beyond Fraunhofer limit?

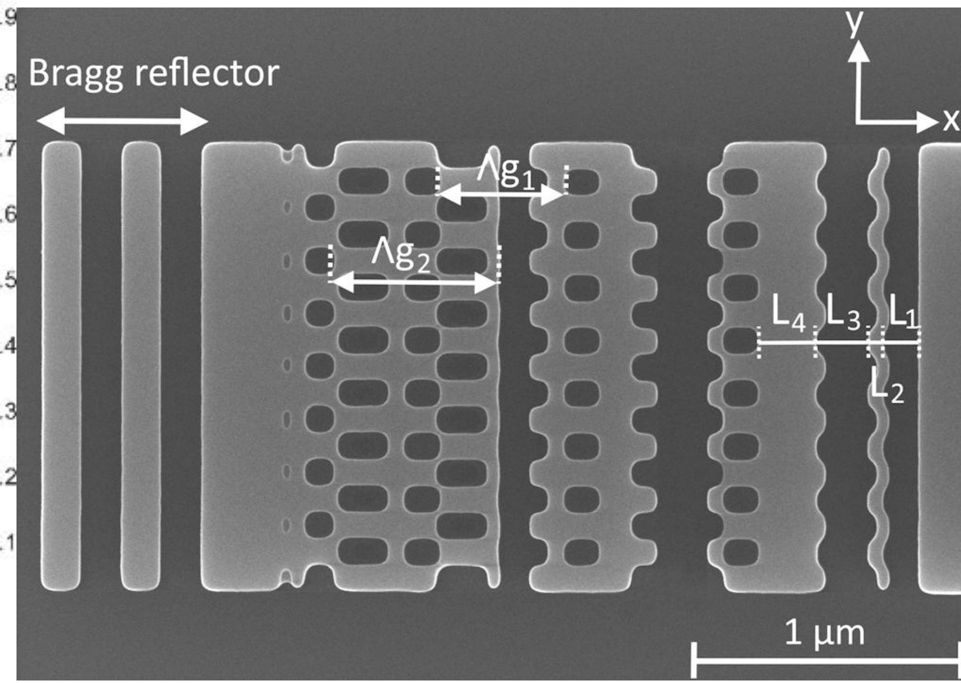
$$U(x,y,z) \propto \iint_A E(x',y')e^{-i\left(\frac{k(x'x+y'y)}{z}\right)}dx'dy'$$



Far field broadening

✓ Far-field beam width: **51°×47°**

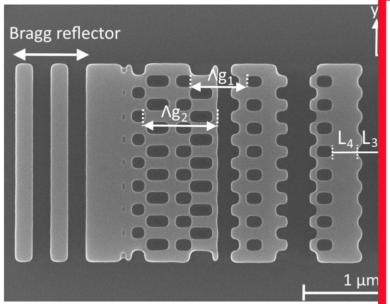


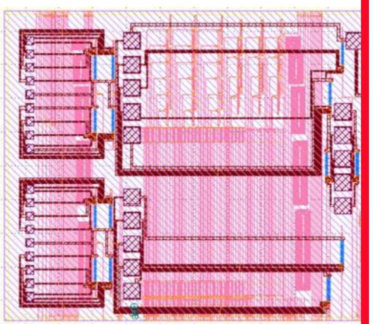


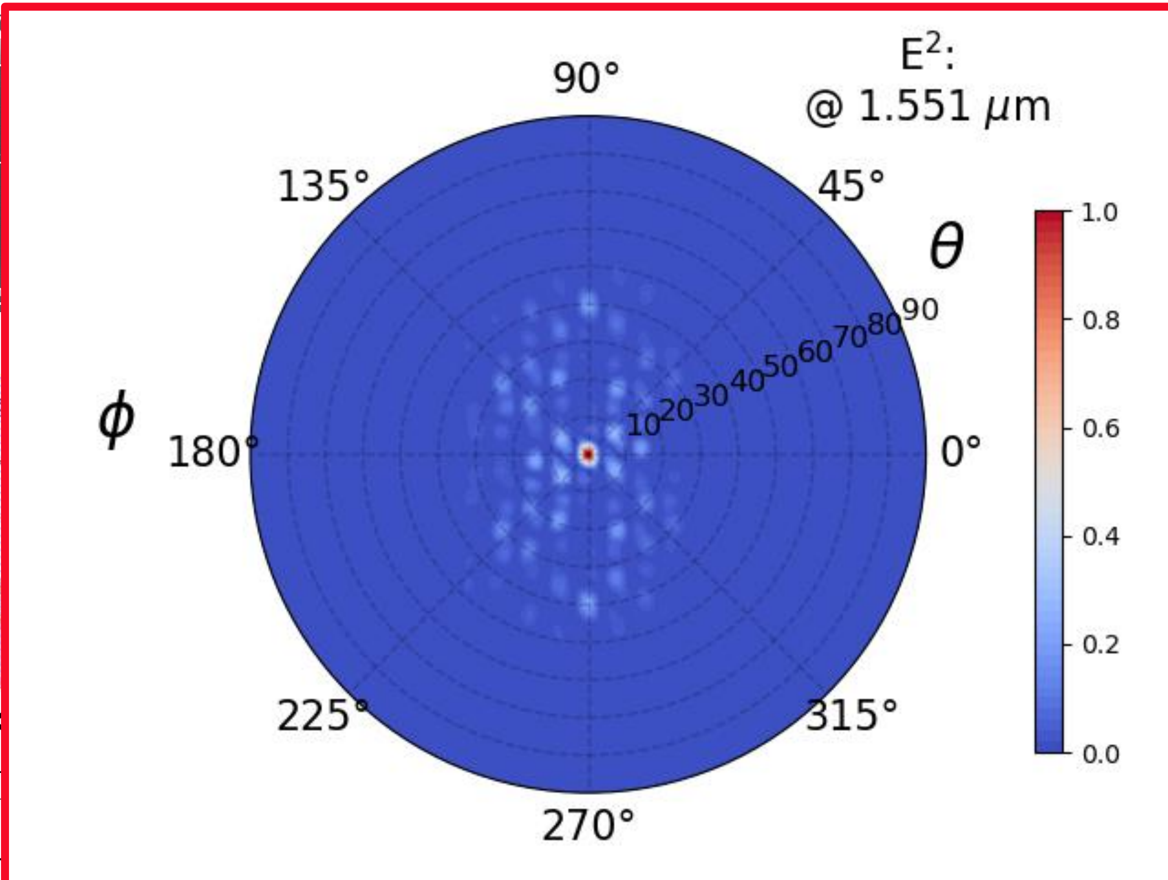
S. Khajavi *et al.*, "Highly efficient ultra-broad beam silicon nanophotonic antenna based on near-field phase engineering", *Sci. Rep.*, 12, 1–8, (2022).

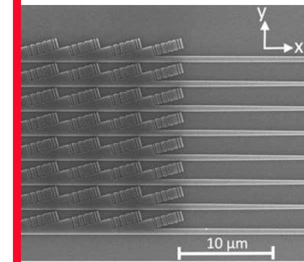
Larger scale array

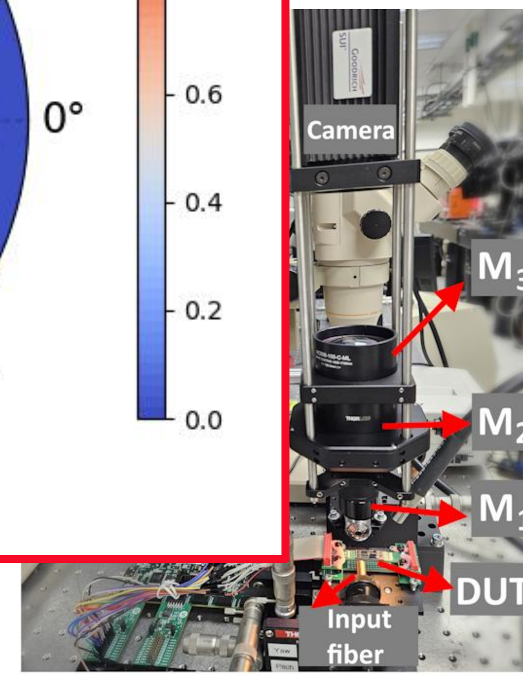
8×20 array









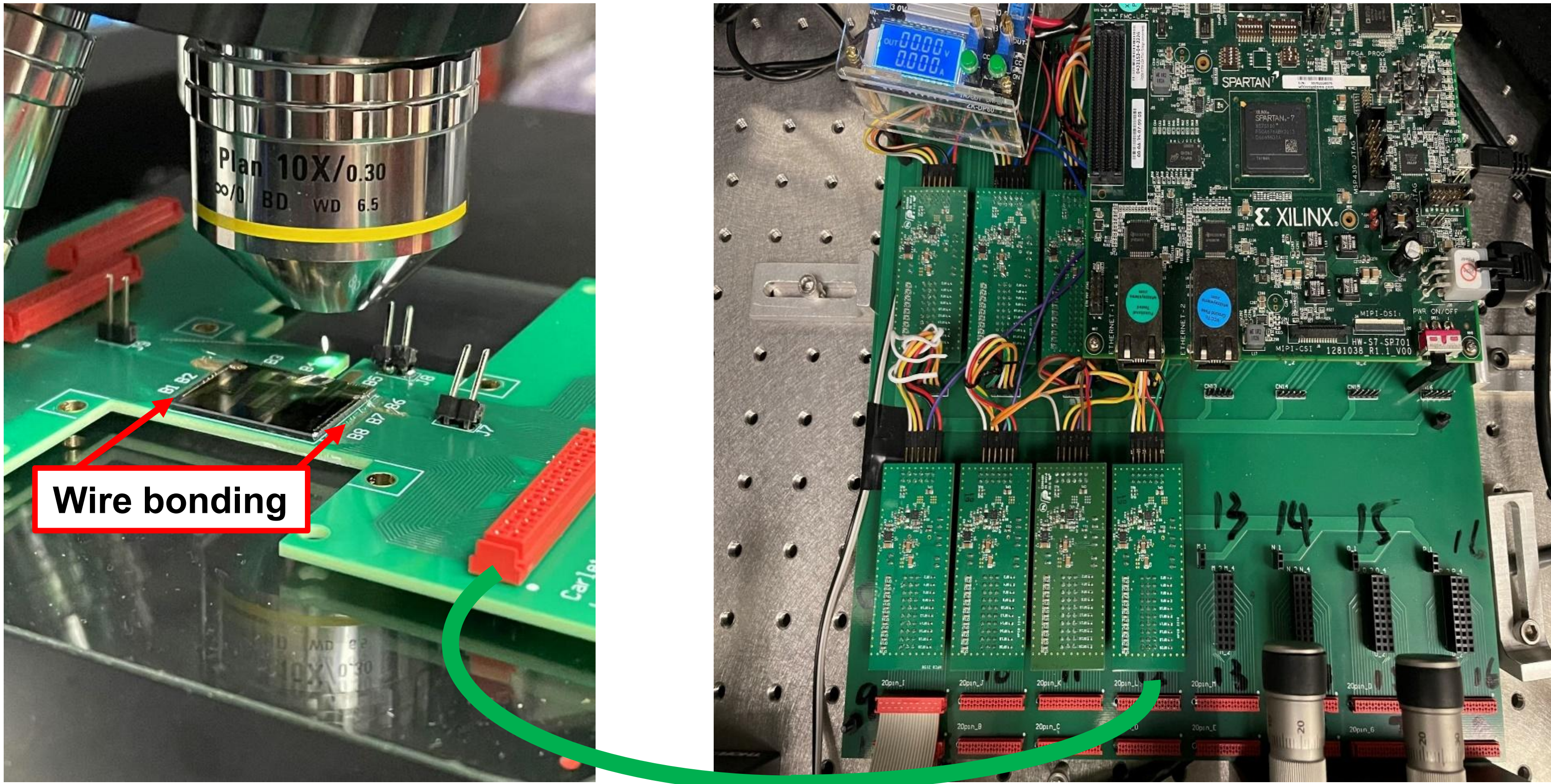


300-nm Si core, 21×

TO Phase shifters: T

S. Khajavi *et al.*, “E
nanophotonic antenna for far-field broadened optical phased arrays”, *Photonics Research, 2024.*

Hardware and control interface



Cable connection between PCB and FPGA

nature.com > nature > review articles > article

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Review Article | Published: 29 August 2018

Subwavelength integrated photonics

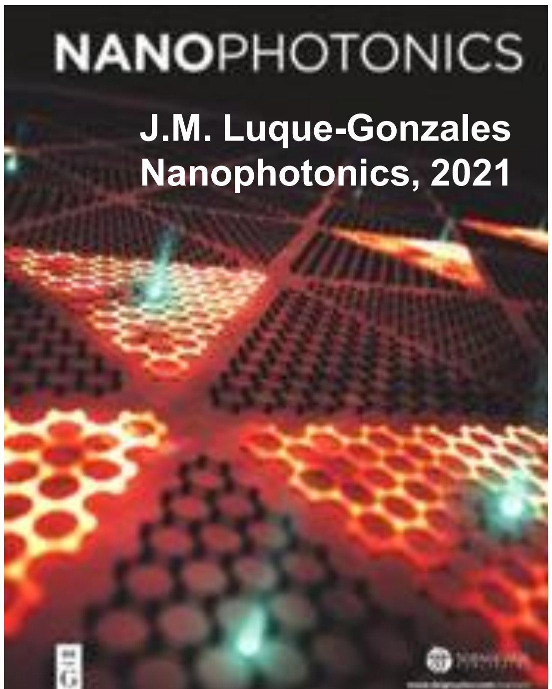
Pavel Cheben, Robert Halir, Jens H. Schmid, Harry A. Atwater & David R. Smith

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

Proceedings OF THE IEEE

Subwavelength-Grating Metamaterial Structures for Silicon Photonic Devices

By Robert Halir, Alejandro Ortega-Moñux, Daniel Benedikovic, Goran Z. Mashanovich, J. Gonzalo Wangüemert-Pérez, Jens H. Schmid, Íñigo Molina-Fernández, and Pavel Cheben



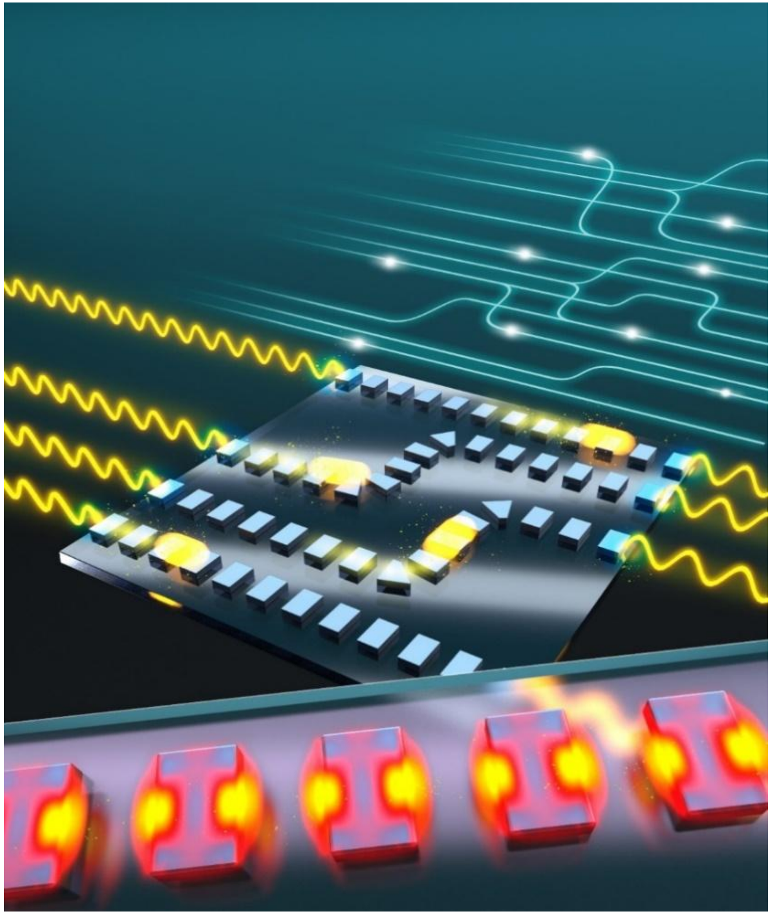
Review | Vol. 15, No. 4 / December 2023 / *Advances in Optics and Photonics* 1033

Advances in Optics and Photonics

Recent advances in metamaterial integrated photonics

Pavel Cheben,[1,*] Jens H. Schmid,[1] Robert Halir,[2] José Manuel Luque-González,[2] J. Gonzalo Wangüemert-Pérez,[2] Daniele Melati,[3] and Carlos Alonso-Ramos[3]

P. Cheben *et al.,* Nature 560, p. 565, 2018
R. Halir *et al.*, Proceedings of the IEEE, 2018
J.M. Luque-Gonzales, Nanophotonics, 2021
P. Cheben et al., Advances in Optics and Photonics, 2023
https://doi.org/10.1364/AOP.495828



Děkuji

This was work supported by: National Research Council of Canada; the Slovak Grant Agency VEGA 1/0113/22 and Slovak Research and Development Agency project APVV-21-0217; University of Malaga; Ministerio de Ciencia e Innovación (TED2021-130400B-I00, PID2022-139540OBI00); European Union Next Generation EU/PRTR; European Union through the European Research Council (ERC) project BEAMS (101041131); University of Paris-Saclay; CNRS France; University of Ottawa.