2572-15

Winter College on Optics: Fundamentals of Photonics - Theory, Devices and Applications

10 - 21 February 2014

Subwavelength silicon photonics

Pavel Cheben
National Research Council of Canada

National Research Council Canada | Conseil national de recherches Canada

Subwavelength silicon photonics

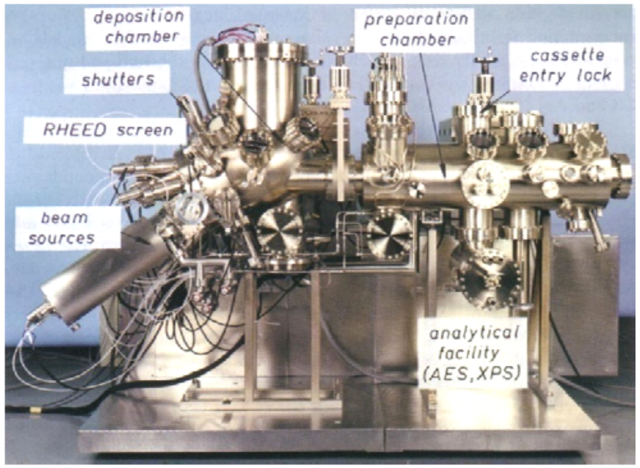
Pavel Cheben, National Research Council of Canada




National Research Council
Information and Communication Technologies

- Federal government agency
- 4,500 full-time employees

Epitaxy (MBE, CBE, MOCVD: InP, GaAs, GaN, GaSb)
Nanofabrication (III-V, Si, organics)
Surfaces and Interfaces (Physical analysis)
Optoelectronic Devices
Organic Materials and Devices (Electronics, LED)
Quantum Physics and Devices (QD, QW, Q-computing)
Thin Films (optical filters, omni-directional coatings)
Canadian Photonics Fabrication Center (CPFC)



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Outline

- ❑ Subwavelength optics and silicon photonics: background
- ❑ Subwavelength structures in integrated optics
  - Antireflective structures and mirrors
  - Waveguide lenses
  - Subwavelength grating waveguides
  - Waveguide crossings
  - Fiber-chip couplers
  - Athermal waveguides
  - Multimode interference couplers
  - Directional couplers
  - Polarization rotators
  - Wavelength multiplexers

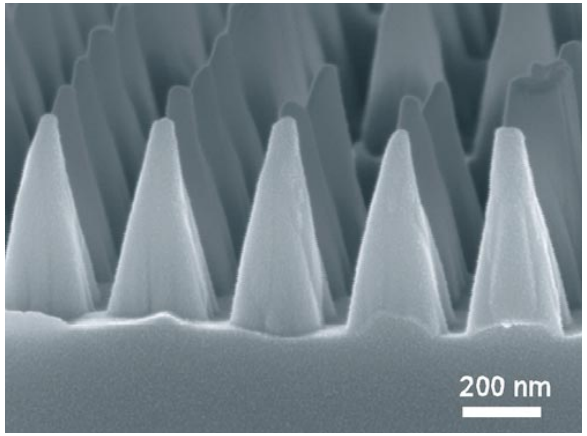
Subwavelength structures

Diffraction effects are suppressed for waves propagating in structures with a periodicity smaller than one half of the wavelength

The principle has long been known: H. Hertz, the late 19th century, a fine grid of parallel metal wires used as a polarizer

Rayleigh, Phil. Mag. (5), **34,** 481, 1892: array of parallel cylinders; “form birefringence”

First observed at optical wavelengths by Bernhard in 1967. Reflection from the corneas of night-flying moths is reduced to protect them from nocturnal predators (C. G. Bernhard, 1967, Endeavour 26, 79, 1967).



Birefringence optics, polarizers , antireflection surfaces, narrow-band filters …

Birefringence optics, polarizers

P. Yeh, Opt. Commun. 26, 289–292 (1978)

Graham, Moharan et al., J. Opt. Soc. Am. A, Vol. 11, 2695, 1994

Antireflection surfaces

S. J. Wilson and M. C. Hutley, Opt. Acta 29, 993–1009, 1982.

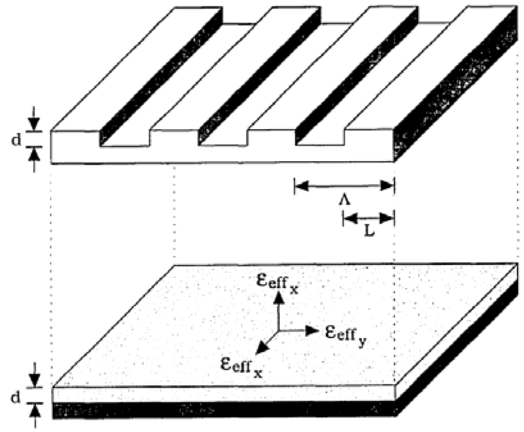
R. C. Enger and S. K. Case, Appl. Opt. 22, 3220–3228, 1983.

M. E. Motamedi et al., Appl. Opt. 31, 4371–4376, 1992.

Narrow-band filters

S. S. Wang et al., J. Opt. Soc. Am. A 8, 1470–1475, 1990

"Artificial" birefringent layer



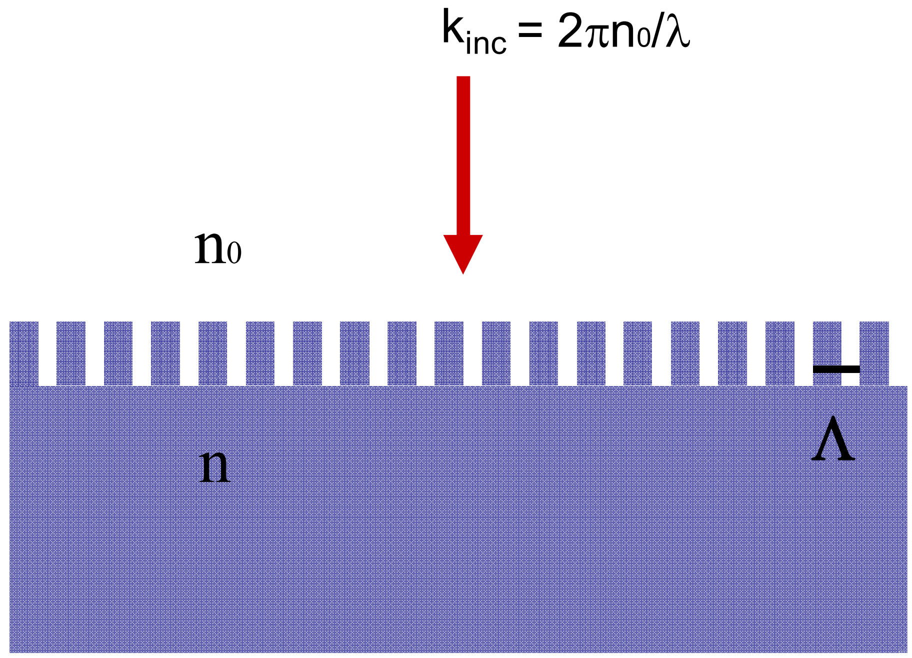
What is "subwavelength region"?

"In most optical materials the atomic or molecular structure is so fine that the propagation of light within them may be characterized by their refractive indices. When an object has structure which is larger than the wavelength of light, its influence on the propagation of light may be described by the laws of diffraction, refraction and reflection. Between these two extremes is a region in which there is structure that is too fine to give rise to diffraction but too coarse for the medium to be considered as [strictly] homogeneous and a full description can only be achieved through a rigorous solution of Maxwell's electromagnetic equation."

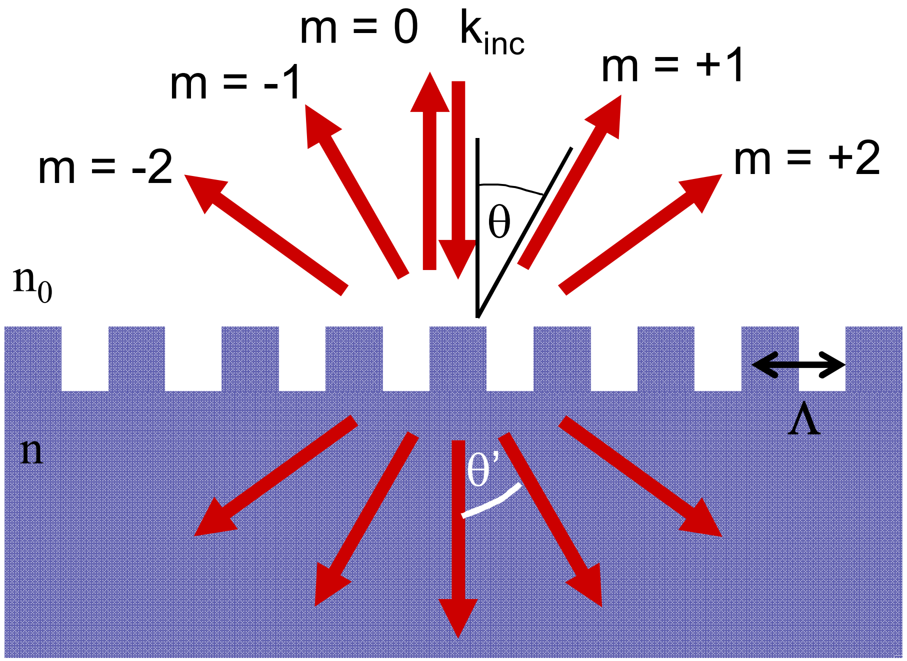
P. Lalanne and M. Hutley, *The optical properties of artificial media structured at a subwavelength scale,* Encyclopedia of Optical Engineering, 2003

Good news for engineers: For many applications, a full description and rigorous solution of Maxwell's electromagnetic equation is not necessary and solutions can be found with sufficient accuracy by approximating subwavelength structure as an effectively homogeneous medium.

Diffraction and subwavelength gratings



Diffraction and subwavelength gratings

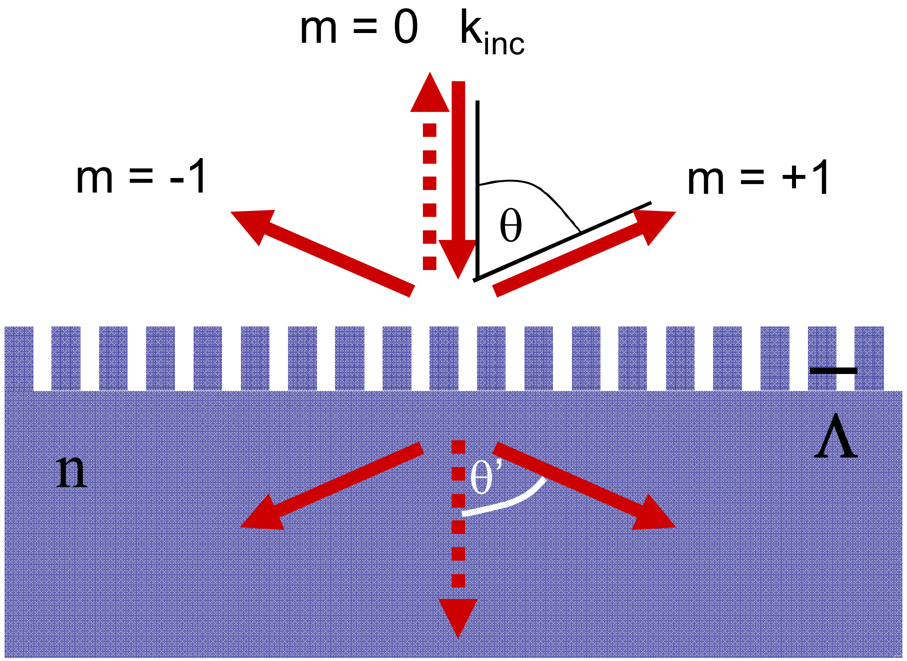


$$\mathbf{k}_{diffr} = m\mathbf{K} + \mathbf{k}_{inc}$$

Grating equation (normal incidence):

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

Diffraction and subwavelength gratings



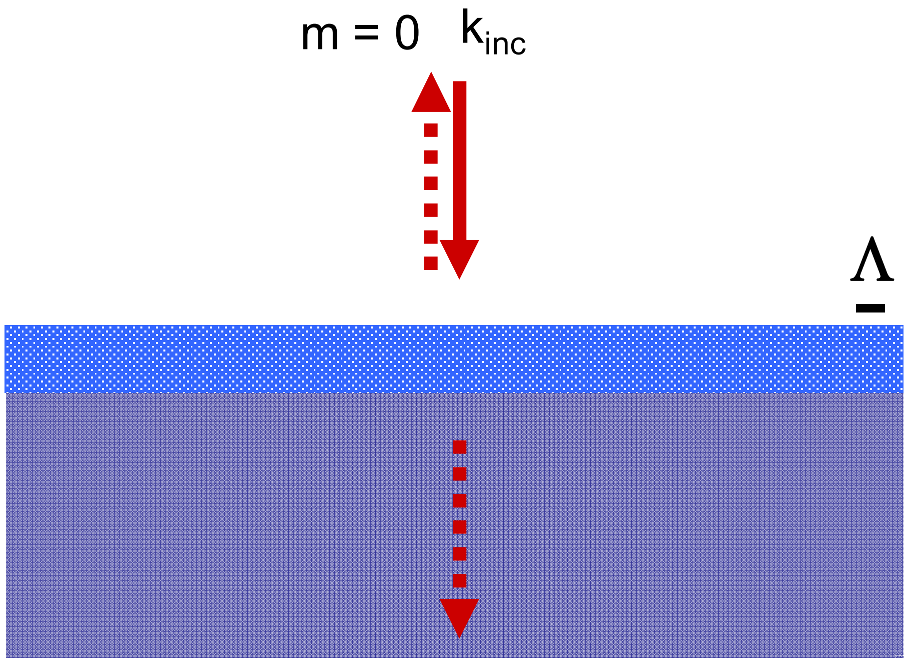
k$_{diffr}$ = m**K** + **k**$_{inc}$

Grating equation (normal incidence):

$$\sin\theta = \frac{m\lambda}{\Lambda}$$

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

Diffraction and subwavelength gratings



Grating Equation
(normal incidence)

$$\sin\theta = m\lambda / \Lambda$$

$$\Lambda < \lambda \longrightarrow \quad m\lambda / \Lambda > 1$$

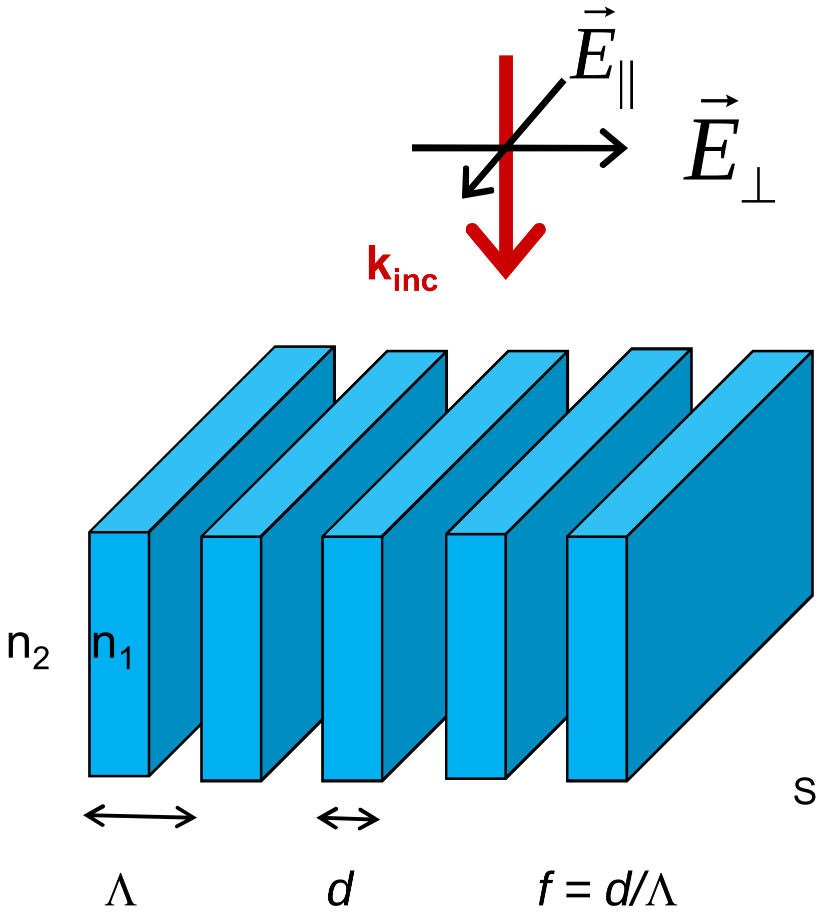
Grating layer can be approximated by an effective homogeneous medium

diffraction is frustrated
all diffraction orders are evanescent
(except m = 0)

E. G. Loewen and E. Popov, Diffraction Gratings and Applications (CRC Press, 1997).

P. Lalanne, M. Hutley, The optical properties of artificial media structured at a subwavelength scale, Encyclopedia of Optical Engineering, 2003.

Effective medium theory: transverse incidence



$$\varepsilon = n^2$$

$$\varepsilon_{\parallel} = f\varepsilon_1 + (1-f)\varepsilon_2$$

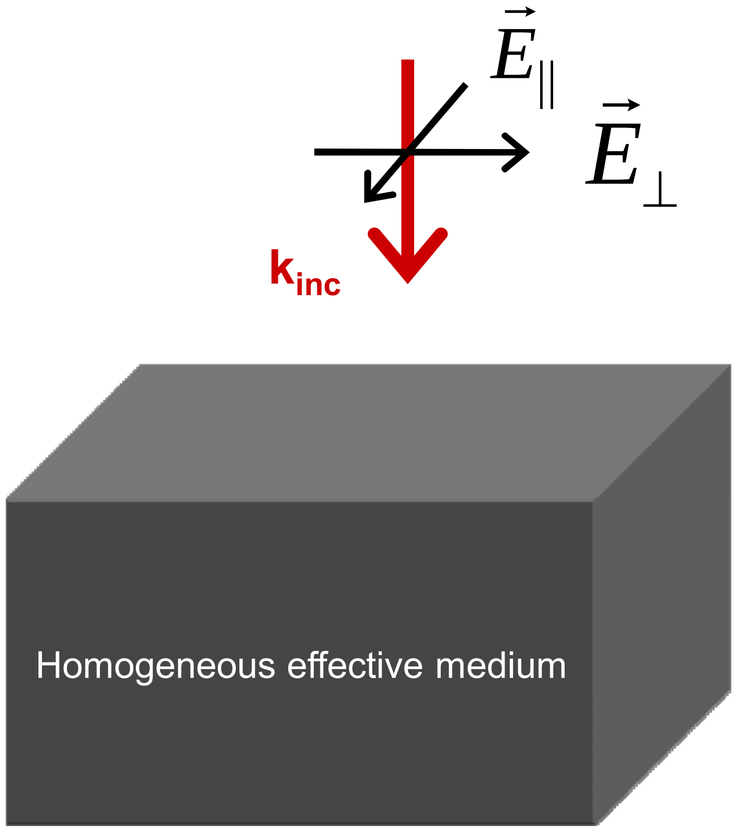
$$\frac{1}{\varepsilon_{\perp}} = \frac{f}{\varepsilon_1} + \frac{(1-f)}{\varepsilon_2}$$

S. M. Rytov, Sov. Phys. JETP 2 (3), 466-475 (1956)

Form birefringence

Rayleigh, Phil. Mag. (5), **34,** 481, 1892

Effective medium theory: transverse incidence



$$n_{\parallel}^{2} = f n_1^2 + (1 - f) n_2^2$$

$$\frac{1}{n_{\perp}^{2}} = \frac{f}{n_1^2} + \frac{(1-f)}{n_2^2}$$

S. M. Rytov, Sov. Phys. JETP 2 (3), 466-475 (1956)

SWG acts as homogeneous effective medium

Useful effective medium theories

SOVIET PHYSICS JETP VOLUME 2, NUMBER 3 MAY, 1956

Electromagnetic Properties of a Finely Stratified Medium

S. M. RYTOV
P. N. Lebedev Physical Institute, Academy of Sciences, USSR
(Submitted to JETP editor June 9, 1954)
J. Exper. Theoret. Phys. USSR 29, 605-616 (November, 1955)

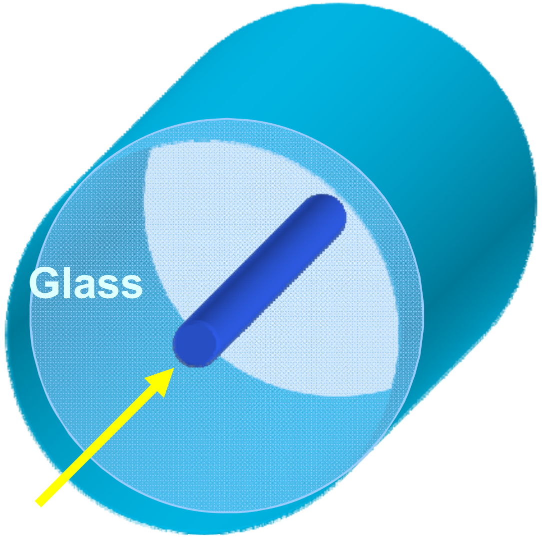
Media composed of alternate layers of two isotropic materials, when the layers are sufficiently thin, behave on the average with relation to an electromagnetic field as if they were homogeneous but anisotropic (uniaxial crystal). The effective permeability tensors ϵ and μ of such a crystal are obtained, and limiting values are derived for thin layers as functions of the parameters of their materials, and of the frequency. Losses in a finely stratified medium are considered, and also boundary conditions at its surface.

$$n_{\parallel}^{2} = f n_1^2 + (1-f) n_2^2$$

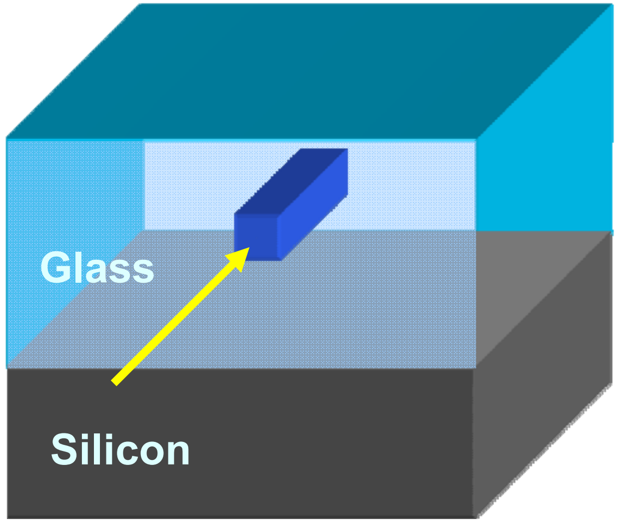
$$\frac{1}{n_{\perp}^{2}} = \frac{f}{n_1^2} + \frac{(1-f)}{n_2^2}$$

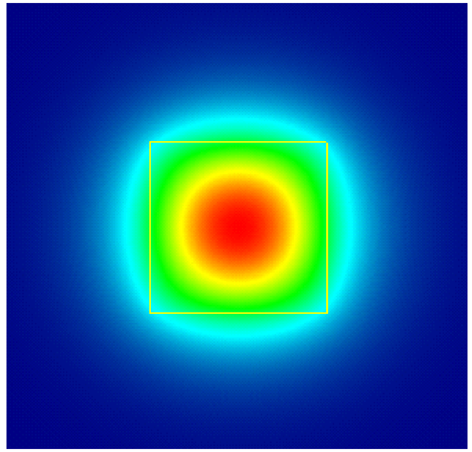
Also: P. Lalanne and J.-P. Hugonin, J. Opt. Soc. Am. A. 15, 1843 (1998)

From glass to silicon waveguides

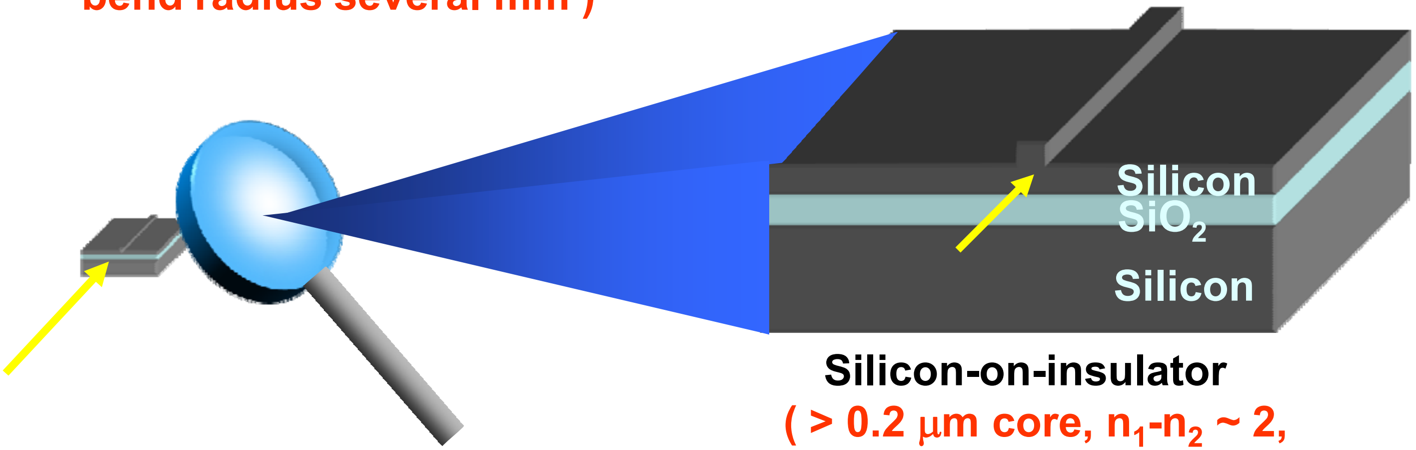


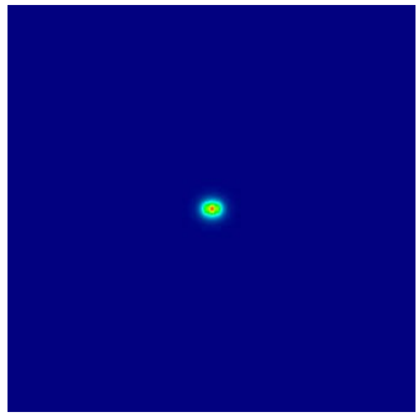
Glass optical fibre
(10 μm core, $n_1 - n_2 \sim 0.01$,
bend radius several mm)





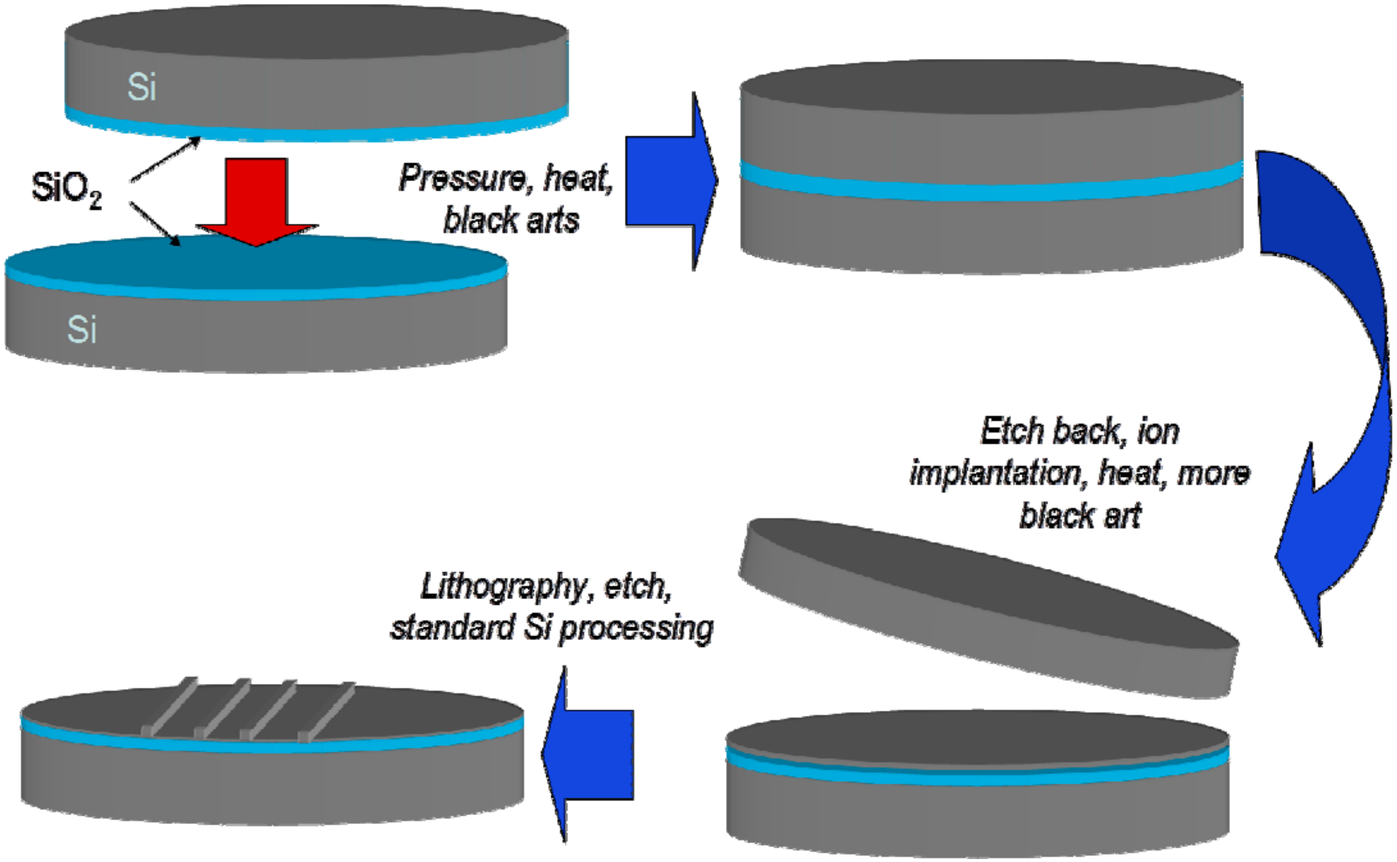
Silica-on-silicon planar waveguides
(6 μm core, $n_1 - n_2 \sim 0.01$)





Silicon-on-insulator
(> 0.2 μm core, $n_1 - n_2 \sim 2$,
bend radius a few micrometers)

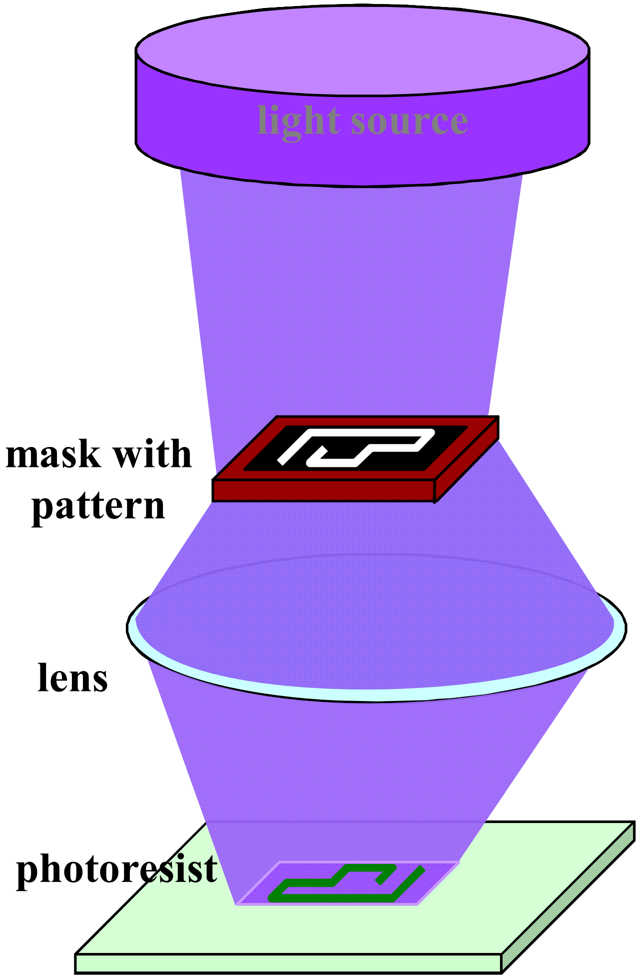
Silicon-on-insulator

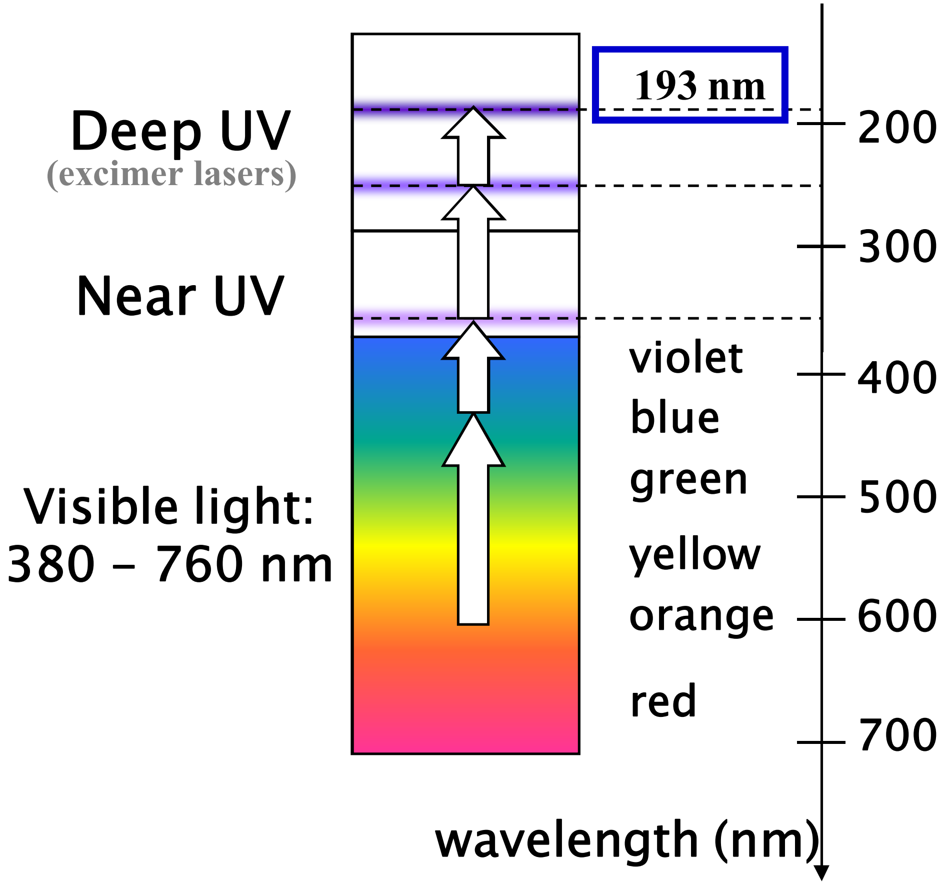


- **SOI was developed in 1970s as a niche substrate technology for military and space applications demanding materials with improved radiation hardness.**

- **SOI in microelectronics: reduced parasitic substrate capacitance and low leakage current thanks to the insulating SiO_2 bottom oxide layer, hence an increased speed and a lower power consumption of the MOSFET devices.**

Optical Lithography



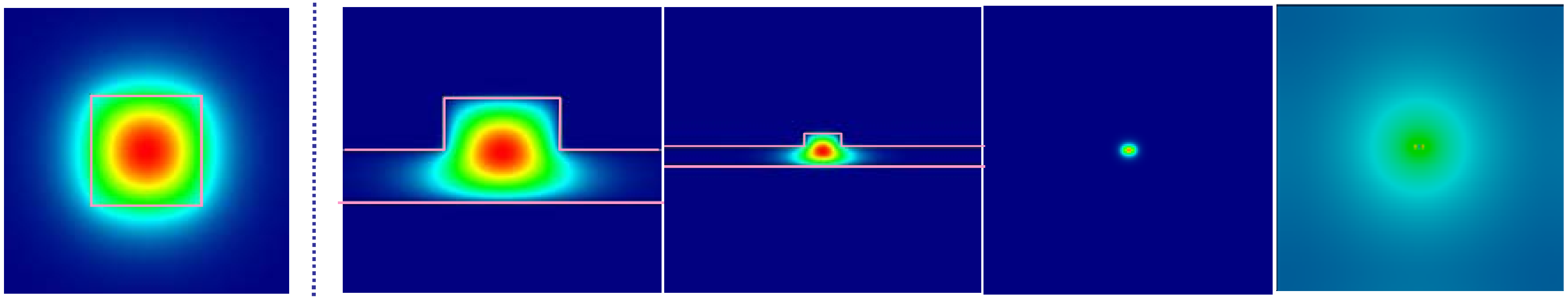


Courtesy: Prof. Roel Baets

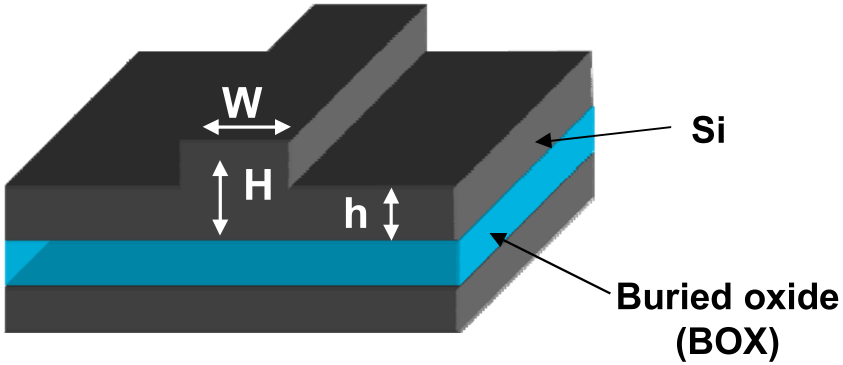
Scaling down SOI waveguides

Glass
$\Delta n = 0.02$

Silicon-on-insulator (SOI)
$\Delta n = 2$



5 μm x 5 μm | W=H=5 μm | W=H=1.5 μm | W=H=0.3 μm | 0.1 μm x 0.1 μm



$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-r^2}}, \quad r = \frac{h}{H}$$

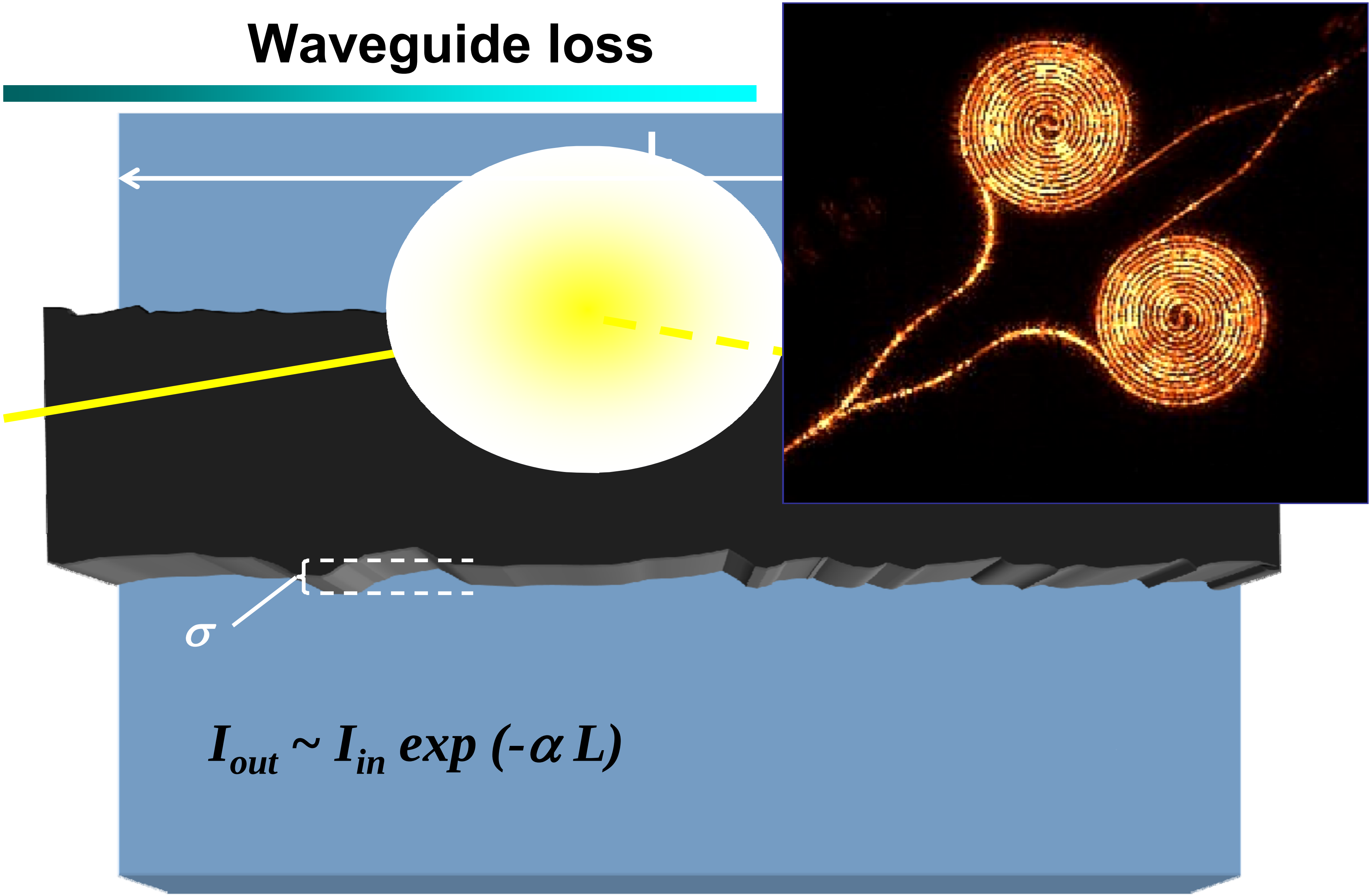
Soref's single mode condition

High index contrast

↕

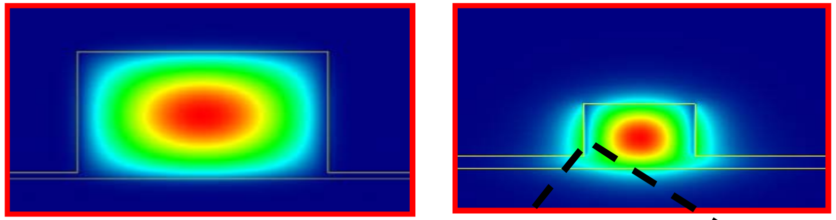
Small core dimensions

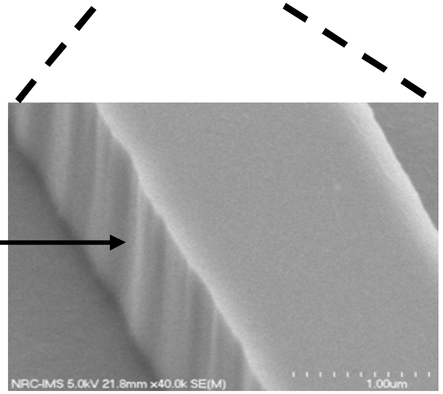
Waveguide loss



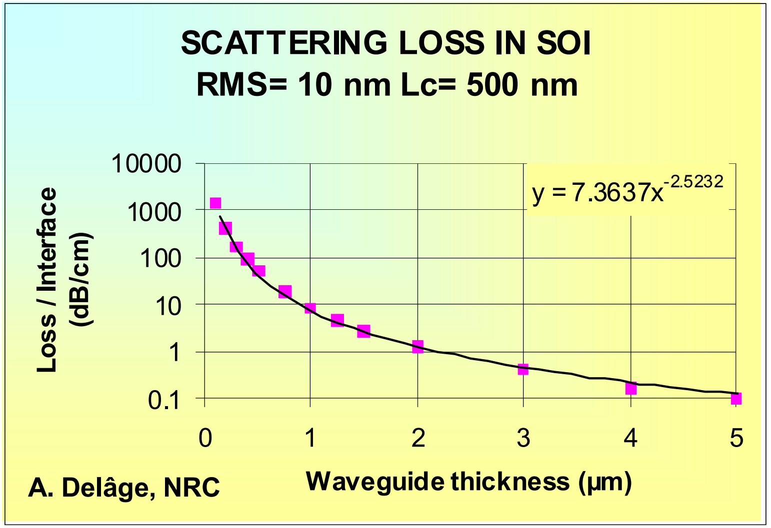
J.P.R Lacey and F.P Payne, Opt. Quantum Electron. 26, 977,1994

Loss in Si waveguides





Light scattering at waveguide sidewall roughness



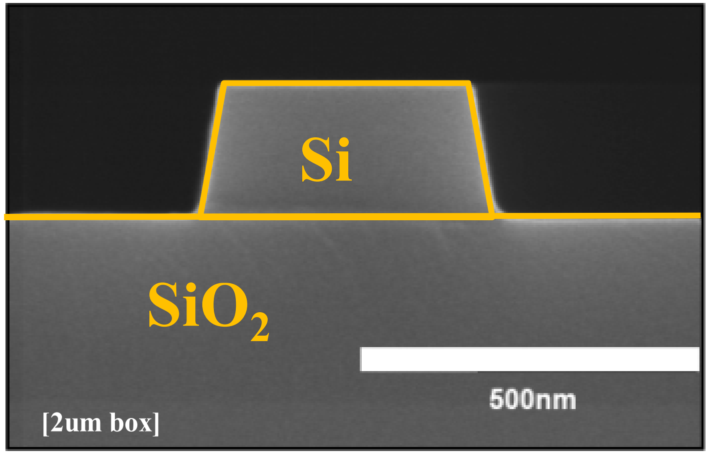
Scattering loss

Scattering strength increases with index contrast

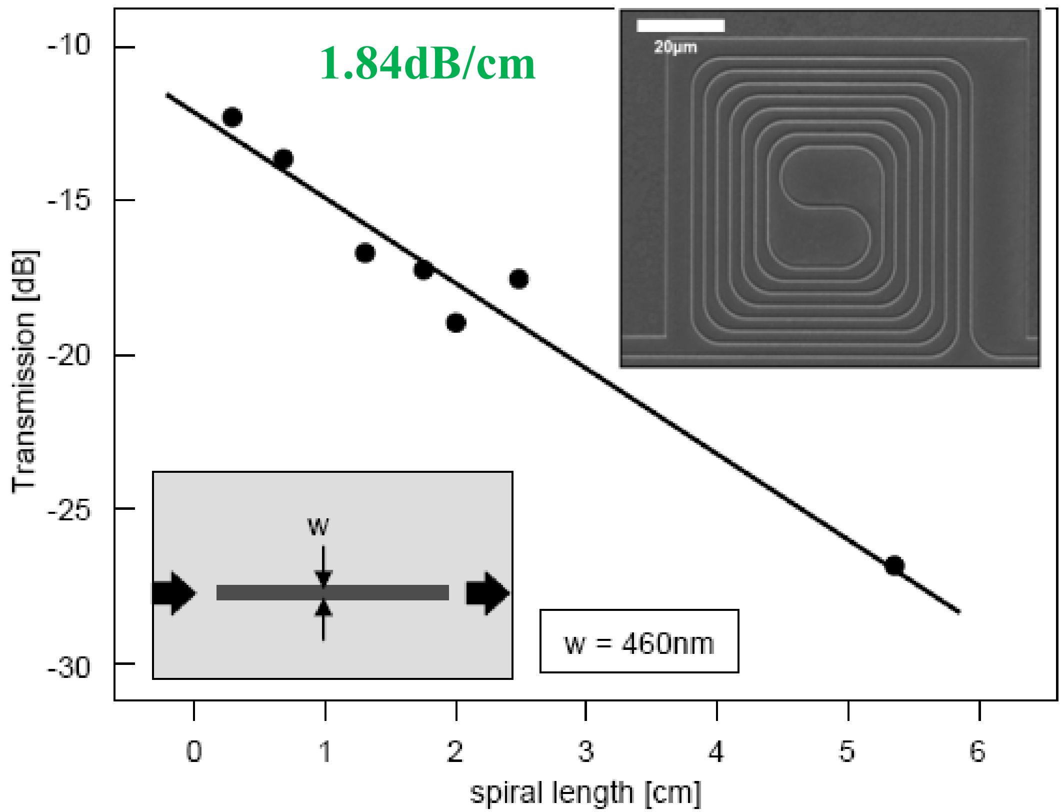
J.P.R Lacey and F.P Payne, Opt. Quantum Electron. 26, 977,1994

Photonic wire waveguide

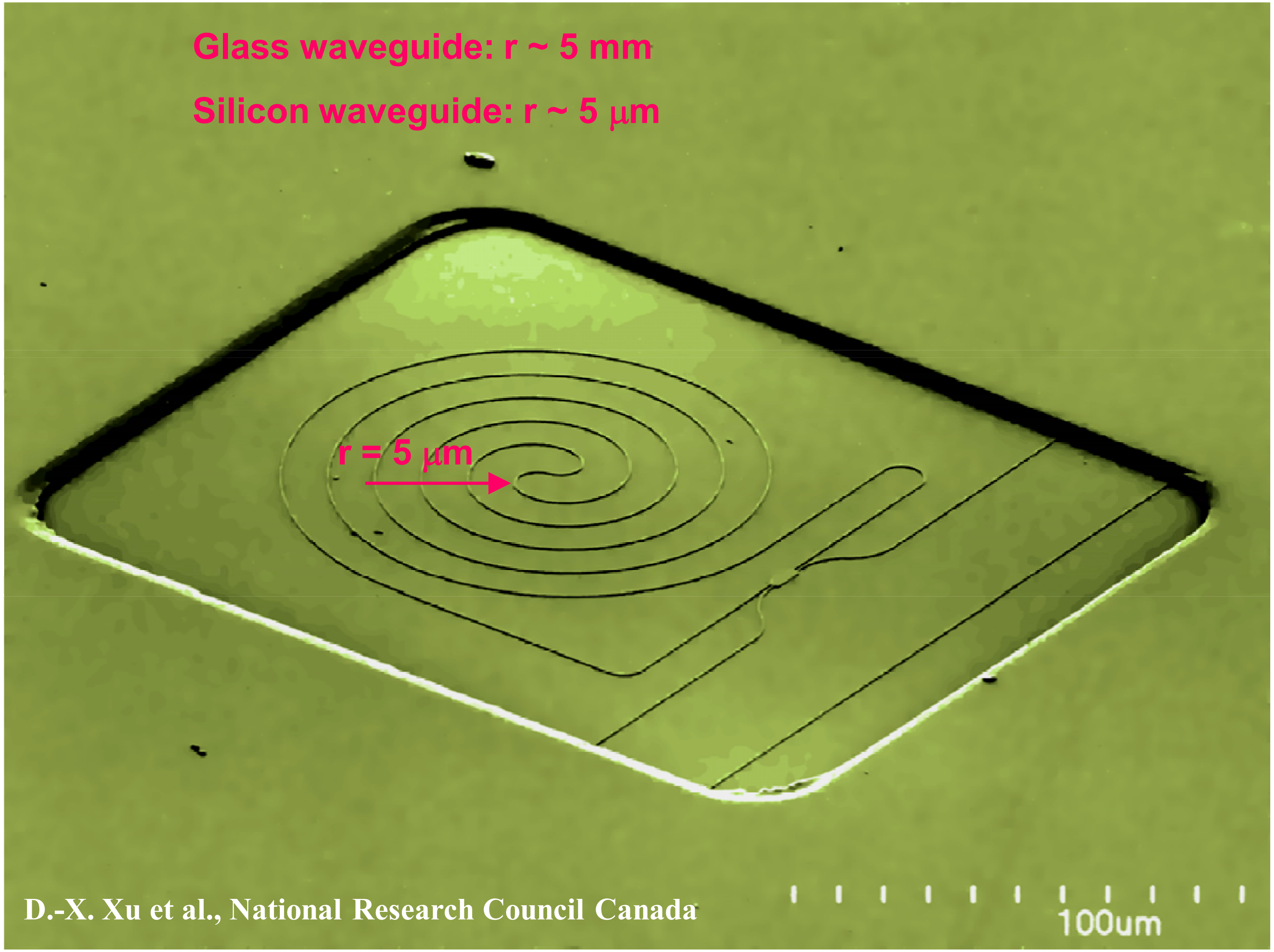
- Standard waveguide: 450nm x 220nm Si (epixfab foundry)
  - Fabricated using 193nm DUV lithography
  - In standard line, on 200mm or 300 mm wafer
  - Starting from Silicon-on-Insulator (SOI)



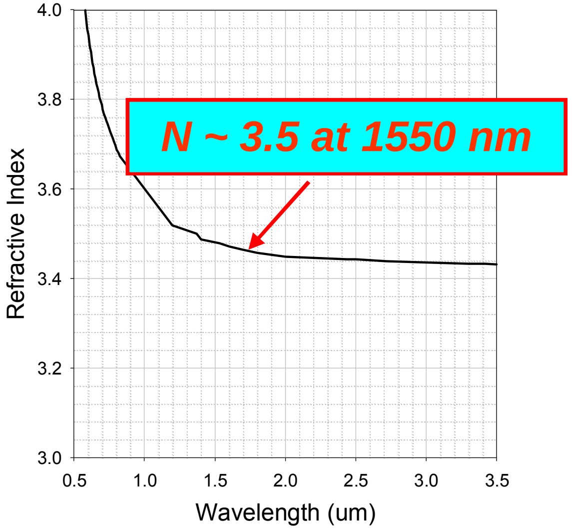
Bogaerts et al., STQE 16, 33-44 (2010)

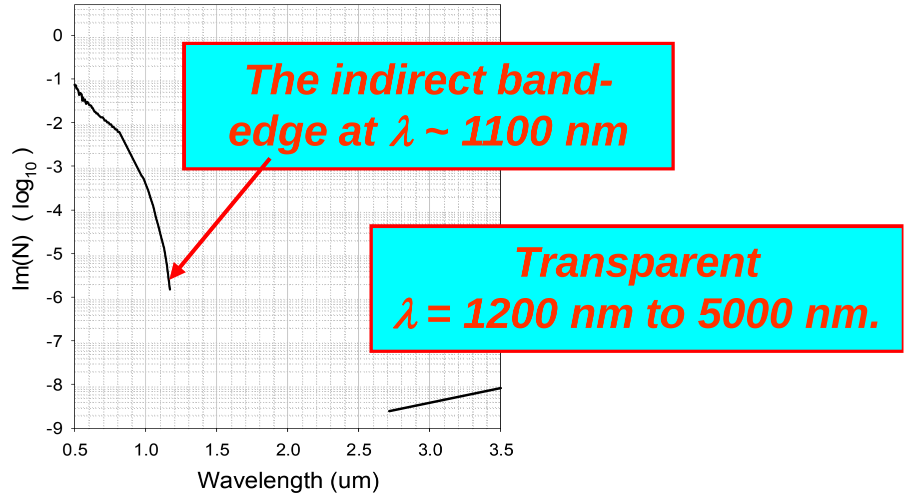


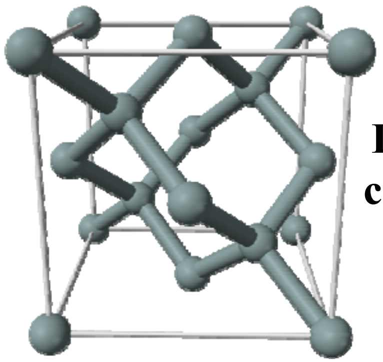
Waveguide bend radius



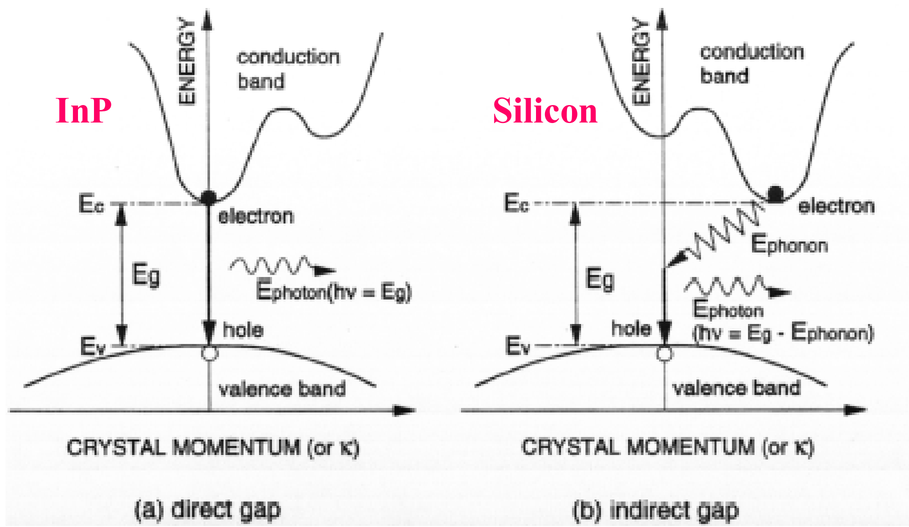
Optical properties of silicon







Diamond cubic crystal structure



- *Centro-symmetric crystal - no linear electro-optic effect – high speed modulation difficult.*
- *Very weak radiative recombination, of the order of one photon per million electrons: making laser is a big challenge*

Silicon does not give the best modulator, not the best detector, and not the best light source.

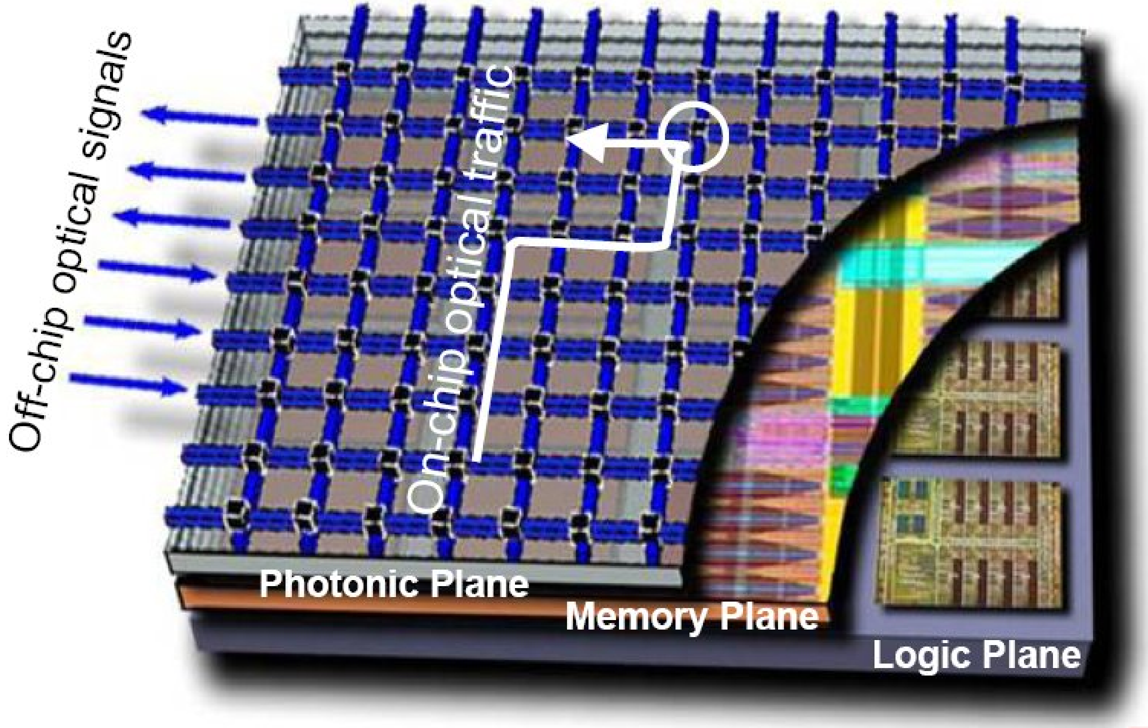
Why then silicon photonics? Because silicon microelectronics

Quad-Core Itanium Tukwila	2,000,000,000[7]	2010	Intel	65 nm	699 mm²
8-core POWER7+ 80M L3	2,100,000,000	2012	IBM	32 nm	567 mm²
Six-Core Core i7/8-Core Xeon E5 (Sandy Bridge-E/EP)	2,270,000,000 [8]	2011	Intel	32 nm	434 mm²
8-Core Xeon Nehalem-EX	2,300,000,000[9]	2010	Intel	45 nm	684 mm²
10-Core Xeon Westmere-EX	2,600,000,000	2011	Intel	32 nm	512 mm²
Six-core zEC12	2,750,000,000	2012	IBM	32 nm	597 mm²
8-Core Itanium Poulson	3,100,000,000	2012	Intel	32 nm	544 mm²
62-Core Xeon Phi	5,000,000,000	2012	Intel	22 nm	

Charm of silicon

- "Accumulation of capital": Enormous existing silicon microelectronic manufacturing infrastructure, microelectronics industry worth hundreds of b$
- "Concentration of capital": Presence of big players defining standards and trends, 90% of the market shared by 10 companies
- Si is widely available, can be purified to an unprecedented level, easy to handle and manufacture, good thermal and mechanical properties
- Natural oxide, effective passivation of the Si surface, excellent insulator, an effective diffusion barrier, high etching selectivity with respect to Si
- High integration densities, 5 billions of transistors in Xeon Phi, node lengths of 15 nm demonstrated (research), very large wafer sizes 400 mm
- The ability of Si industry to "face improvements": SiGe, low k-materials, Cu wires for high speed operation

Vision for 22nm CMOS (circa 2018) - 10 TFLOPs on a 3D chip



36 "Cell" chip (~300 cores)

System level study:
IBM, Columbia, Cornell, UCSB

Co-PIs:
Jeff Kash (IBM)
Keren Bergman (Columbia)
Yurii Vlasov (IBM)

Logic plane	~300 cores
Memory plane	~30GB eDRAM
Photonic plane	On-Chip Optical Network
	>70Tbps optical on-chip
	>70Tbps optical off-chip

Photonic layer is not only connecting various cores, but also routes the traffic

All future dates and specifications are estimations only. Subject to change without notice.

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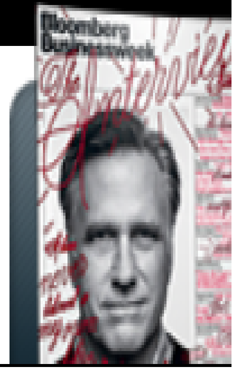

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Bloomberg News

Cisco Buys Lightwire for $271 Million to Add Optical Technology

EE Times News & Analysis

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Luxtera, ST in deal to take silicon photonics mainstream

Peter Clarke

3/1/2012 10:17 AM EST

http://www.eetimes.com/electronics-news/4237315/Luxtera-ST-silicon-photonics

STMicroelectronics and Luxtera Inc. will develop a dedicated silicon photonics process at its 300-mm research and pilot production wafer fab in Crolles, France. Integration of silicon photonic with CMOS integrated circuits. Optical transceivers, etc.

Big industry players recognize the advantages of silicon photonic for building practical devices.

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July 10, 2012 12:07 am

Intel invests $4bn in ASML to back R&D

By Chris Nuttall in San Francisco

13.5 nm extreme UV lithography by 2016

Si-photonics will go subwavelength (deep-subwavelength)

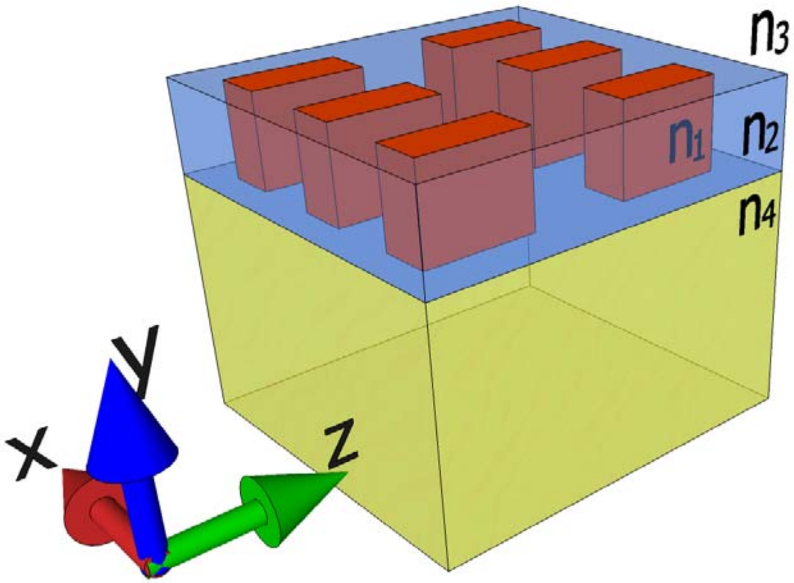
We can use silicon to do things that we could not do in optics before:

Integrated optical devices can be scaled down by an order of magnitude or more – <u>high index contrast.</u>

A new ability to engineer light at the sub-wavelength scale.

Subwavelength structures: geometries

Structures with a pitch small enough to suppress diffraction.



- **Propagation along *y***
- **Propagation along *z* (or *x*)**

M. C. Huang et al., Nat. Photonics, vol. 1, no. 2, pp. 119-122, 2007

D. Fattal et al., Nat. Photonics, vol. 4, no. 7, pp. 466–470, 2010

C. J. Chang-Hasnain, Advances in Optics and Photonics 4, 379–440, 2012

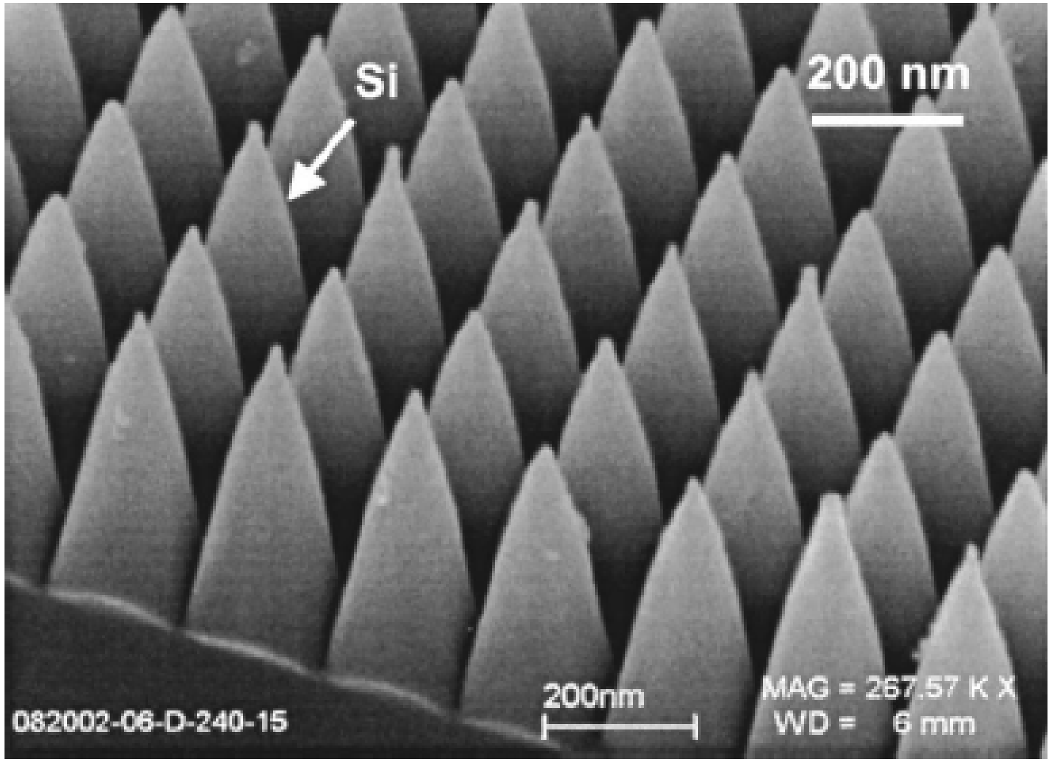
P. Cheben, Optics Express, vol. 14, pp. 4695-4702, 2006

R. Halir et al., J. Sel. Top. Quantum Electron, vol. 20, no. 4, pp. 8201313, 2014

U. Levy, et al., Phys. Rev. Lett., vol. 98, p. 43901, 2007

Subwavelength gratings in silicon

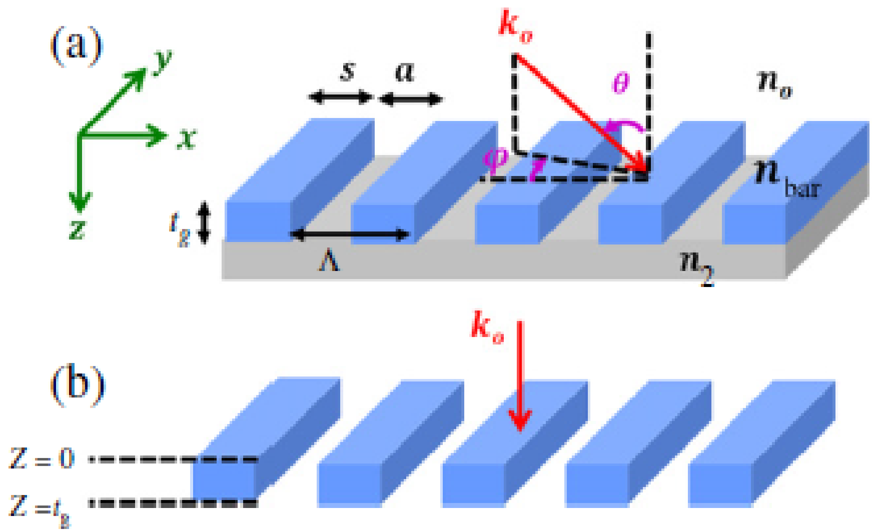
SWG used as an alternative to optical thin film anti-reflective coating

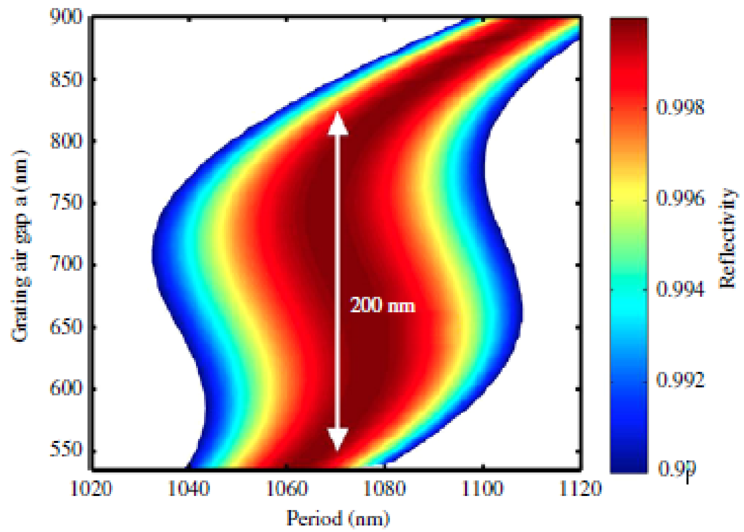


Antireflective Si surface grating

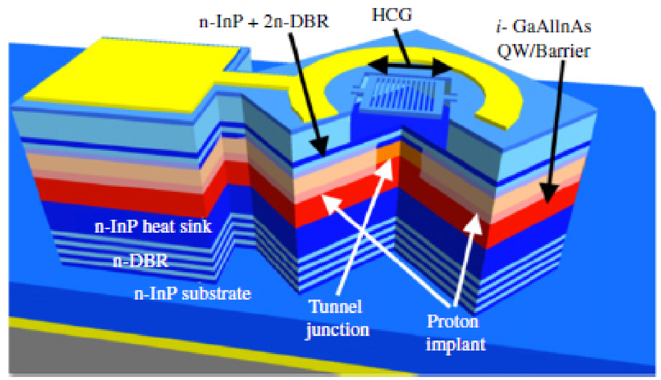
Z. Yu et al. (Princeton) , JVST B 21(6) 2874 (2003)

High-reflectivity gratings





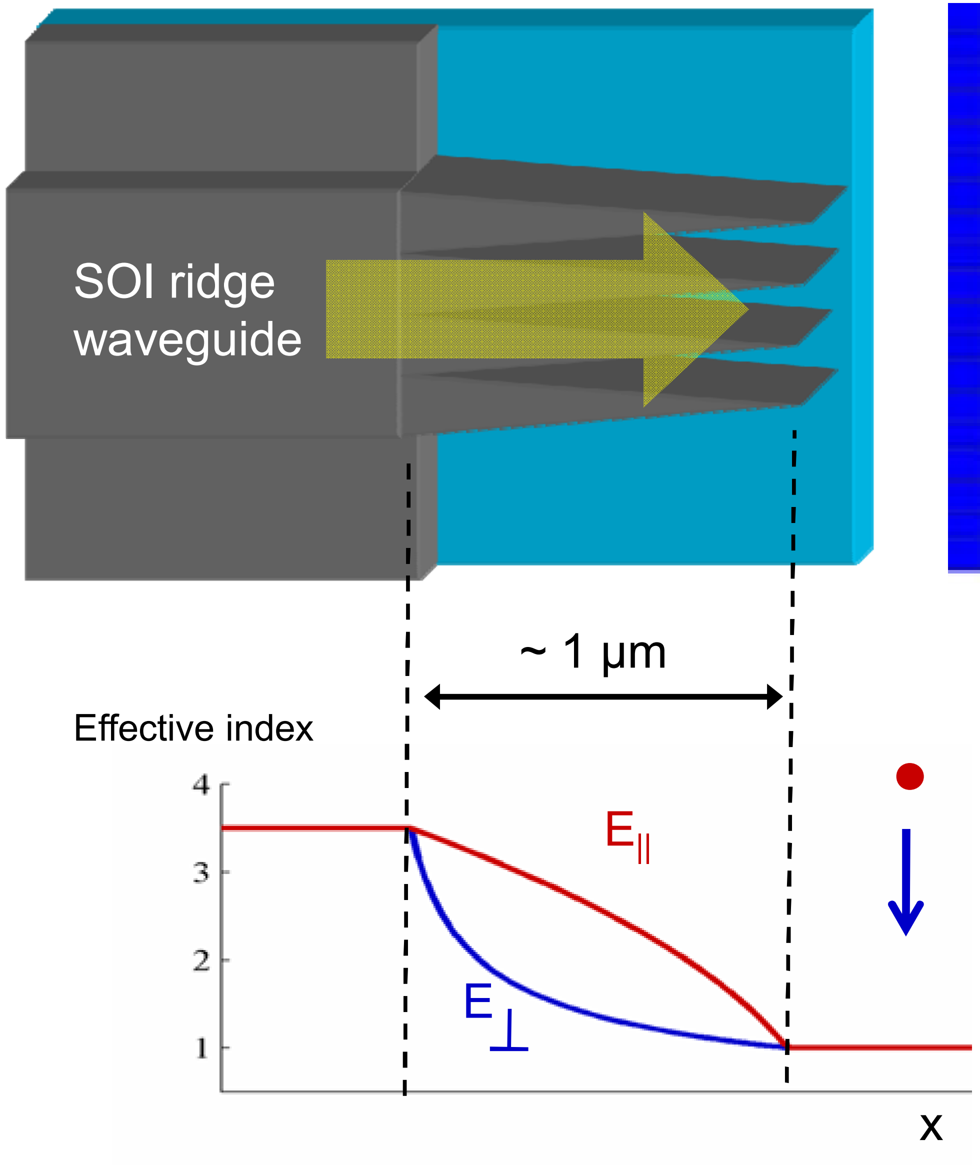
Prof. Connie Chang-Hasnain
UC Berkeley

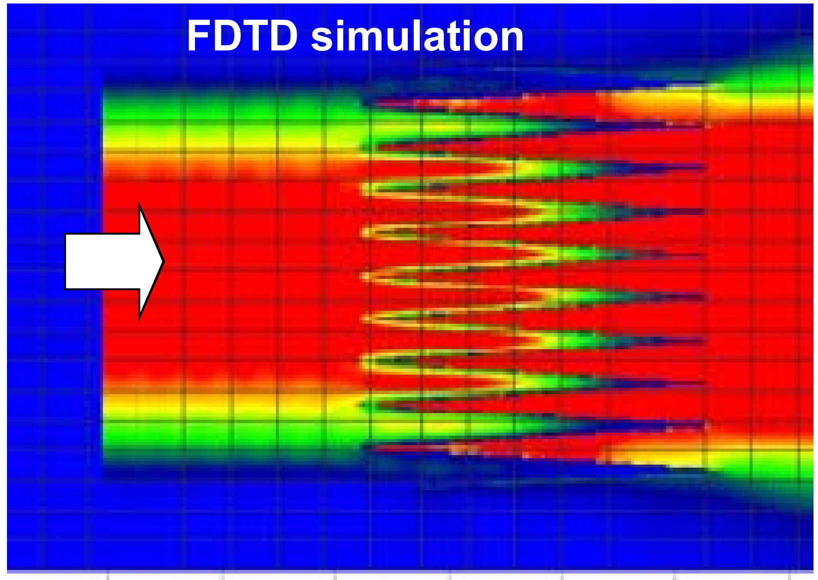


Schematic of a 1550 nm VCSEL with a suspended TE HCG in place of a typical top DBR. Current confinement is provided through the use of a proton-implant-defined aperture [19].

C. F. R. Mateus et al., PTL 16(2) 518 (2004)
M.C.Y. Huang et al., Nature Photonics 1, 119 (2007)
C. J. Chang-Hasnain, Advances in Optics and Photonics 4, 379–440, 2012 (Tutorial)

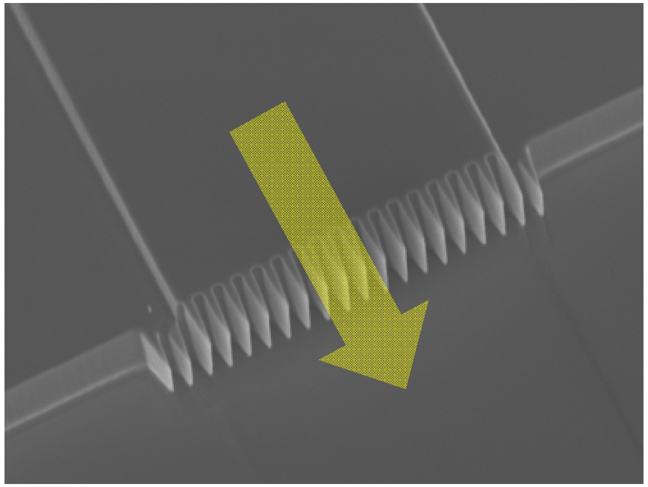
“Moth eye” anti-reflective facets in SOI waveguides



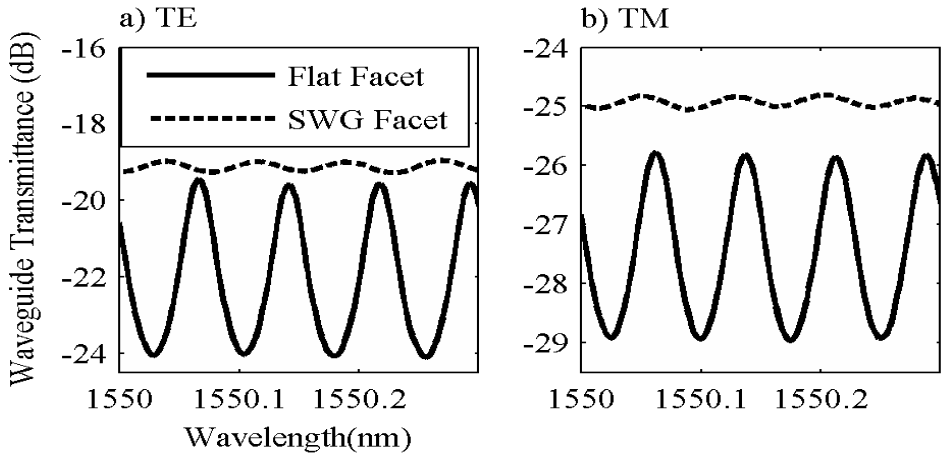


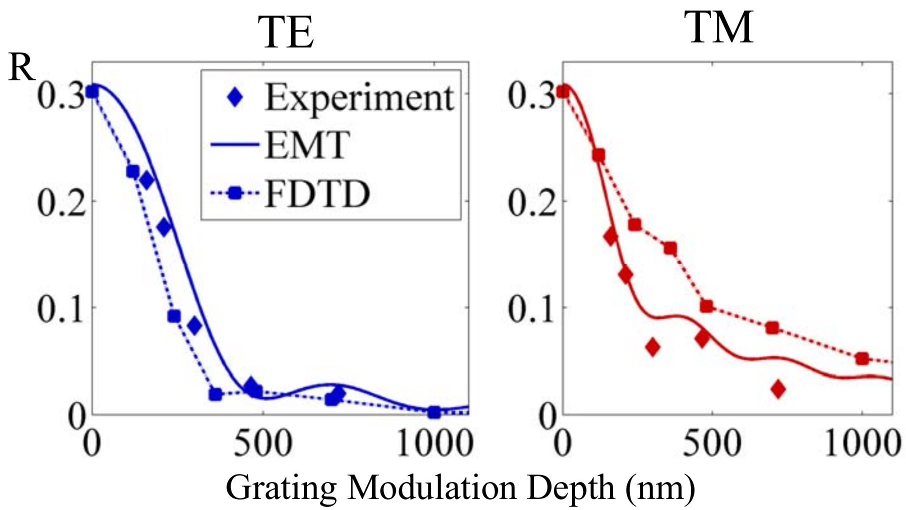
J.H. Schmid, P. Cheben, et al., Opt. Lett., vol. 32, p. 1794, 2007

Anti-reflective SOI waveguide facet experiment



Measured Fabry-Pérot fringes

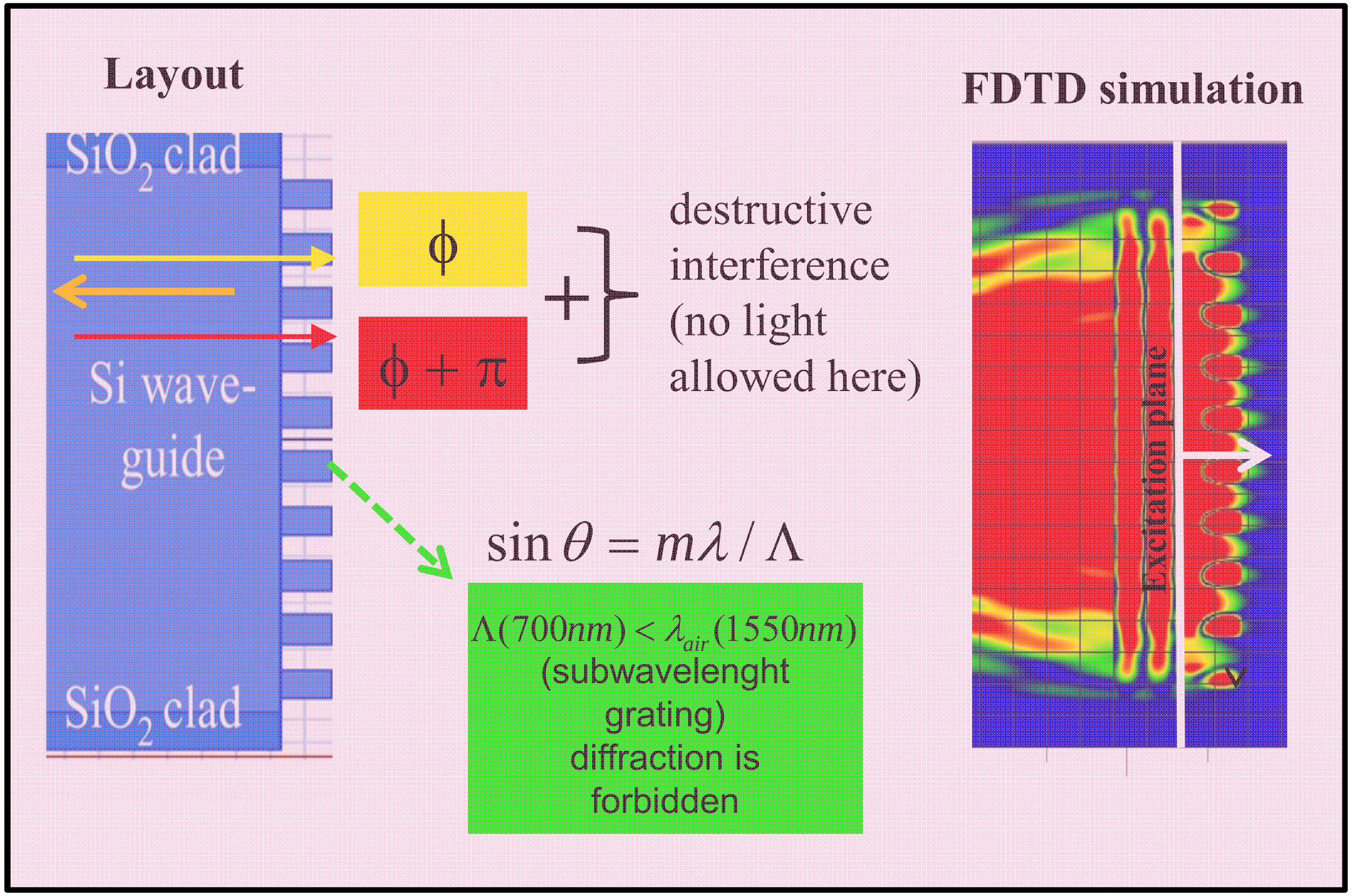




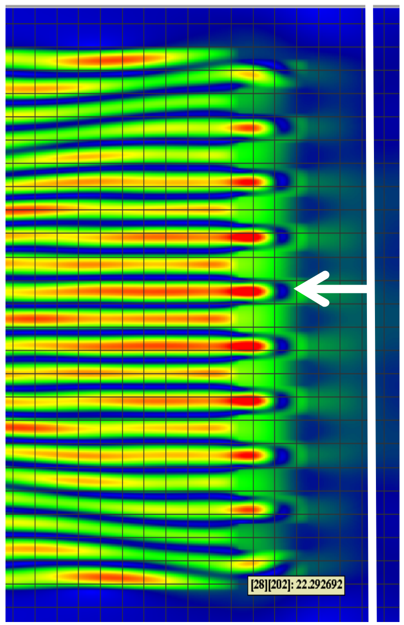
Broadband (GRIN)
R = 0.2 % (theory)
1.5% (experiment)

J.H. Schmid, P. Cheben, S. Janz, J. Lapointe, E. Post, and D.-X. Xu, Optics Letters, vol. 32, 2007

SWG mirror on a Si waveguide facet



But:
if light incident
from outside



$\Lambda(700nm) > \lambda_{Si}(440nm)$

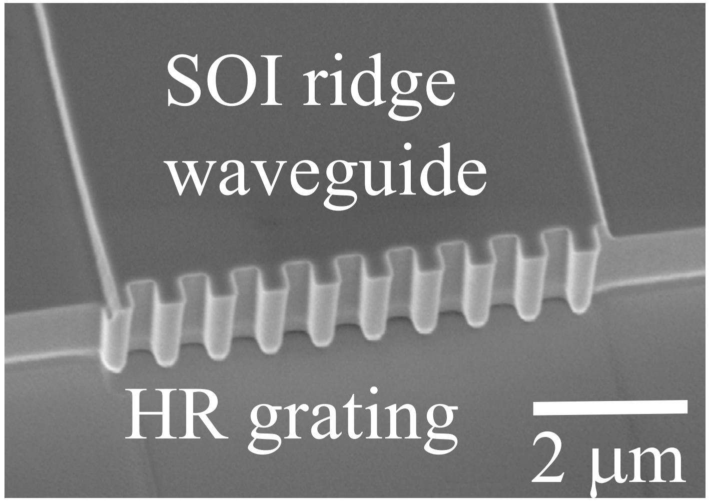
Diffraction is allowed
Interference between
$\pm 1^{st}$ diffraction orders

P. Cheben et al., Photon. Technol. Lett., vol. 18, no. 1, 2006

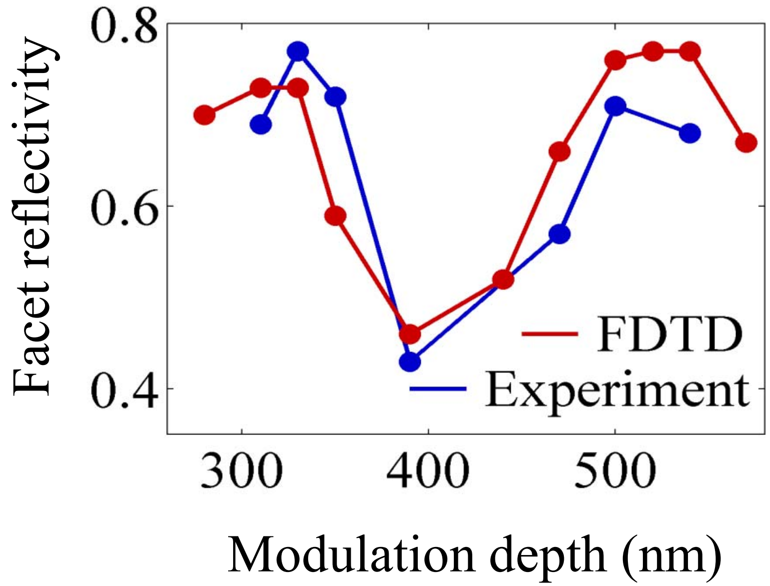
J. Schmid, P. Cheben, et al., Opt. Express, vol. 16, p. 16481, 2008

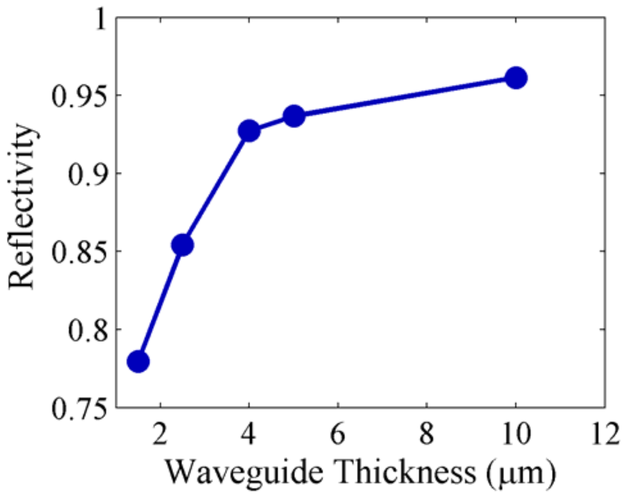
SWG mirror on a Si waveguide facet

SEM



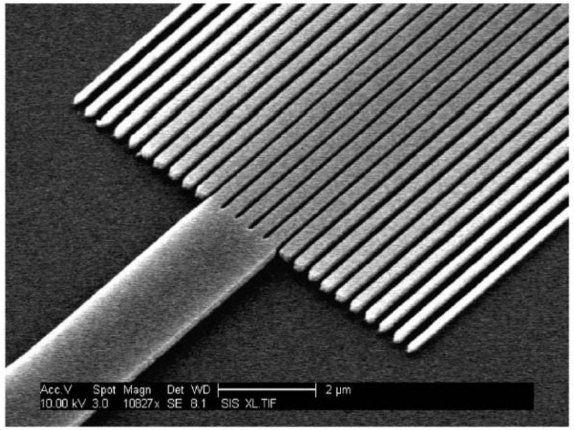
Measured reflectivity and 3D-FDTD



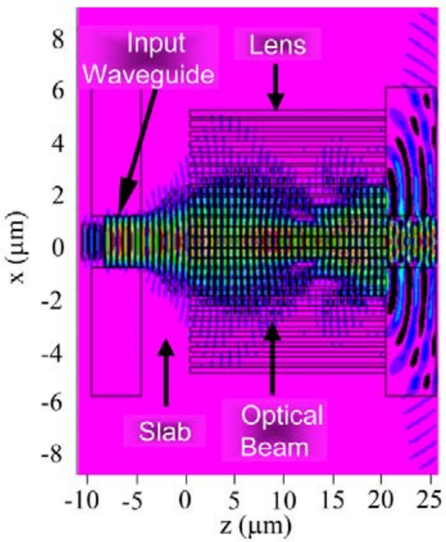


3D-FDTD reveals waveguide size effect:
R = 96% for 10 µm waveguide thickness
R = 99.99% for 2D gratings (Λ = 700 nm, D = 470 nm, DR = 0.54)

Subwavelength grating waveguide lenses



Light is focused by creating an artificial slab material with graded refractive index profile (controlling the duty cycle of the SWG).



UofC and Sun Microsystems,
Uriel Levy, PRL 98, 243901, 2007

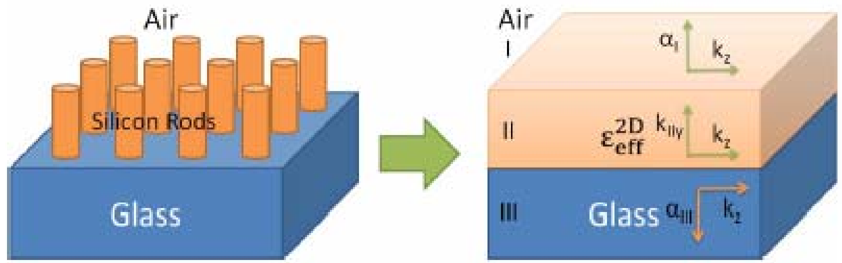
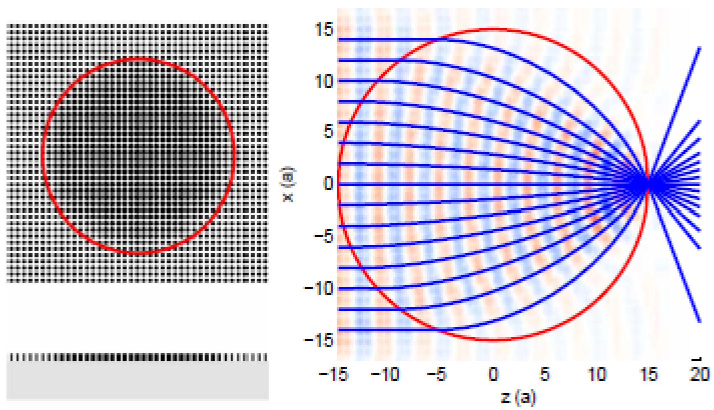


Fig. 2. Effective guiding medium (EGM) approximation of 2D finite height rod lattice structure.

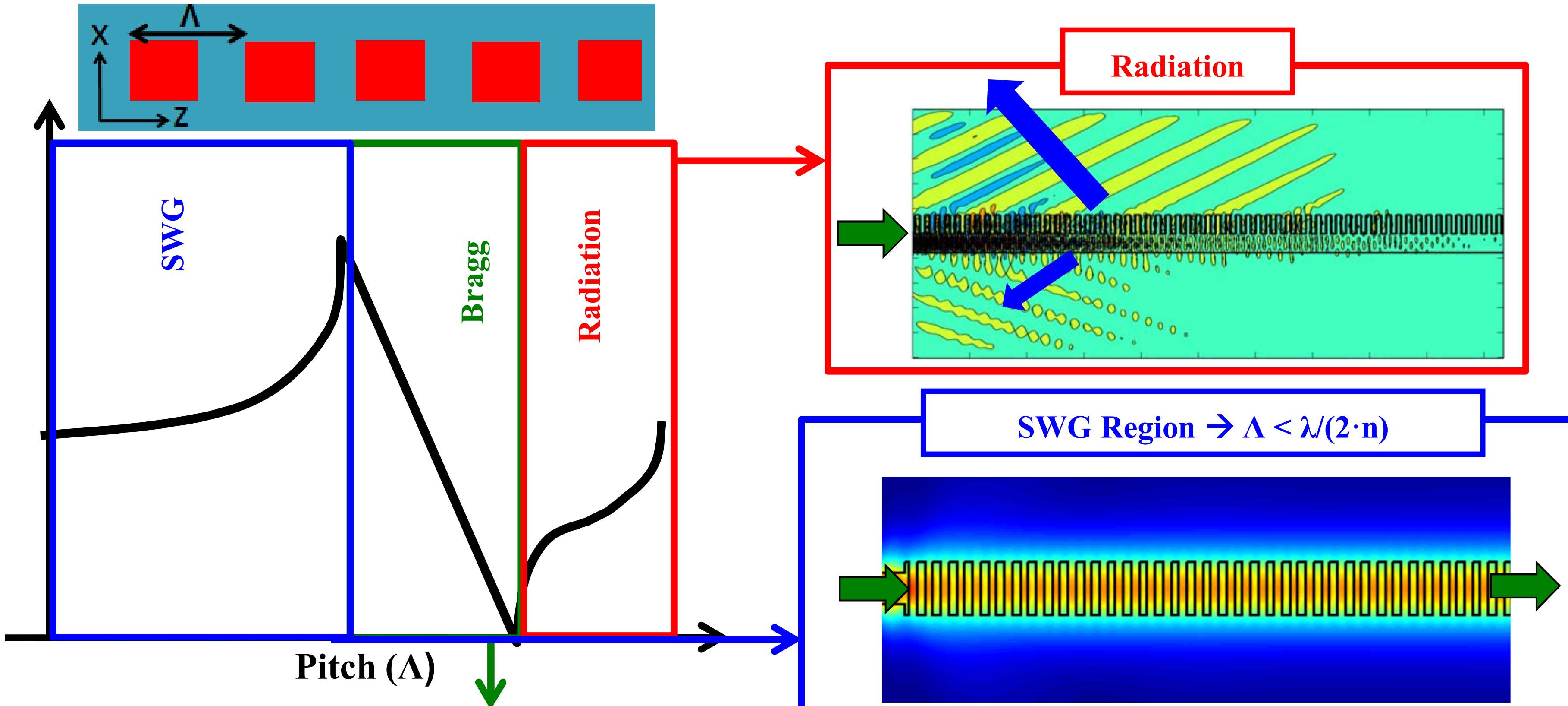
Lüneburg distribution $n(\rho) = n_0\sqrt{2-(\rho/R)^2}$

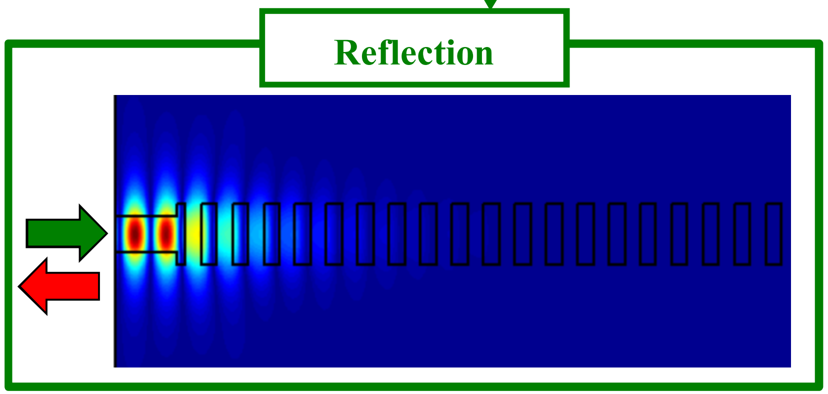
Solved by FDTD or Hamiltonian ray tracing



MIT: Gao et al., Optics Express 2012

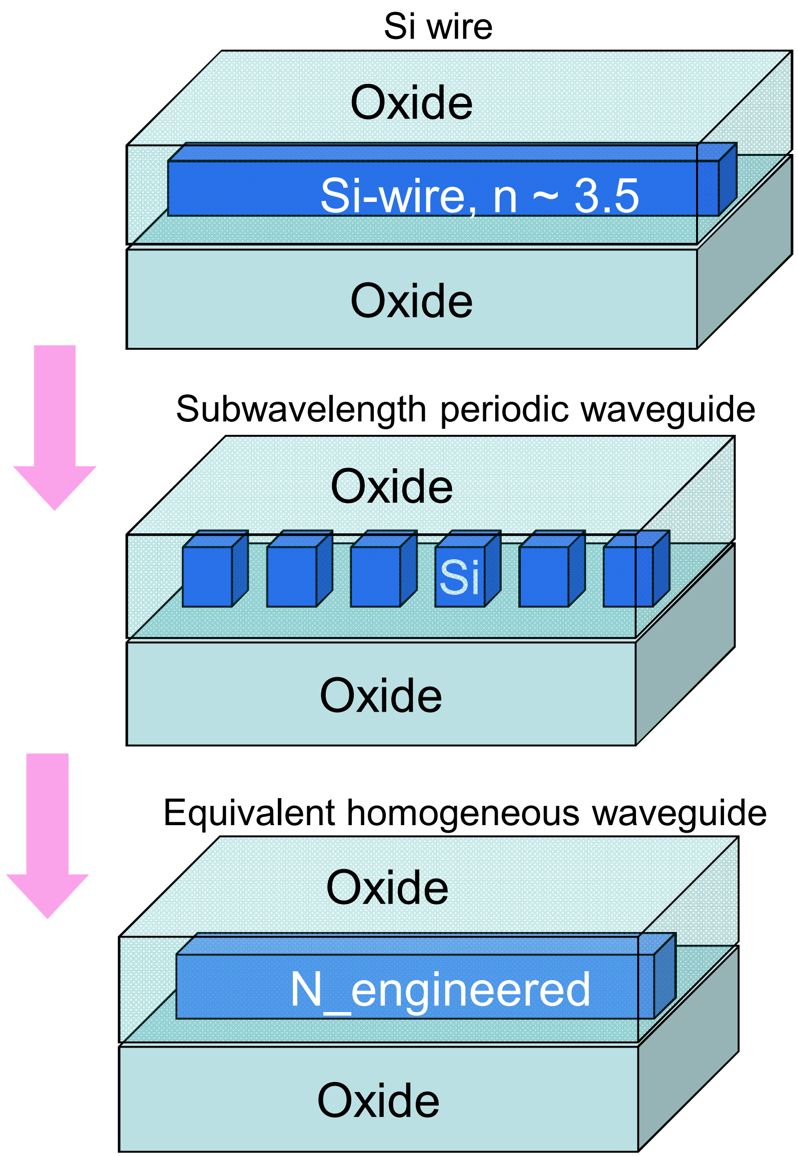
Periodic waveguide



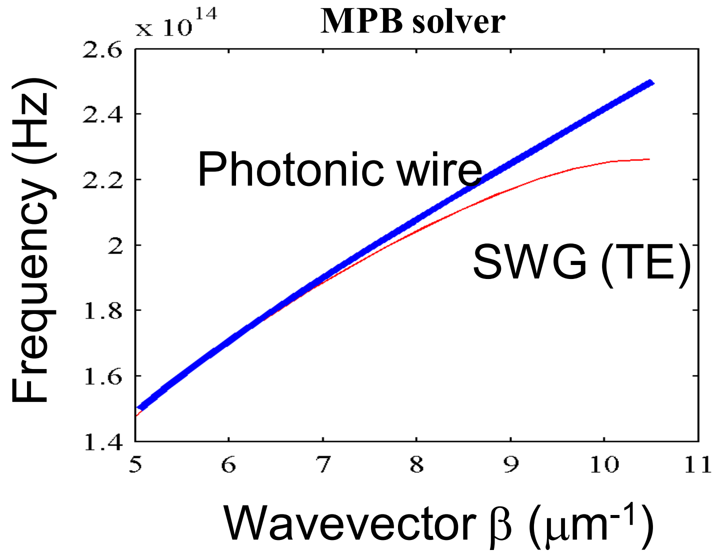


- **Diffraction is suppressed → homogenous medium.**
  - **Properties of the medium can be engineered by SWG geometry:**
- **R. index, birefringence & dispersion**

Subwavelength grating waveguides in SOI



n = 2.65 for 300 nm pitch, 260 nm x 450 nm segments, 50% DC

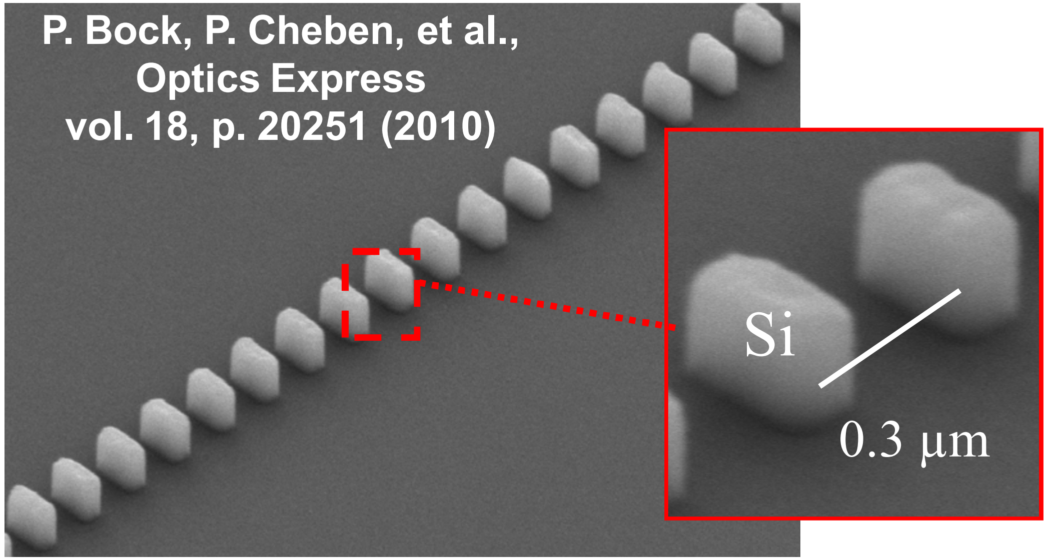


SWG waveguide propagation constant similar to homogeneous waveguide with core material of n = 2.65.

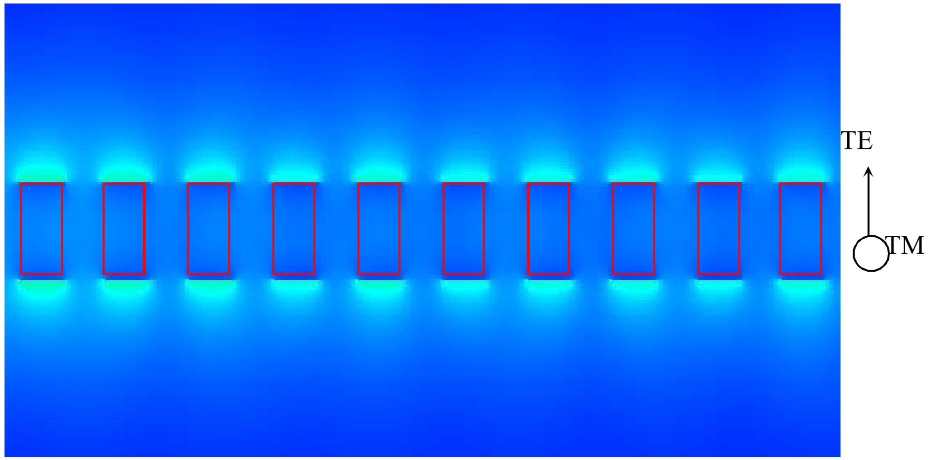
Effective core refractive index determined by the grating duty ratio.

A wide range of effective material refractive indices can be obtained by “mixing” Si and SiO_2 by changing grating duty ratio

Fabricated SWG waveguides



Over a 1-cm-distance light crosses over 33,000 boundaries between high- and low-refractive-index segments with an index contrast of $\Delta n \sim 1.9$ (!)

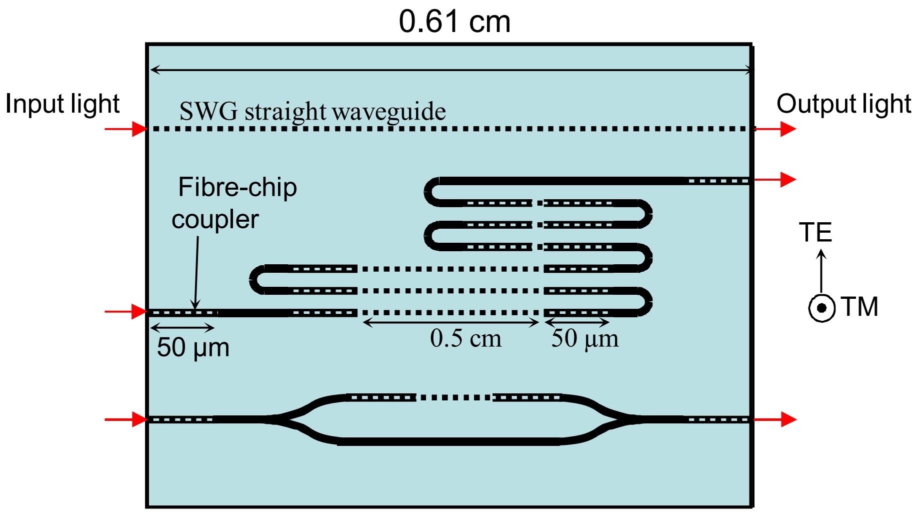


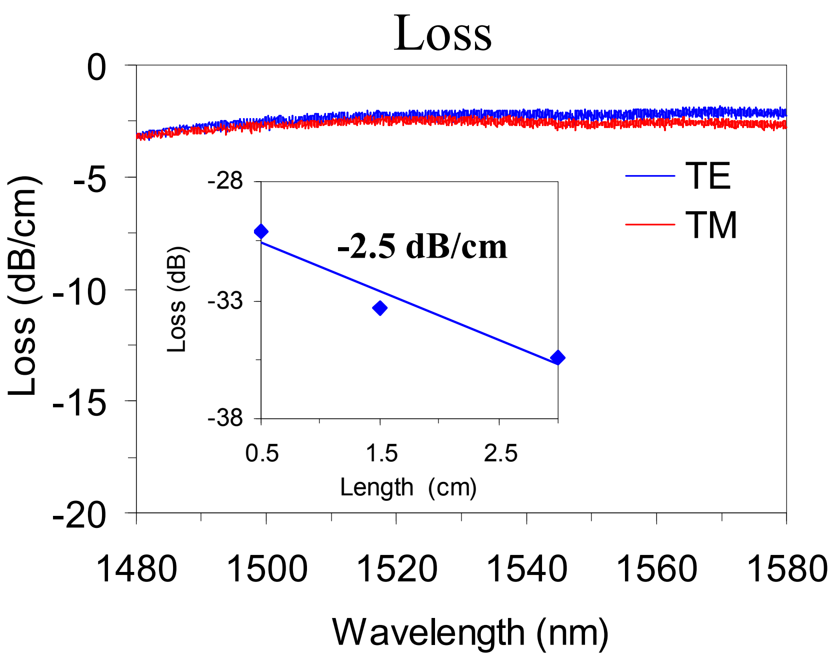
Light propagates as the Bloch modes (in theory lossless) of the periodic structure

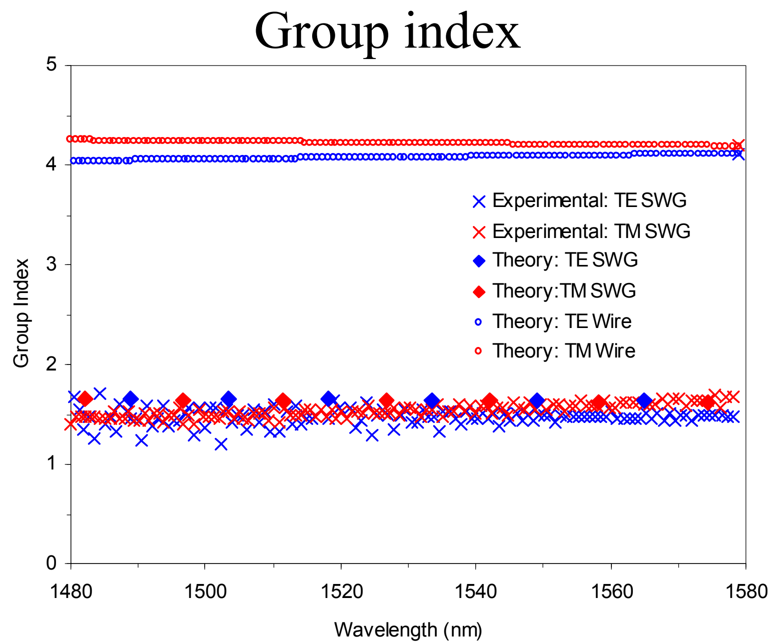
J.D. Joannopoulos, R.D. Meade, and J.N. Winn, Photonic Crystals–Molding the Flow of Light (Princeton University Press, 1995).

W. Śmigaj, P. Lalanne et al., Applied Physics Letters 98, 111107, 2011

Waveguide loss and group index measurement







Typical loss ~ 2.5 dB/cm

PDL < 0.5 dB

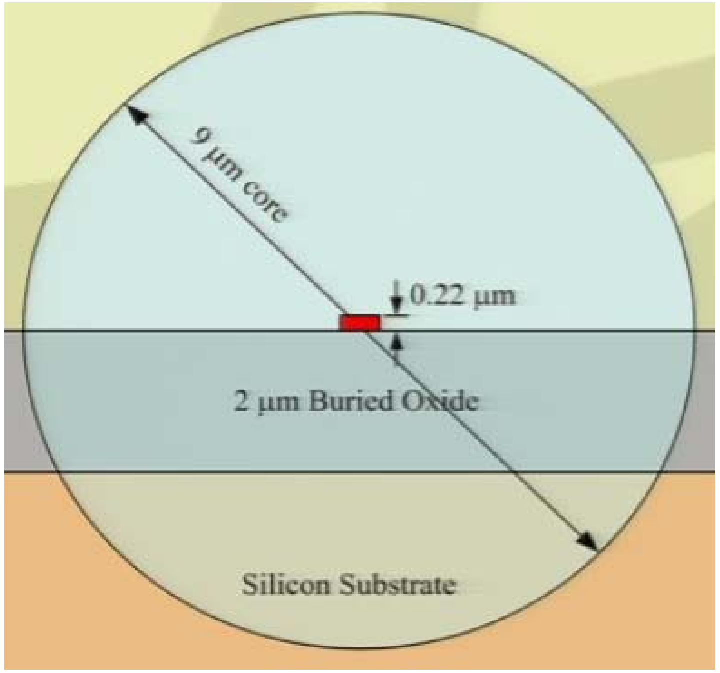
Wavelength range: 1480 – 1580 nm

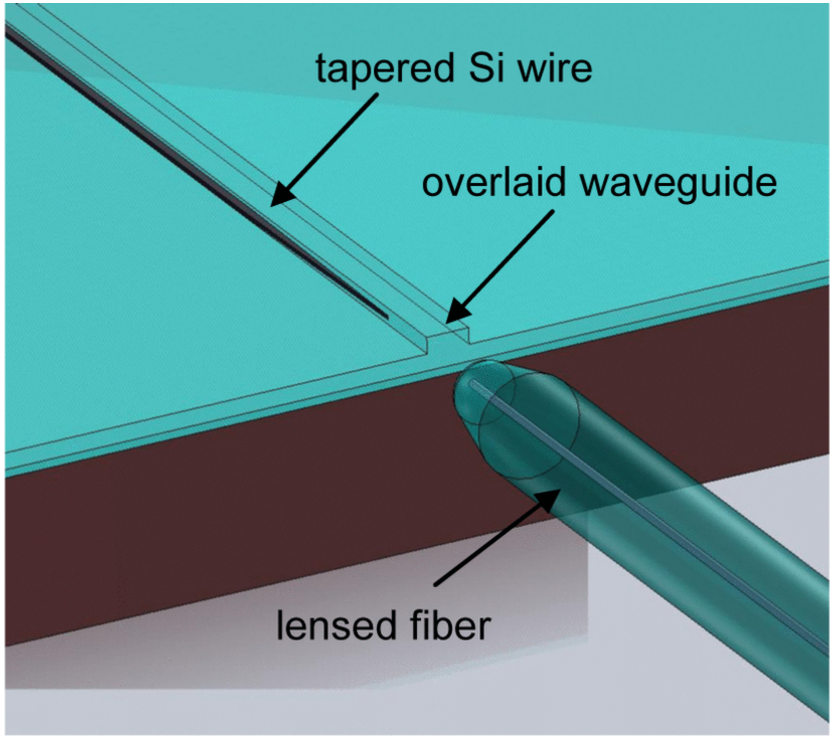
Group index n_g ~ 1.5 (33% DC)

P. Bock et al., Optics Express, vol. 18, p. 20251 (2010)

Fiber-chip coupling problem

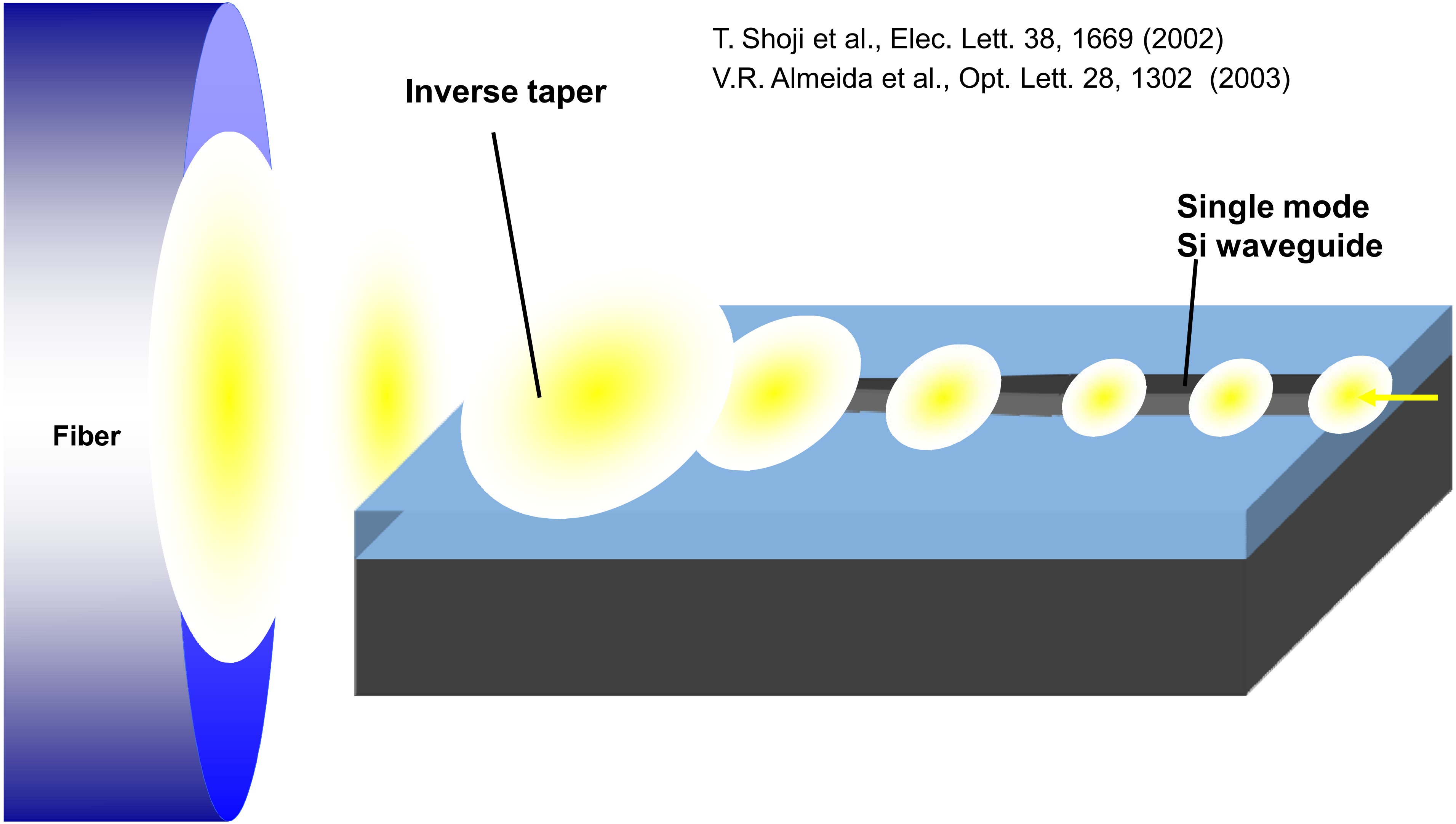
A very large mismatch between the mode size of an optical fiber and a silicon wire waveguide





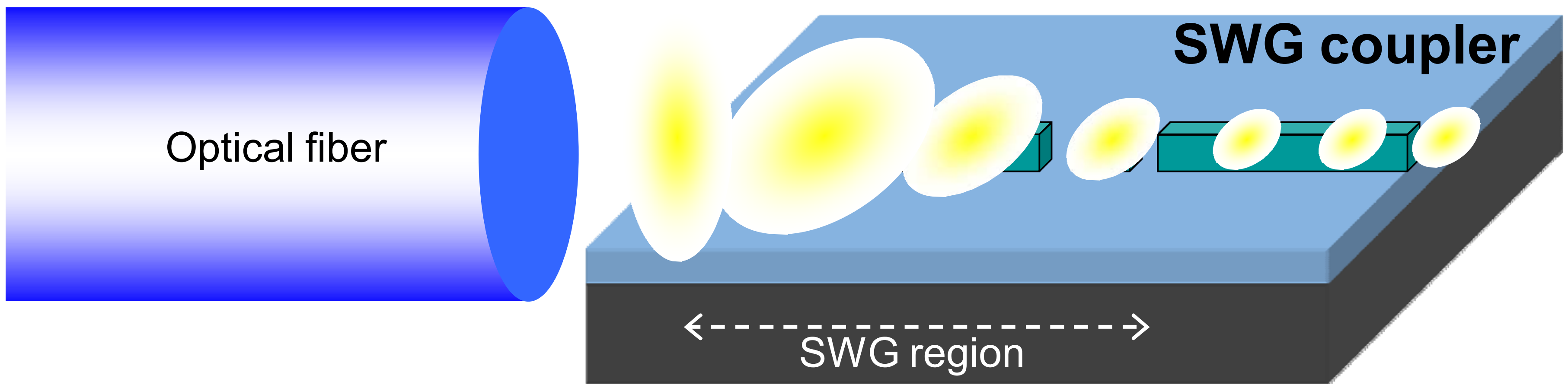
Inverse tapers: coupling by mode expansion

T. Shoji et al., Elec. Lett. 38, 1669 (2002)
V.R. Almeida et al., Opt. Lett. 28, 1302 (2003)



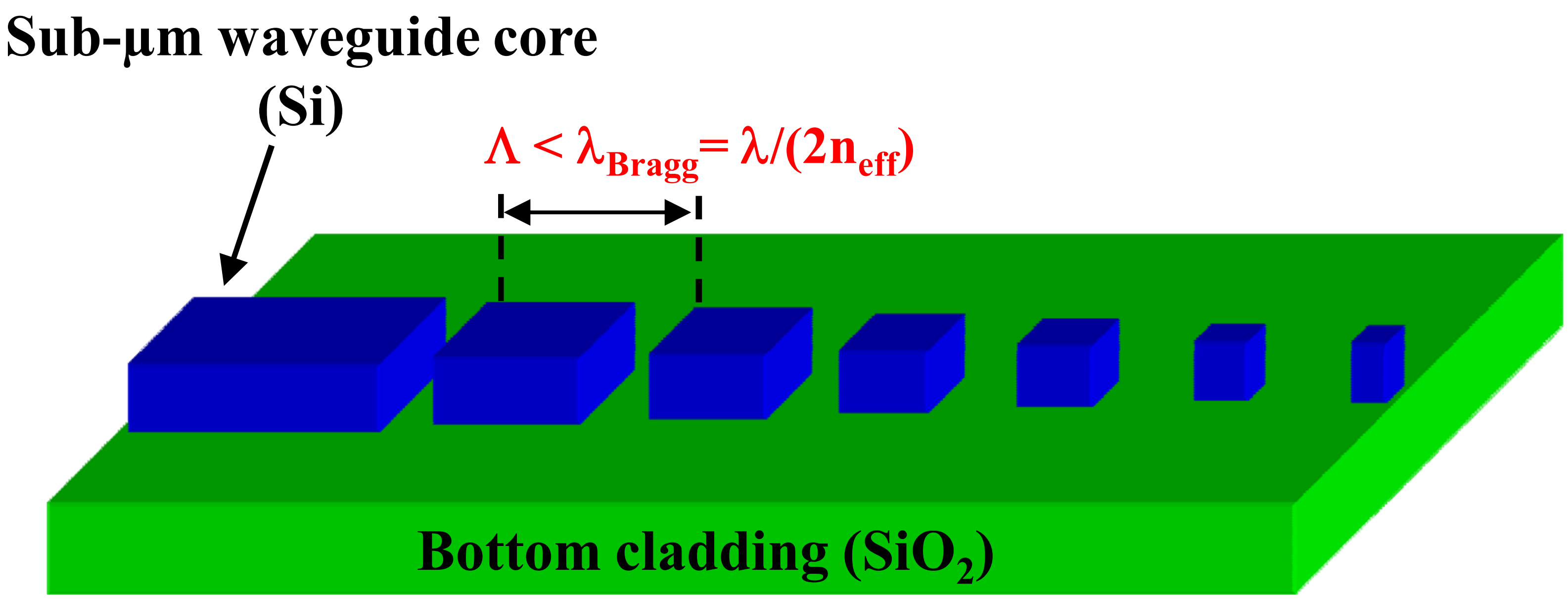
Requires fabrication of ~ 100 nm wide tip with high accuracy

Subwavelength grating fiber-chip coupler

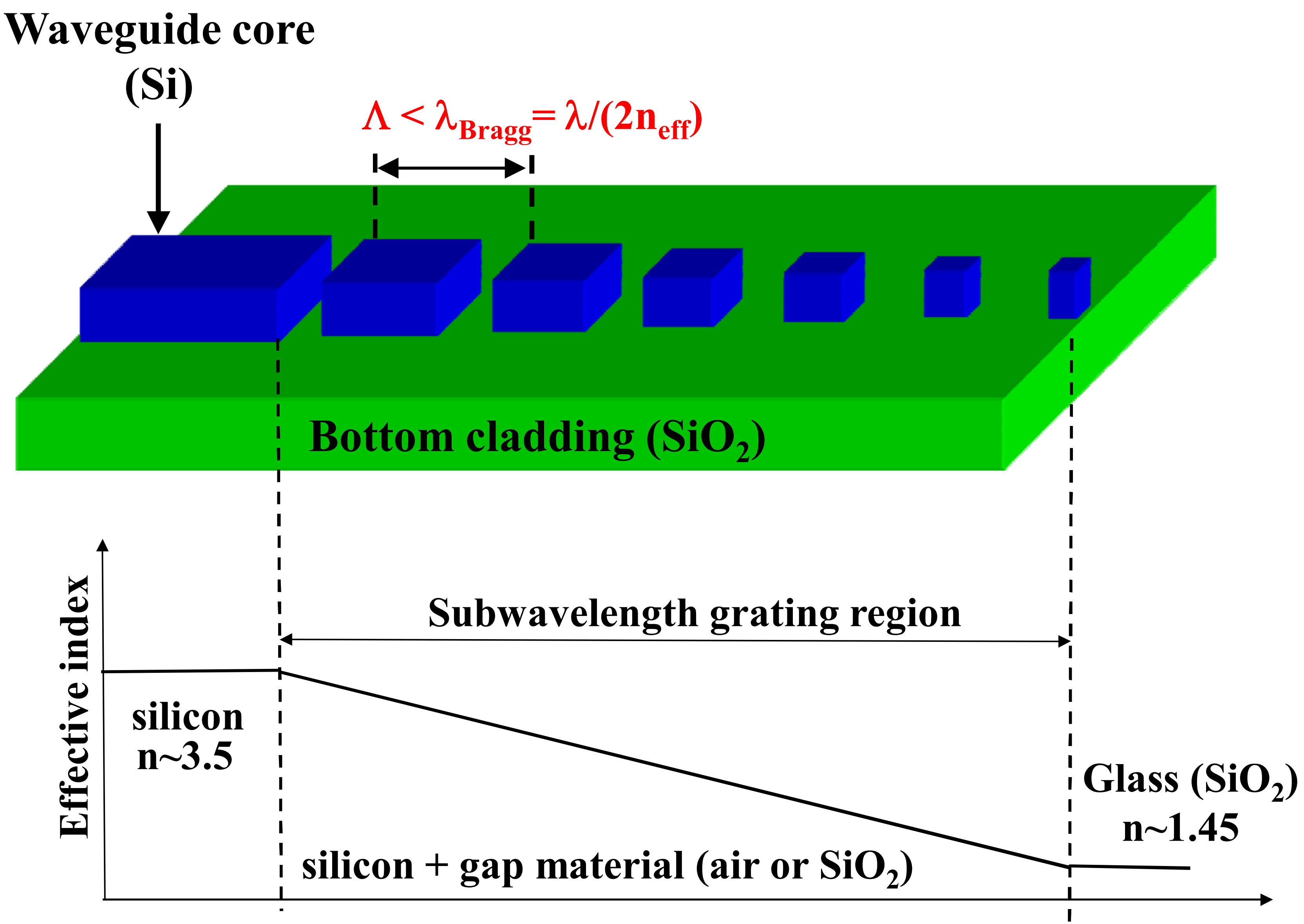


P. Cheben et al., Optics Express, vol. 14, 4695-4702 (2006)

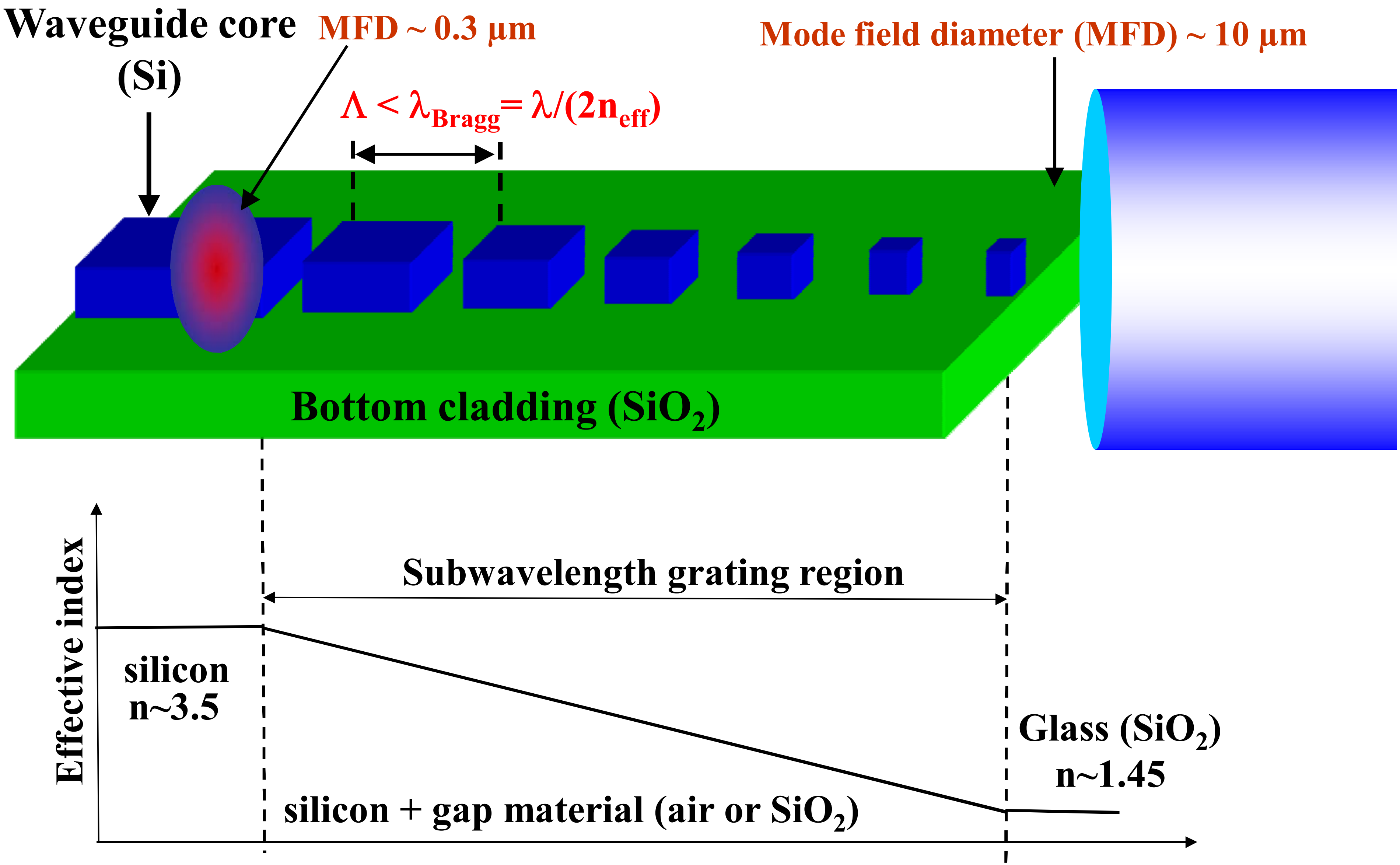
Subwavelength grating fiber-chip coupler



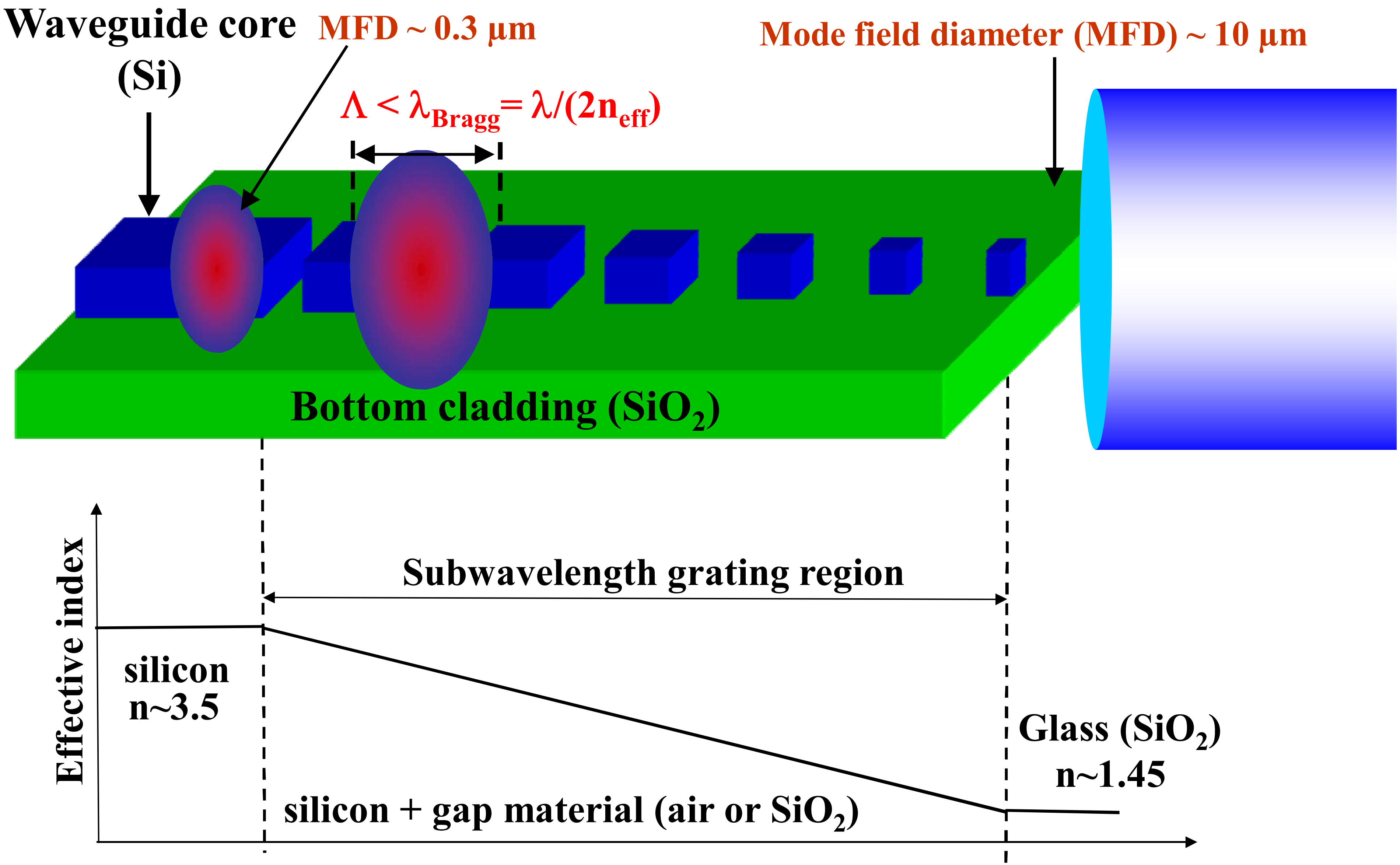
Subwavelength grating fiber-chip coupler



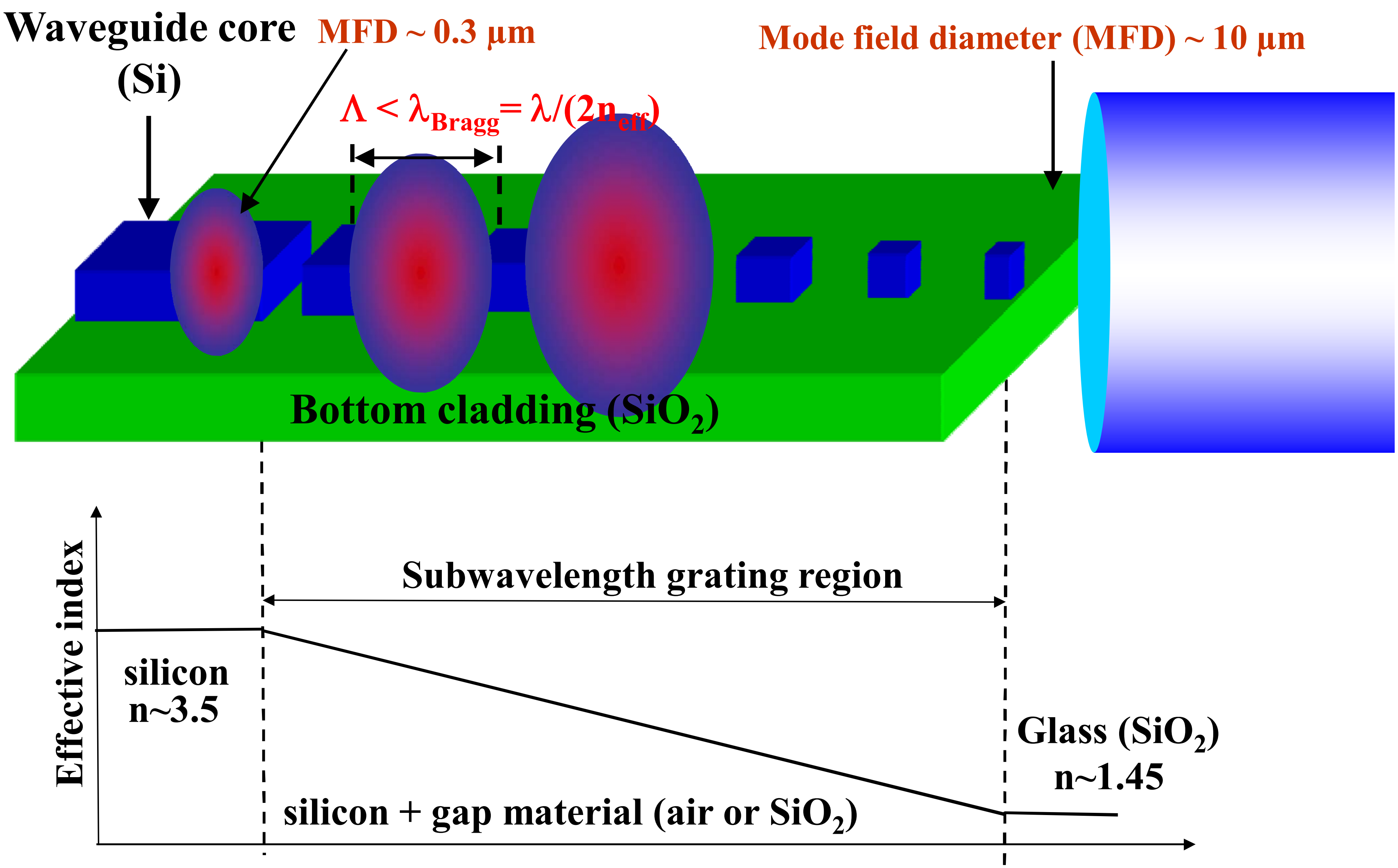
Subwavelength grating fiber-chip coupler



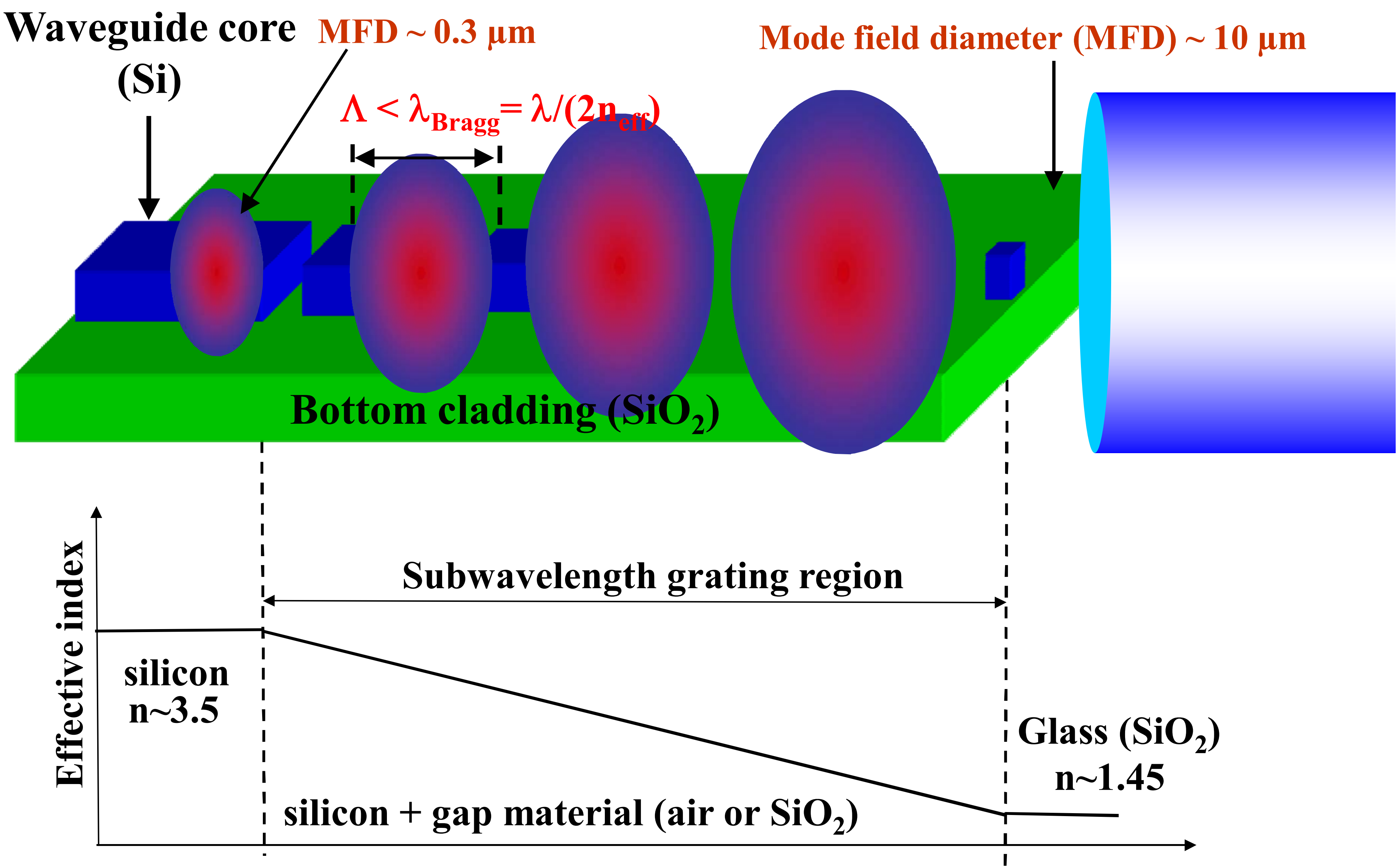
Subwavelength grating fiber-chip coupler



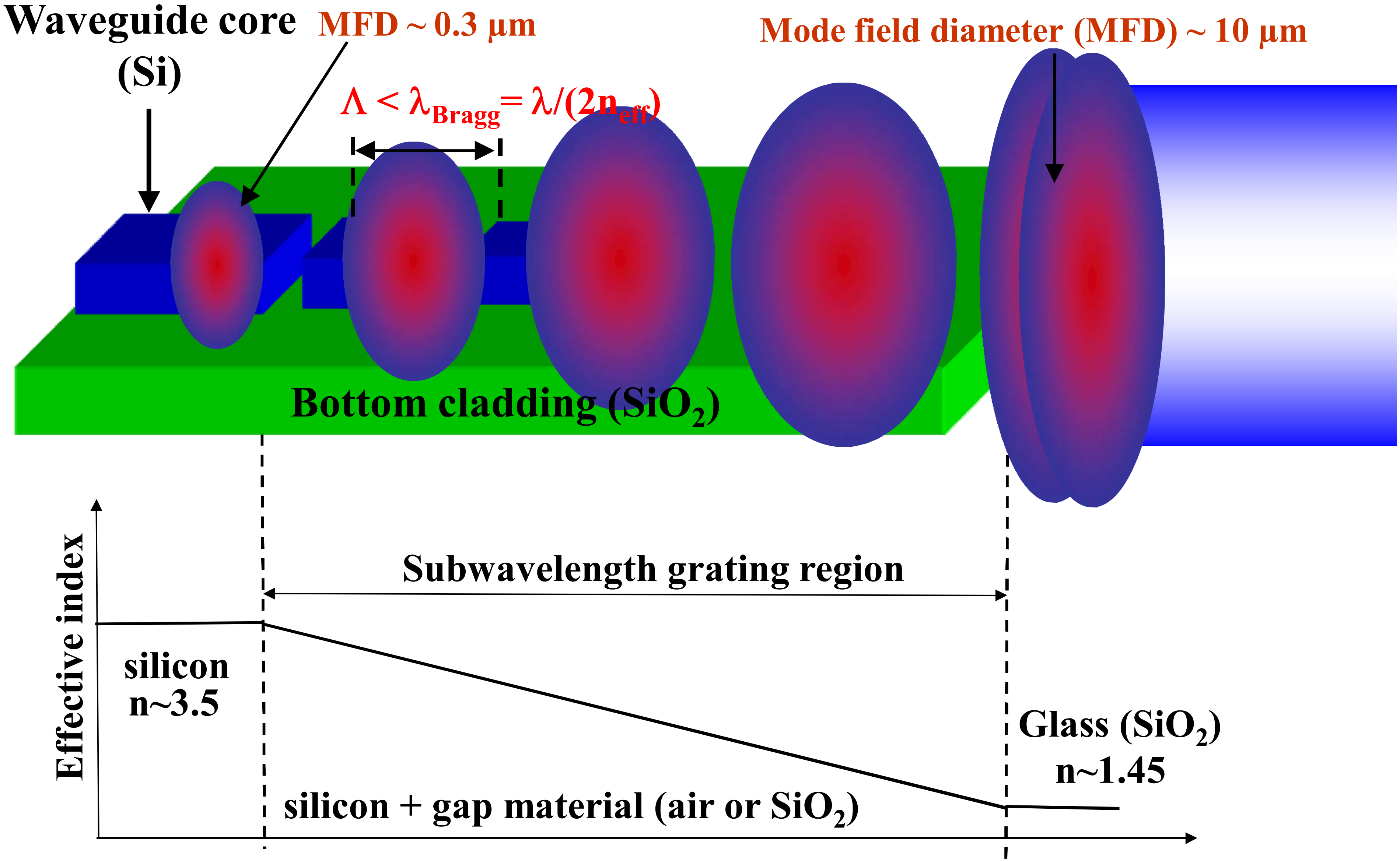
Subwavelength grating fiber-chip coupler



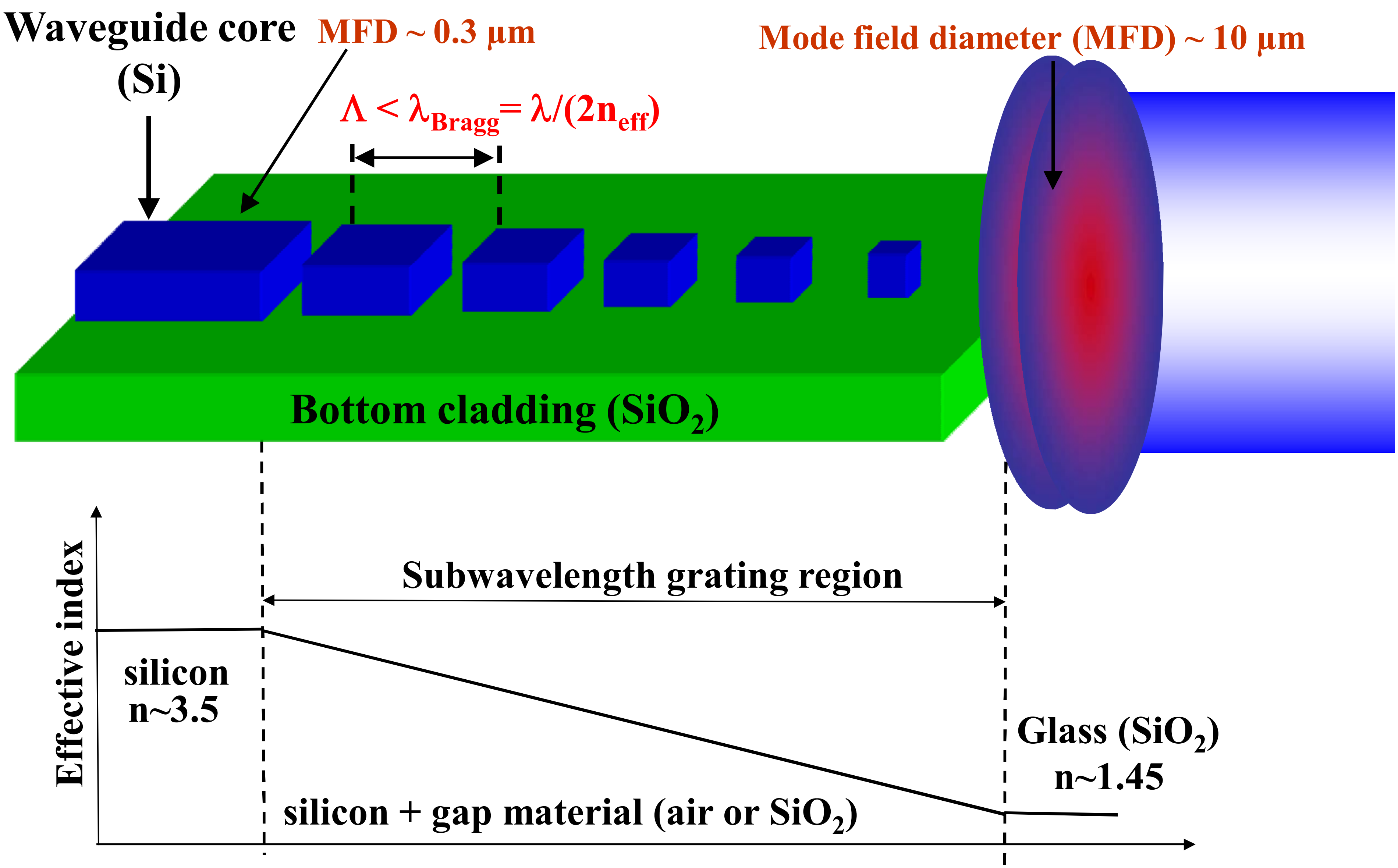
Subwavelength grating fiber-chip coupler



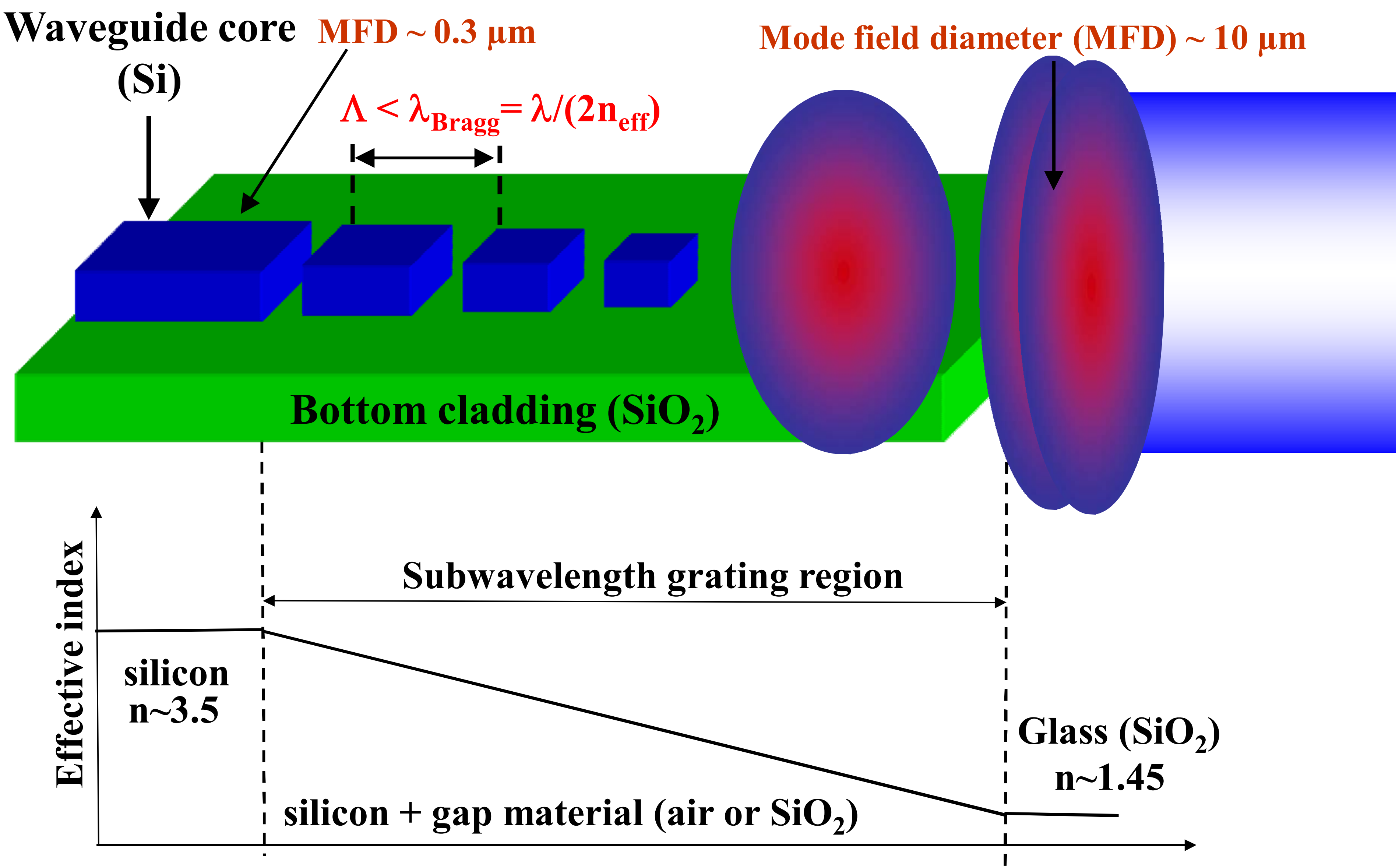
Subwavelength grating fiber-chip coupler



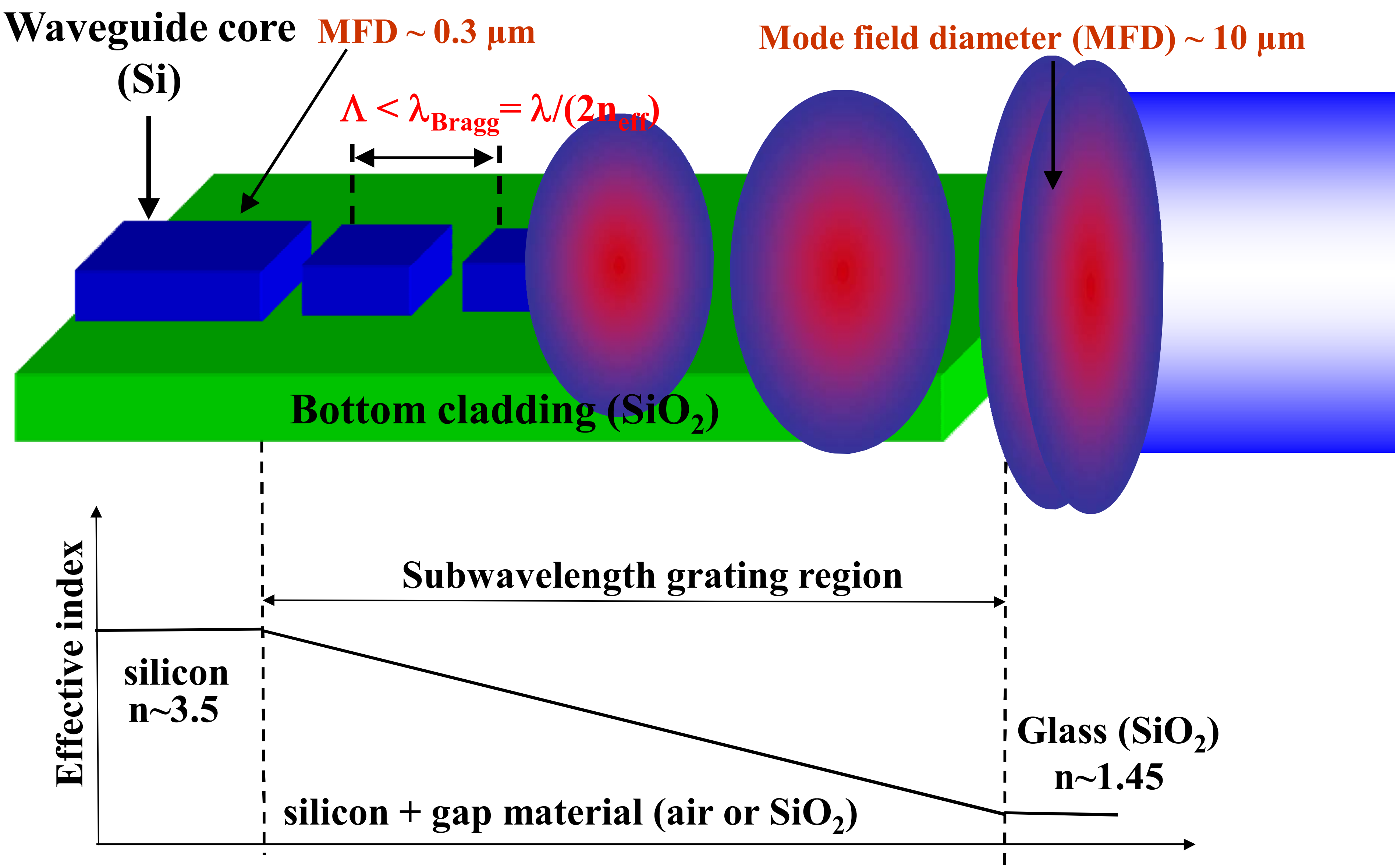
Subwavelength grating fiber-chip coupler



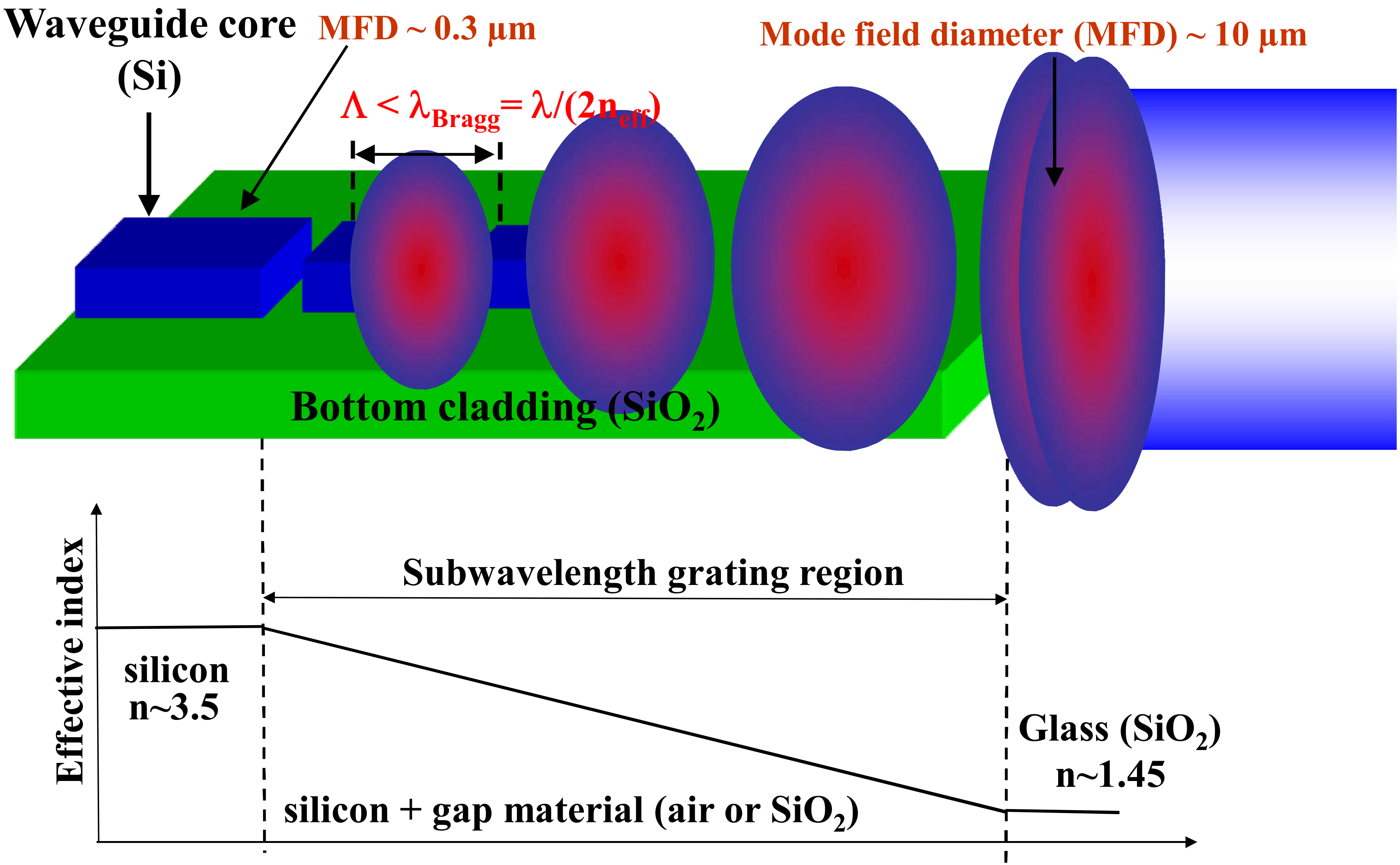
Subwavelength grating fiber-chip coupler



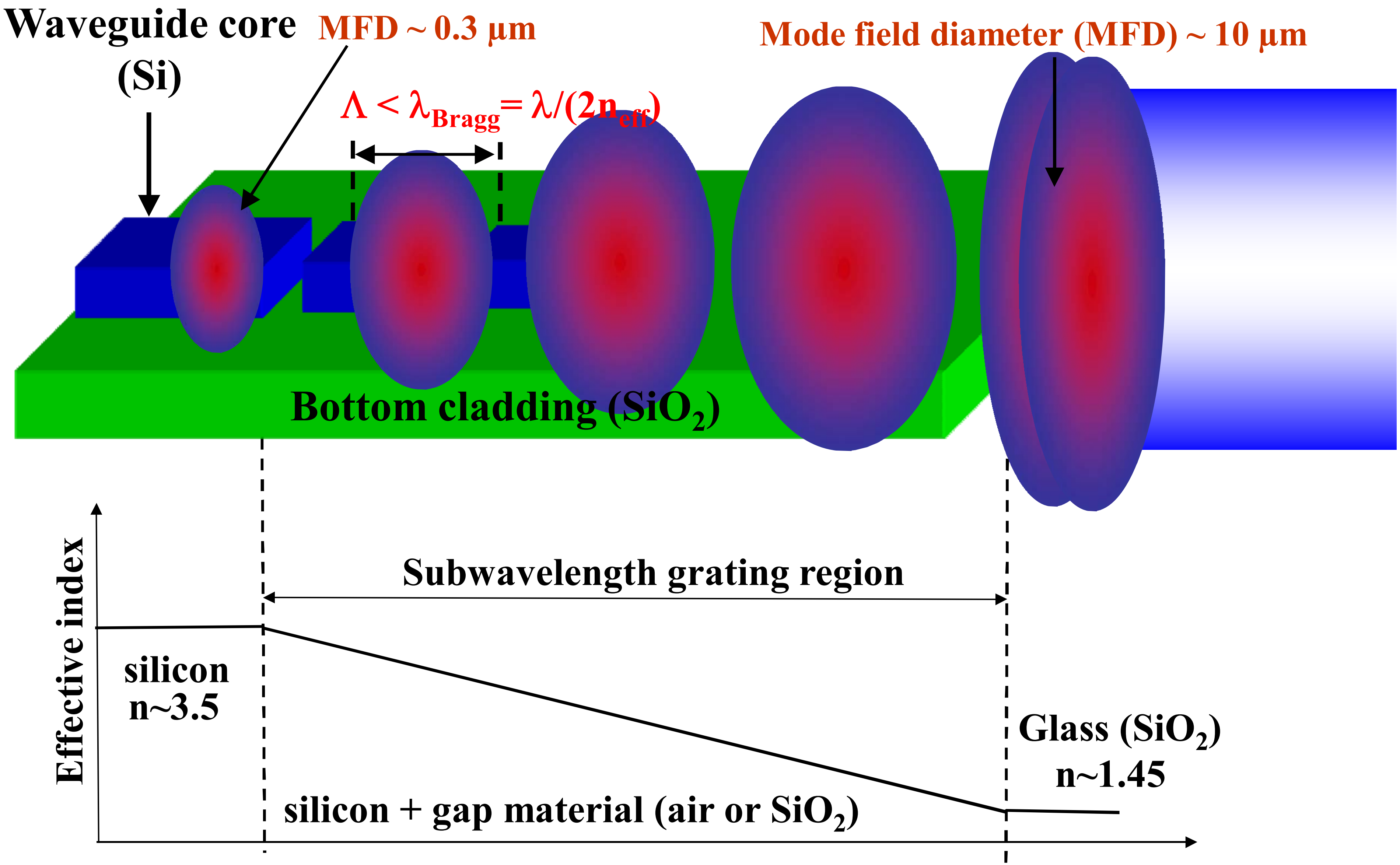
Subwavelength grating fiber-chip coupler



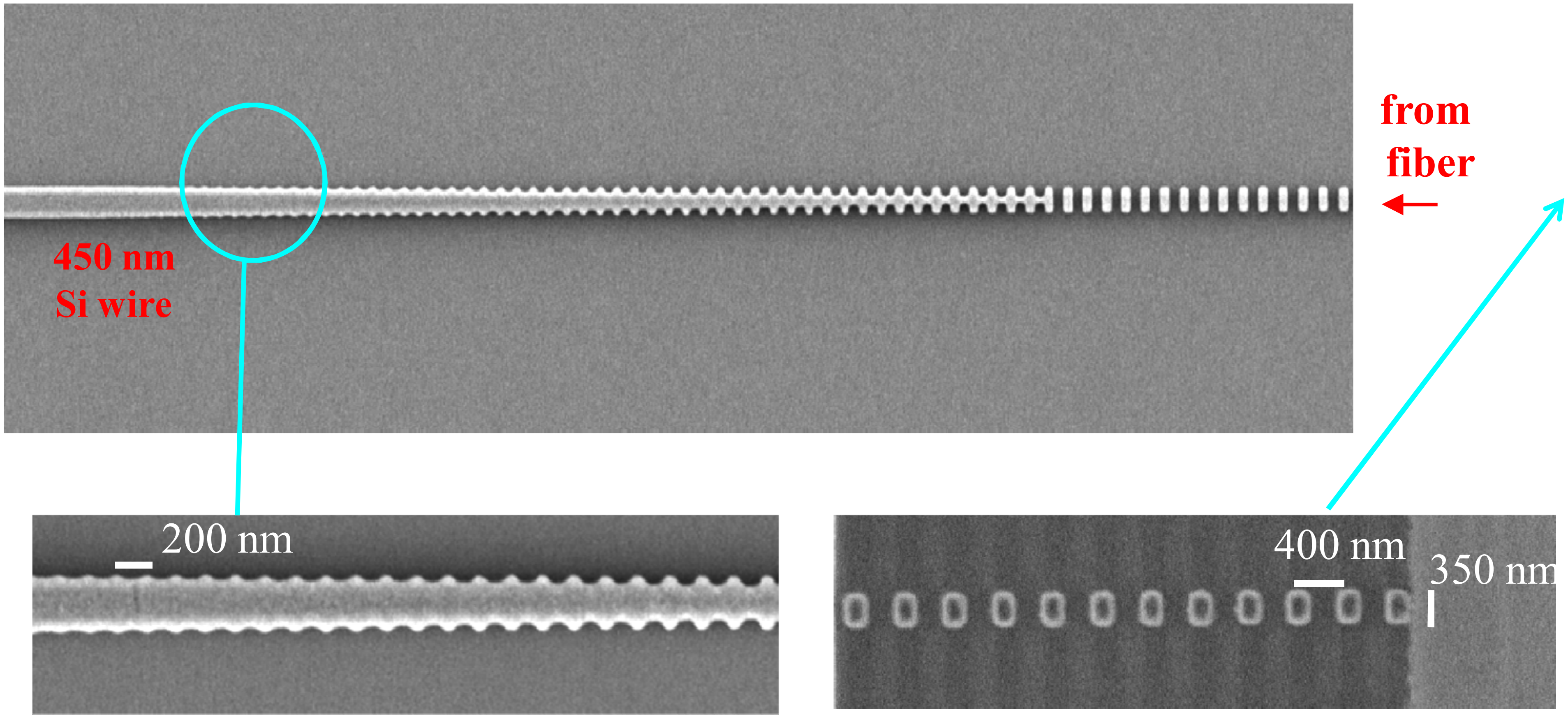
Subwavelength grating fiber-chip coupler



Subwavelength grating fiber-chip coupler



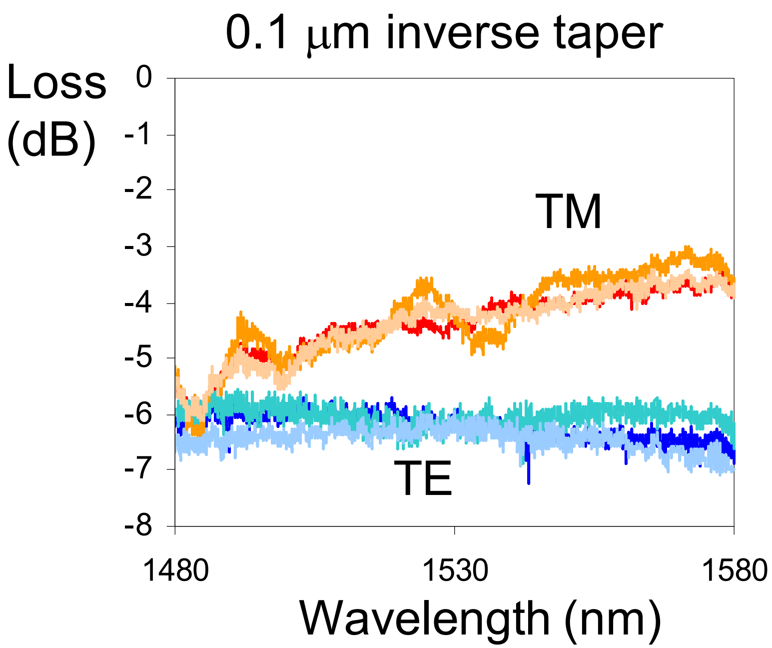
Subwavelength grating fiber-chip coupler

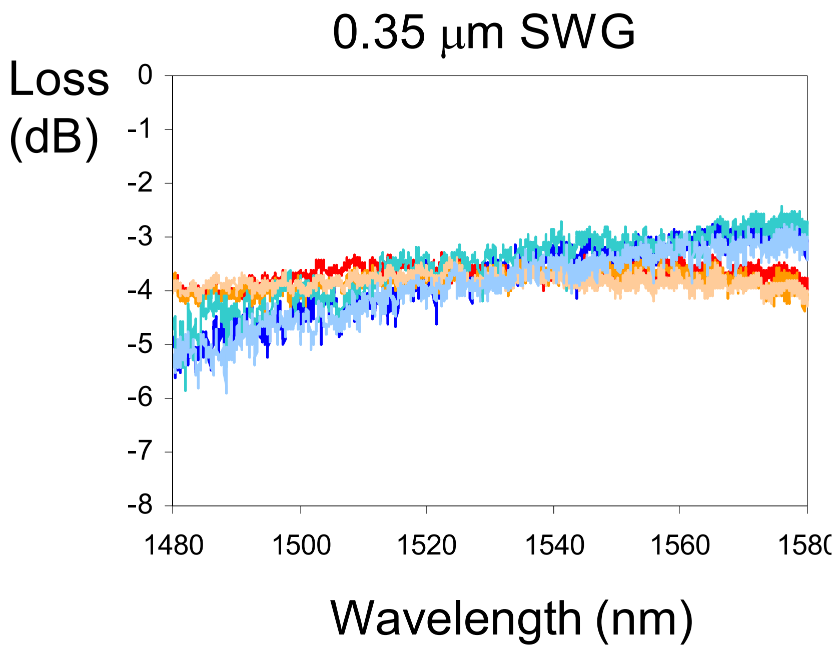


Minimum feature size 100 nm
Compatible with deep UV (193 nm) lithography

P. Cheben et al., Opt. Lett., vol. 35, p. 2526, August 2010

SWG fiber-chip coupling experiment





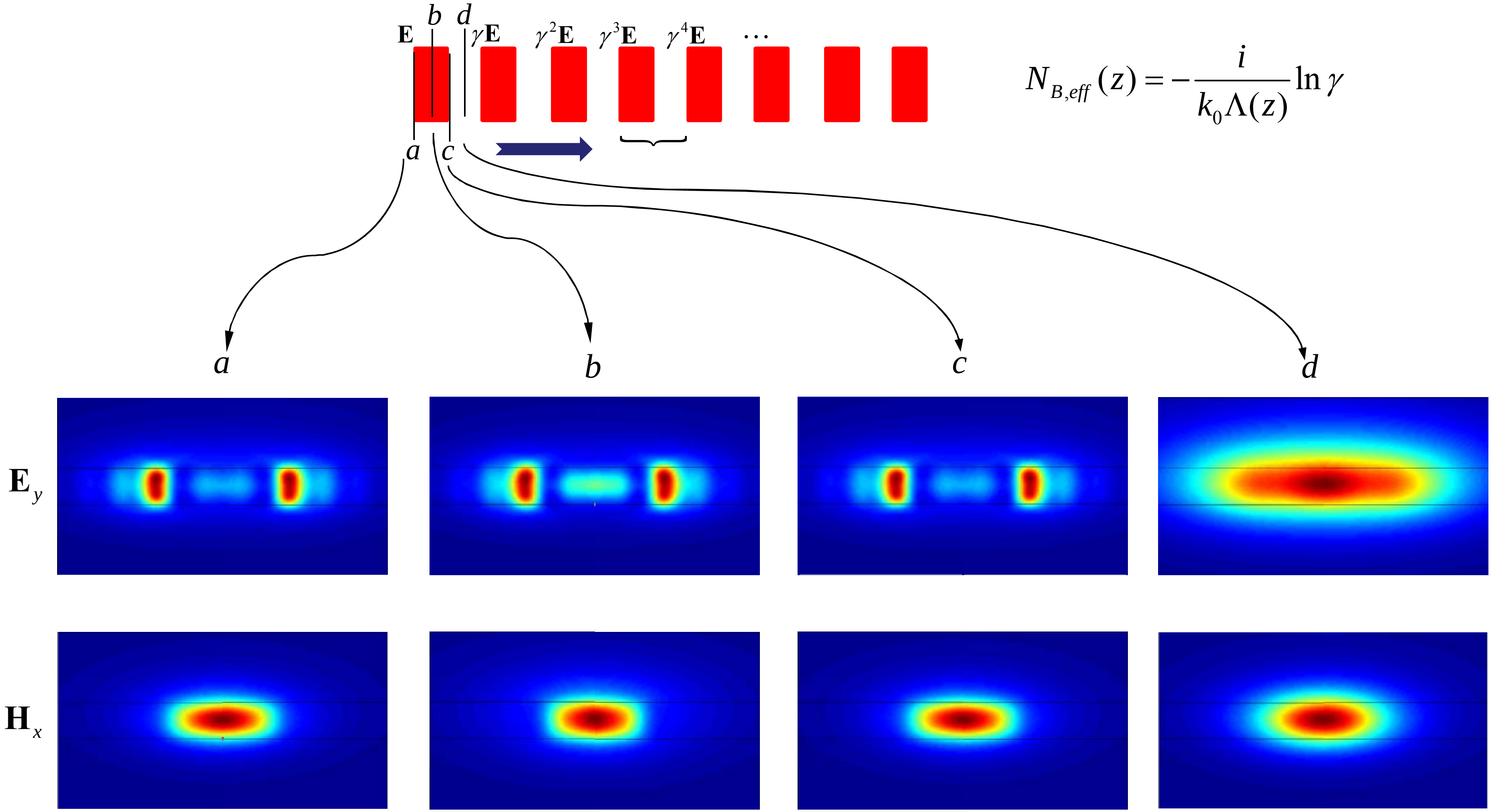
(+ insertion loss of 5 mm long photonic wire waveguide)

Advantages of SWG coupler:
- Coupling loss: -0.9 dB for TE and -1.5 dB for TM
- Broadband
- Robust: >3x larger tip width compared to the inverse taper
  -0.1 dB coupling loss penalty for a 50 nm width change

P. Cheben et al., Opt. Lett., vol. 35, p. 2526, August 2010

FORWARD-PROPAGATING BLOCH MODE

in the output periodic SWG waveguide



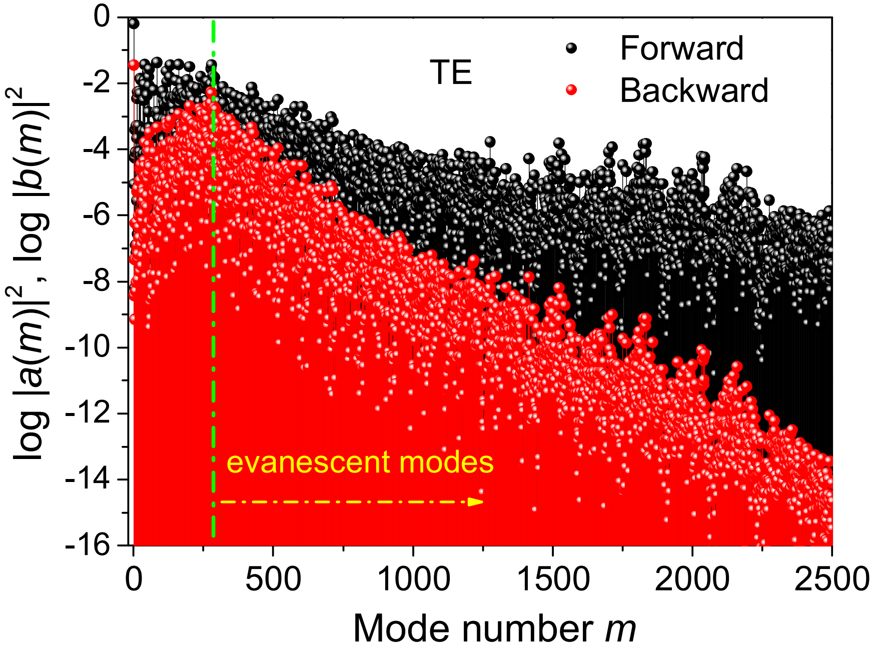
$$N_{B,eff}(z) = -\frac{i}{k_0 \Lambda(z)} \ln \gamma$$

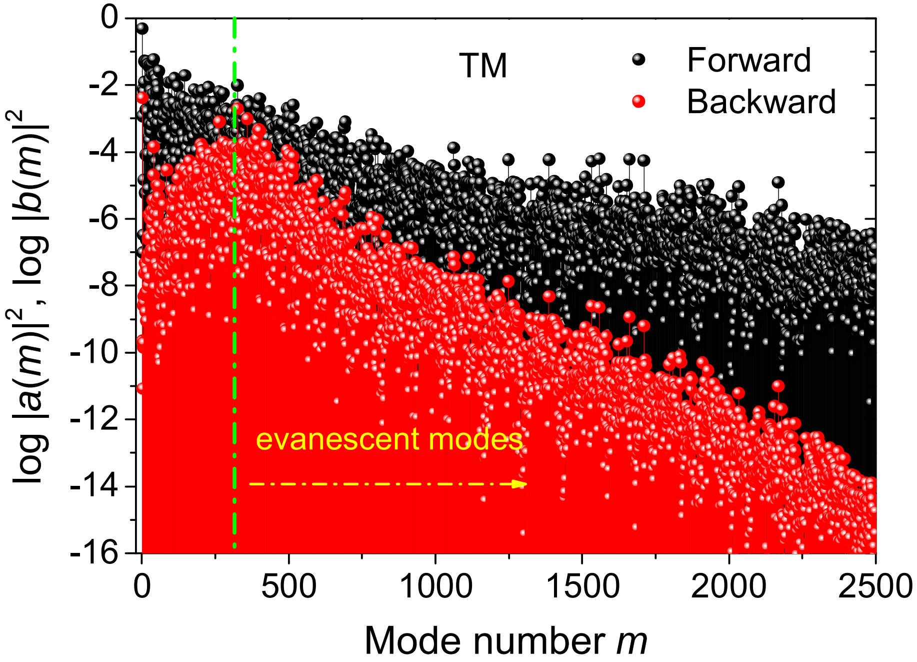
J. Čtyroký, P. Kwiecien, I. Richter, P. Cheben, SPIE Proc. Optics and Optoelectronics, 2013

EXPANSION OF THE BLOCH MODE

into the forward and backward local normal modes

Amplitudes of the modes of the Si nanowire 350×260 nm





Bi-directional mode Expansion propagation method (BEP)

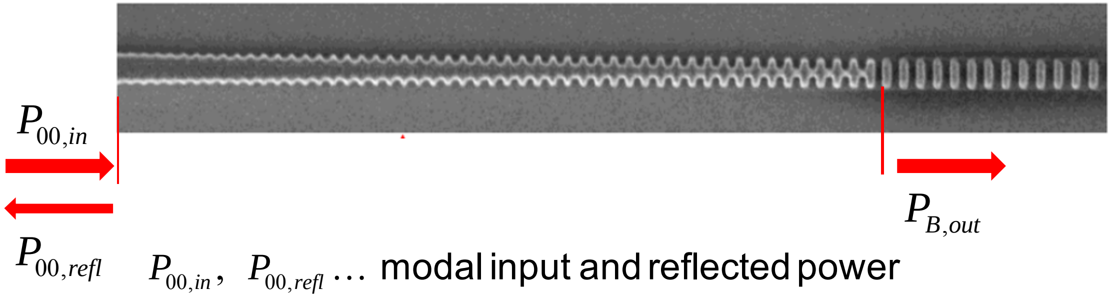
2D: J. Čtyroký, *J. LightwaveTechnol.* vol. 25, pp. 2321-2330, 2007.
J. Čtyroký, P. Kwiecien, and I. Richter, *J. LightwaveTechnol.* vol. 28, pp. 2969-2976, 2010.

3D: J. Čtyroký, *J. LightwaveTechnol.* vol. 30, pp. 3699-3708, 2012.

Since dimensions are sub-wavelength, contributions of evanescent modes are important

J. Čtyroký, P. Kwiecien, I. Richter, P. Cheben, SPIE vol. 8781, p. 87810B-1 (2013)

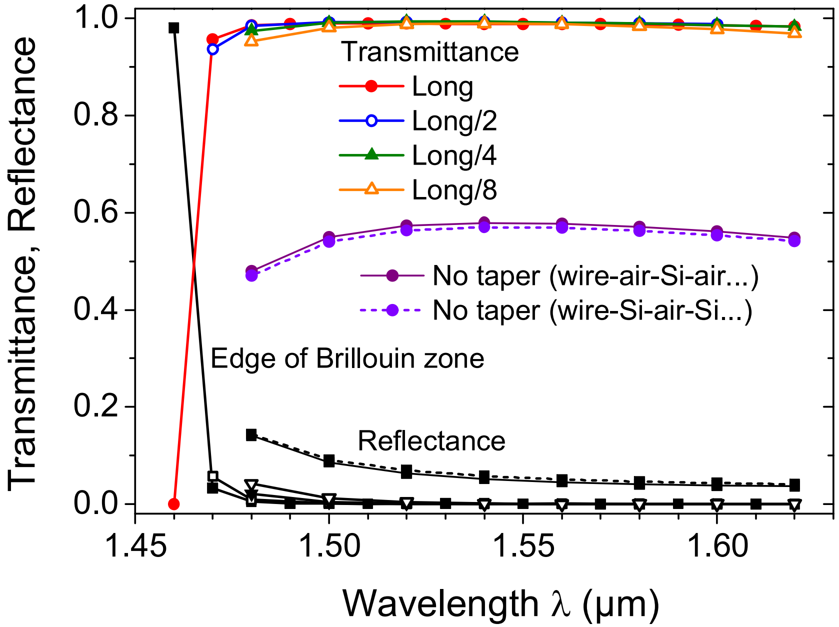
TRANSMITTANCE AND REFLECTANCE OF THE NANOWIRE TO SWGW COUPLER



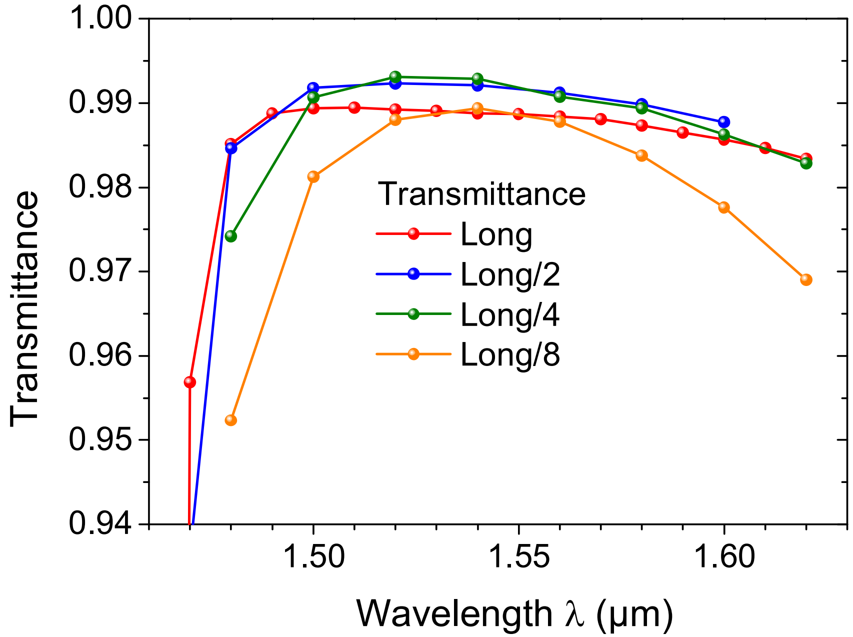
$$T = \frac{P_{B,out}}{P_{00,in}}, \quad R = \frac{P_{00,refl}}{P_{00,in}}$$

$P_{00,in}$, $P_{00,refl}$ … modal input and reflected power

$P_{B,out}$ … power of the fundamental forward Bloch mode

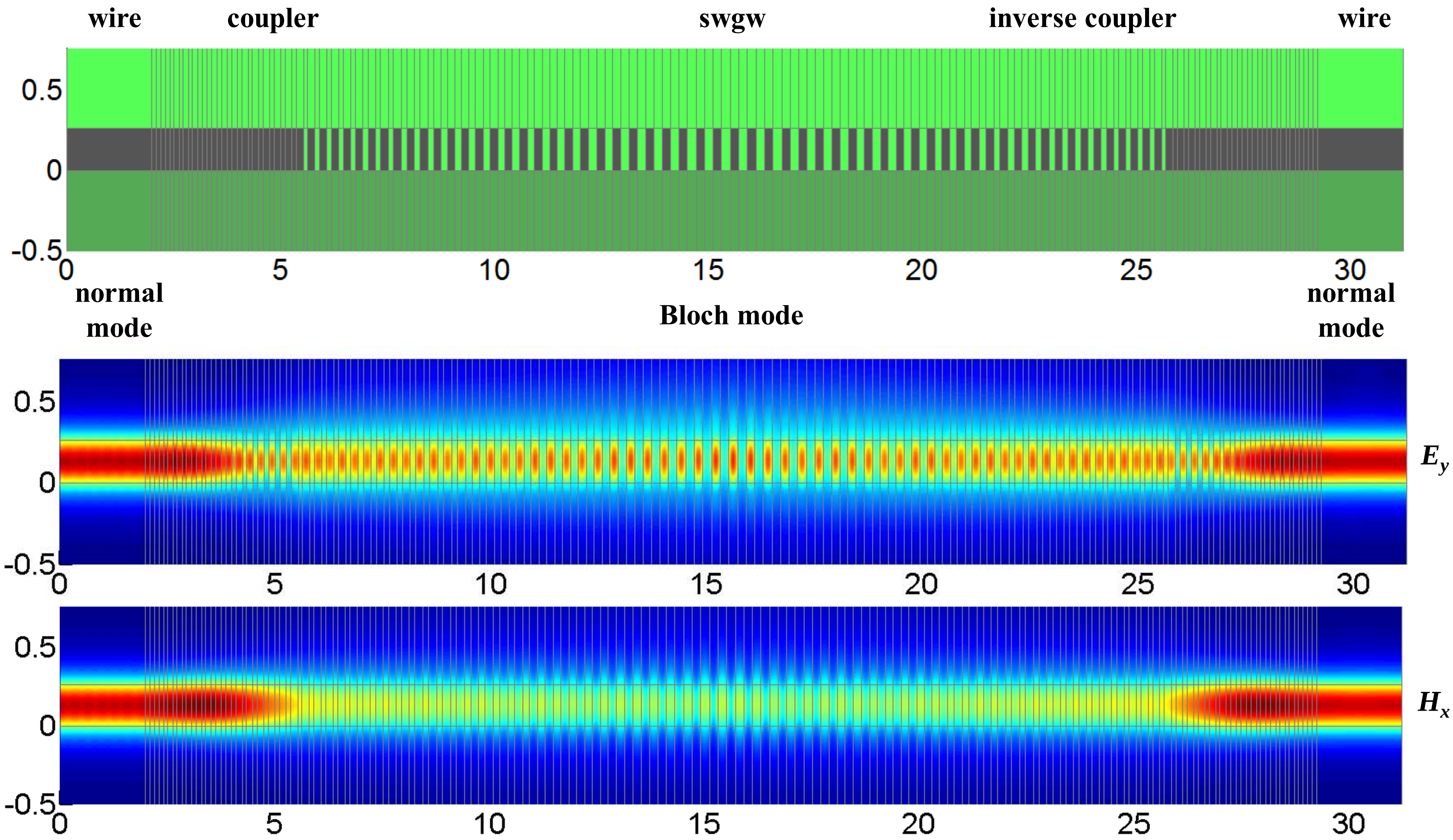


TE polarization



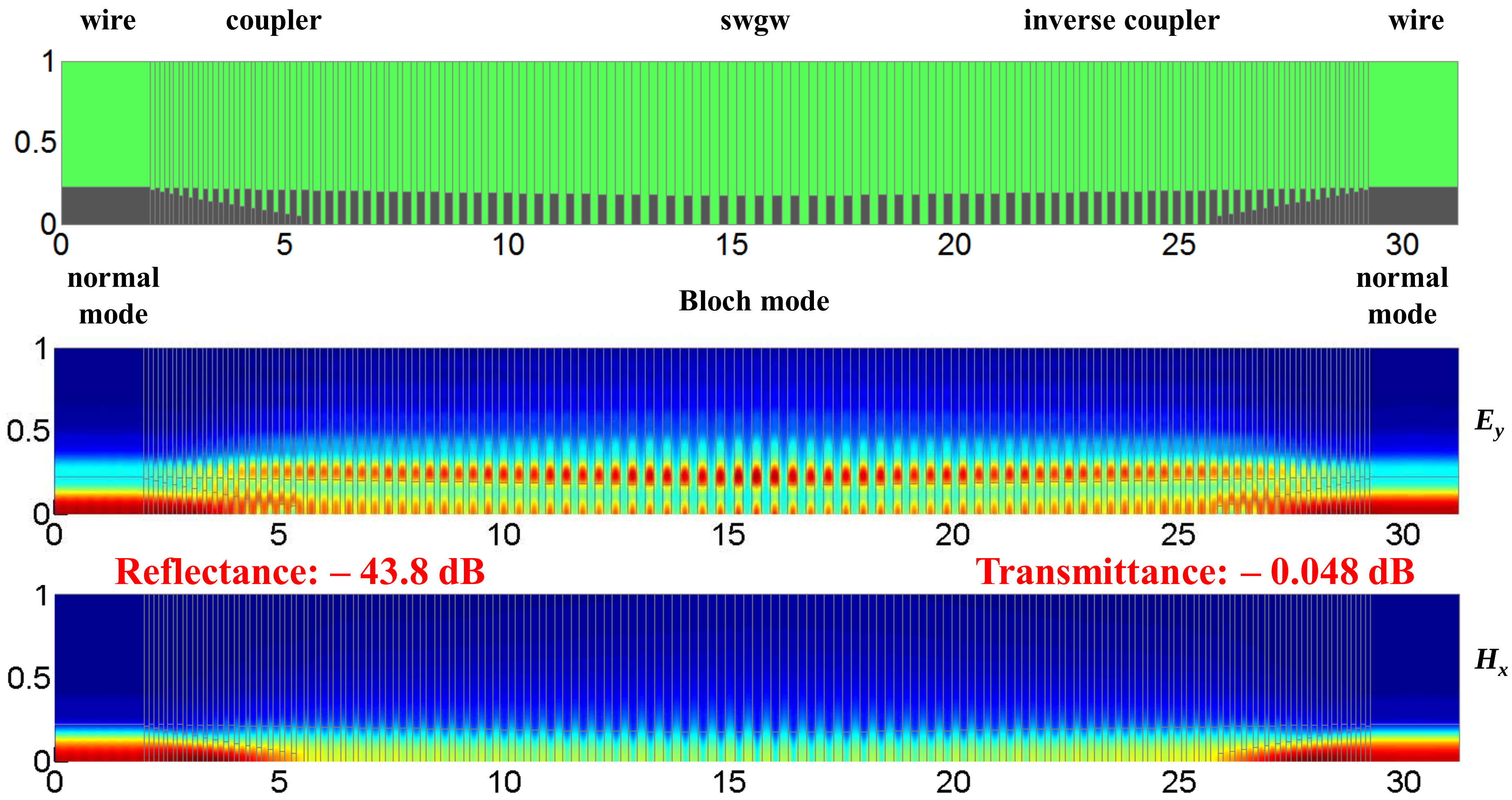
J. Čtyroký, P. Kwiecien, I. Richter, P. Cheben, SPIE Proc. Optics and Optoelectronics, 2013

TE_{00} MODE FIELD DISTRIBUTION IN THE long/4 BI-COUPLER: SIDE VIEW



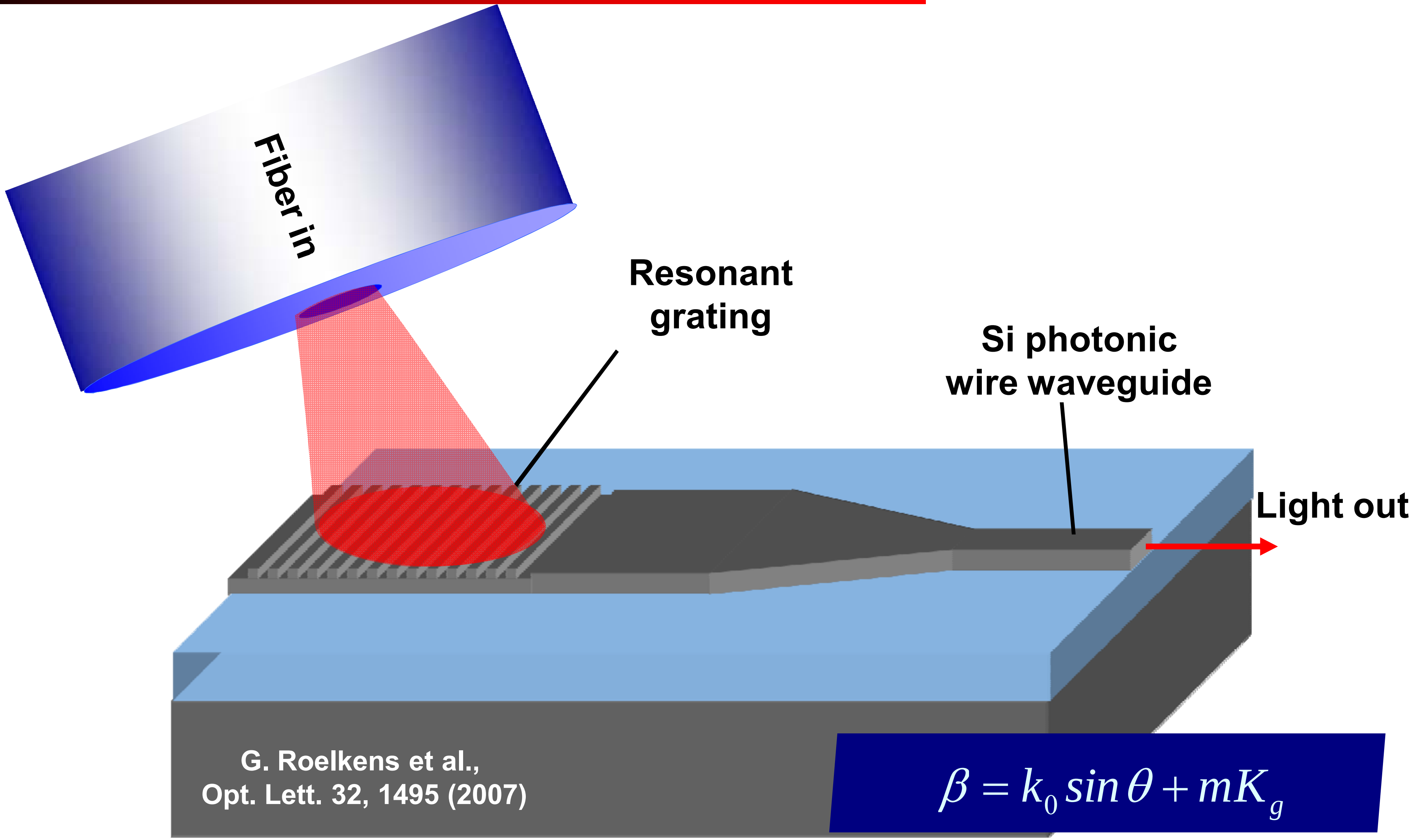
J. Čtyroký, P. Kwiecien, I. Richter, P. Cheben, SPIE Proc. Optics and Optoelectronics, 2013

TE_{00} MODE FIELD DISTRIBUTION IN THE long/4 BI-COUPLER: TOP VIEW (ONE HALF)

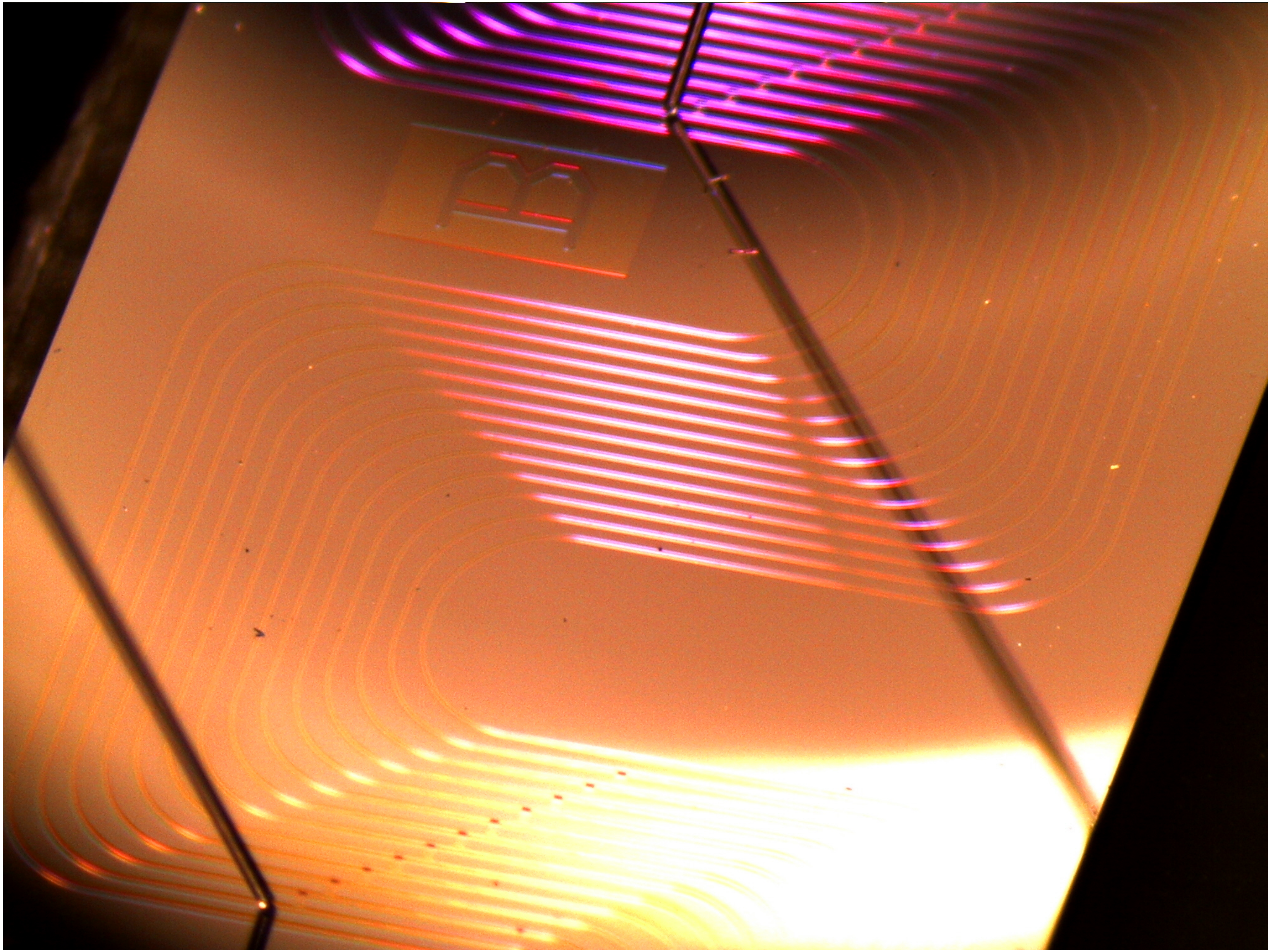


J. Čtyroký, P. Kwiecien, I. Richter, P. Cheben, SPIE Proc. Optics and Optoelectronics, 2013

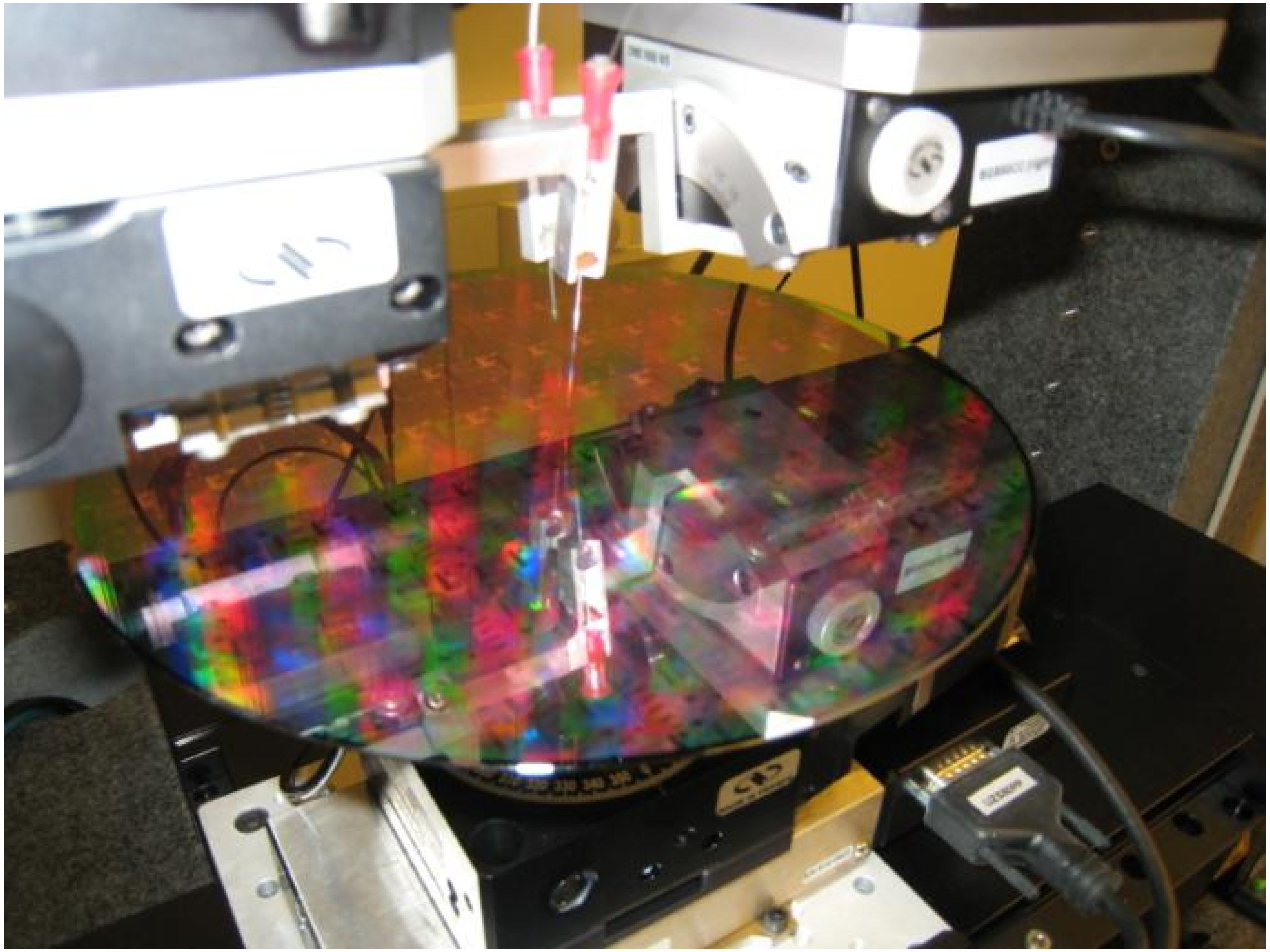
Surface grating couplers



- Eliminates the need for polished waveguide facets
- Makes it possible wafer scale testing of devices

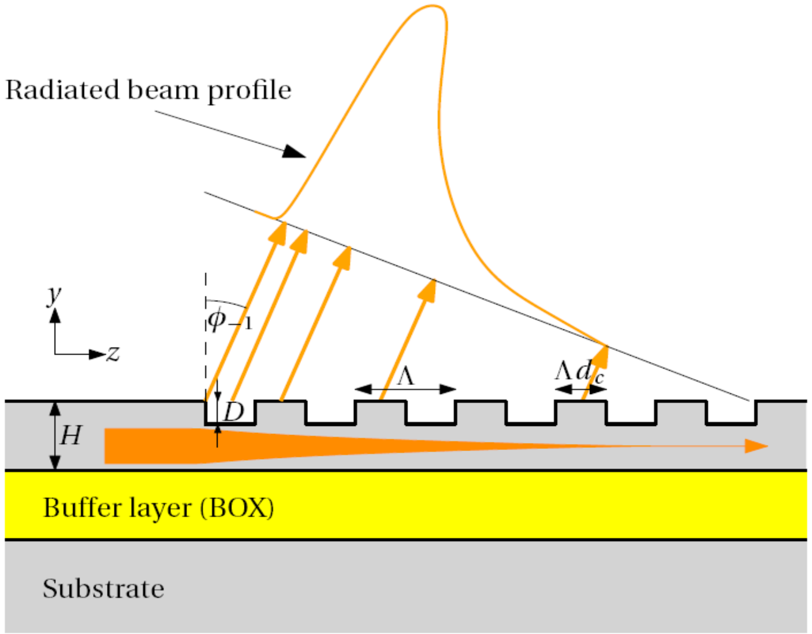


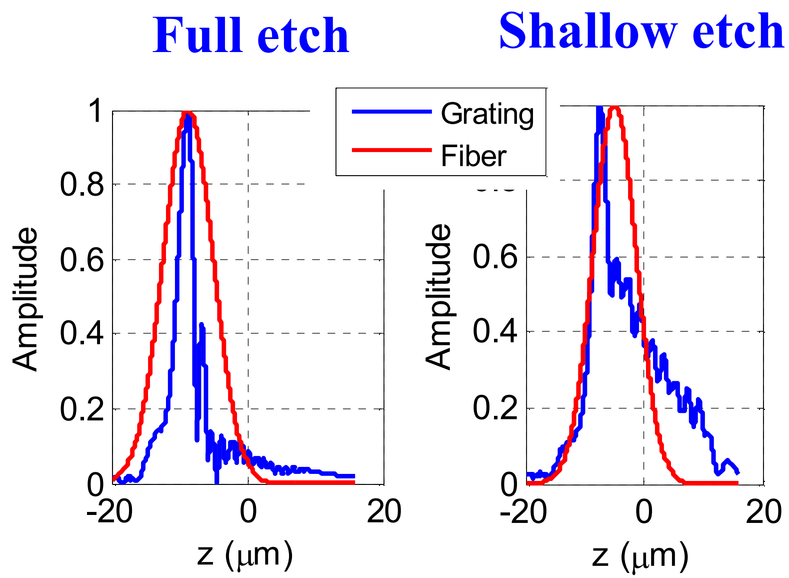
Automated wafer-scale measurement set-up



Courtesy: Prof. Roel Baets

Surface grating coupler basics

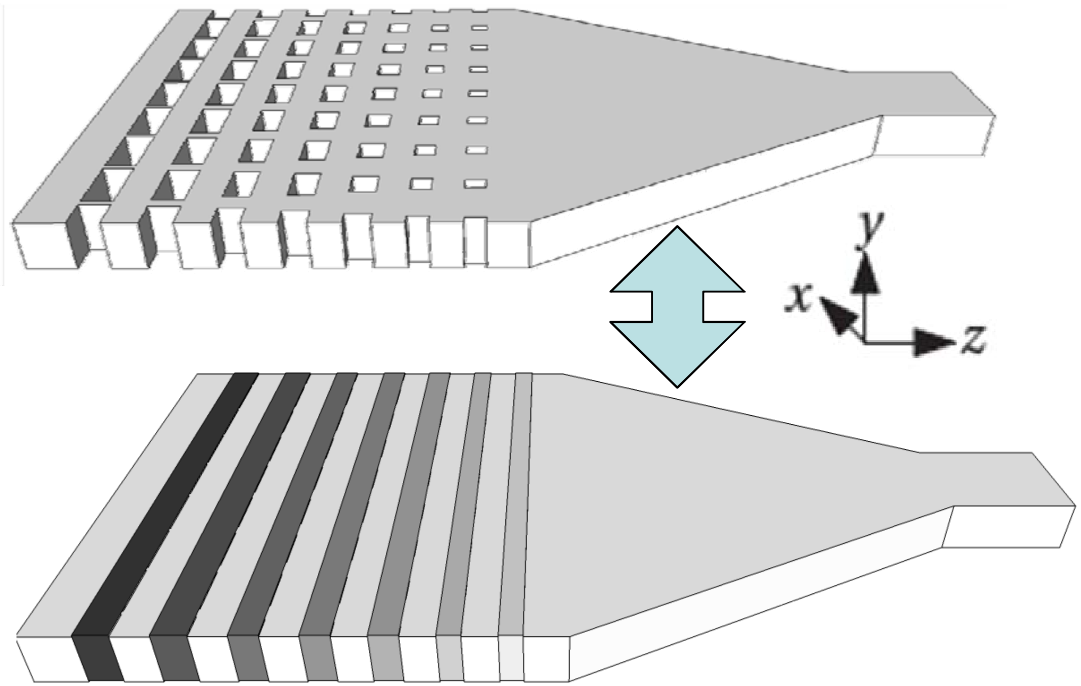




$$E(z) = \sum_{k=0}^{k=\infty} f(z - k\Lambda)\, e^{(\alpha_0 + j\beta_0)k}$$

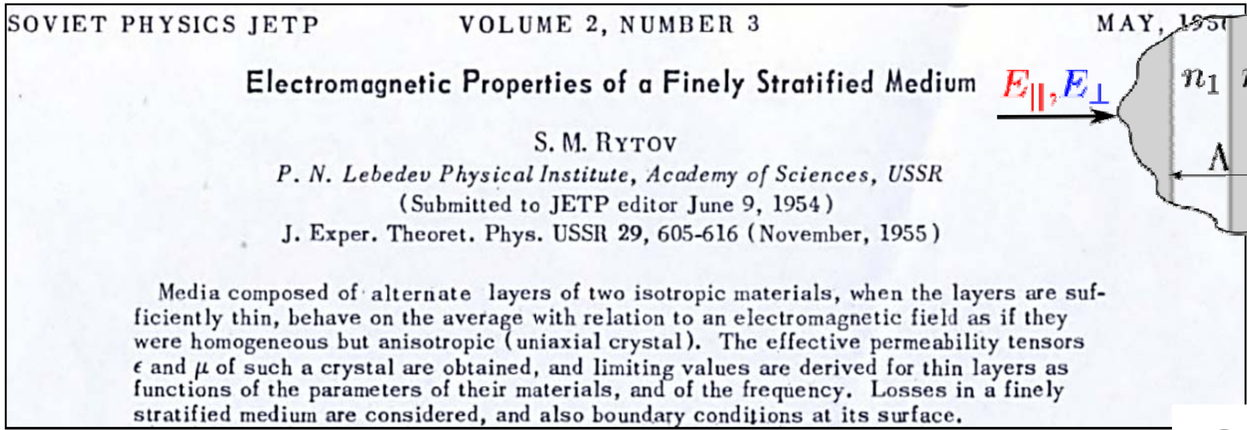
- Periodic perturbation ⇨ One of the harmonics radiates.
- Grating "strength" depends on etch depth ⇨ shallow etch for field matching with SMF-28

Subwavelength patterned surface grating coupler



- Diffractive grating along the z-direction
- Non-diffractive SWG along x-direction emulates shallow etch
- With SWG a range of effective refractive indexes can be created
- Control of grating strength - apodization
- One fabrication step required for coupler and waveguides

Designing with SWGs


SOVIET PHYSICS JETP VOLUME 2, NUMBER 3 MAY, 1956

Electromagnetic Properties of a Finely Stratified Medium

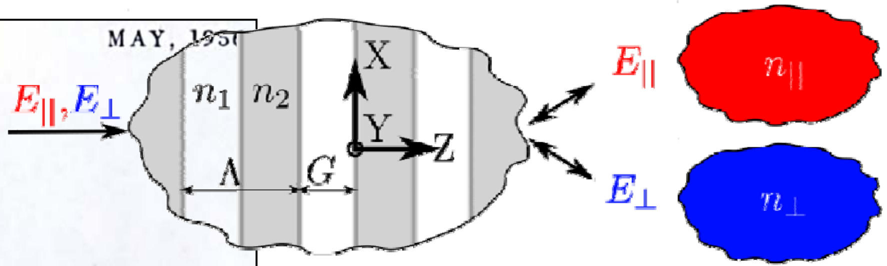
S. M. RYTOV

P. N. Lebedev Physical Institute, Academy of Sciences, USSR

(Submitted to JETP editor June 9, 1954)

J. Exper. Theoret. Phys. USSR 29, 605-616 (November, 1955)

Media composed of alternate layers of two isotropic materials, when the layers are sufficiently thin, behave on the average with relation to an electromagnetic field as if they were homogeneous but anisotropic (uniaxial crystal). The effective permeability tensors ϵ and μ of such a crystal are obtained, and limiting values are derived for thin layers as functions of the parameters of their materials, and of the frequency. Losses in a finely stratified medium are considered, and also boundary conditions at its surface.

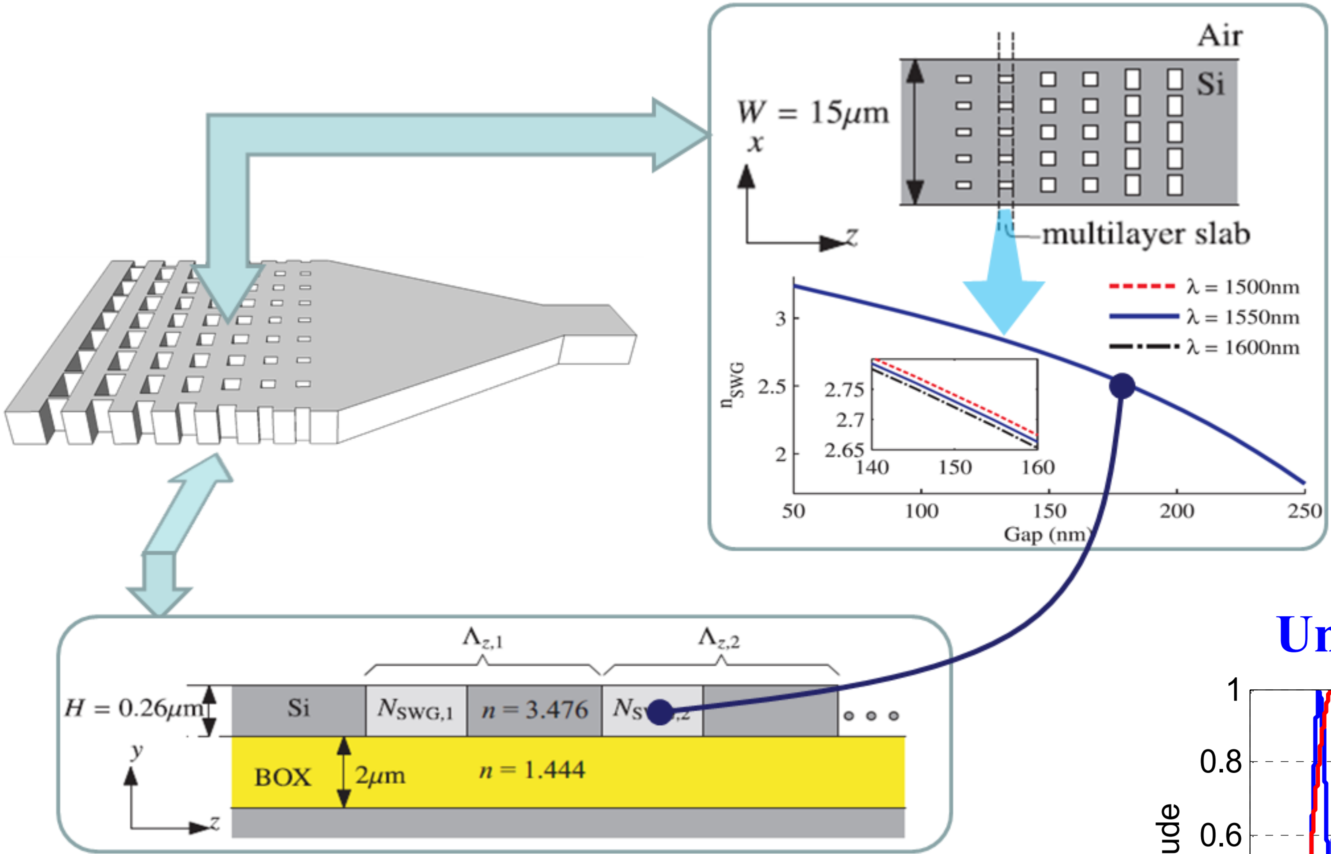


$$n_{\|}^2 = \frac{G}{\Lambda} n_1^2 + \frac{\Lambda - G}{\Lambda} n_2^2$$

$$n_{\perp}^2 = \left[\frac{G}{\Lambda} n_1^{-2} + \frac{\Lambda - G}{\Lambda} n_2^{-2} \right]^{-1}$$

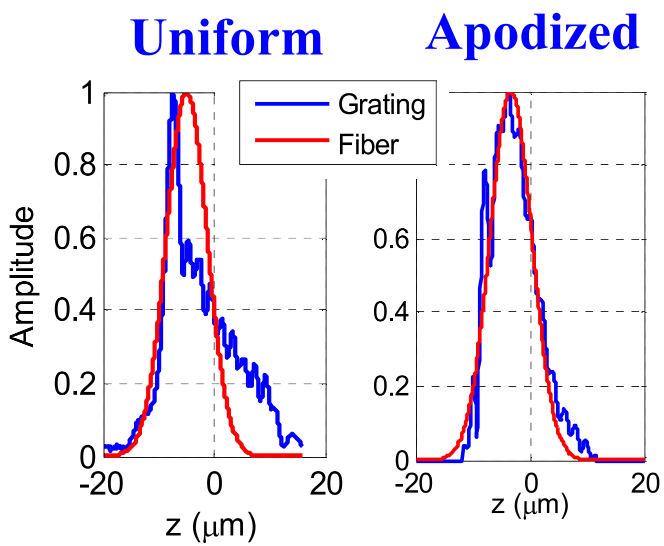
- Rytov's formulas, assume bulk media.
- Highly birefringent material.
- Simulation software is needed to account for waveguiding effects (higher order Floquet modes).
- *CAMFR* (P. Bienstman, Univ. of Ghent), *BEP* (J. Ctyroky, Academy of Sciences of the Czech Republic), and tools (3D) developed by Philippe Lalanne.
- *Fexen* – Fourier expansion tool (Univ. of Malaga).
- Finite Difference Time Domain (FDTD)

Subwavelength surface grating coupler design



Coupling = P_{up} x Overlap

Power up: 55%

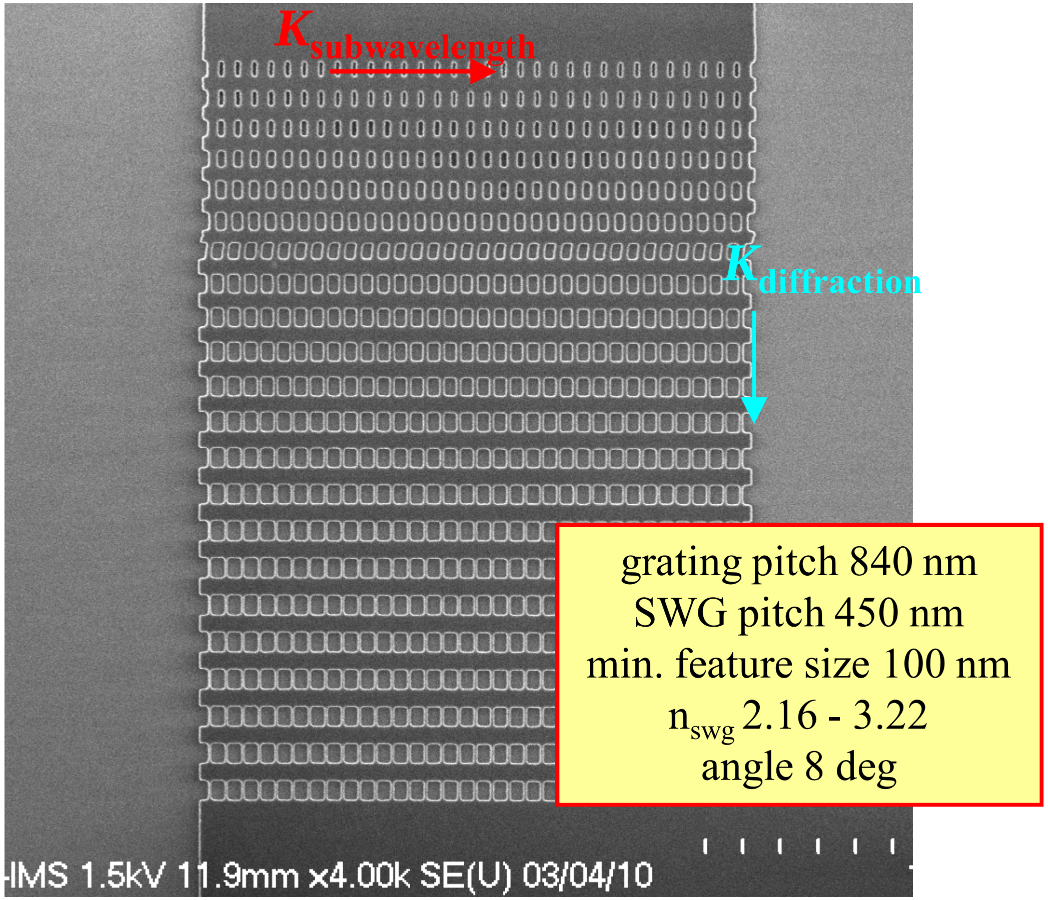


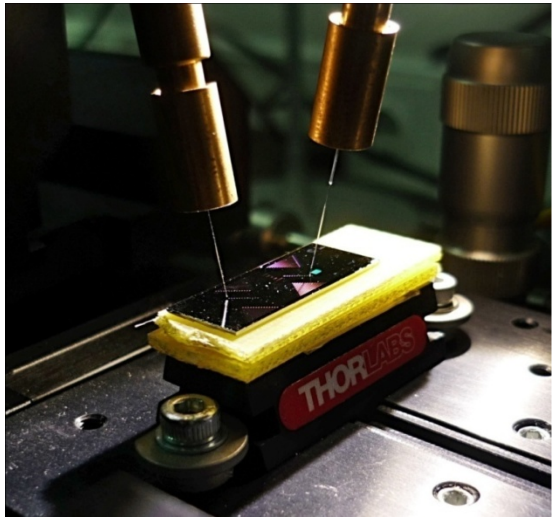
Uniform grating: design is straightforward.
Overlap integral with SMF-28 fiber mode is 75%
Apodization improves field overlap to 95%

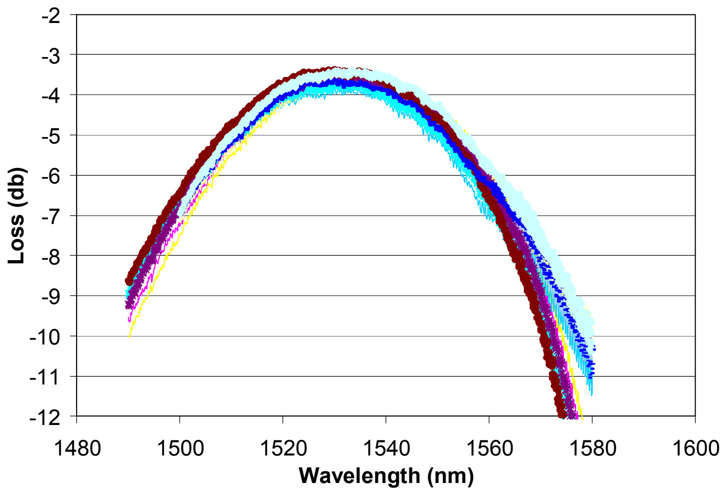
1) $N_{SWG,i}$ shapes amplitude
2) $\Lambda_{x,i}$ shapes phase front: has to be linear!

R. Halir, U of Malaga and NRC

Fabricated apodized SWG surface grating coupler







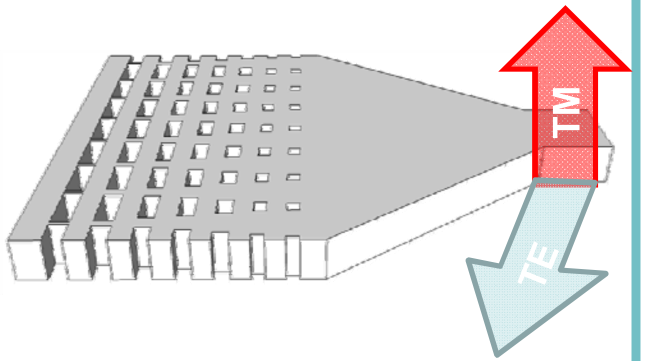
R. Halir et al., Opt. Lett., 34, 1408, 2009
R. Halir et al., Opt. Lett., 35, 3243, 2010

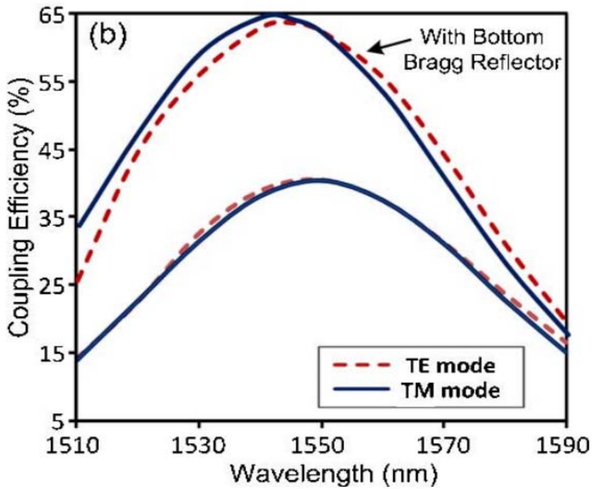
Chen et al., IEEE Photonics, 2009
Liu et al., Appl. Phys. Lett., 2010
Y. Ding, et al, Opt. Lett., vol. 38, pp. 2732-2735, Aug. 2013
X. Chen, et al, " Opt. Lett., vol. 37, pp. 3483–3485, 2012

Compatible with deep-UV 193 nm lithography

Some more SWG Grating Couplers

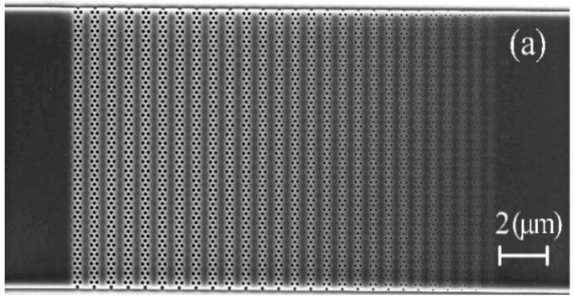
Polarization

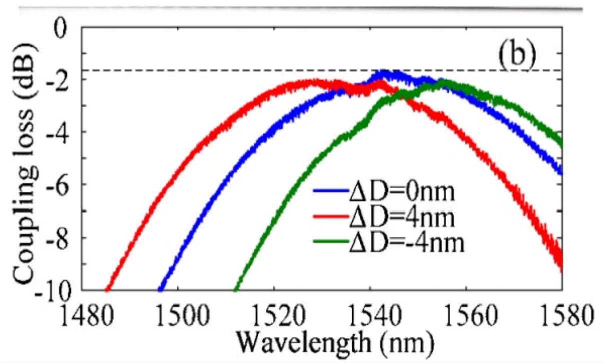




X. Chen et al, *Opt. Lett.*, vol. 36, no. 6, pp. 796–798, Mar 2011.

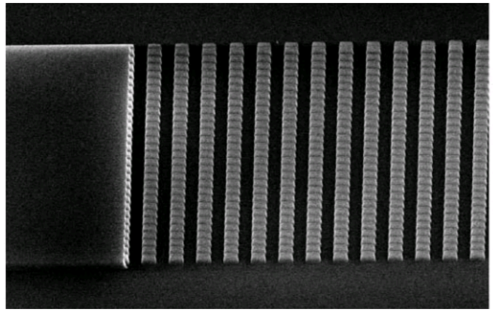
Efficiency

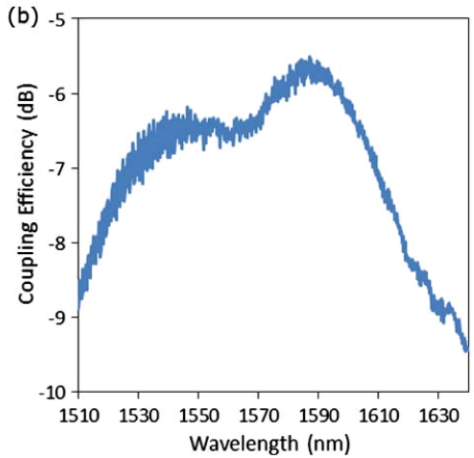




Y. Ding, et al, Opt. Lett., vol. 38, pp. 2732-2735, Aug. 2013

Bandwidth



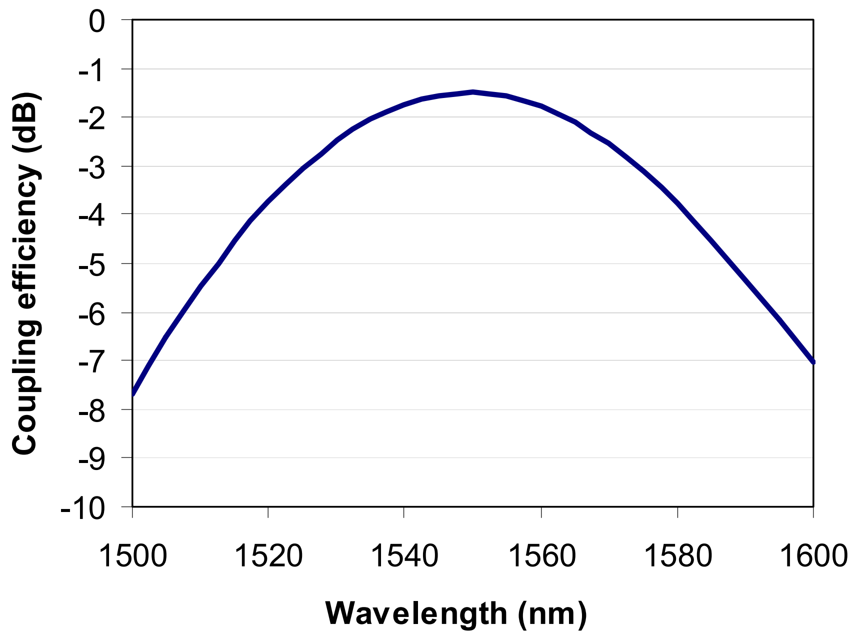


X. Chen, et al, " Opt. Lett., vol. 37, pp. 3483–3485, 2012

$$\beta = k_0 \sin\theta + mK_g$$

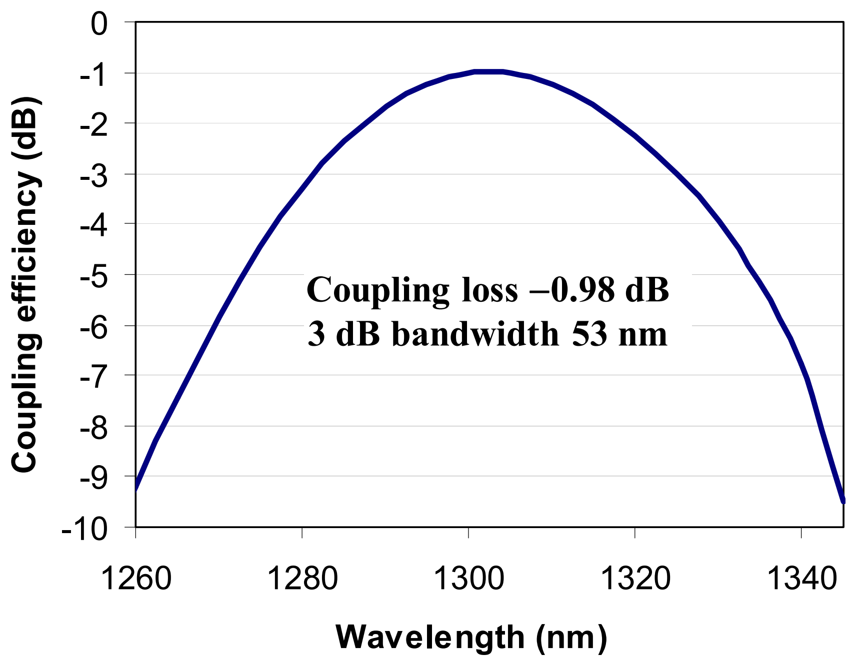
Recent design examples

1550 nm band



TE polarization, 220 nm silicon
One step full etch

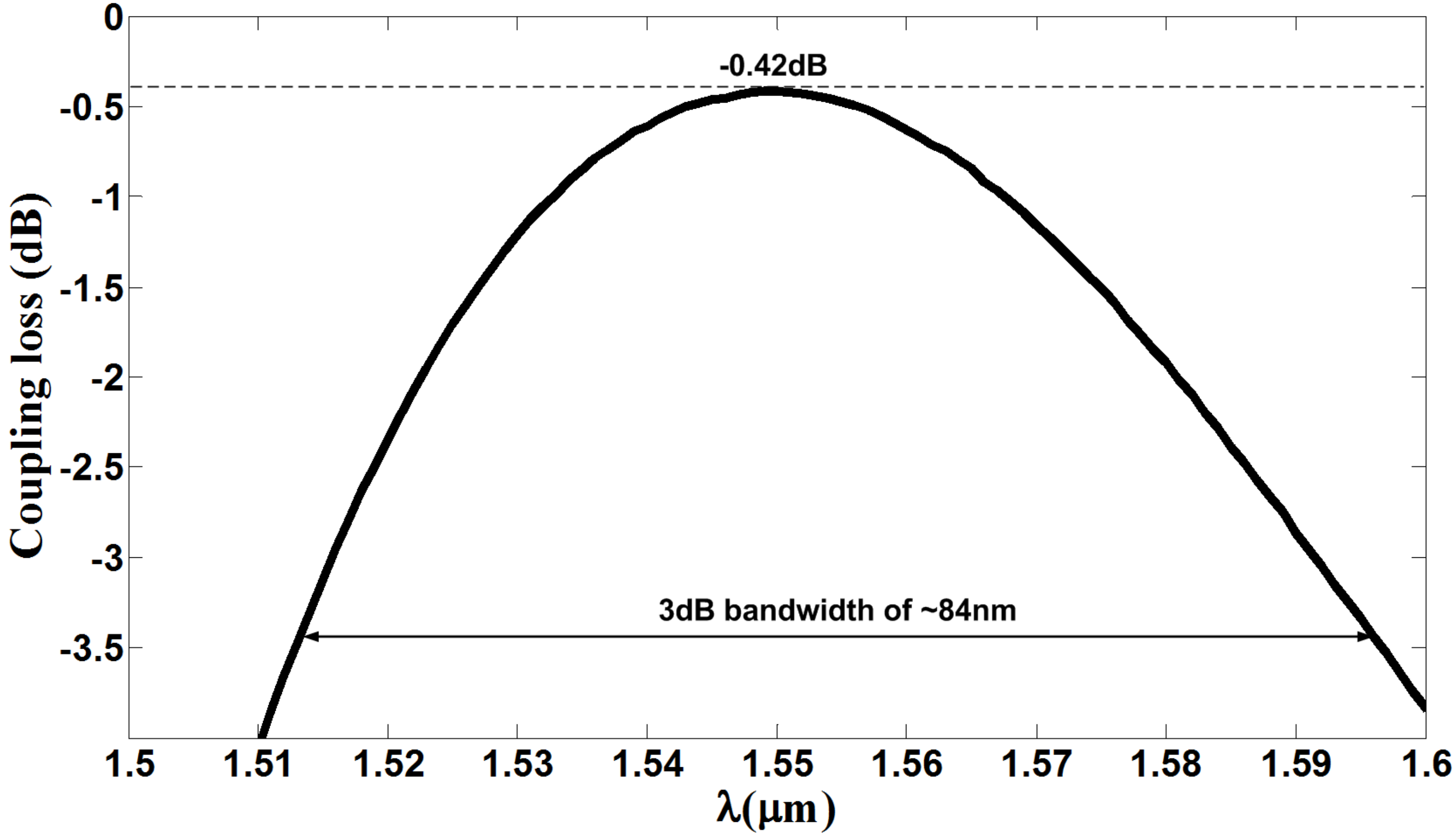
1300 nm band



TE polarization
220 nm silicon with an overlayer

D. Benedikovic et al.

Recent design examples

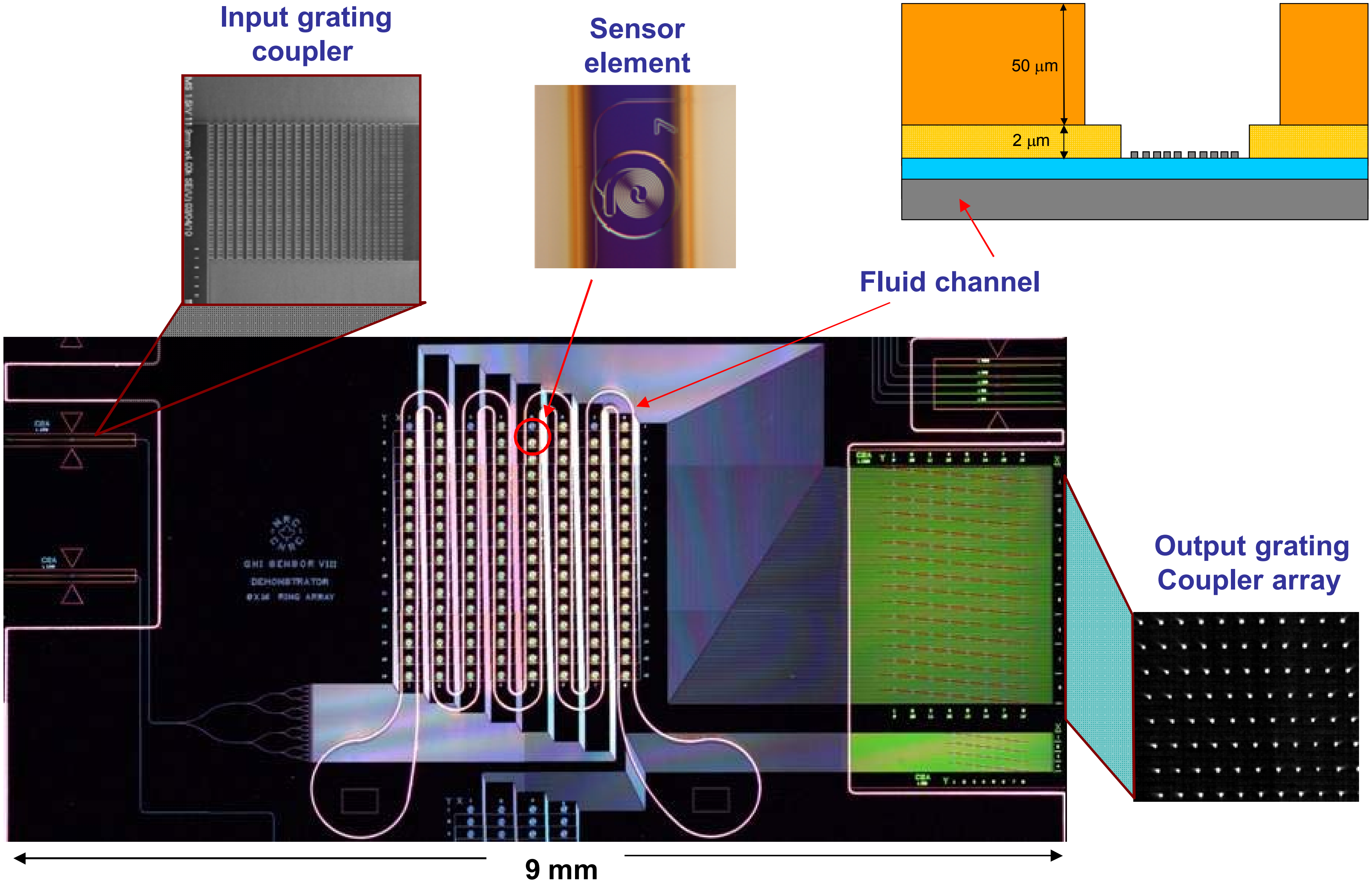


TE polarization, 220 nm silicon

Coupling loss -0.42 dB (FDTD)

D. Benedikovic et al.

128 biosensor array chip with SWG grating couplers

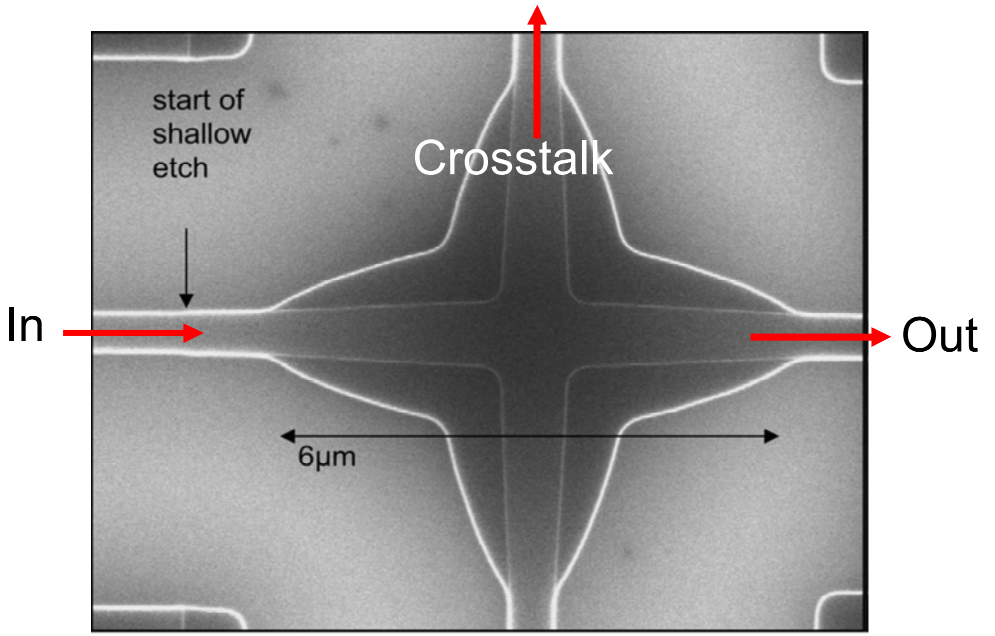


S. Janz et al., Optics Express 4623, Vol. 21, No. 4, 25 February 2013

Photonic wire waveguide crossings

Ability to cross waveguides with low loss and crosstalk is critical for complex optical circuits which require many optical paths to cross on chip

<u>Crossing loss</u> and <u>cross-talk</u> - straight photonic wire crossing loss is -1.2 dB and crosstalk is -12 dB



Double etch step
Loss -0.16 dB for TE (TM unknown)
Crosstalk -40 dB

W. Bogaerts et al., Opt. Lett. **32** (19) 2801-2803 (2007)

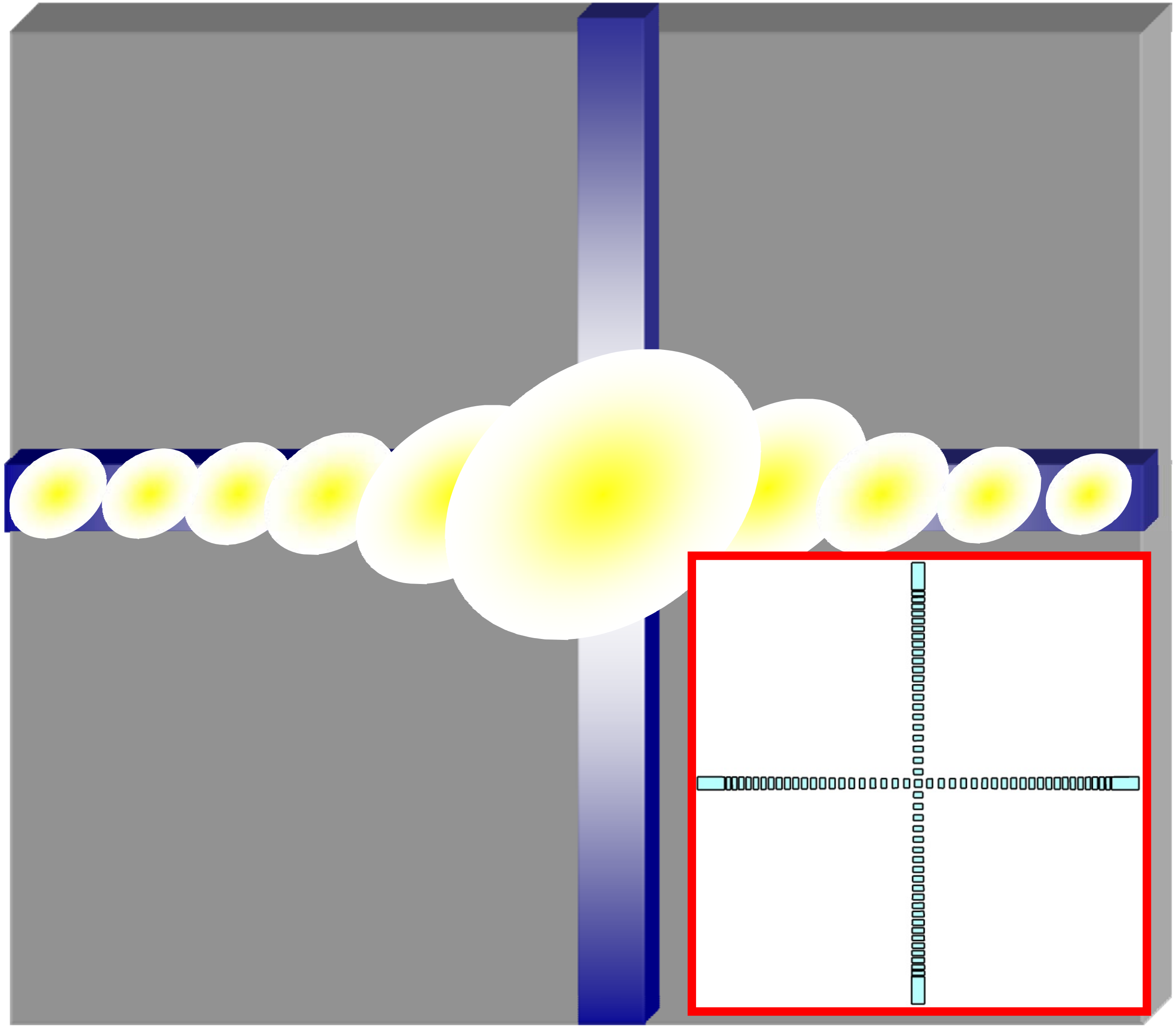
Graded index waveguide crossing

Gradually change the effective index of the waveguide

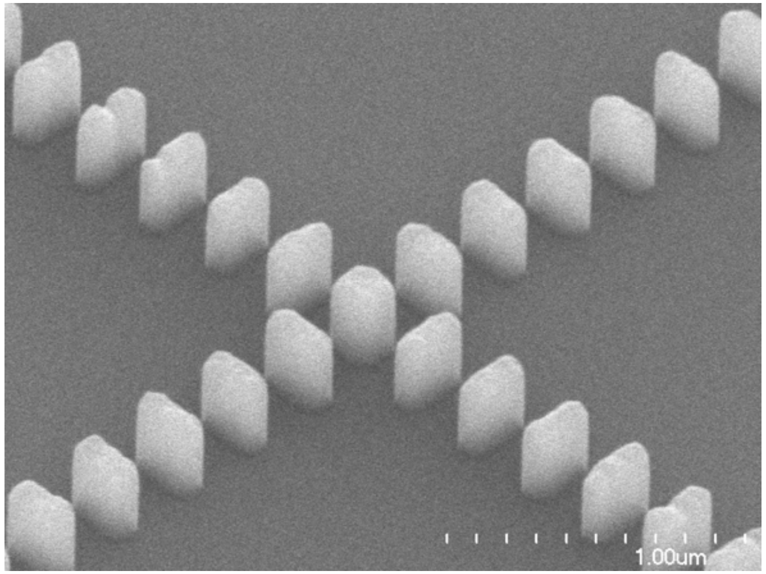
Mode delocalization and low index contrast at the crossover reduce interaction of light with the intersecting waveguide

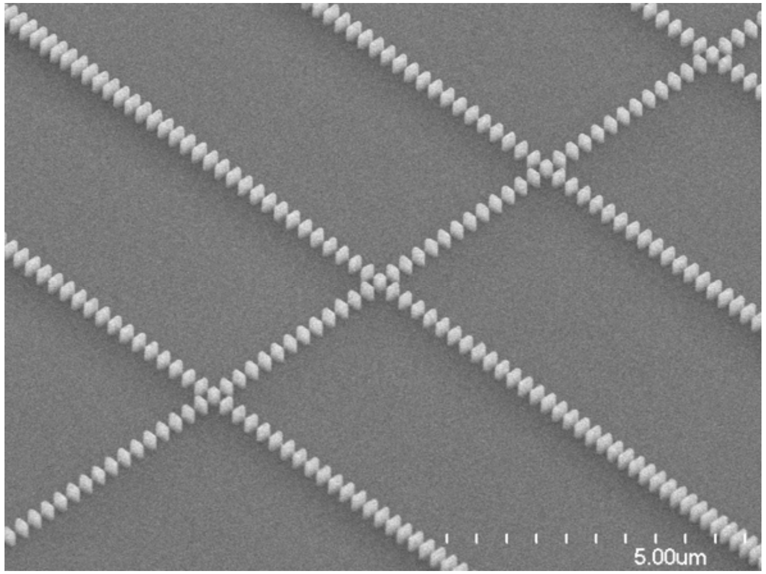
N_{eff} controlled by a chirped subwavelength grating

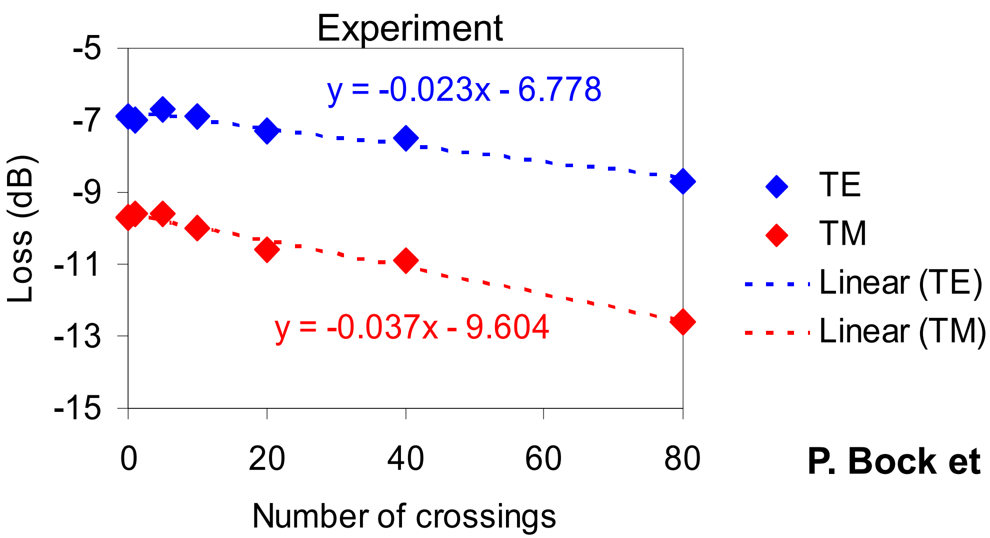
Single etch step fabrication



Graded-index SWG waveguide crossing experiment







Measured loss per crossing
0.02 dB (TE)
0.04 dB (TM)

Measured cross talk < -35 dB

P. Bock et al., Optics Express, vol. 18, p. 16146, July 2010

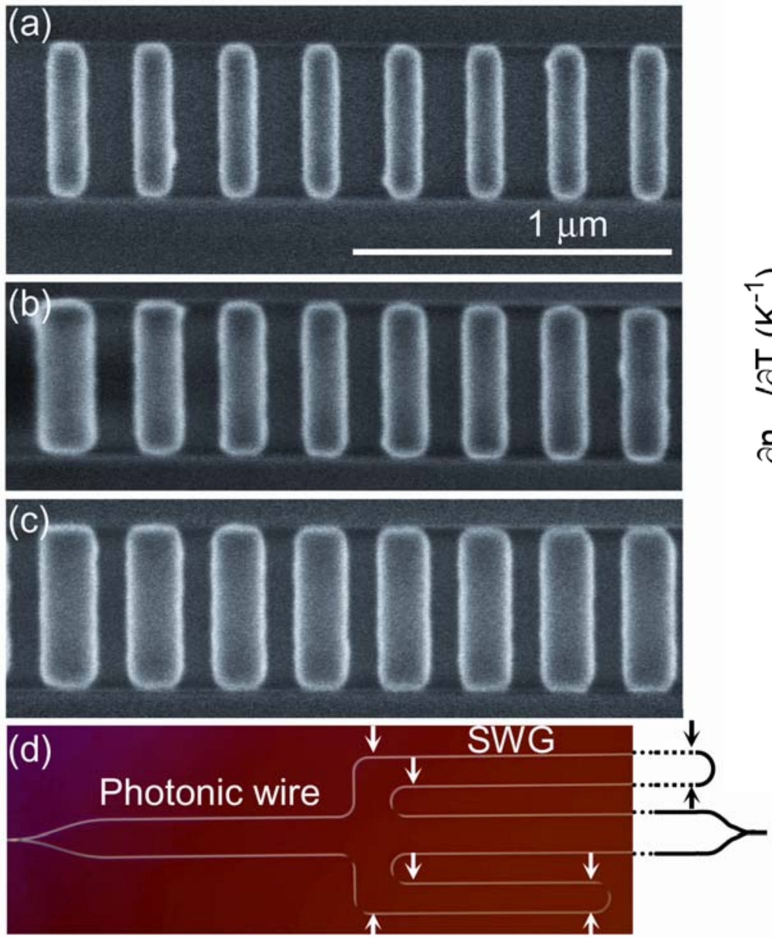
NRC & U of Ottawa

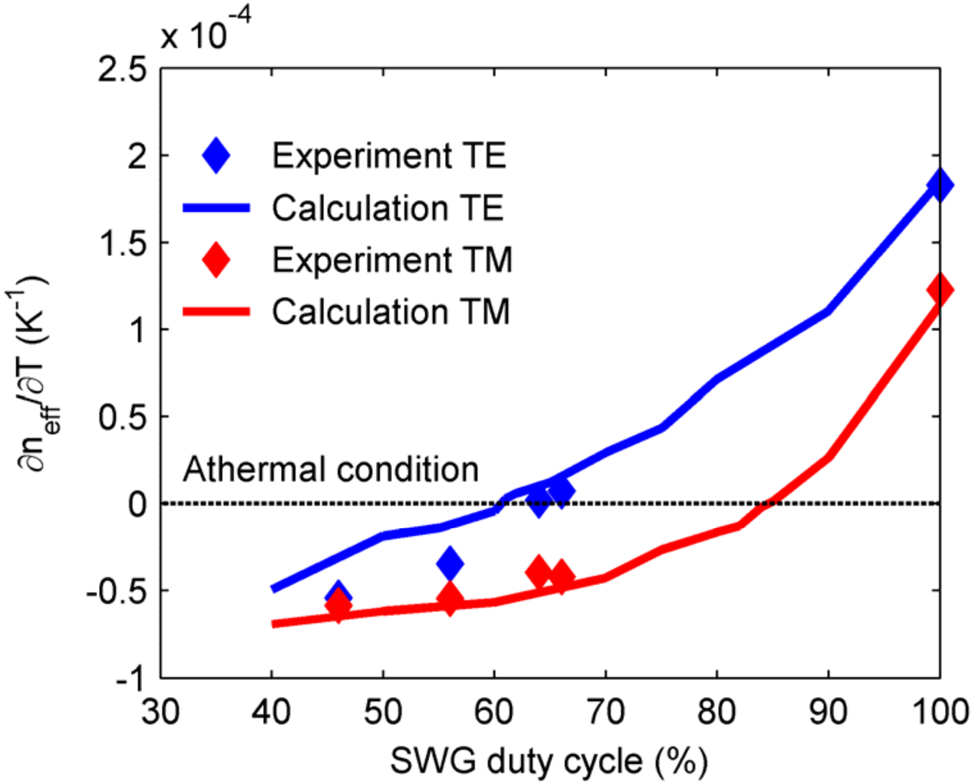
Athermal waveguides

46% Si

56% Si

66% Si





Si, $dn_{Si}/dT = 1.8 \times 10^{-4}\ K^{-1}$

SU-8, $dn_{SU8}/dT = -1.1 \times 10^{-4}\ K^{-1}$

Waveguide $dn/dT = 1.8 \times 10^{-6}\ K^{-1}$ for a duty ratio of 64%

Duty ratios required for athermal behavior: 64% (TE) and 85% (TM)

For TM polarization impractically small gaps (50 nm) are required

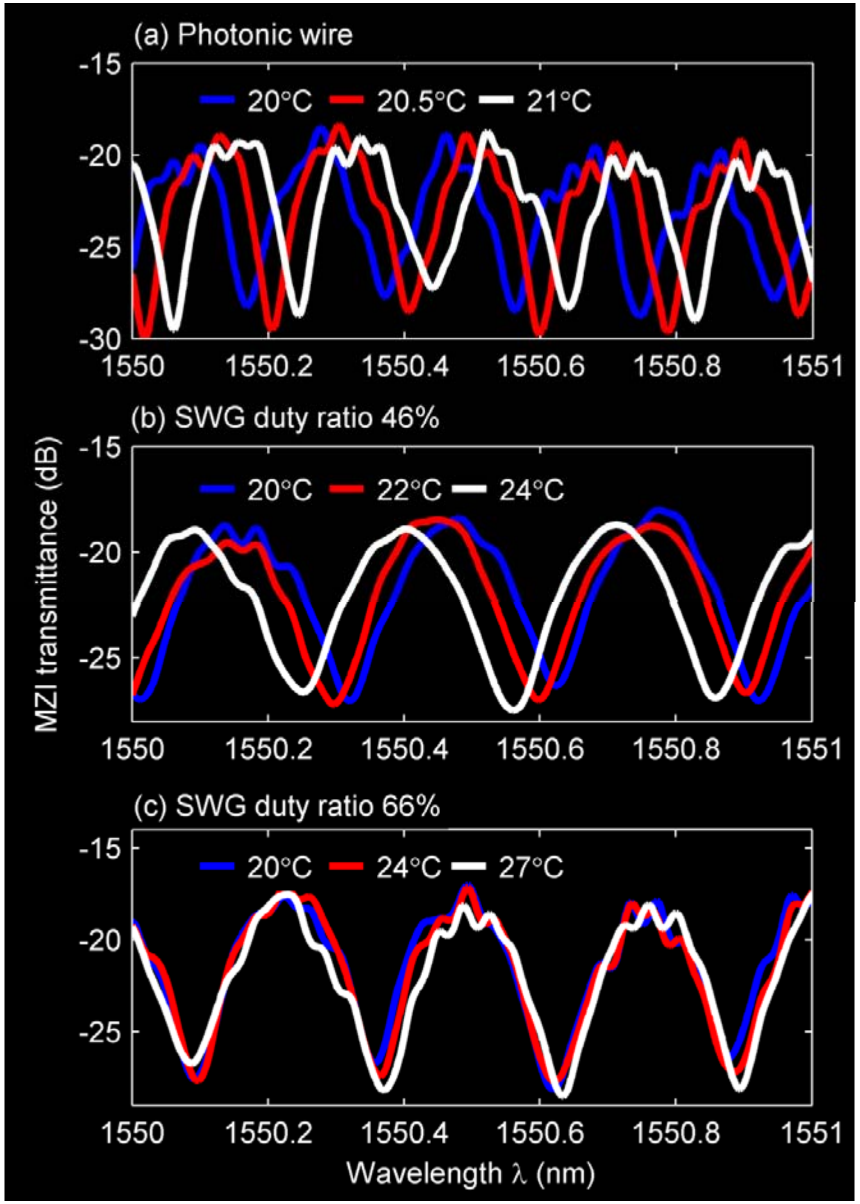
J. Schmid et al., Opt. Lett., vol. 36, p. 2110 (2011)

Temperature dependent SWG MZI transmission

Conventional photonic wire MZI

SWG duty ratio 46%

SWG duty ratio 66%



Temperature rise causes:

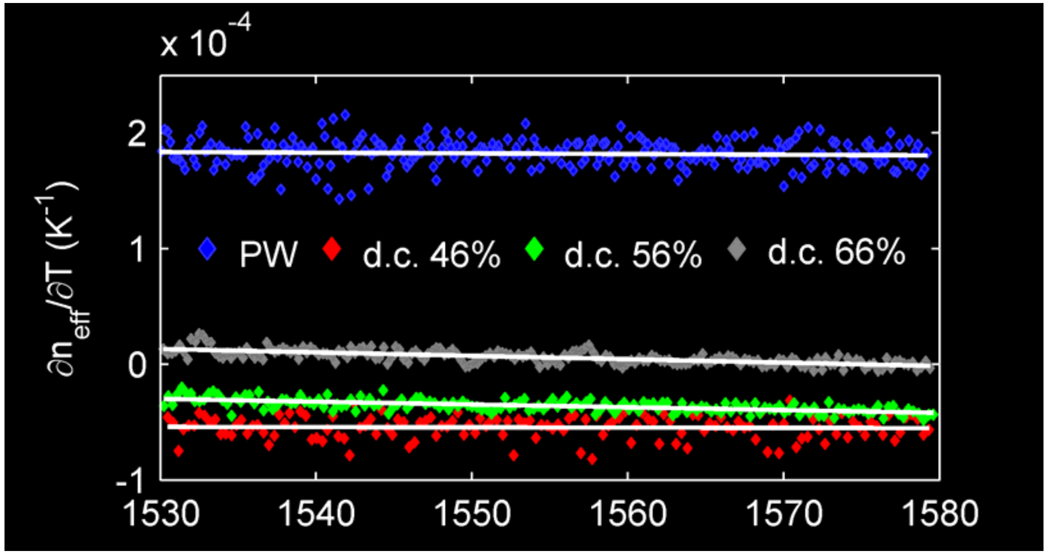
Red-shift

Blue-shift

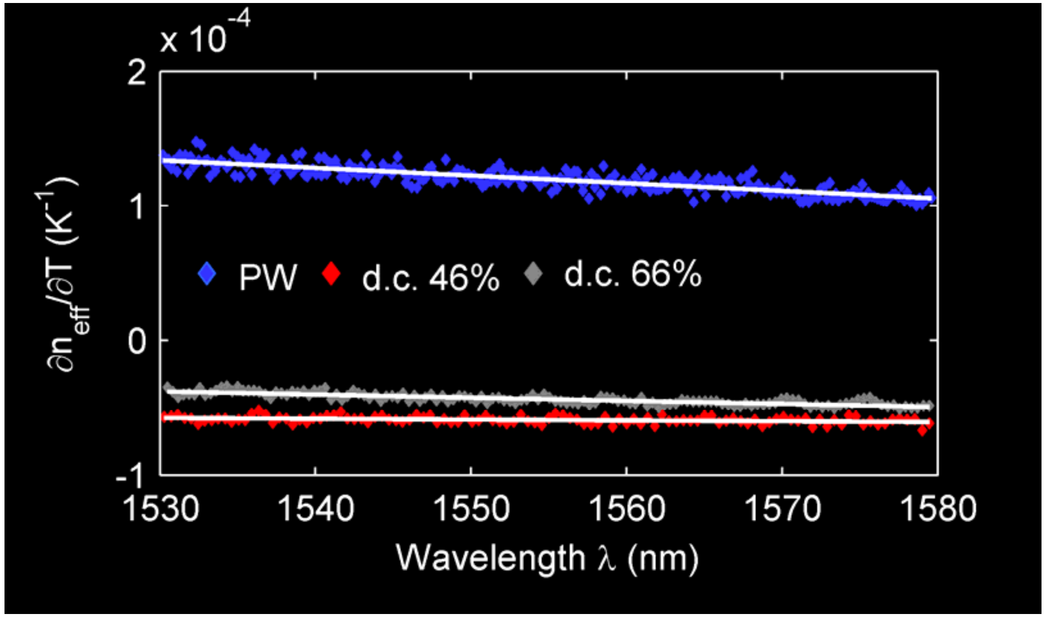
No shift

Waveguide thermo-optic coefficient

TE polarization



TM polarization

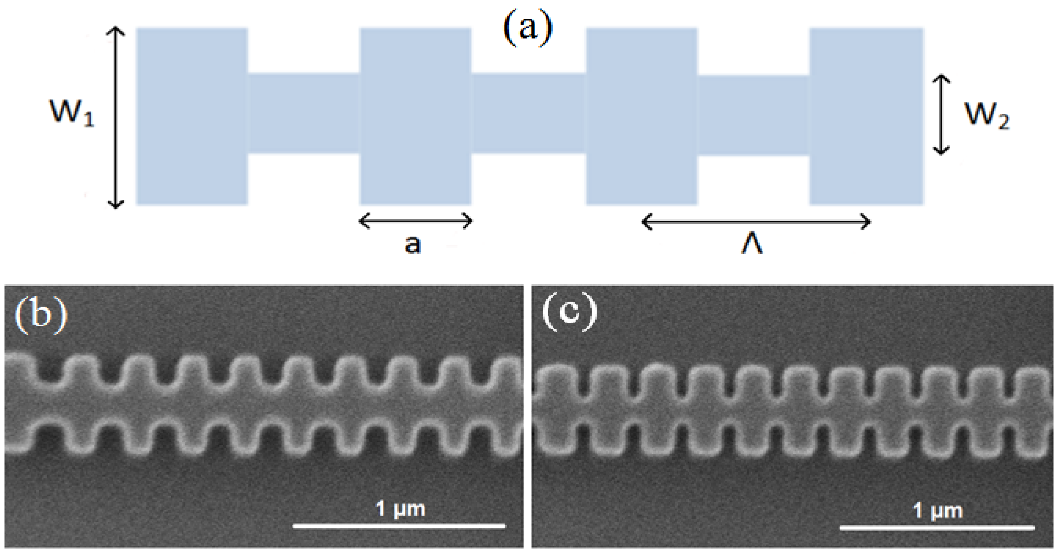


Near athermal behavior for 66% duty ratio

$$\frac{dn_{eff}}{dT} = \frac{n_g}{\lambda}\frac{d\lambda}{dT}$$

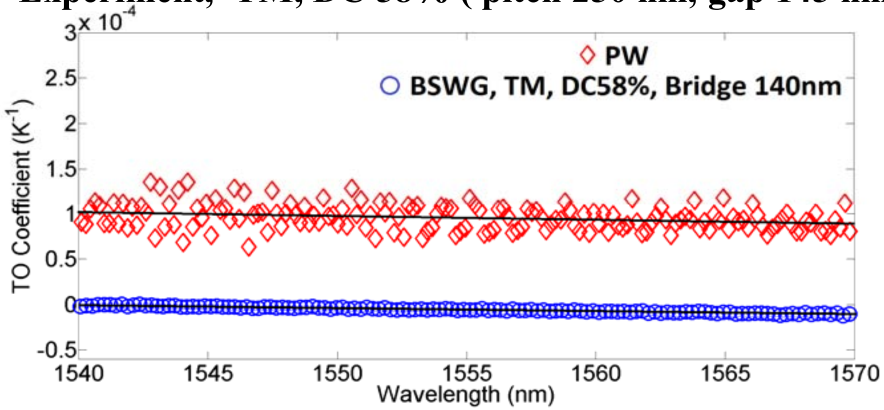
SWG waveguides have negative thermo-optic coefficient

Sidewall subwavelength grating athermal waveguides



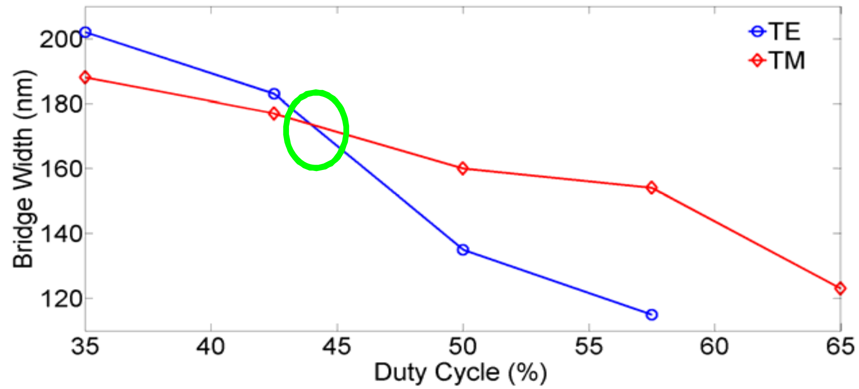
This geometry allows to increase minimum gap size for TM polarization:

Experiment, TM, DC 58% (pitch 250 nm, gap 145 nm)



Athermal operation simultaneously for TE and TM is possible:

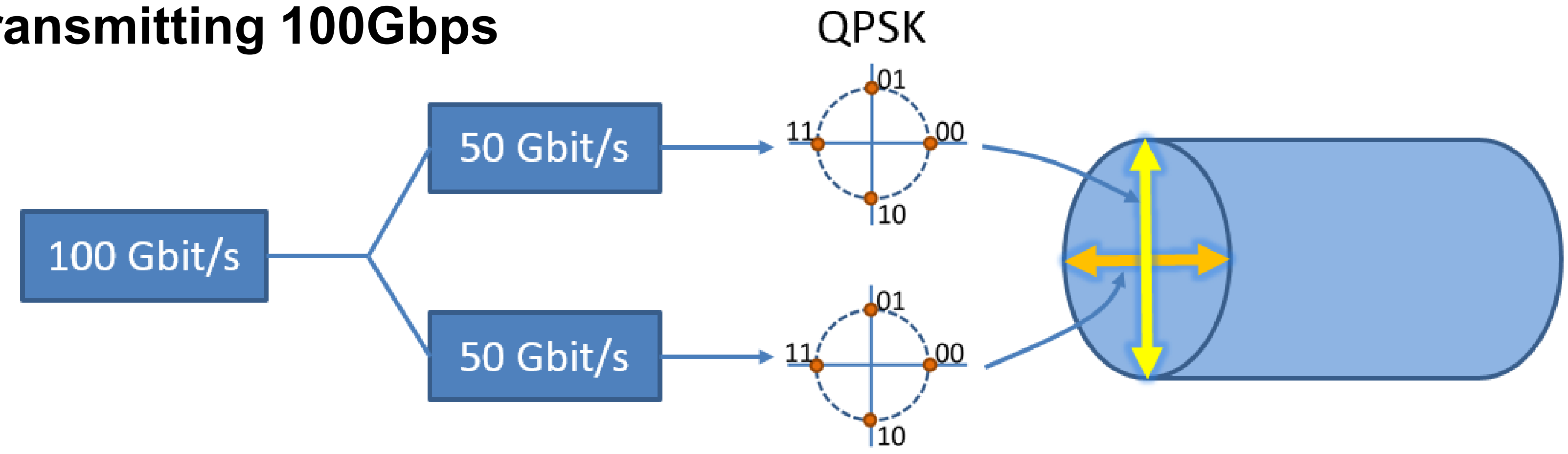
Theory, TM and TE



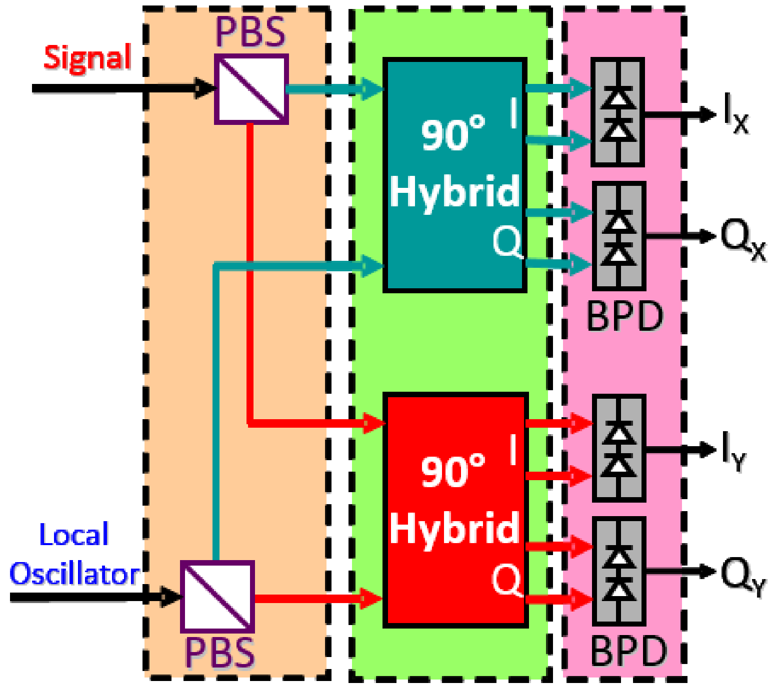
M. Ibrahim et al., Athermal silicon waveguides with bridged subwavelength gratings for TE and TM polarizations, Optics Express, 2012 NRC & Carleton University

Coherent receiver

- **Transmitting 100Gbps**

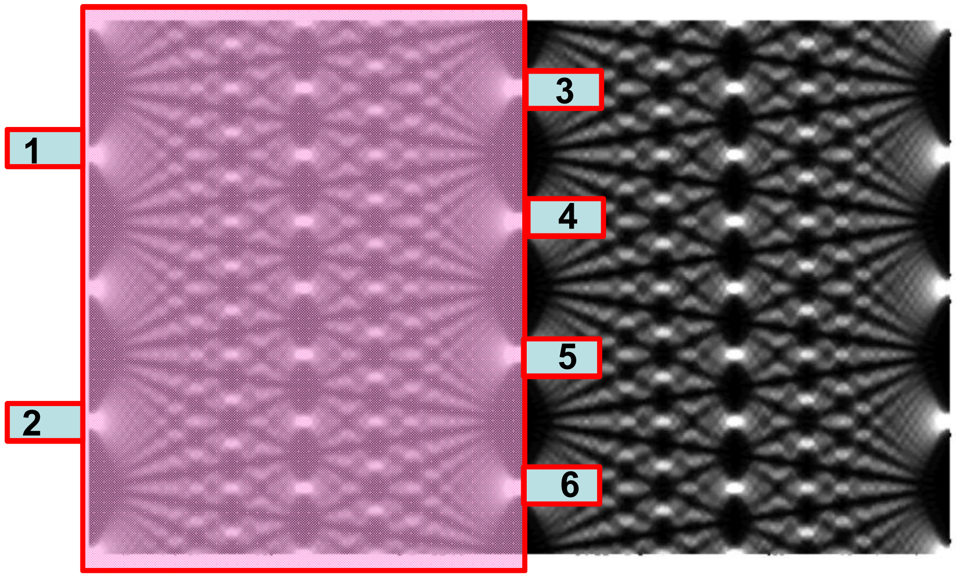


- **Integrated receivers**
  - **Low loss, low PDL fiber-to-chip coupling**
  - **High speed photodiodes**
  - **Polarization splitters**
  - **High performance 90º hybrids**



MMI coupler principle

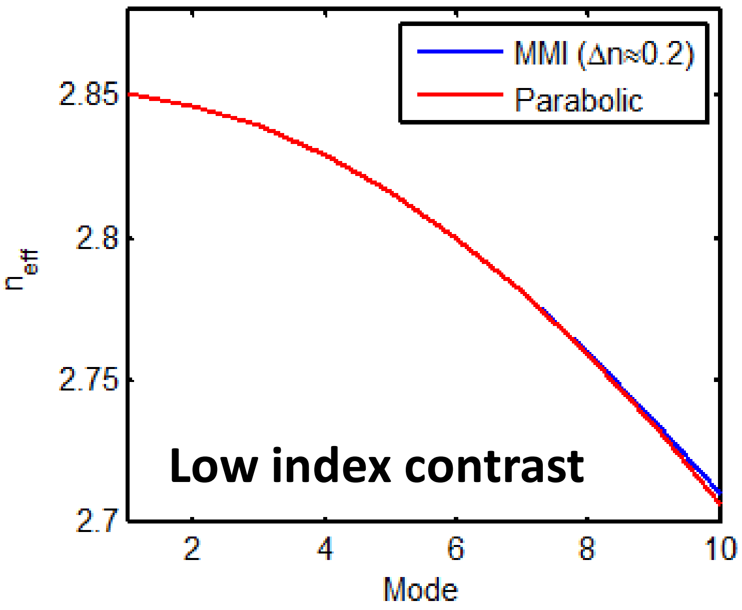
When a plane wave is incident on a periodic structure (grating), the image of the structure is repeatedly formed at specific distances.
H. F. Talbot, "Facts relating to optical science" No. IV, Philos. Mag. 9, 1836.

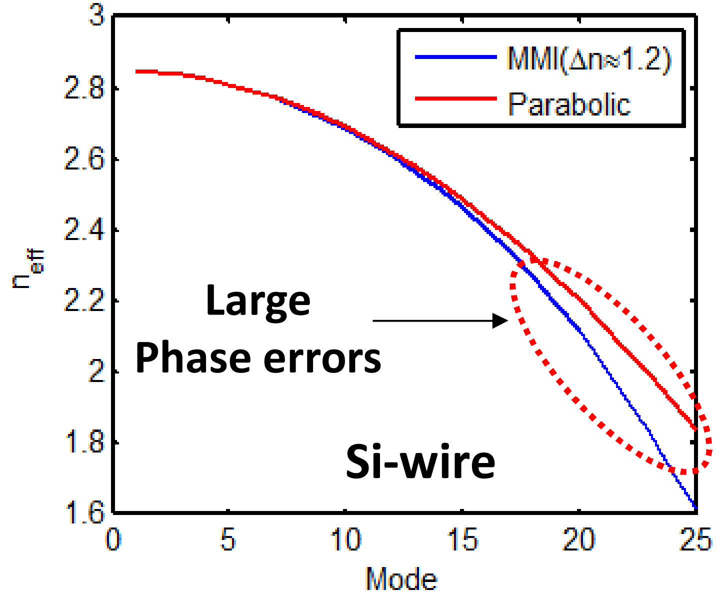


Inputs	Outputs			
	3	4	5	6
1	0	135	-45	0
2	-45	0	0	135

MMI performance limits in SOI

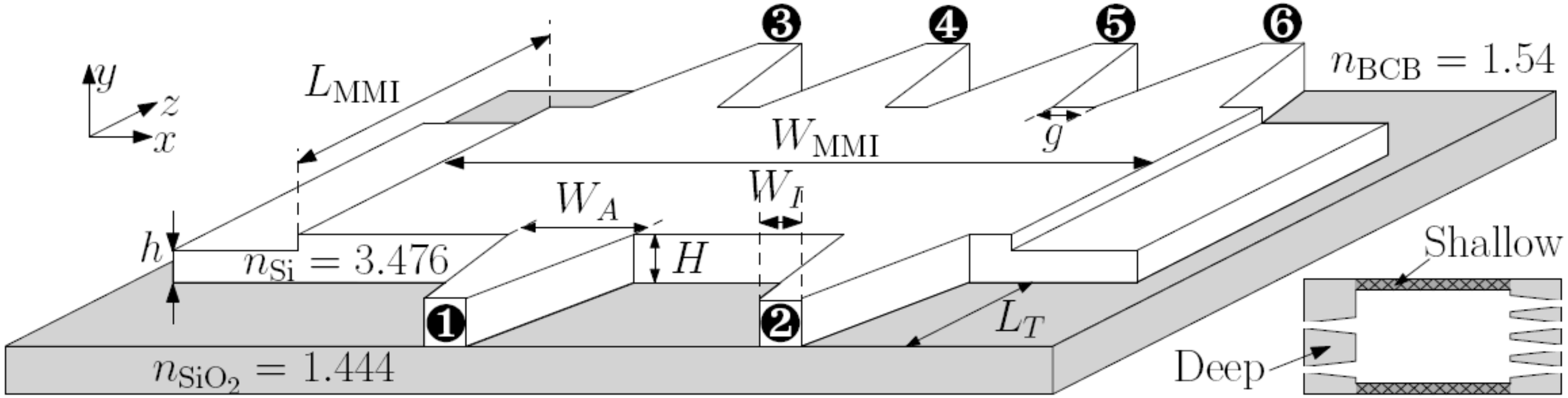
Modal effective index





MMIs conventional design performs poorly for Si-wire waveguides

4x4 MMI hybrid in Si-wire platform

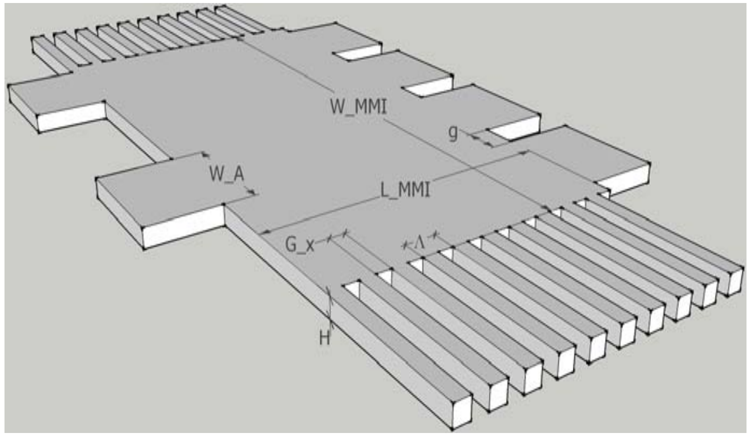


R. Halir, G. Roelkens, et al., *Opt. Lett.*, *36*, 178-180 (2011)

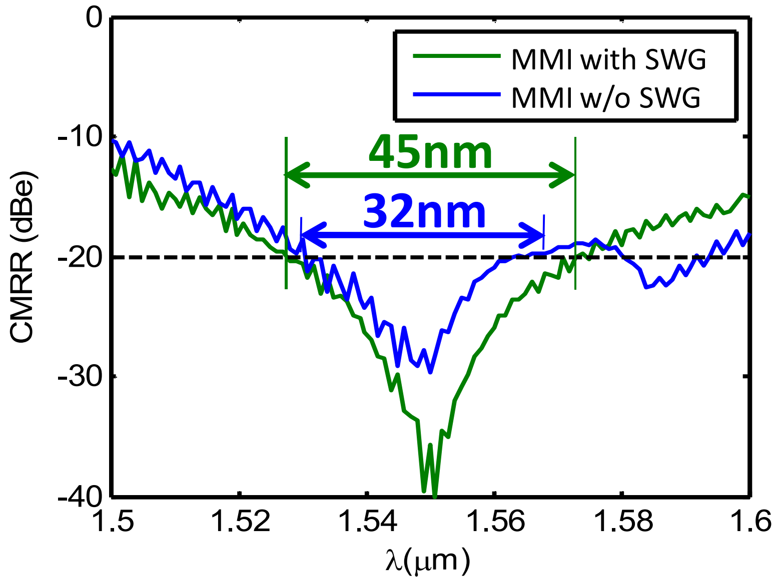
Index contrast (and phase errors) reduced by using a shallow-etch lateral cladding region.

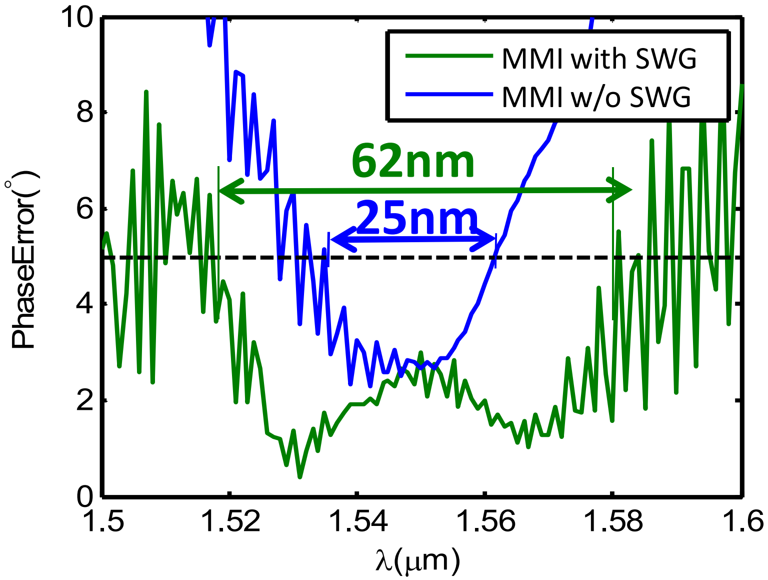
Can single-etch process be used?

MMI hybrid in SOI with subwavelength structured cladding



- Use SWG as an effective cladding medium
- Optimum index contrast can be engineered using the geometrical parameters of the SWG (pitch and duty cycle)



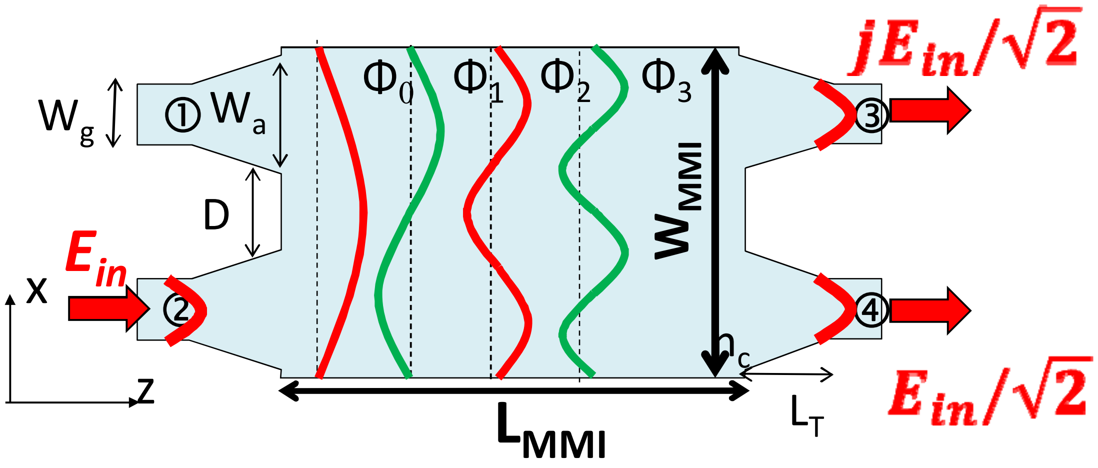


A significant improvement in MMI performance by using sub-λ engineering

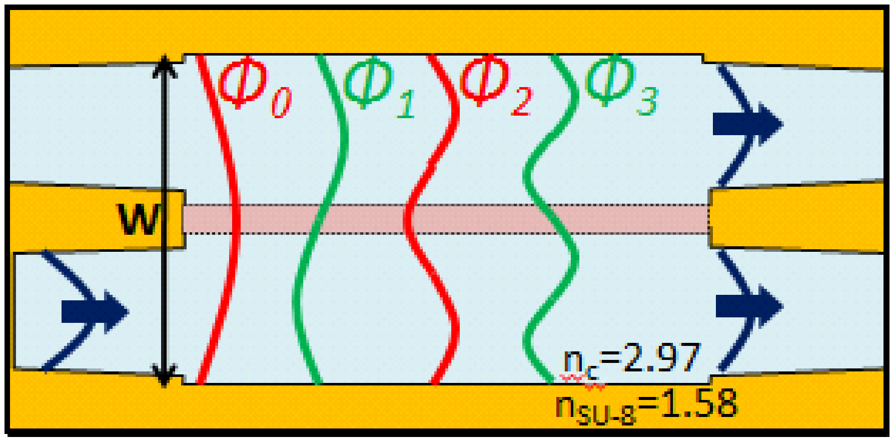
A. Ortega-Moñux et al.," IEEE PTL 23, 1406, 2011

U of Malaga & NRC

Slotted MMI: Concept



- Input is "imaged" to output waveguide by modal interference.
- Imaging length depends on the beat length of the two first order modes.

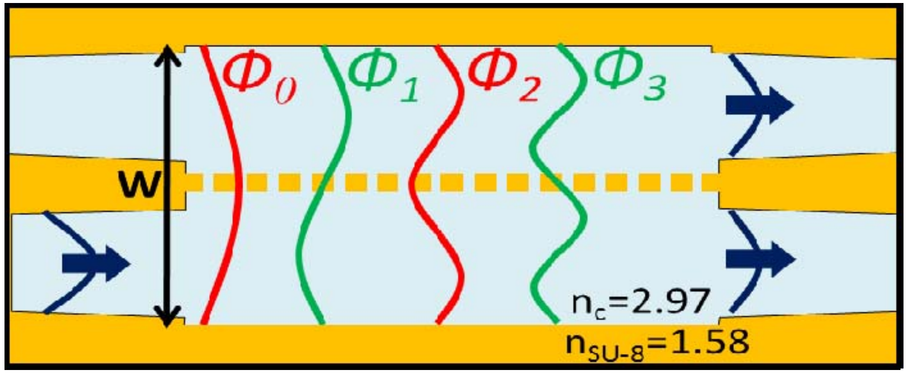


- Small index change in "slot" only affects even mode.
- Imaging length is halved if:

$$\Delta n_{slot} \approx \frac{W}{16 \cdot n_c \cdot w_s} \cdot \left(\frac{\lambda}{W}\right)^2$$

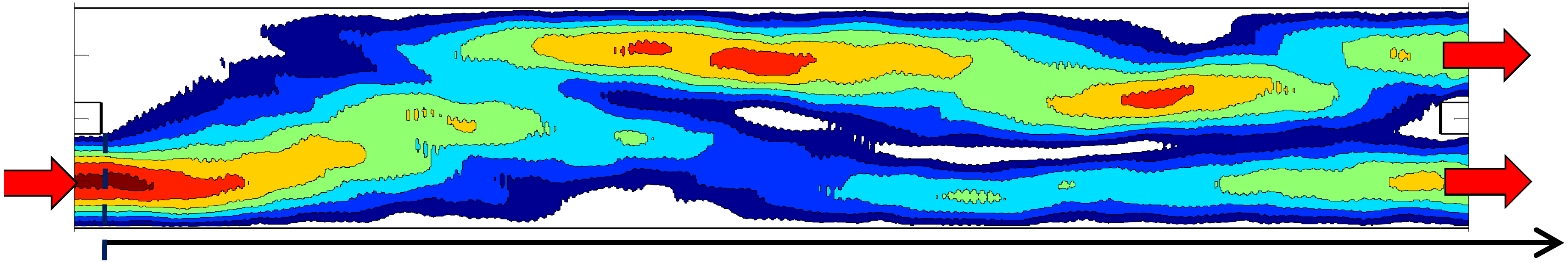
J. C. Campbell and T. Li, J. Appl. Phys 50, 6149–6154, 1979
D. M. Mackie and A. W. Lee, *Appl. Optics* 43, 6609-6619, 2004

SWG Slotted MMI

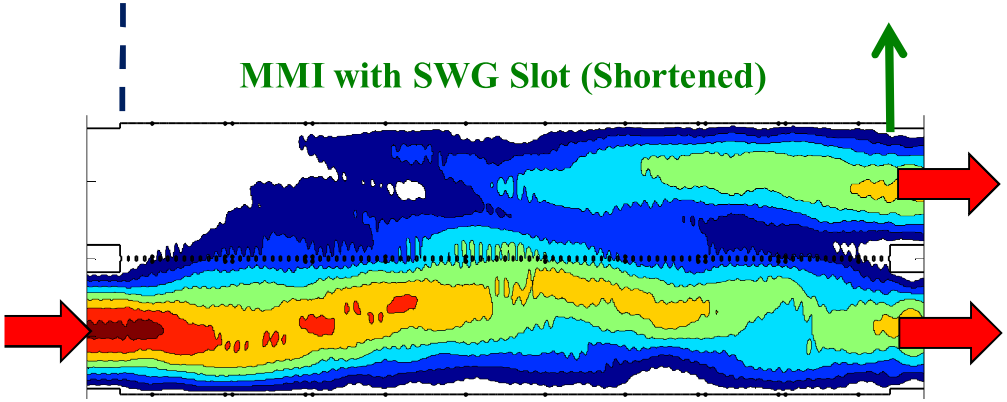


- Synthesize index variation with a fully etched SWG slot.
- Preliminary design with Rytov.
- *Optimization* by numerical simulation (FEXEN: Higher order Floquet modes).

MMI without Slot (Reference)



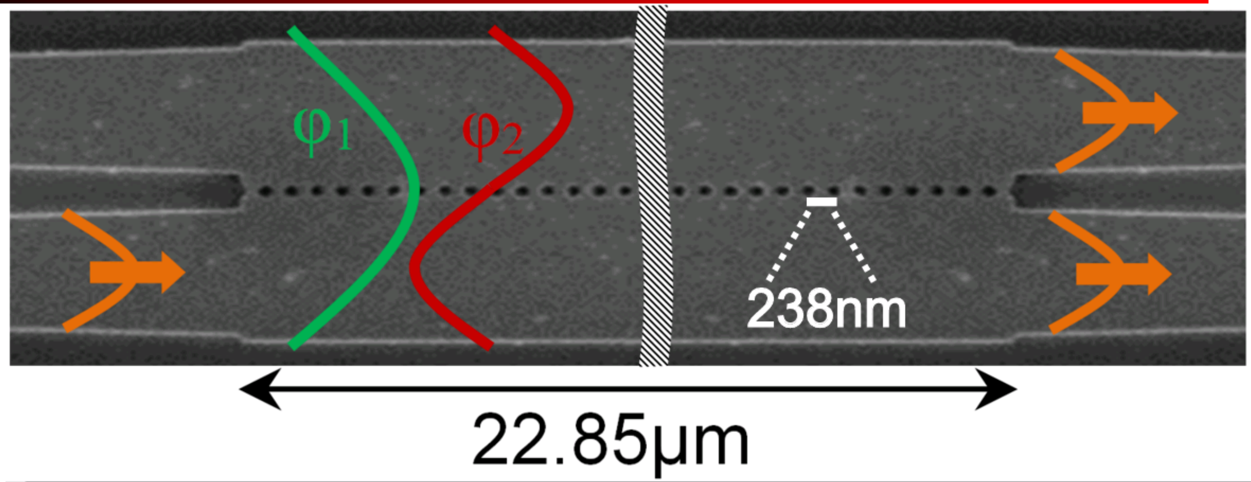
MMI with SWG Slot (Shortened)

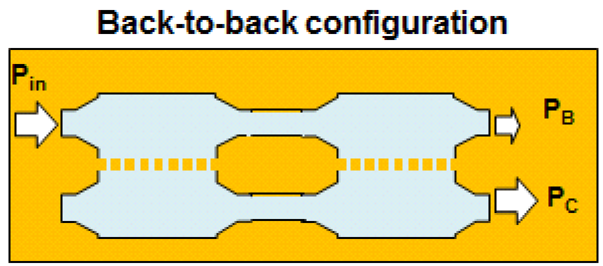


Two-fold length reduction !

A. Ortega-Moñux, *et al.*, Laser & Photonics Reviews, vol. 7, no. 2, pp. L12-L15, 2013

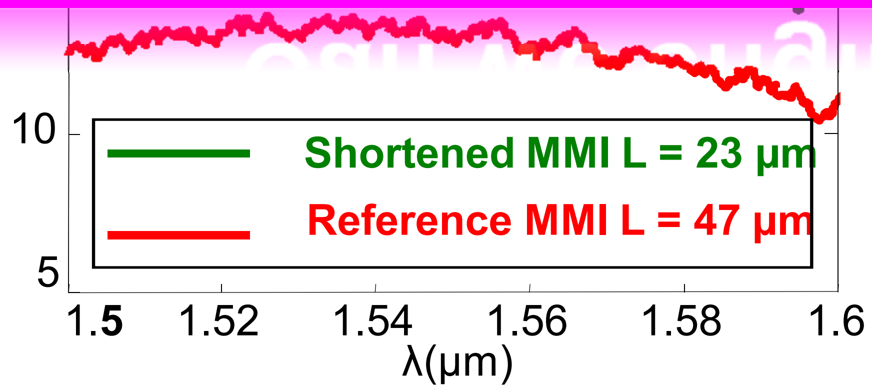
SWG Slotted MMI





Index engineering works…

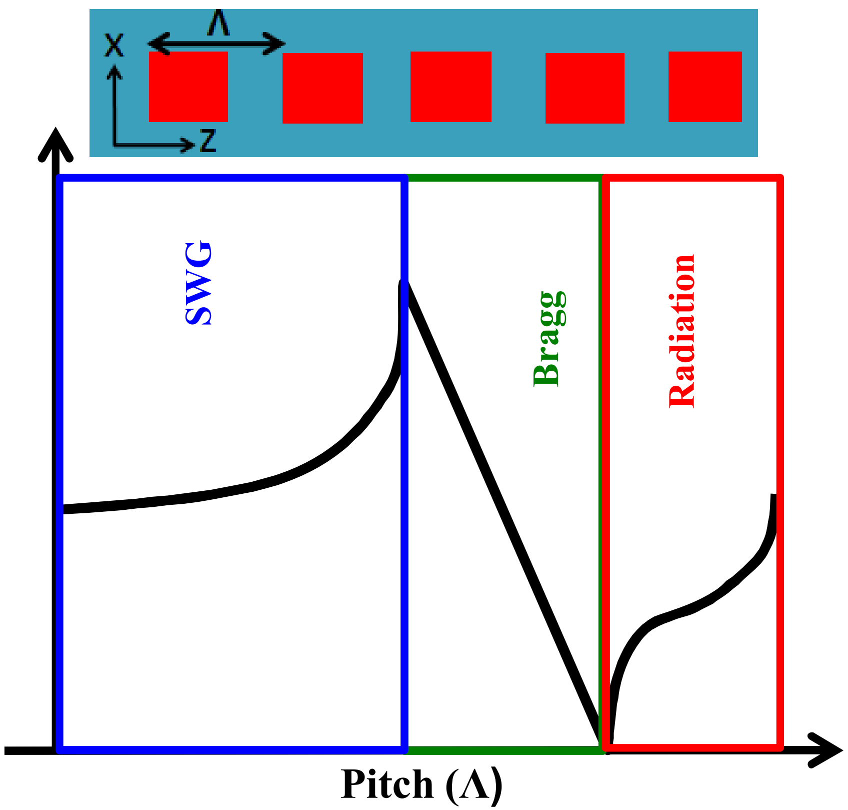
Can we engineer dispersion?

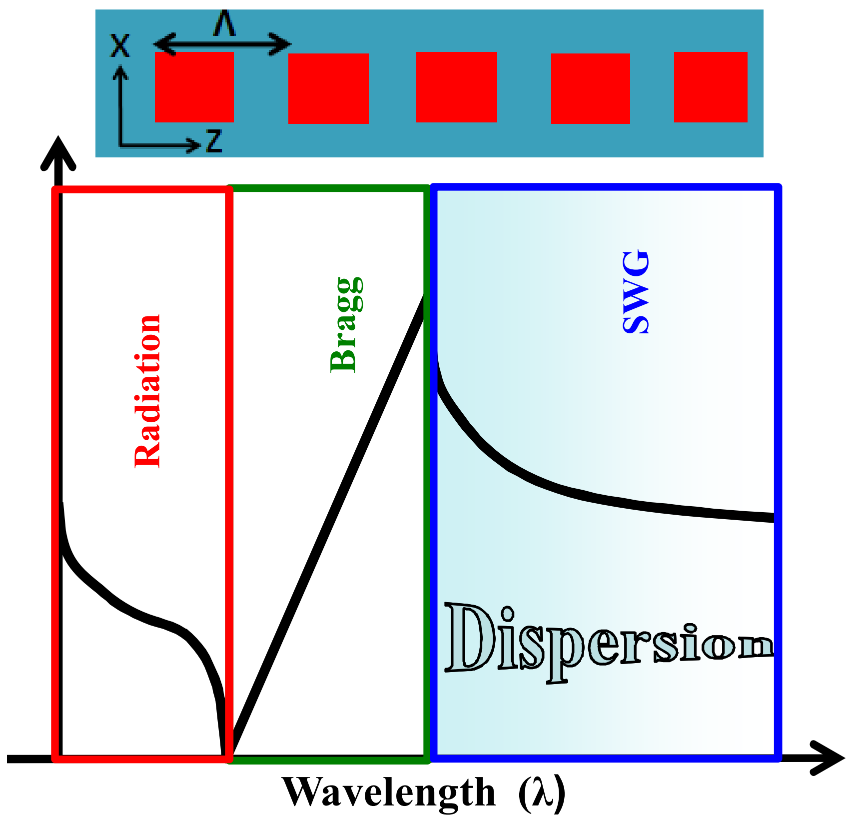


- No performance penalty (small improvement).
- Extinction Ratio (C-band) >15 dB
- Power Imbalance (C-band) < 1.3dB
- Phase Error (C-band) < 5º

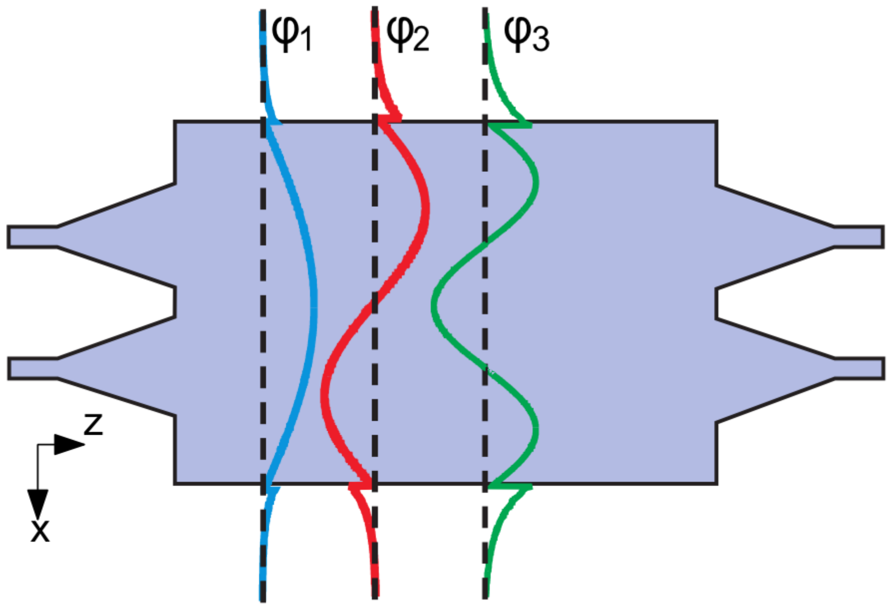
A. Ortega-Moñux, *et al.*, Laser & Photonics Reviews, vol. 7, no. 2, pp. L12-L15, 2013

Can we engineer dispersion?





Broadband MMI: Bandwidth limitation



$$L_\pi = \frac{\pi}{\beta_1 - \beta_2}$$

$$L_\pi = \frac{\lambda}{2(n_1(\lambda) - n_2(\lambda))}$$

$$\beta_1 - \beta_m = \frac{(m^2 - 1)\pi}{3L_\pi}$$

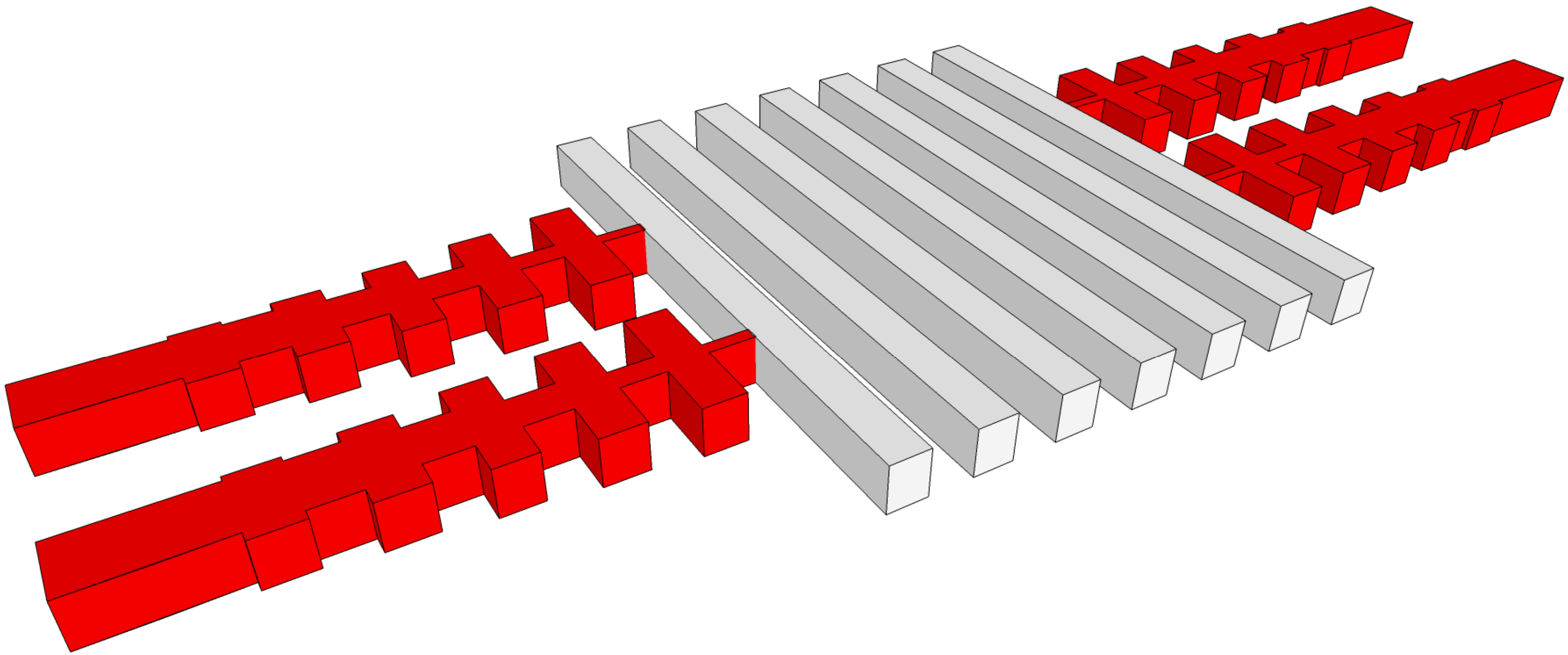
Image formation requires:

- Device length proportional to beat length, but
  - ***Beat length decreases with increasing wavelength.***
- Parabolic relation of propagation constants, but
  - ***Does not hold for large m***

For broadband operation we need to achieve:

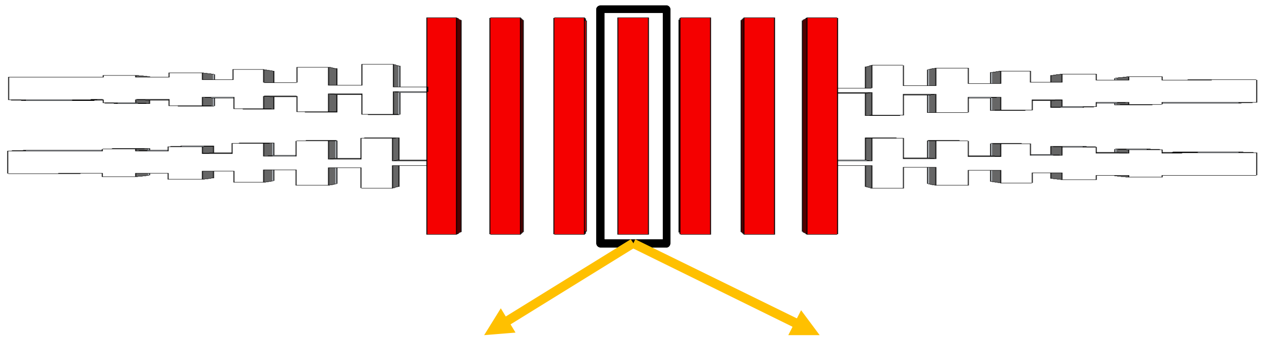
- **Constant beat length → *as wavelength increases, so does*** $(n_1 - n_2)$
- ***Excite only lower order modes.***

Broadband MMI: Device

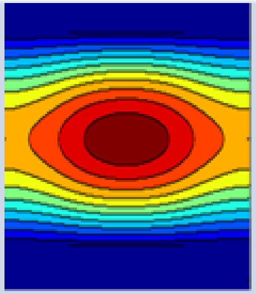
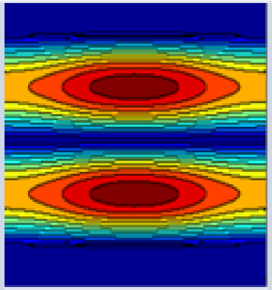
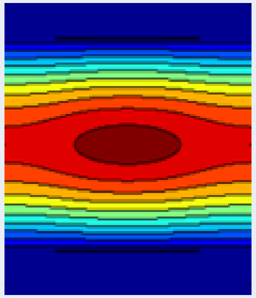
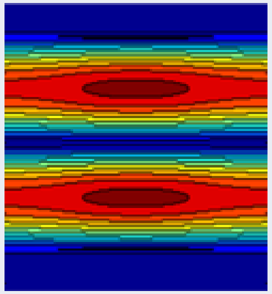


- **Fully segmented multimode region provides flat beat length.**
- **SWG tapers:**
  - **Expand mode field to excite only lower order modes**
  - **Index matching: high n_{eff} waveguide and low n_{eff} multimode region.**

Segmented multimode section

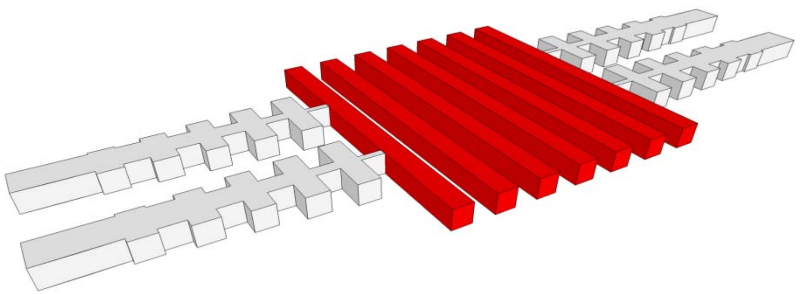


$$L_\pi = \frac{\lambda}{2(n_1 - n_2)}$$

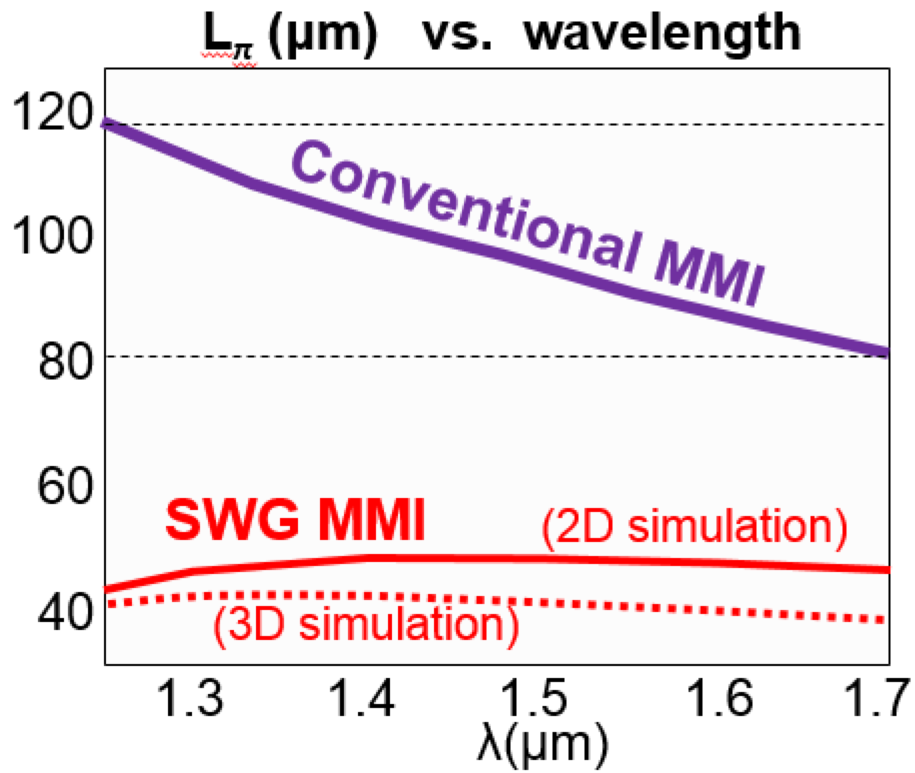
Wavelength	Mode 1	Mode 2	$n_1 - n_2$
$\lambda = 1.3\mu m$			0.015
$\lambda = 1.7\mu m$			0.02

- Short wavelength $\rightarrow$ strong longitudinal confinement in silicon $\rightarrow$ small $(n_1 - n_2)$
- Long wavelength $\rightarrow$ weak longitudinal confinement in silicon $\rightarrow$ large $(n_1 - n_2)$
- Beat length should be constant.

Segmented multimode section



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

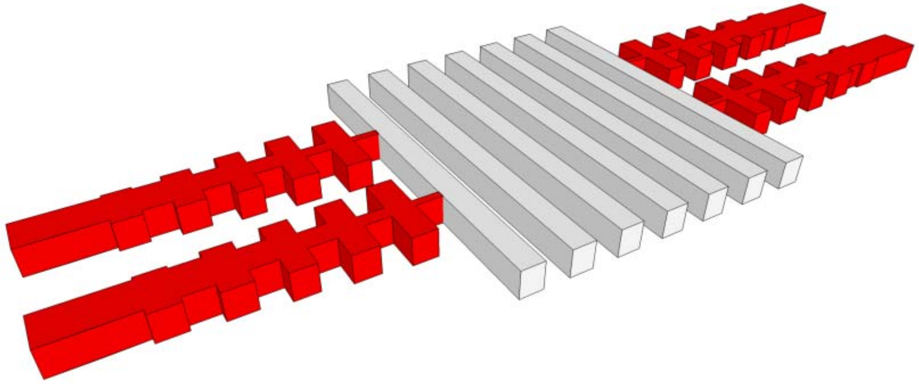


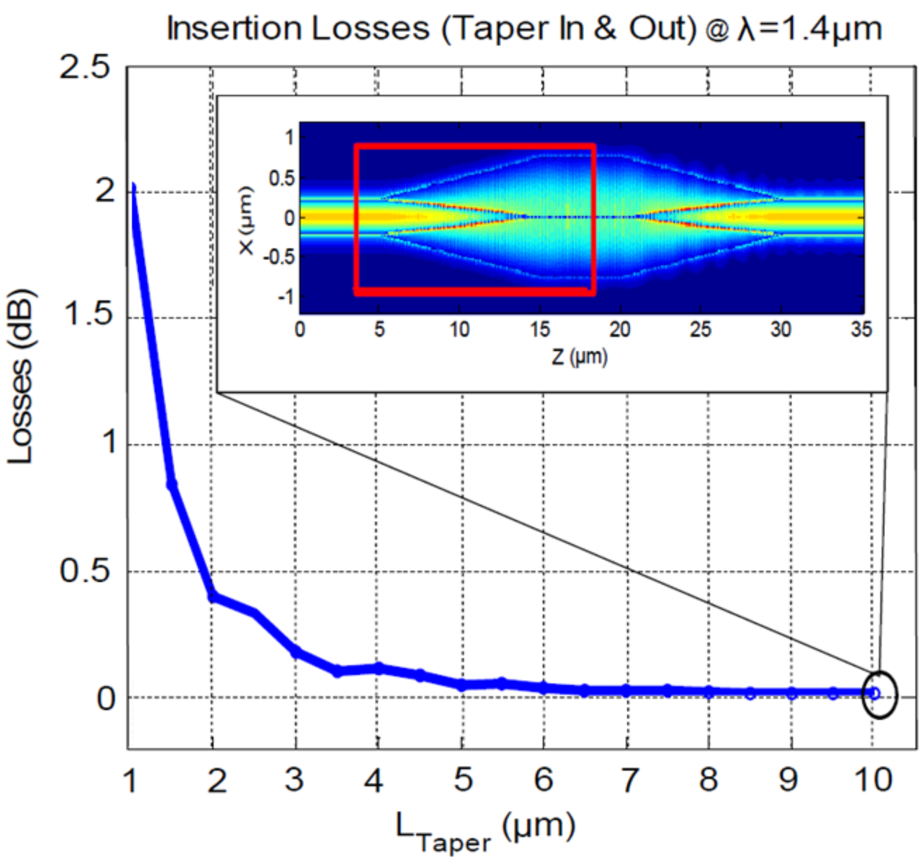
<u>Flat beat length:</u>

- **50% duty cycle, pitch 190 nm, 122 periods**
- **Optimized using Fexen**
- **Flat over more than 400nm**
- **Shortened multimode section**

A. Maese et al., Optics Express, Vol. 21 Issue 6, pp.7033-7040 (2013)

Access Tapers

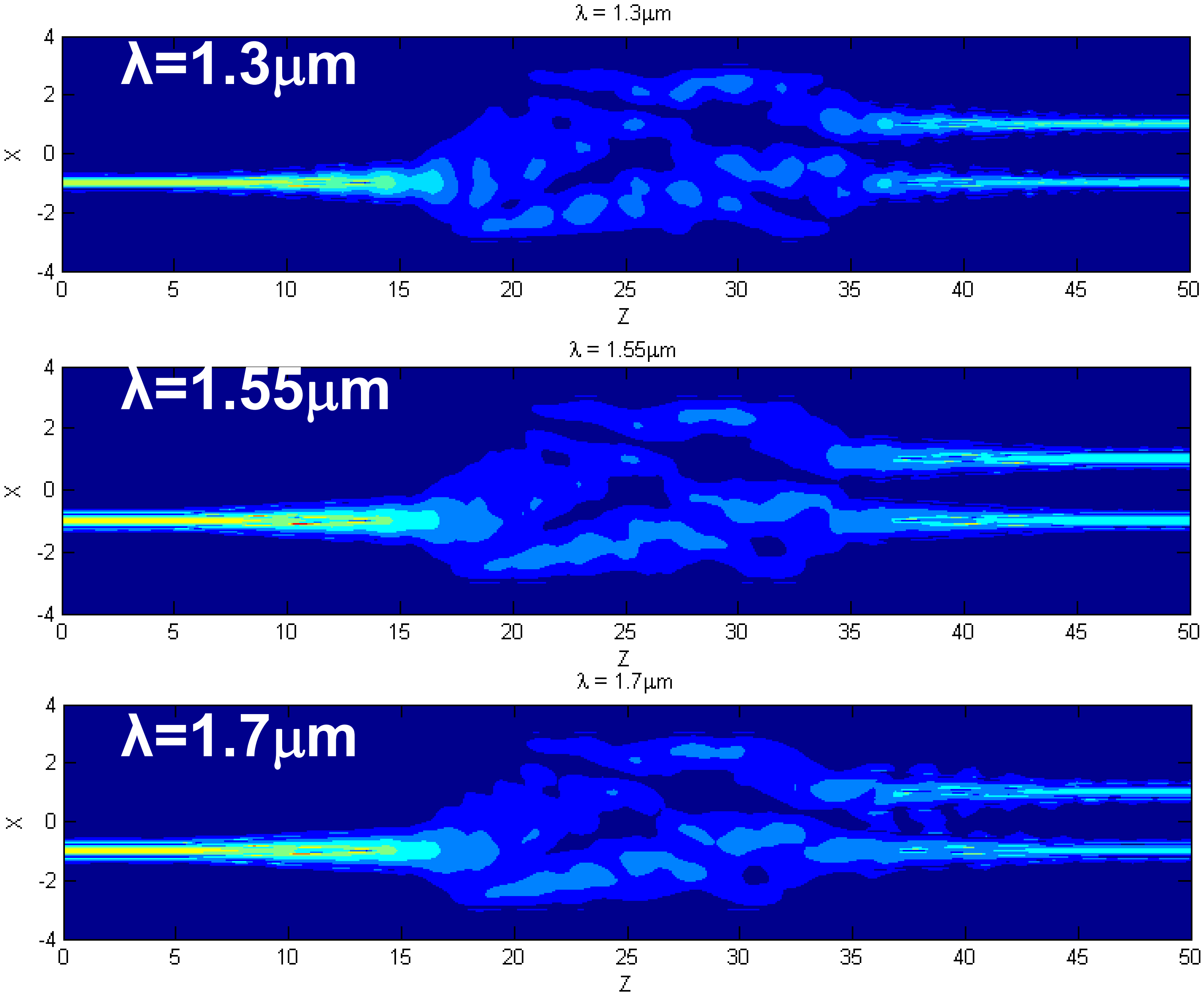




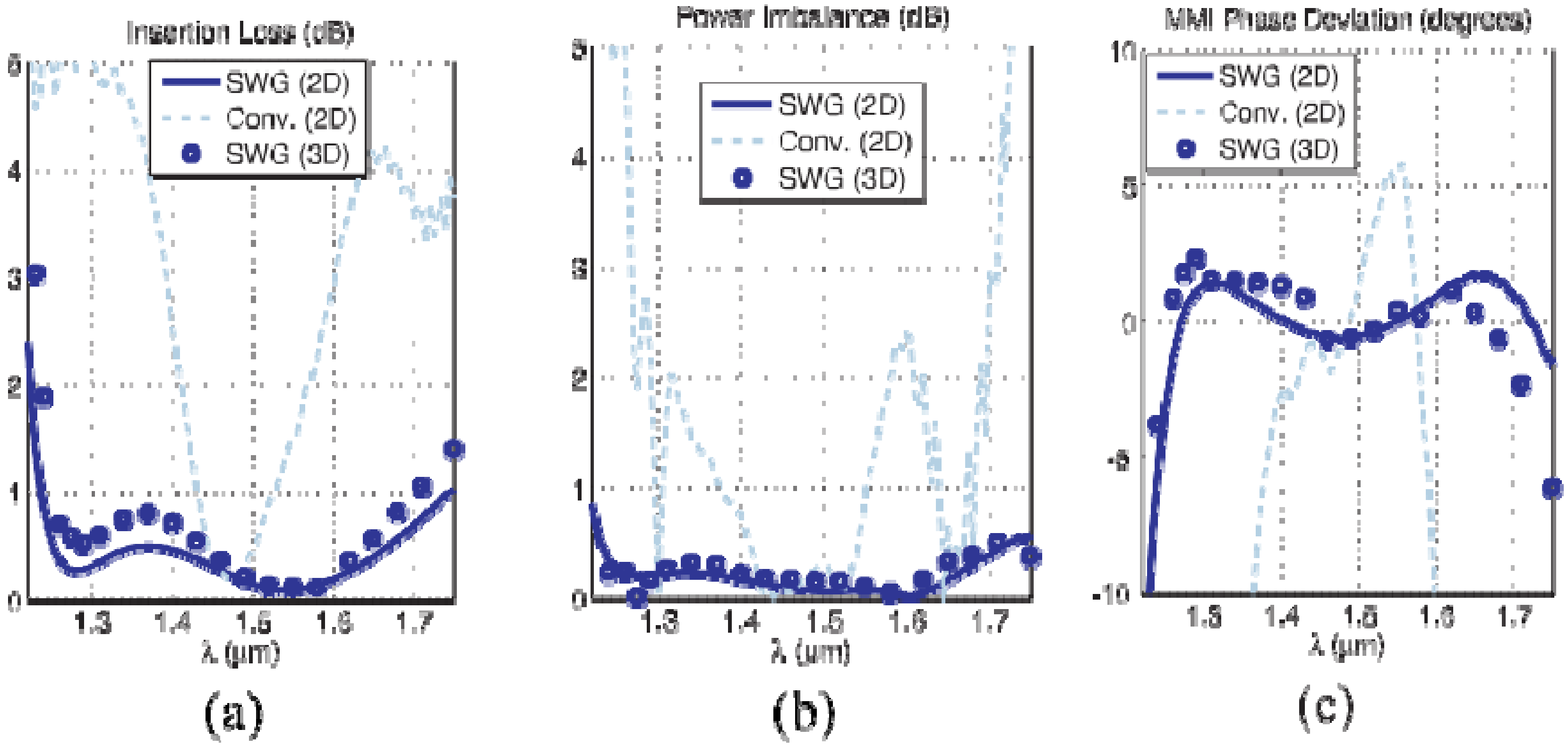
Access tapers:

- **Linear shape: width & core**
- **Length: 10 µm**

Broadband MM Performance



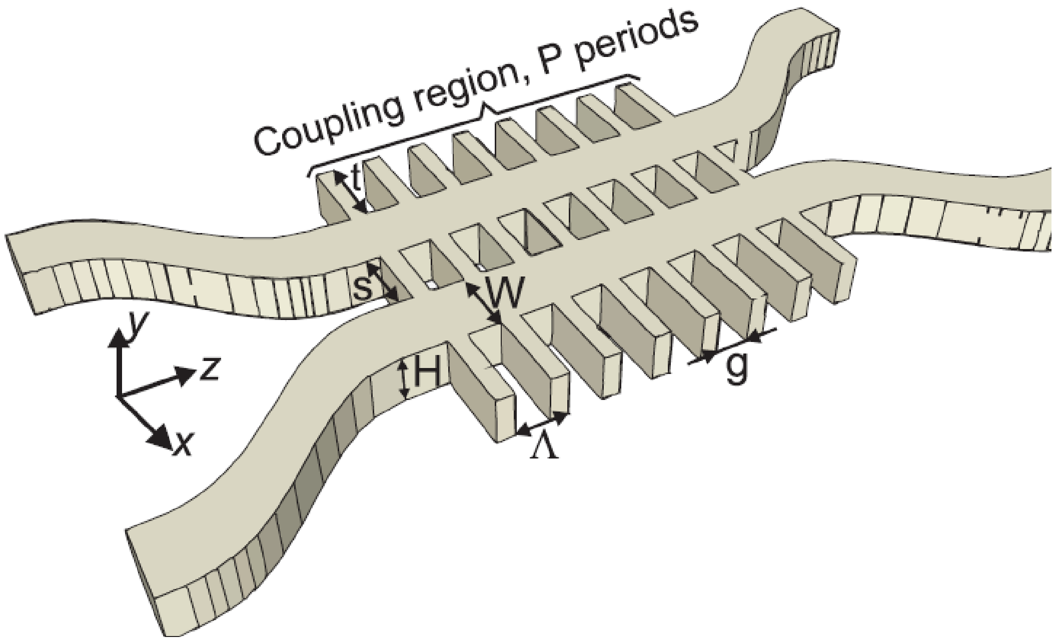
Broadband MM Performance

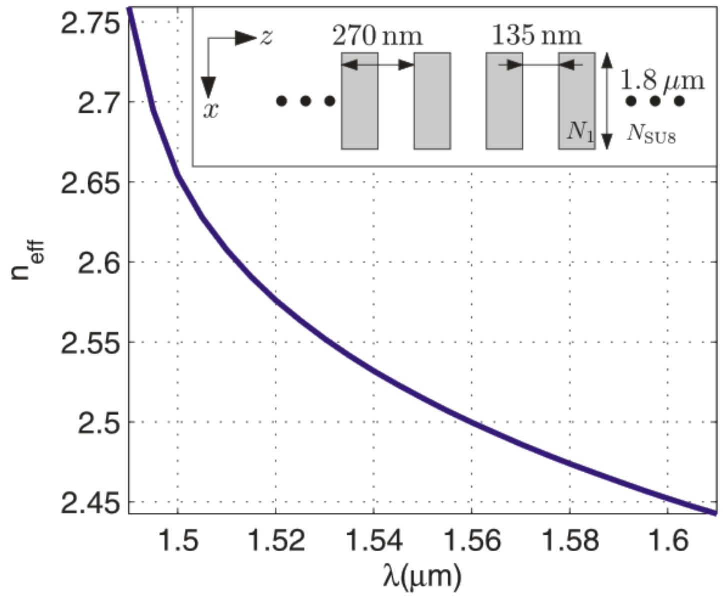


- Calculated insertion loss, power imbalance and phase deviations of less than 1dB, 0.6dB and 3◦.
- 450nm bandwidth, ~5x enhancement compared to a conventional design.
- The wavelength range (1260nm - 1675nm) exceeds the O, E, S, C, L and U optical communication bands

A. Maese et al., Optics Express, Vol. 21 Issue 6, pp.7033-7040 (2013)

Colorless directional coupler with dispersion engineered subwavelength grating

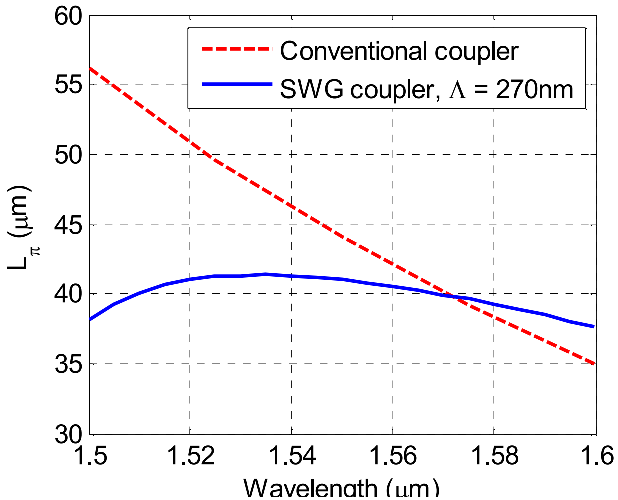


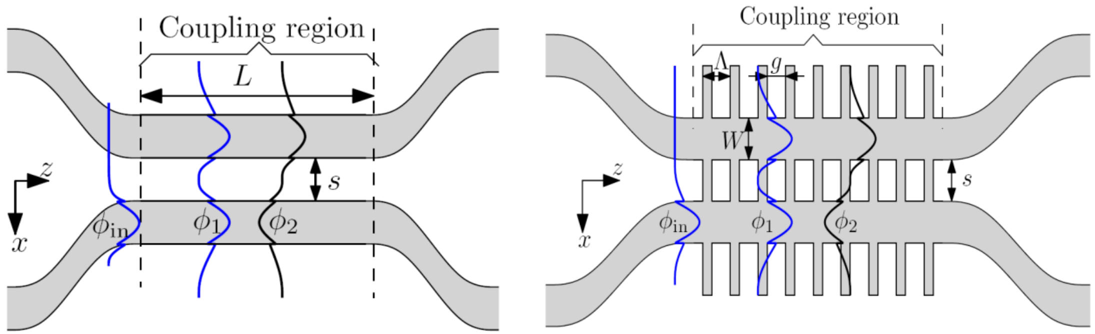


- Directional coupler is a fundamental building block in photonic circuits
- Intrinsic wavelength dependence – limited operational bandwidth
- The dispersive property of a sub-wavelength grating is used to compensate for intrinsic wavelength dependence of a directional coupler

U of Malaga and NRC, R. Halir et al., Optics Express, Vol. 20, No. 12, p. 13470, 2012

Conventional DC versus colorless DC design



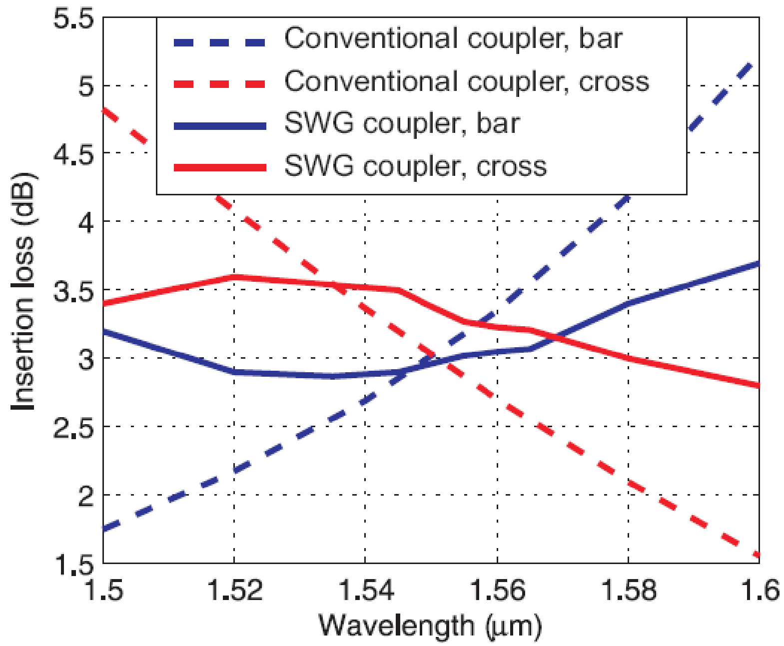


$$L_\pi = \pi/(\beta_0 - \beta_1)$$

Conventional coupler:
Wavelength decreases -> modal confinement increases -> coupling length **L_π increases**

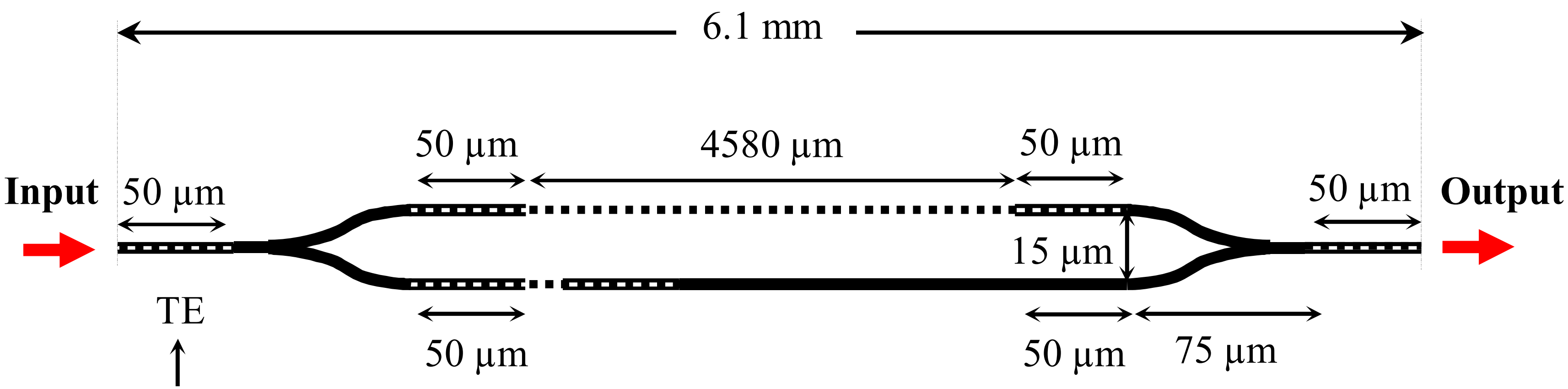
SWG coupler:
Wavelength decreases -> SWG effective index increases → n_{eff} even increases more than n_{eff} odd → **L_π decreases**

Coupling length is wavelength flattened.
5-fold increase in the operation bandwidth.
100 nm bandwidth with an imbalance of ≤0.6 dB (3D FDTD simulations).

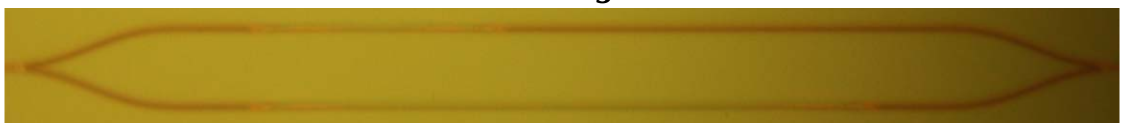


R. Halir et al., Optics Express, Vol. 20, No. 12, p. 13470, 2012

Terabit integrated all-optical switch

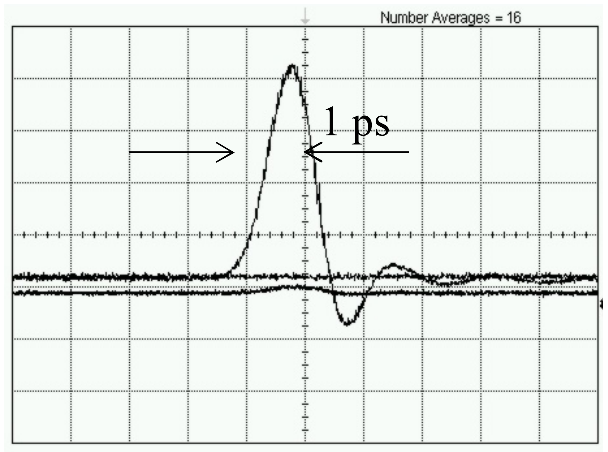


SWG waveguide



Nanowire

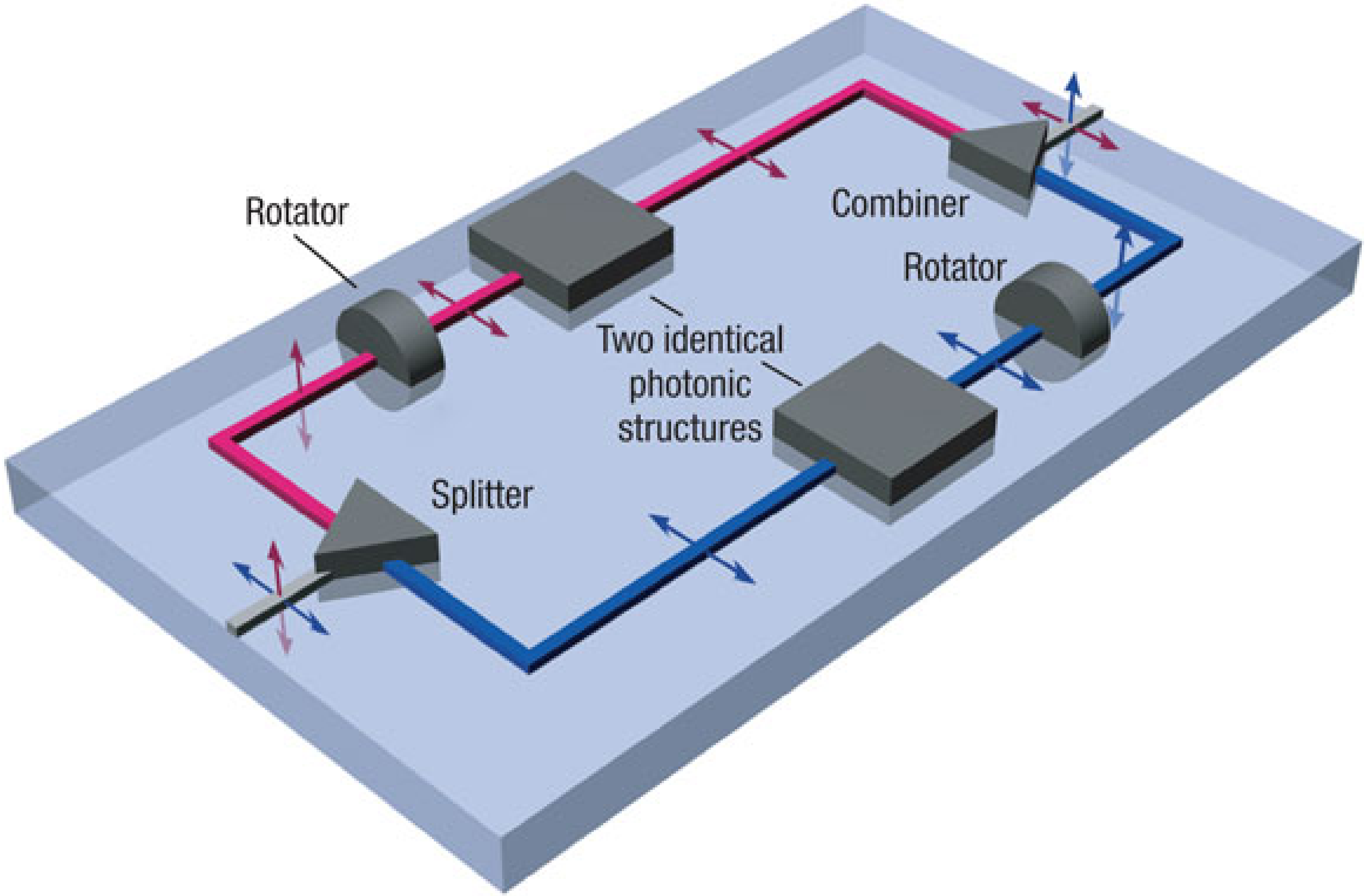
Pump/clock: Mode locked Er doped fiber laser, 1 ps, λ_c = 1558 nm
rep. rate 18.54 MHz, average power 0.54 mW (29 W peak)
Signal: cw, 1535



1 Tb/s all-optical - Demultiplexing
- Wavelength conversion

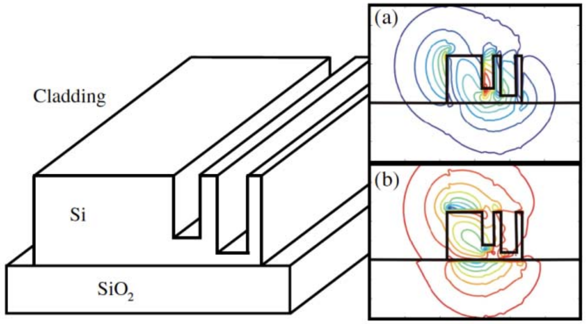
Ivan Glesk at al., Optics Express 19(15), pp. 14031-14039 (2011)

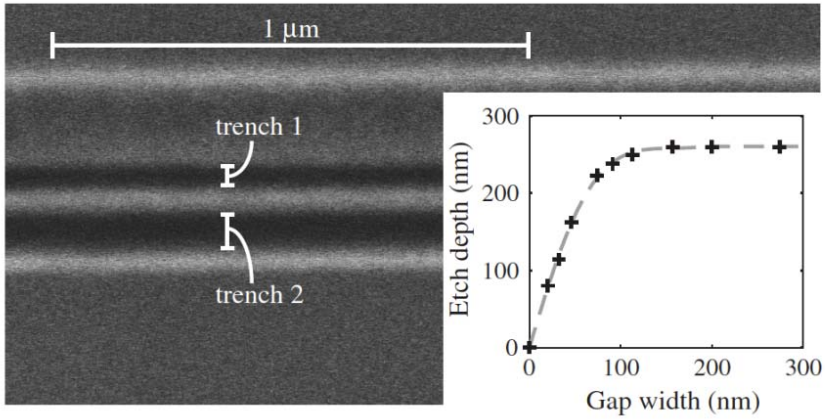
Polarization diversity



Tymon Barwicz, *Nature Photonics* 1, 57 - 60 (2007)

Polarization rotator

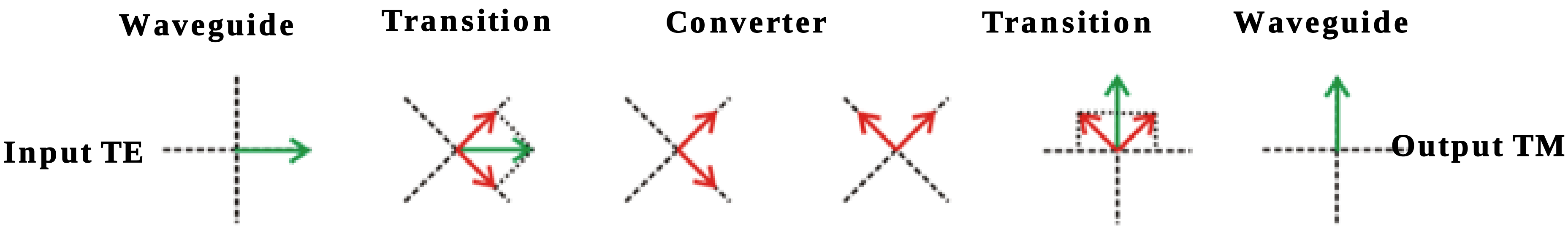




- Two subwavelength trenches generate hybrid modes with a 45° offset in their polarization angles
- The two hybrid modes have different propagation constants, resulting in polarization conversion at each half-beat length
- Single $L_{1/2}=\pi/(\beta_1-\beta_2)$
- Different depths are achieved by using RIE Lag effect

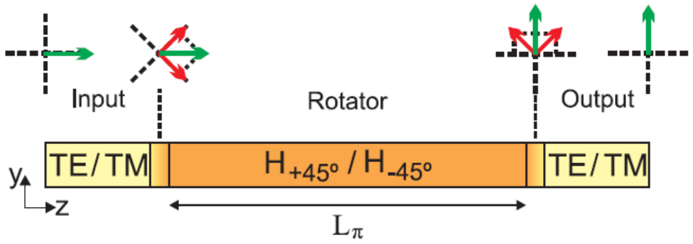
NRC and Complutense University of Madrid
A.V. Velasco et al., Opt. Lett., vol. 37, January 15, 2012

Extinction ratio 16 dB
Device Length = 10 µm



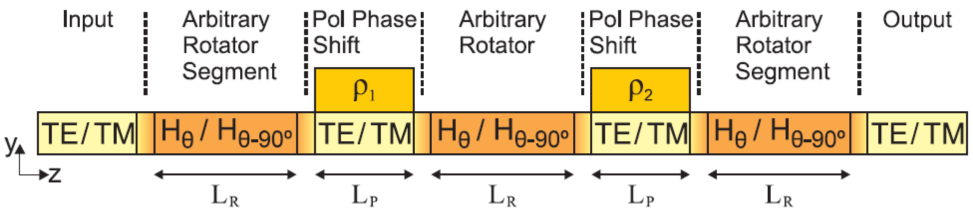
Robust polarization rotator scheme

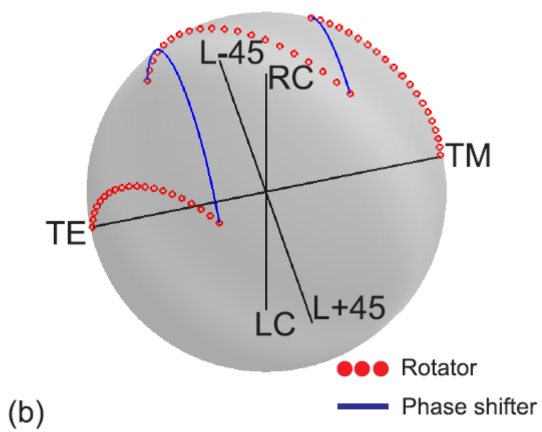
Conventional rotator scheme:



U of Malaga, Univ. Paris Sud, CNRS and NRC

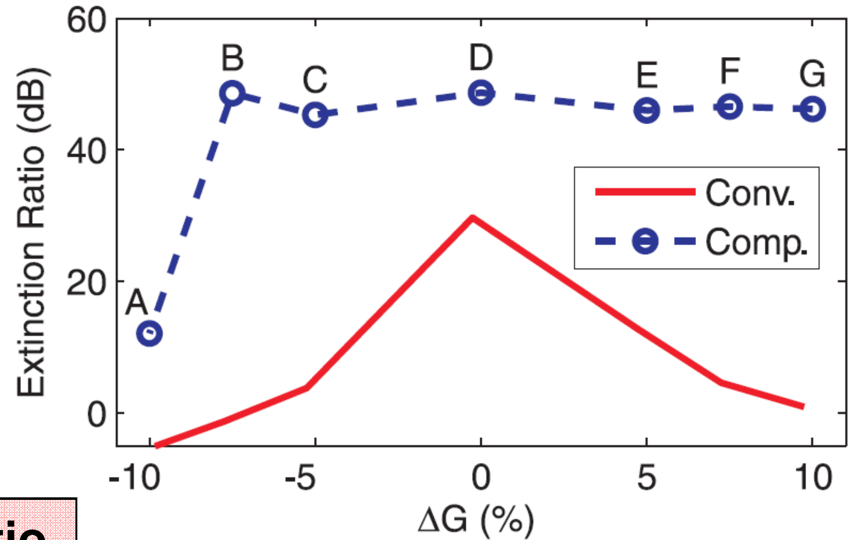
Segmented rotator scheme:





3 rotator segments
+ 2 phase shifters

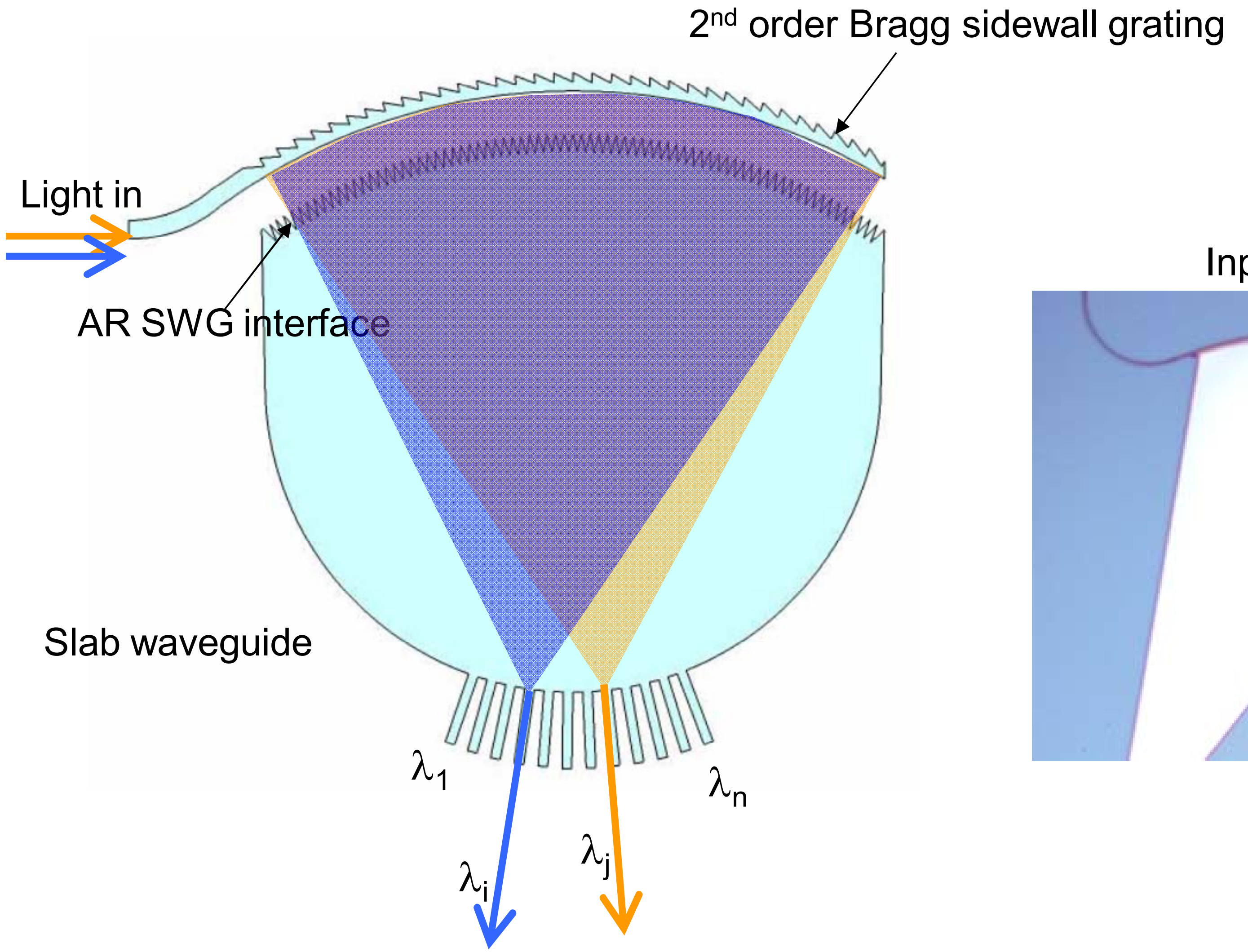
Perfect polarization rotation is possible even for a “bad” rotator by adjusting the phase shifts

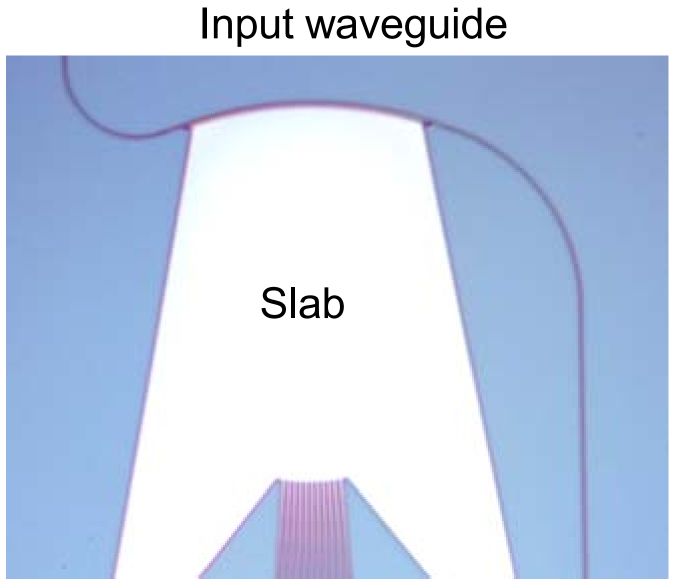


Robust design and 40dB extinction ratio

C. Alonso-Ramos et al., Optics Letters, 37, 3534, 2012

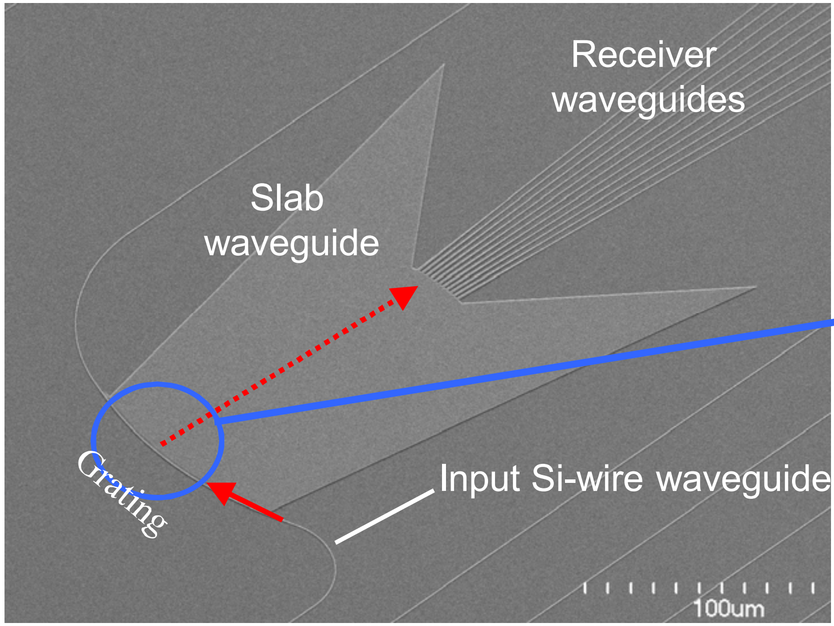
Curved waveguide sidewall grating demultiplexer

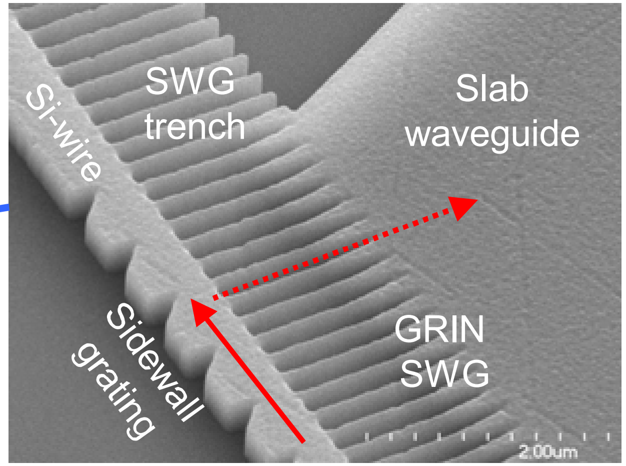




P. J. Bock, P. Cheben, et al., Optics Express **16**(22) 17616-17625 (2008)

Subwavelength grating demultiplexer





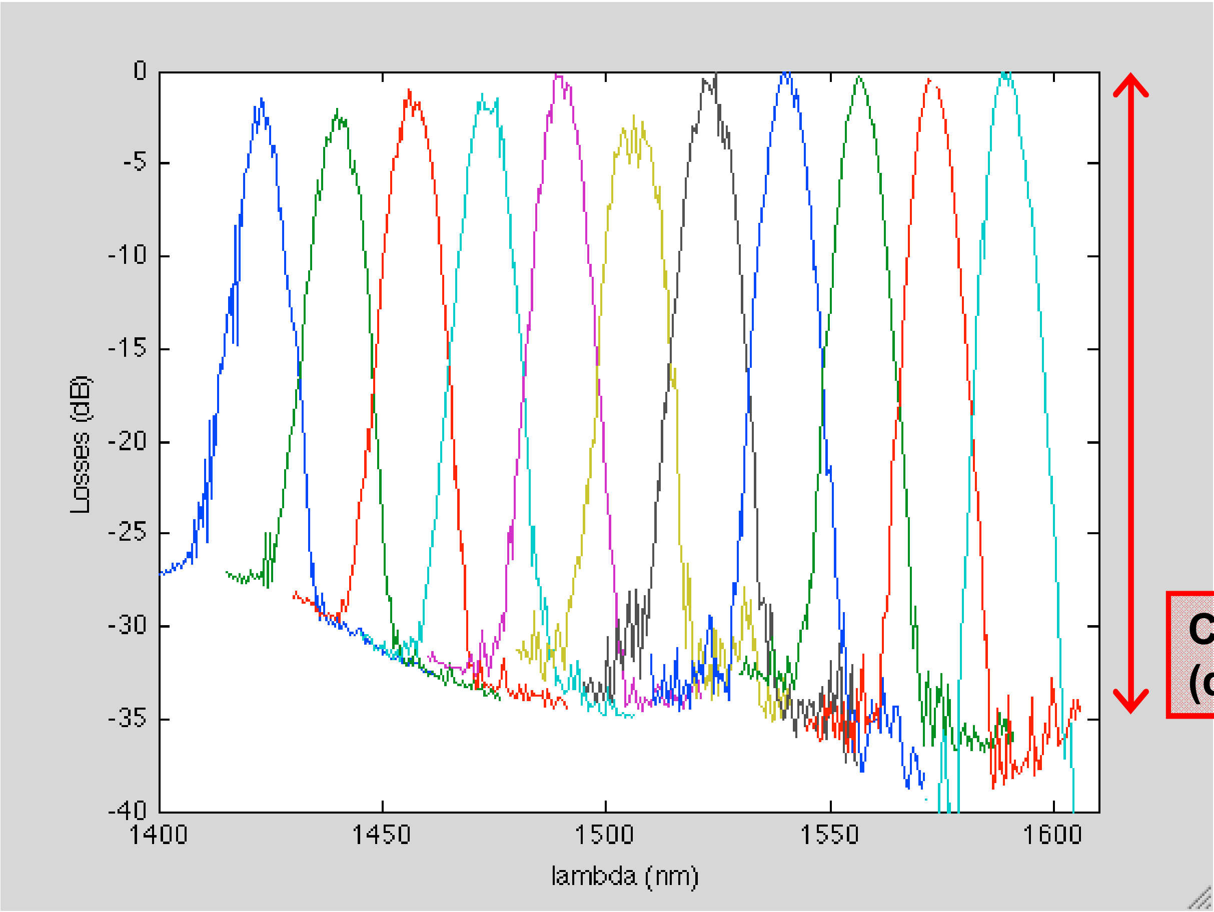
SWG acts as:

1) Lateral cladding for the strip waveguide
2) Slab waveguide for light diffracted by the grating
3) GRIN anti-reflective interface

P. J. Bock et al., Opt. Express 16, 2008
P. Cheben et al., Opt. Lett. 35, p. 2526, 2010
P. J. Bock et al., Optics Express 20, p. 19882, 2012

Measured demultiplexer spectrum

CWDM
11 channels spaced at 18 nm
200 nm bandwidth

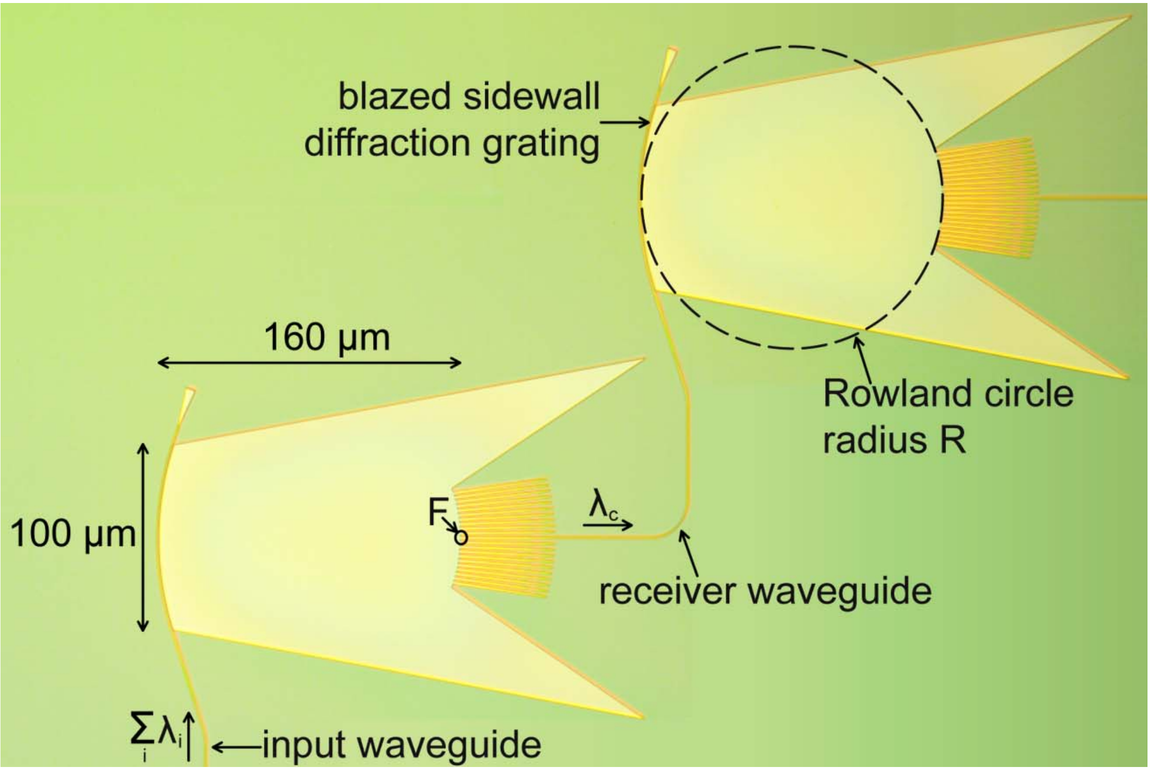


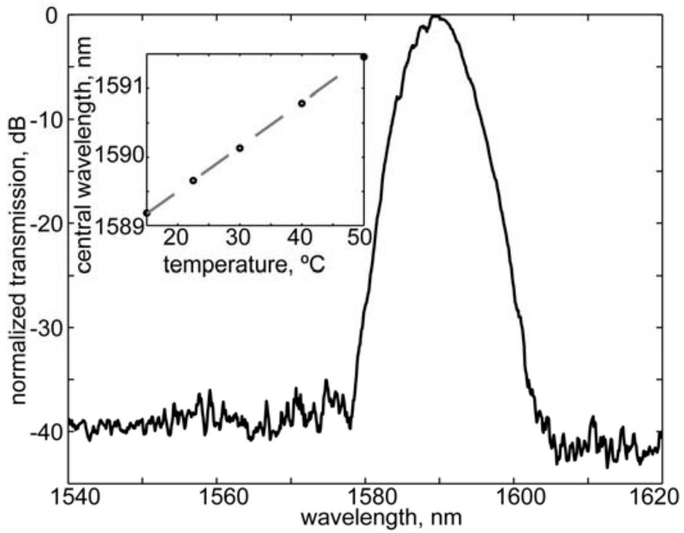
Crosstalk -35dB (double pass)

Size: 160μm×100μm

P. J. Bock et al., Optics Express 20, 19882, 2012

Band-pass filter





A bandwidth of 6.2 nm measured near 1590 nm
A roll-off 4 dB/nm at the pass-band edge
Stop-band rejection ~40 dB.

A. Villafranca et al., Electronics Letters, vol. 48, no. 12 (2012)

Conclusions

Subwavelenth structures offer exciting new opportunities for integrated optics.

Effective refractive index can be chosen from a broad range by lithographic patterning using just two materials.

Many practical subwavelength engineered devices already demonstrated, with superior performance compared to their conventional counterparts and likely many more to come.