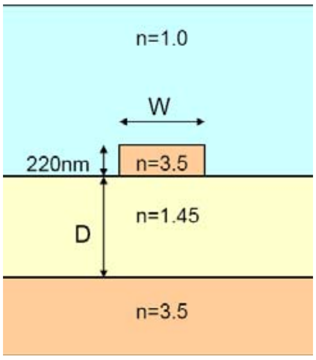
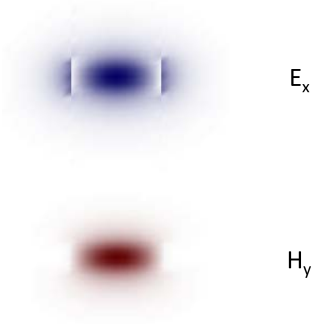
Vlnovody s velkým kontrastem indexu lomu

„Fotonický drát“

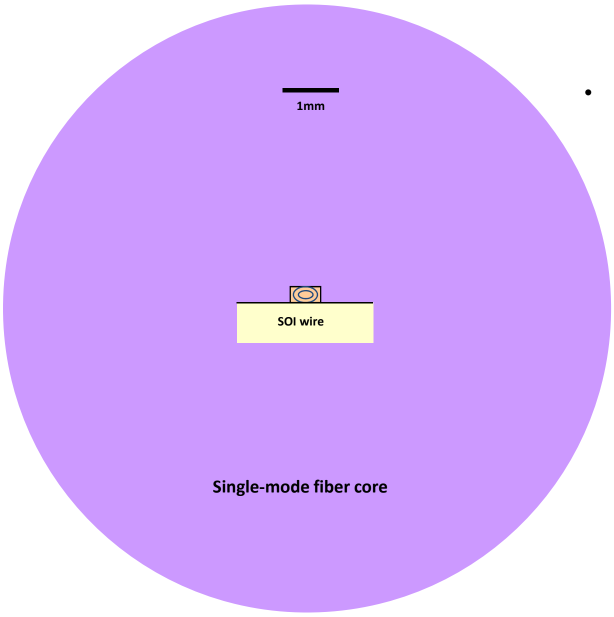
(vlnovod s velkým kontrastem indexu lomu)



Rozložení elektromagnetického pole základního vidu TE_{00}

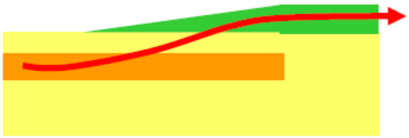


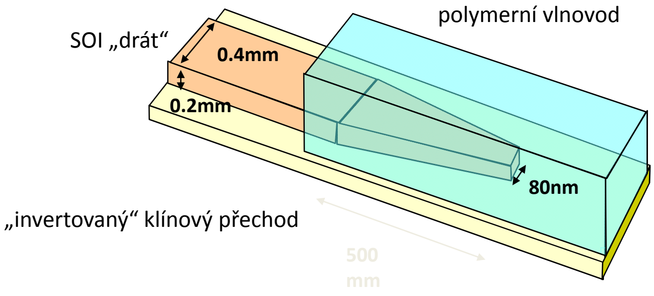
Vazba do „nanofotonických“ vlnovodů



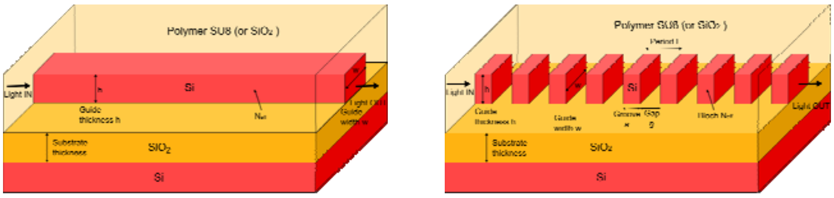
- **Problémy:**
  - Účinná vazba mezi submikrometrovým vlnovodem a vláknem
  - Je nutný konvertor velikosti vidového pole:
    - v horizontální rovině
    - ve vertikální rovině (obtížnější)
  - Polarizační problém

„Adiabatický přechod“ mezi vlnovody velmi různých profilů / kontrastů

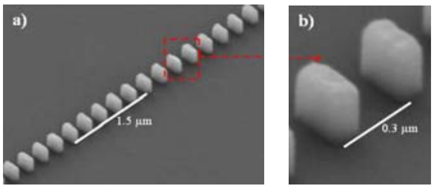




Křemíkové vlnovody se subvlnovými strukturami (subwavelength grating waveguide, SWG)



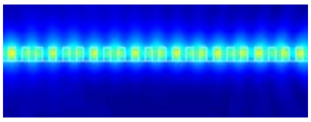
Schematic picture of (a) a strip channel waveguide and (b) SWG waveguide considered in this contribution. In both cases, Si guide (either continuous or segmented) on SiO_2 substrate, embedded in SU8 polymer (or, alternatively in SiO_2 cladding) are considered; h represents the guide thickness, w guide width, L is the SWG period (with Si groove dimension a, and gap g).



Scanning electron microscope (SEM) images of fabricated structures including: a) SWG straight waveguide with Λ = 300 nm, w = 250 nm and a duty cycle of 33%. b) Detail of two SWG segments.

P. J. Bock, Optics Express, 18(19), 20251 (2010).

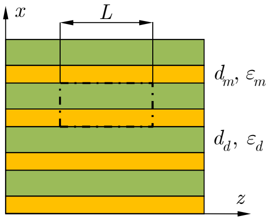
- SWG waveguide - a new type of microphotonic waveguide
- Practical implementations to fiber-chip coupling, waveguide crossing and refractive index engineering



ELEMENTÁRNÍ TEORIE EFEKTIVNÍHO PROSTŘEDÍ (Effective medium theory, EMT)

Vrstevnaté prostředí s parametry $\varepsilon_1,\ d_1$ a $\varepsilon_2,\ d_2$

$d_1,\ d_2 \ll \lambda$



Ekvivalentní kapacitor s deskami podél x:

$$C_{eq} = \frac{\varepsilon_1 d_1}{L} + \frac{\varepsilon_2 d_2}{L} = \frac{\varepsilon_{\|}(d_1+d_2)}{L};$$

$\varepsilon_{\|}$ …eff. permittivita

Tedy $\boxed{\varepsilon_{\|} = f\varepsilon_1 + (1-f)\varepsilon_2,}$ $\boxed{f = \frac{d_1}{d_1+d_2} = \frac{d_1}{L}}$

Ekvivalentní kapacitor s deskami podél z: $0 \le f \le 1.$

$$\frac{1}{C_{eq}} = \frac{d_1}{\varepsilon_1 L} + \frac{d_2}{\varepsilon_2 L} = \frac{(d_1+d_2)}{\varepsilon_{\perp} L}$$

$\varepsilon_{\perp}$ …eff. permittivita,

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

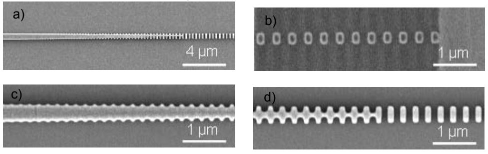
Efektivní prostředí je anizotropní, jednoosé, **s tenzorem permitivity**

$$\boxed{\boldsymbol{\varepsilon}_{eff} = \begin{pmatrix} \varepsilon_{\perp} & 0 & 0 \\ 0 & \varepsilon_{\|} & 0 \\ 0 & 0 & \varepsilon_{\|} \end{pmatrix}}$$

J. C. Maxwell Garnett, "Colours in metal glasses and in metallic films,“ *Philosophical Transaction of the Royal Society London* **203**, 385-420 (1904).

Složitější subvlnové vlnovodné struktury

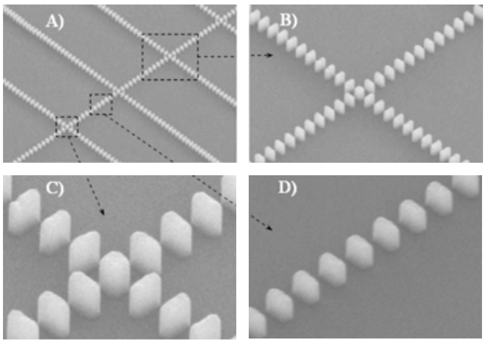
Vazební člen - vidový transformátor



Subwavelength grating mode transformer.
a) SEM image of the coupler,
b) low - confinement section near the chip edge,
c) high-confinement section near the strip waveguide,
d) Intermediate section.

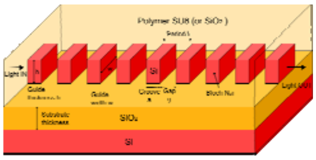
P. J. Bock et al., 7th IEEE Conference on Group IV Photonics, Sept. 2010, Beijing

Křížení segmentovaných vlnovodů



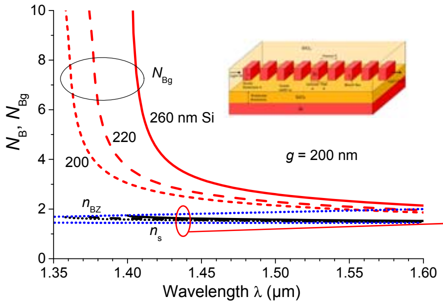
Scanning electron microscope images of SWG crossings:
A) multiple SWG crossings,
B) one SWG crossing,
C) detail of the crossing region with square center segment,
D) SWG straight waveguide.

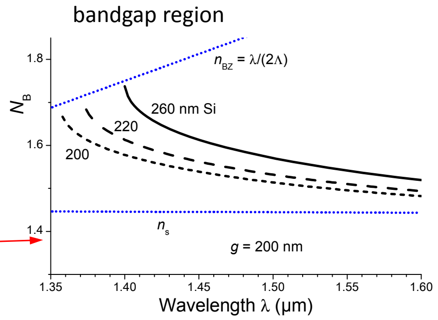
P. J. Bock et al., Optics Express, 18(15), 16146 (2010).



Disperzní vlastnosti SWG vlnovodů

Standard SWGW, *w* = 350 nm, Λ = 400 nm, *g* = 200 nm, TE polarization



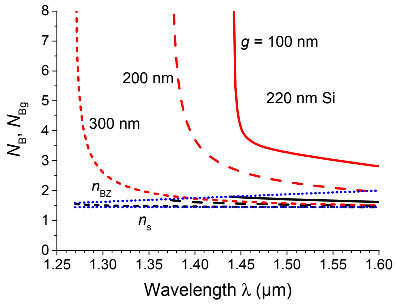


phase and group effective indices N_B , N_{Bg}

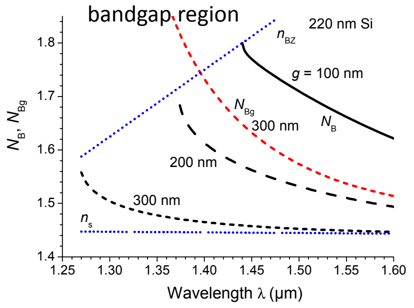
phase effective index N_B

Disperzní vlastnosti SWG vlnovodů

Standard SWGW, *w* = 350 nm, Λ = 400 nm, **various gap sizes** *g*, TE polarization



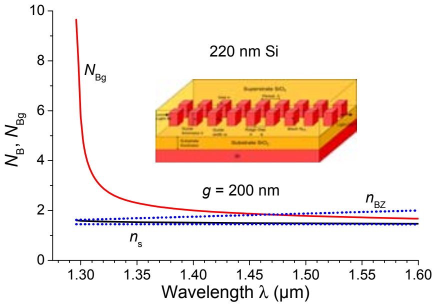
phase and group effective indices N_B , N_{Bg}



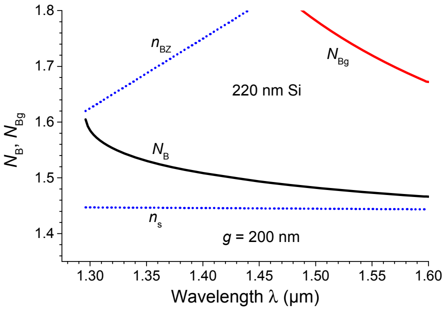
phase effective index N_B

Disperzní vlastnosti *štěrbinového* SWG vlnovodu

slot SWGW, width 2×200 nm+100 nm slot, Λ = 400 nm, *g* = 200 nm, TE polarization



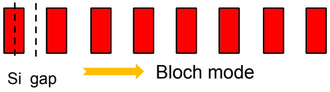
phase and group effective indices N_B , N_{Bg}



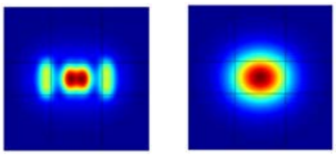
phase effective index N_B

POWER DENSITY DISTRIBUTION

standard SWG waveguide

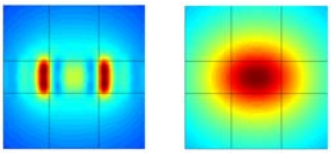


λ = 1.3 µm, *g* = 100 nm



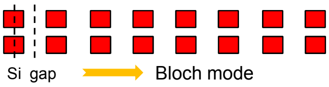
Si segment gap

λ = 1.55 µm, g = 360 nm
(Si filling fraction = 0.1)

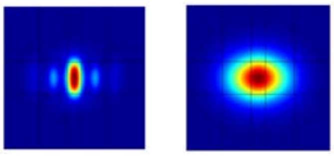


Si segment gap

slot SWG waveguide



λ = 1.3 µm, *g* = 200 nm

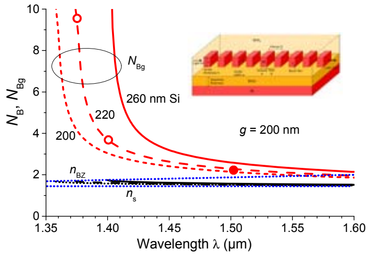


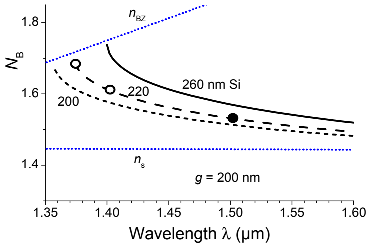
Si segment gap

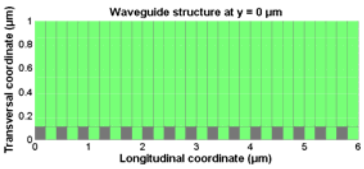
Power of the Bloch mode
of the slot SWG waveguide
is ***very strongly*** localized
in a low-index medium,
similarly as a mode of a uniform
slot waveguide

BLOCH MODE FIELD PROPAGATION

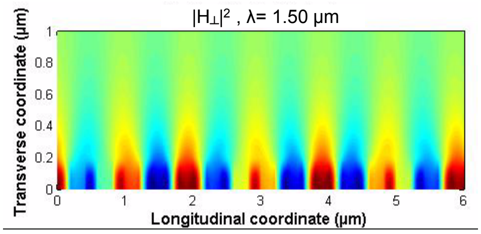
Vertical component of the magnetic field intensity @ λ = 1500 nm

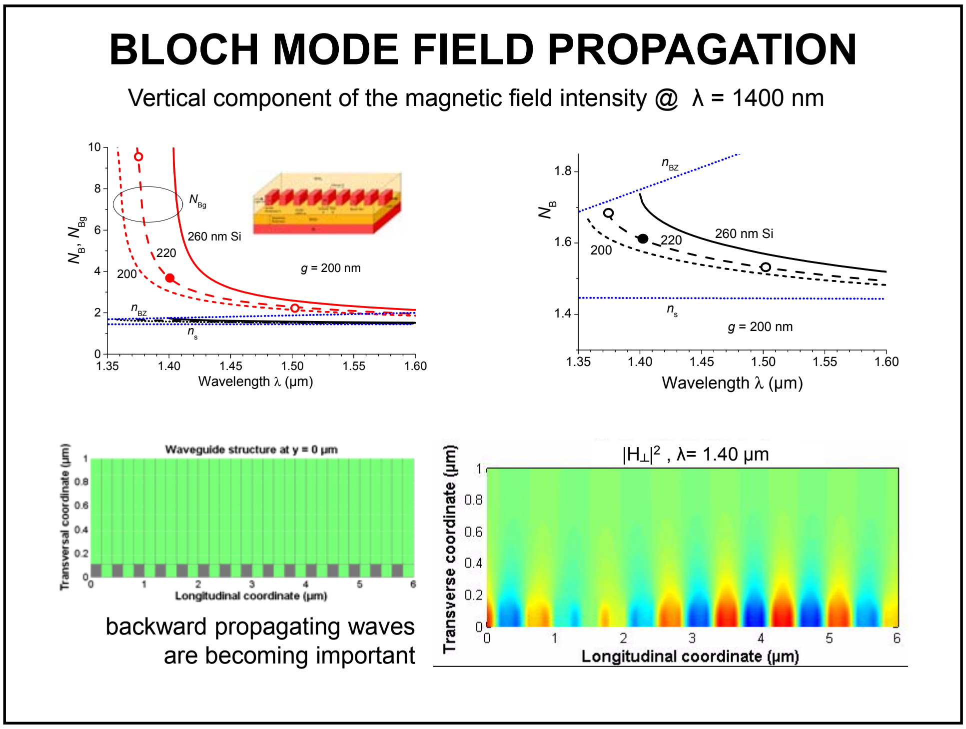






character quite similar
to a uniform waveguide

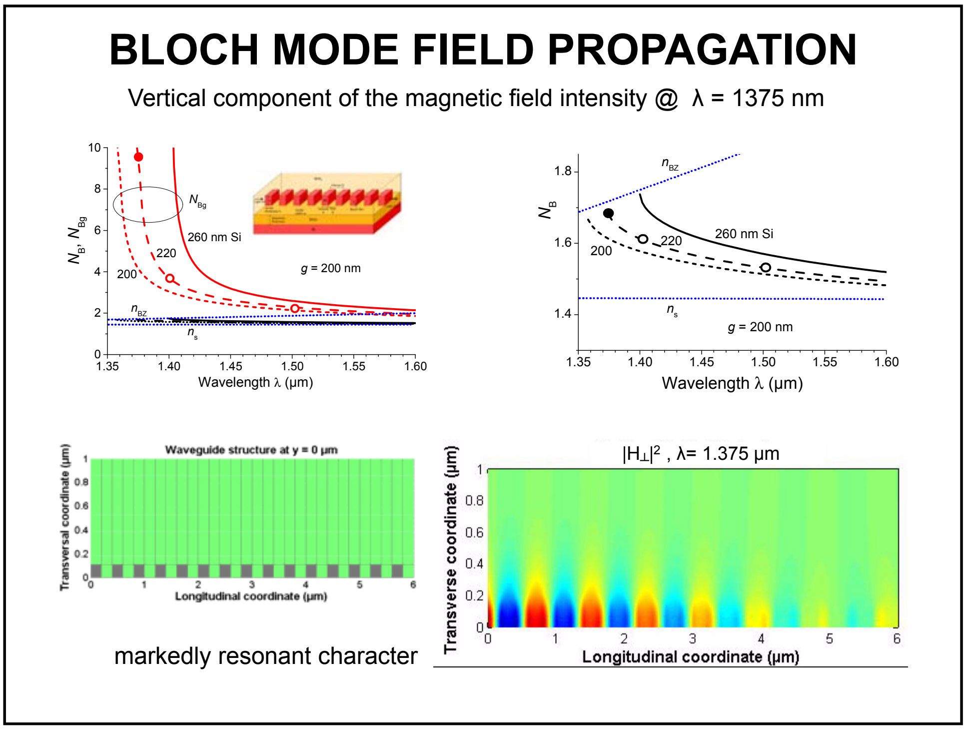




BLOCH MODE FIELD PROPAGATION

Vertical component of the magnetic field intensity @ λ = 1400 nm

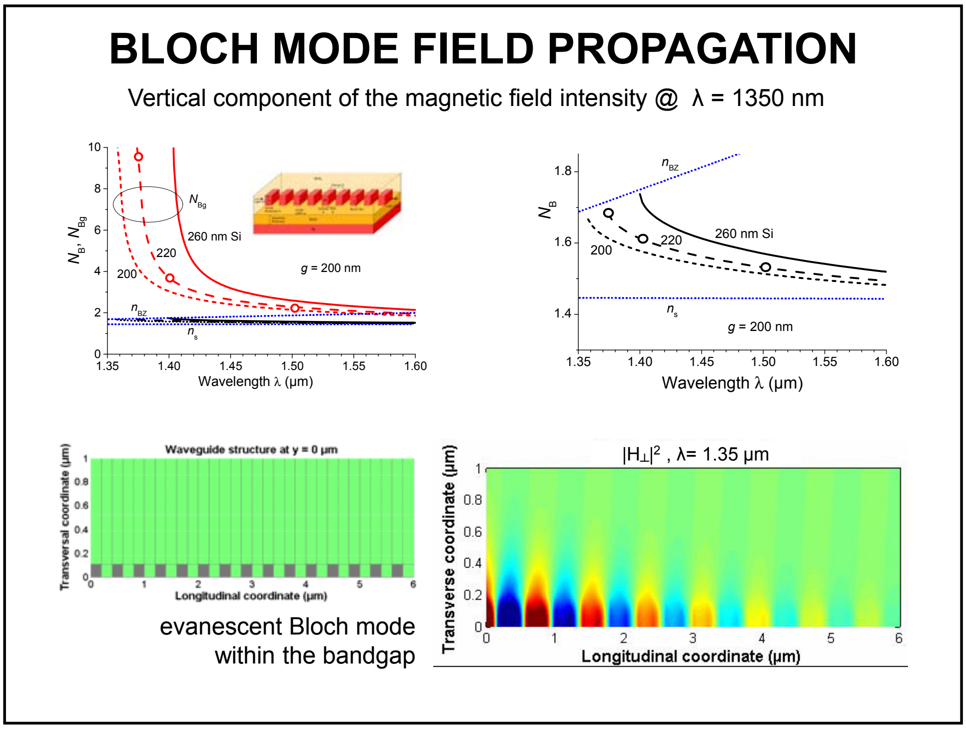
backward propagating waves are becoming important



BLOCH MODE FIELD PROPAGATION

Vertical component of the magnetic field intensity @ λ = 1375 nm

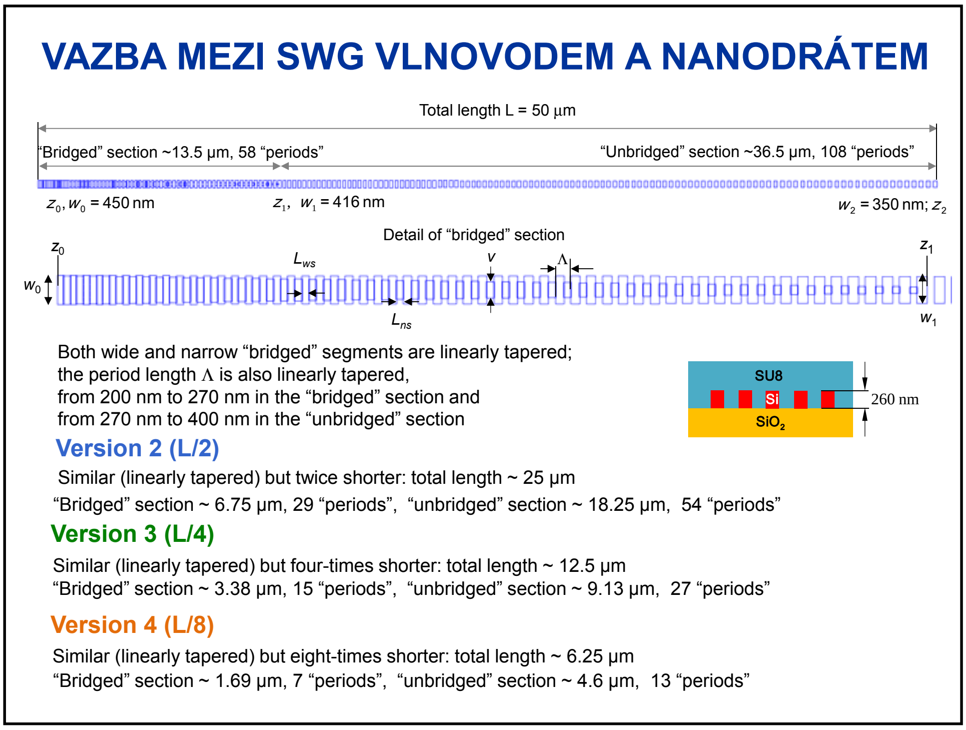
markedly resonant character



BLOCH MODE FIELD PROPAGATION

Vertical component of the magnetic field intensity @ λ = 1350 nm

evanescent Bloch mode within the bandgap



VAZBA MEZI SWG VLNOVODEM A NANODRÁTEM

Both wide and narrow "bridged" segments are linearly tapered;
the period length Λ is also linearly tapered,
from 200 nm to 270 nm in the "bridged" section and
from 270 nm to 400 nm in the "unbridged" section

Version 2 (L/2)

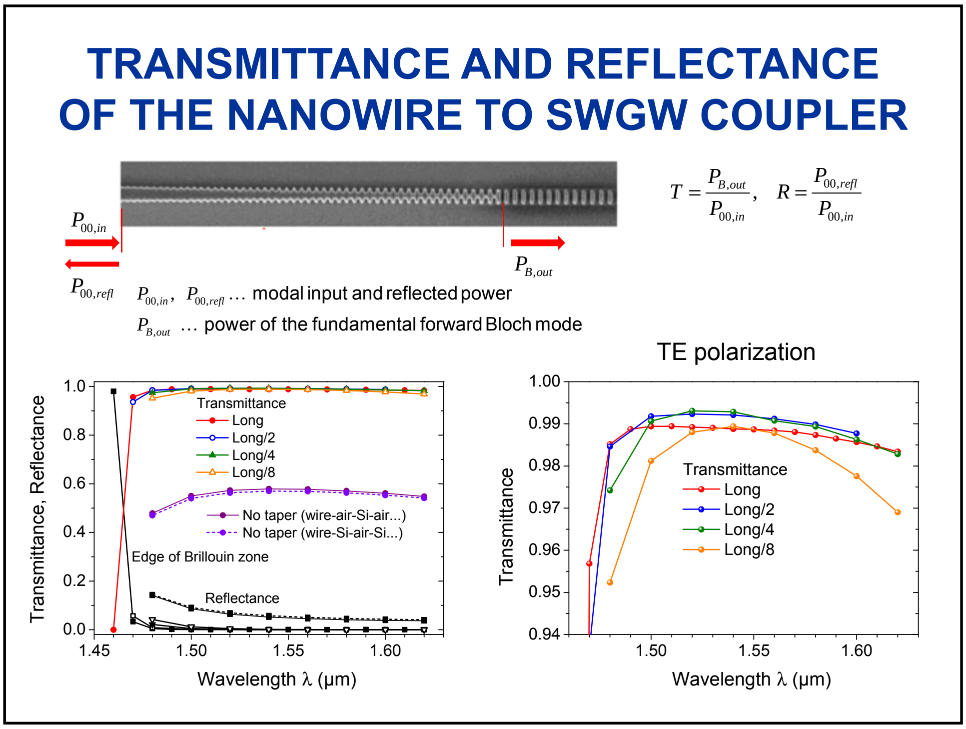
Similar (linearly tapered) but twice shorter: total length ~ 25 μm
"Bridged" section ~ 6.75 μm, 29 "periods", "unbridged" section ~ 18.25 μm, 54 "periods"

Version 3 (L/4)

Similar (linearly tapered) but four-times shorter: total length ~ 12.5 μm
"Bridged" section ~ 3.38 μm, 15 "periods", "unbridged" section ~ 9.13 μm, 27 "periods"

Version 4 (L/8)

Similar (linearly tapered) but eight-times shorter: total length ~ 6.25 μm
"Bridged" section ~ 1.69 μm, 7 "periods", "unbridged" section ~ 4.6 μm, 13 "periods"

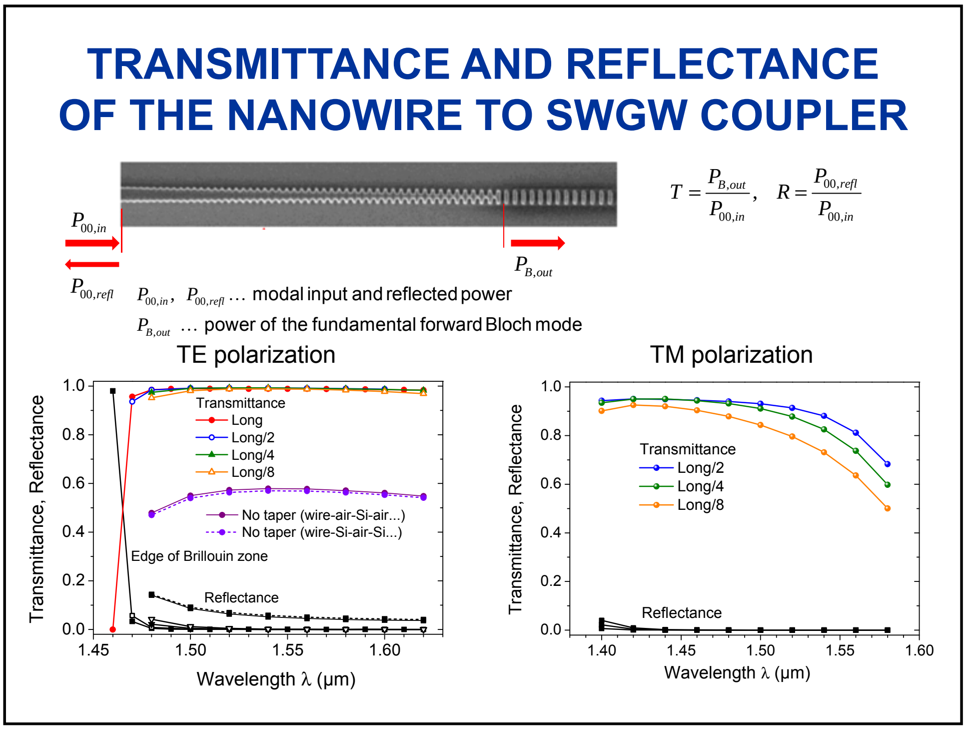


TRANSMITTANCE AND REFLECTANCE OF THE NANOWIRE TO SWGW COUPLER

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

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

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



TRANSMITTANCE AND REFLECTANCE OF THE NANOWIRE TO SWGW COUPLER

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

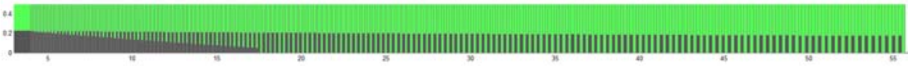
$P_{00,in}$, $P_{00,refl}$ … modal input and reflected power

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

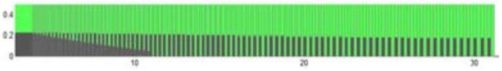
COUPLERS OF DIFFERENT LENGTHS

Version 1 (L)

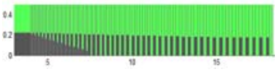
vertical view; only upper half is shown because of structure symmetry



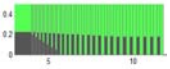
Version 2 (L/2)

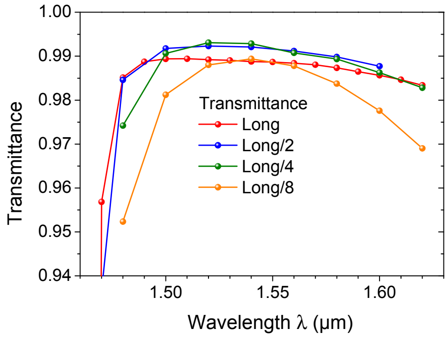


Version 3 (L/4)

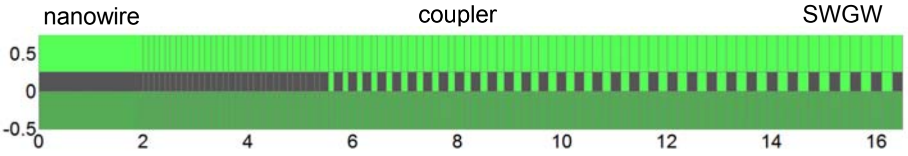


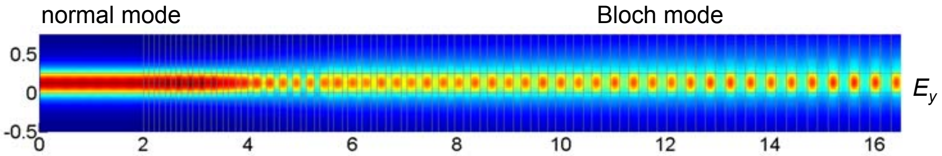
Version 4 (L/8)





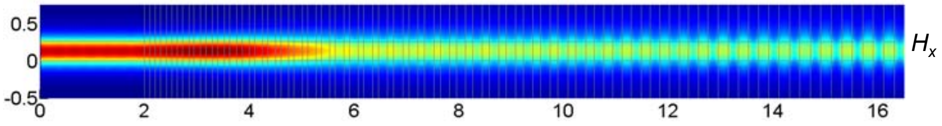
TE$_{00}$ MODE FIELD DISTRIBUTION IN THE L/4 COUPLER: VERTICAL PLANE



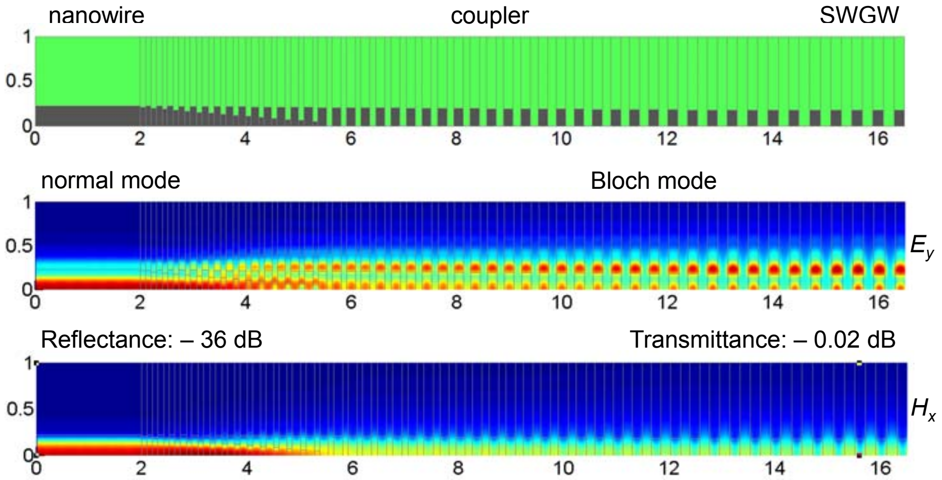


Reflectance: – 36 dB

Transmittance: – 0.02 dB



TE$_{00}$ MODE FIELD DISTRIBUTION IN THE L/4 COUPLER: HORIZONTAL PLANE (upper half)

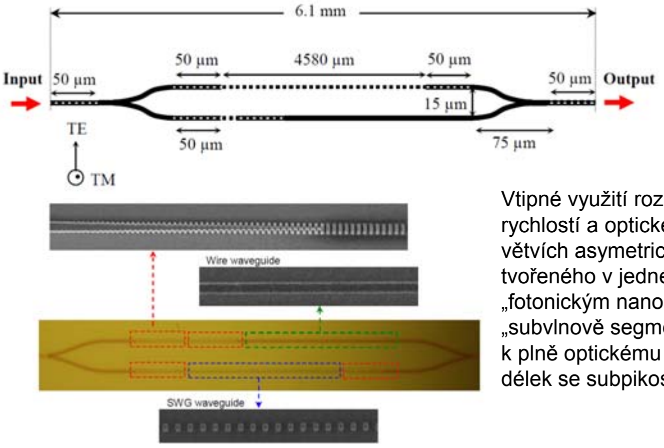


Reflectance: – 36 dB

Transmittance: – 0.02 dB

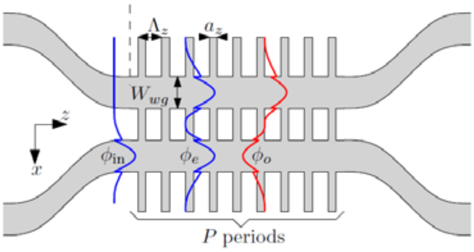
Aplikace subvlnových segmentovaných vlnovodů na optický konvertor vlnových délek

I. Glesk, P. J. Bock, P. Cheben *et al.*, Optics Express, 19 (15), 14031 (2011).



Vtipné využití rozdílu fázových a grupových rychlostí a optické lokalizace v jednotlivých větvích asymetrického MZ interferometru tvořeného v jedné větvi homogenním „fotonickým nanodrátem“ a ve druhé větvi „subvlnově segmenovaným“ vlnovodem k plně optickému spínání a konverzi vlnových délek se subpikosekundovou rychlostí

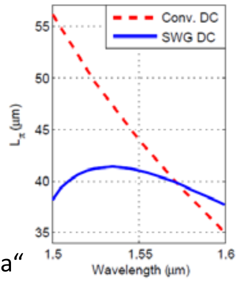
Aplikace subvlnových segmentovaných vlnovodů na směrovou odbočnici

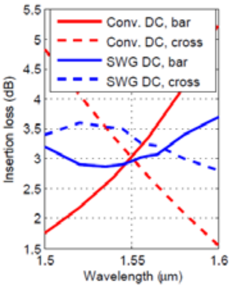


„Vložný útlum“
v obou větvích

Optimalizace parametrů
umožňuje využít
větší šířku pásma:

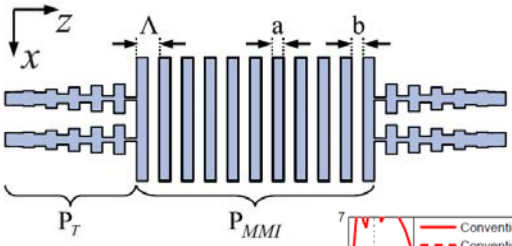
„Vazební délka“



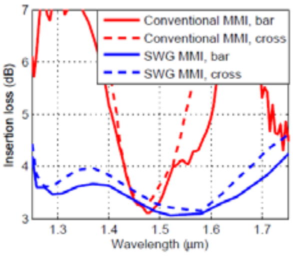


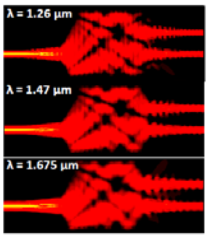
Aplikace subvlnových segmentovaných vlnovodů na vazební člen s mnohovidovou interferencí

P. Cheben et al., Wavelength-Independent Multimode Interference Coupler, Opt. Express 2012
NRC, Ottawa, Canada, and University of Malaga, Spain

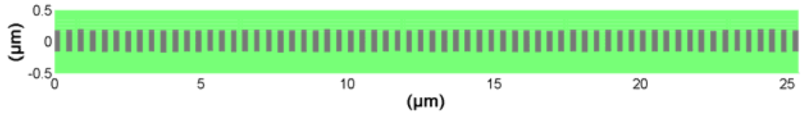


Optimalizace parametrů
umožňuje širokopásmové
použití

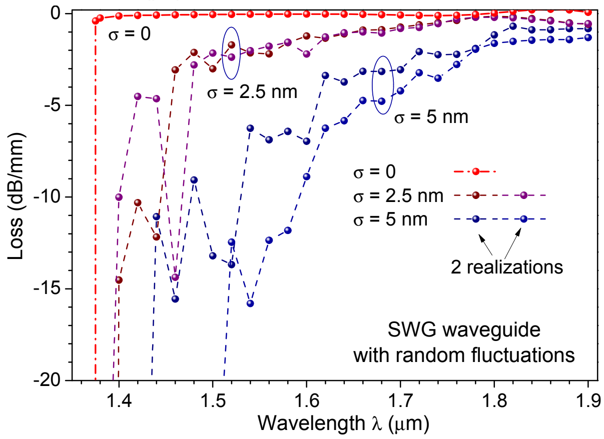




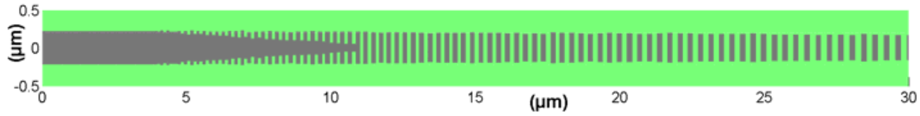
INFLUENCE OF RANDOM FLUCTUATIONS ON SWGW PERFORMANCE

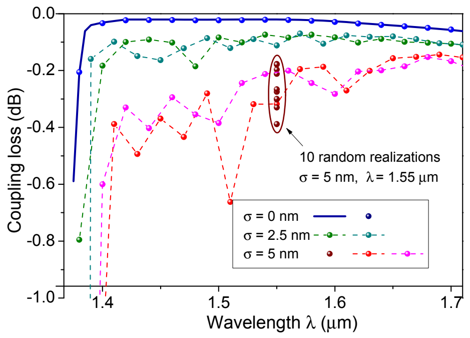


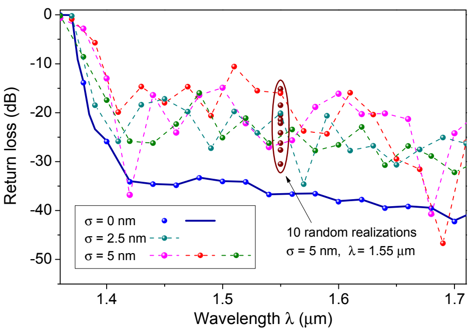
Positions and dimensions of Si segments fluctuate with normal distribution and standard deviation σ



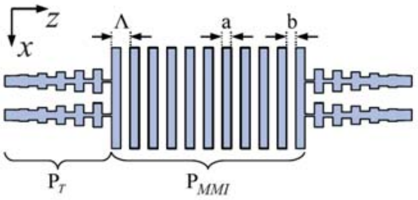
INFLUENCE OF RANDOM FLUCTUATIONS ON SWGW COUPLER PERFORMANCE







BROADBAND SWGW MMI COUPLER



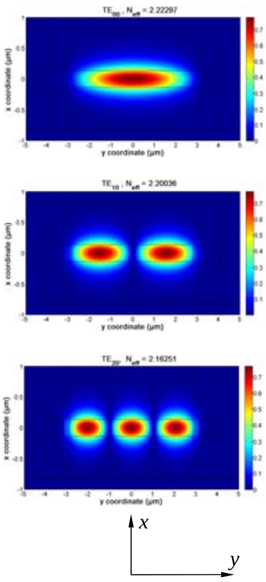
1. Optimization of MMI section for broadband operation
2. Check of imaging properties of the MMI section
3. Verification of taper function
4. Analysis of possible mutual coupling between tapers
5. Field distribution and scattering matrix of the complete coupler

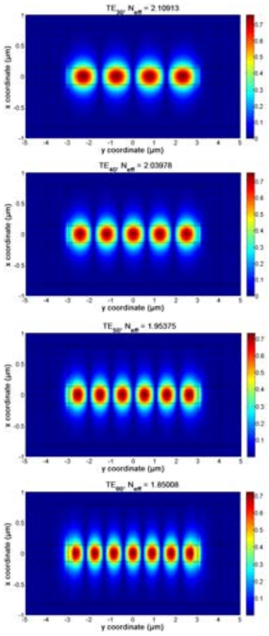
A. Maese-Novo, R. Halir, S. Romero-García, D. Pérez-Galacho, L. Zavargo-Peche, A. Ortega-Moñux, I. Molina-Fernández, J. G.Wangüemert-Pérez, and P. Cheben, *Opt. Express* vol 21, 7033-7040 (2013)

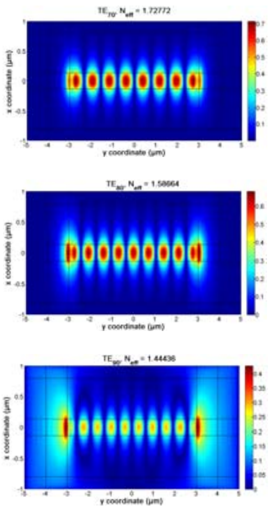
BLOCH MODES IN THE SWG MULTIMODE REGION

$|E_y(x,y)|$, $\lambda = 1.55$ μm

$\Lambda = 180$ nm







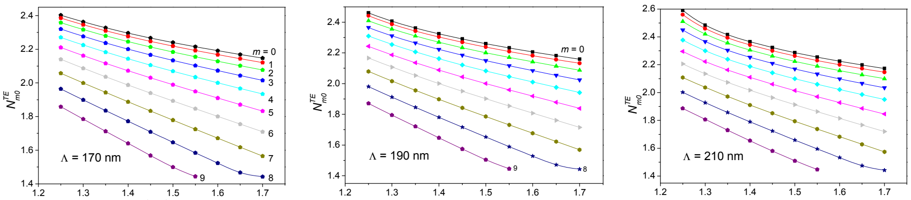
TE_{90} mode is weakly guided and for $\lambda > 1.55$ μm is cut-off

OPTIMIZATION OF MMI SECTION FOR BROADBAND OPERATION

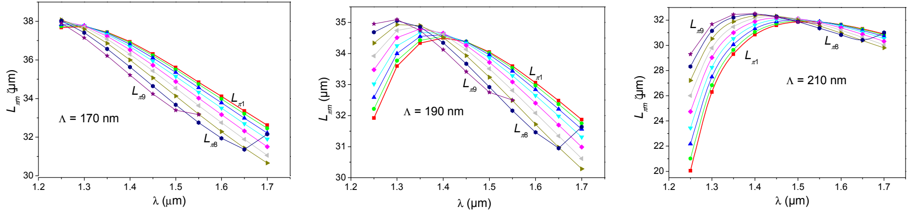
Minimize wavelength dependence of the beat length between several lowest-order lateral Bloch modes by optimization of period length; MMI section width = 6 µm

$$\text{"ideal" beat length}: \; L_{\pi m} = \frac{\left[(m+1)^2-1\right]\pi}{3(\beta_0-\beta_m)} = \frac{m(m+2)}{6(N_{00}-N_{0m})}, \quad m=1,\ 2,\ \ldots,\ 8$$

Eff. indices



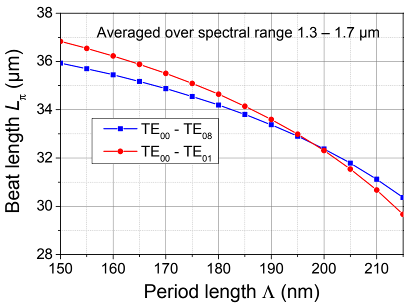
Beat lengths

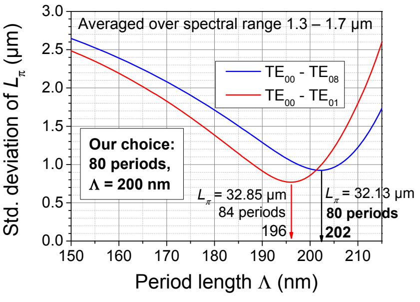


OPTIMIZATION OF THE MMI SECTION FOR 1.3 – 1.7 µm WAVELENGTH RANGE

Average beat lengths

Standard deviations of the beat lengths





Averaging over wavelengths and modes:

$$\Lambda_{opt}^{0-1} = 196\text{ nm},\quad L_\pi^{0-1} = 32.85\ \mu\text{m},\quad NoP^{0-1} \doteq L_\pi^{0-1}\big/(2\Lambda_{opt}^{0-1}) = 84\ \text{periods},$$

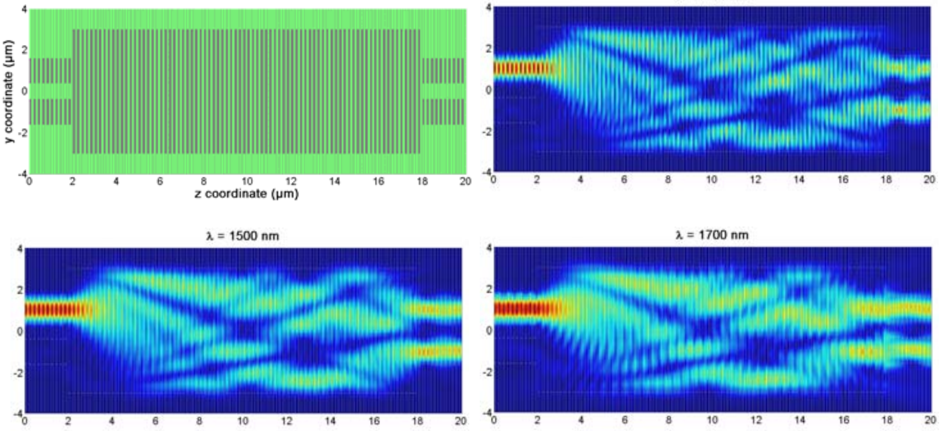
$$\Lambda_{opt}^{0-8} = 202\text{ nm},\quad L_\pi^{0-8} = 32.13\ \mu\text{m},\quad NoP^{0-8} \doteq L_\pi^{0-8}\big/(2\Lambda_{opt}^{0-8}) = 80\ \text{periods}.$$

IMAGING PROPERTIES OF THE SWG MMI SECTION

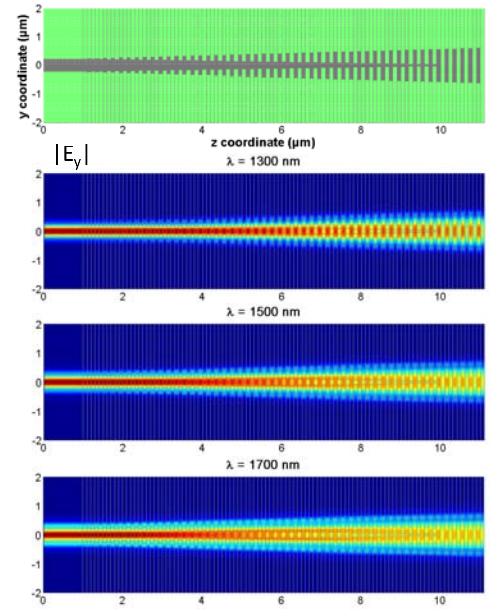
Excitation of the SWG MMI section with SWG “ports”
by the superposition of symmetric and antisymmetric Bloch modes

MMI: 80 periods, Λ = 200 nm

|E_y|



PROPERTIES OF INPUT AND OUTPUT COUPLERS



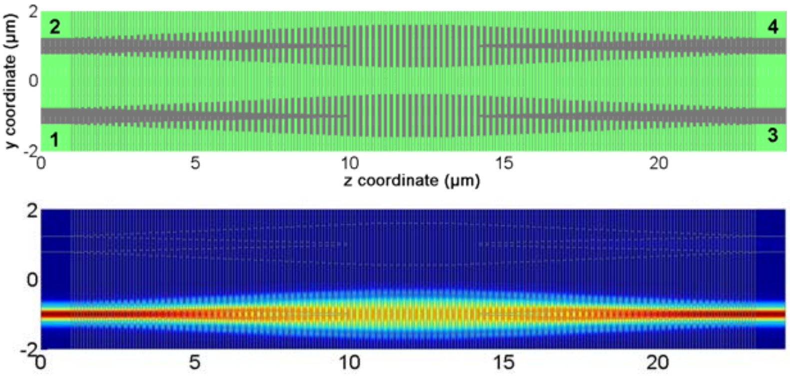
Estimated SWG period Λ = 200 nm

Conversion from photonic wire
into Bloch mode of the SWG output:

Very high conversion efficiency
difficult to reliably calculate
(loss <= 0.01 dB),
very small return loss –
reflected power <= – 45 dB
for all wavelengths
1.3 µm, 1.5 µm, and 1.7 µm.

Shorter taper could probably
work well, too.

CHECK OF MUTUAL COUPLING IN THE TAPERS

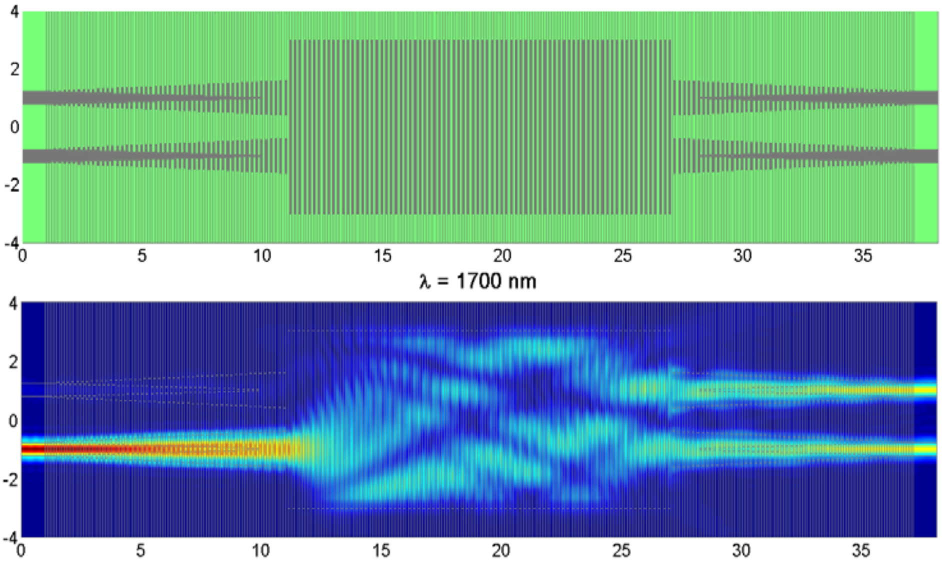


Calculated scattering parameters:

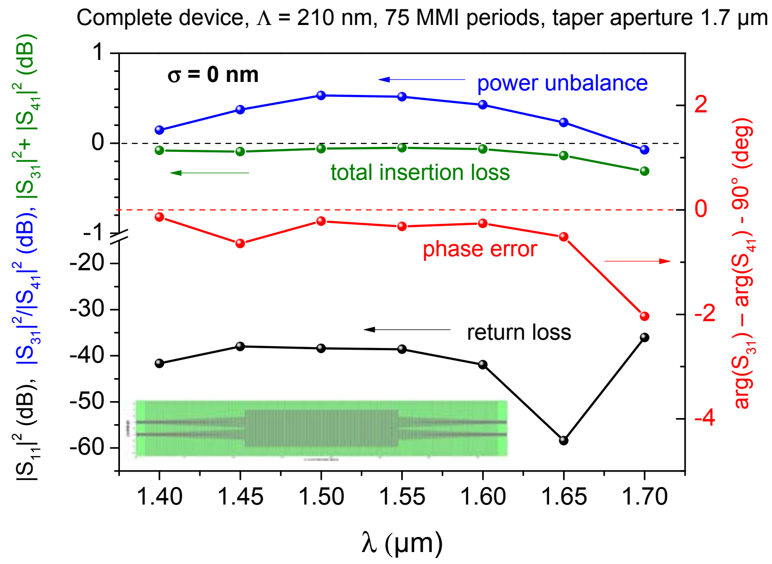
λ (µm)	$\lvert S_{11}\rvert^2$	$\lvert S_{31}\rvert^2$	$\lvert S_{41}\rvert^2$	Loss
1.70	2.304×10^{-5}	0.995	4.963×10^{-3}	-1.561×10^{-5}
1.50	2.804×10^{-5}	0.993	6.991×10^{-3}	-2.611×10^{-4}
1.30	4.149×10^{-5}	0.988	1.260×10^{-2}	-3.966×10^{-4}

Mutual coupling in tapers is unimportant

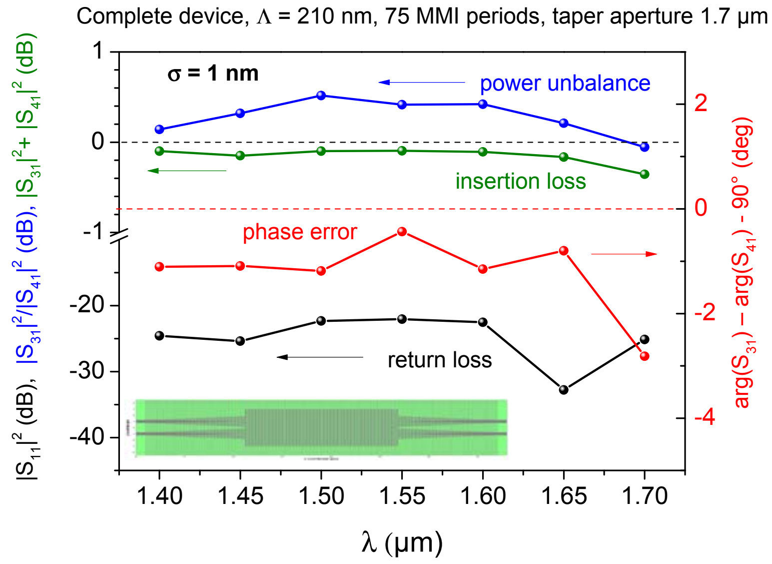
FIELD DISTRIBUTION IN THE SWG MMI COUPLER



S-PARAMETERS OF THE COMPLETE MMI DEVICE



INFLUENCE OF RANDOM FLUCTUATIONS



INFLUENCE OF RANDOM FLUCTUATIONS

Complete device, Λ = 210 nm, 75 MMI periods, taper aperture 1.7 µm