lecture: *Silicon Photonic Devices*

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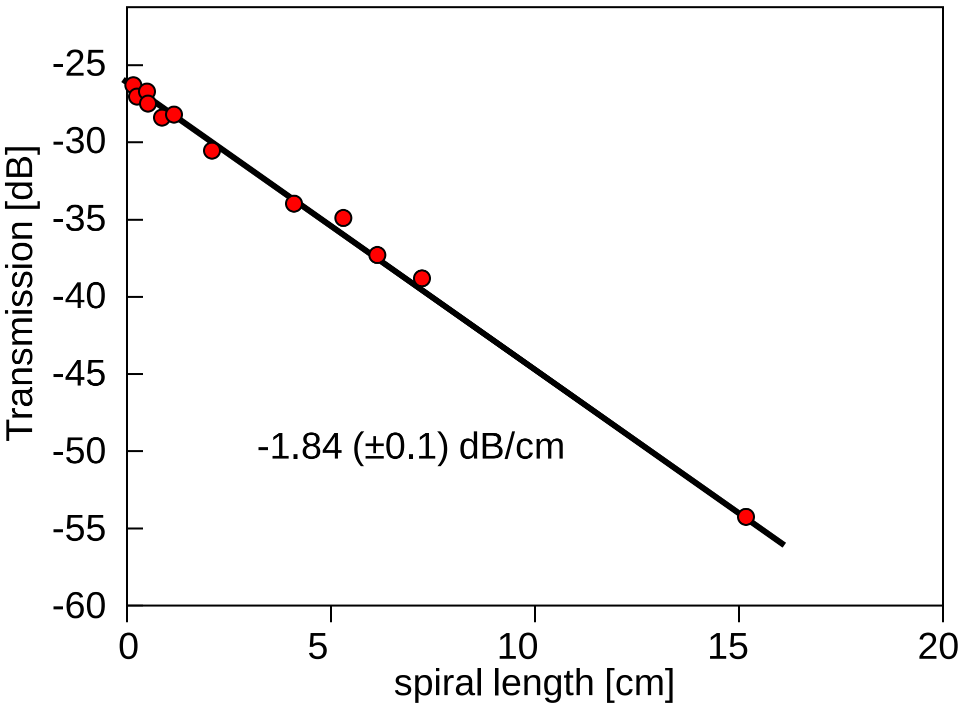
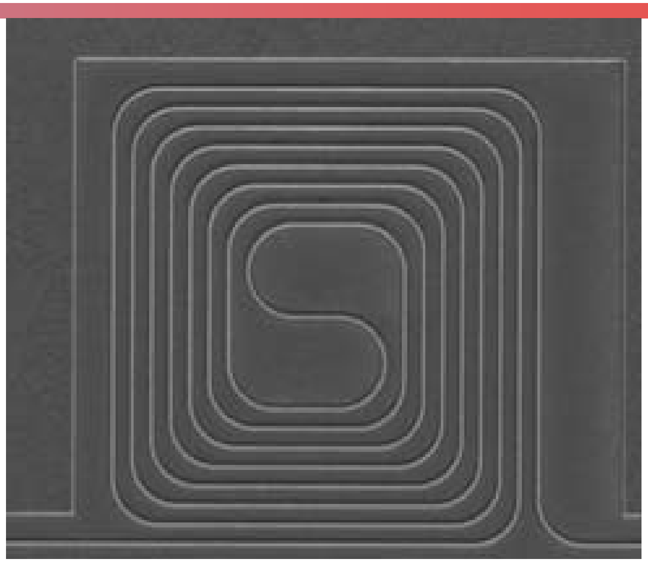
Outline

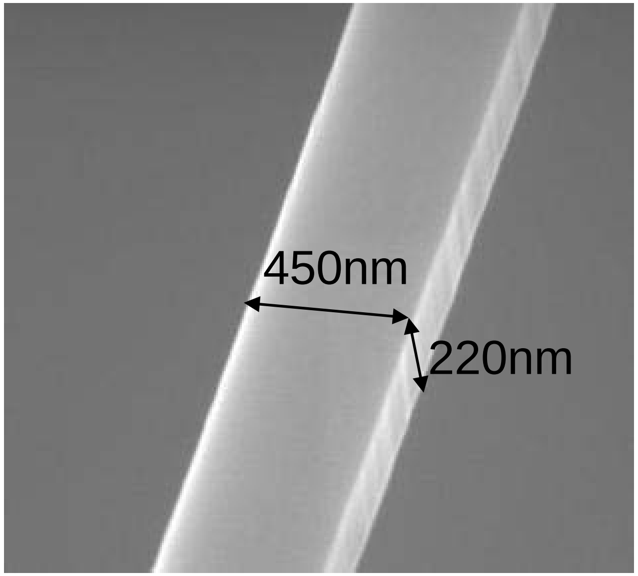
- **The Straight Waveguide**
- The Waveguide Bend
- The Directional Coupler
- Star coupler
- The Multimode Interference Coupler
- The Y-junction
- The Mach–Zehnder Interferometer
- The AWG

Straight Waveguides

- Etched wire in silicon
  - 450 x 220 nm^2
  - straight loss: 1.84dB/cm (1.55um wavelength)







Straight Waveguides

- Propagation loss in waveguides
  - Interaction light-material → **absorption**
  - Imperfections in the waveguide → **scattering**
    → spatial refractive index variations
    → rough interfaces
  - Imperfect guiding → **radiation**

→ Guided optical power decreases:

$$P(z) = P_0 e^{-\alpha z}$$

for a uniform distribution of the losses

Losses by absorption

- Semiconductors:
  - photon $h\nu > E_{bandgap}$: creation of e^-h^+ pair
    $\rightarrow$ wanted in detectors
    $\rightarrow$ unwanted in waveguides
  - Choose a material with sufficiently large $E_{bandgap}$
  - Silicon: no loss if λ>1.1μm
- Dielectrics: absorption by molecular and atomic energy transitions
  - Silicon waveguides: absorption by surface states has strong impact
  - Solution: surface passivation **Painter e.a.**
- Free carriers (metals and semiconductors): carriers absorb energy from electric field **Soref e.a. , JQE 22, p. 873 (1986)**

Straight Waveguides

Scattering losses

- Volumetric scattering: by spatial refractive index variations
  - Less relevant for silicon waveguides
- Surface scattering (dominant in waveguides): roughness of the interfaces
  - etched sidewalls of the waveguide
  - interface between grown layers

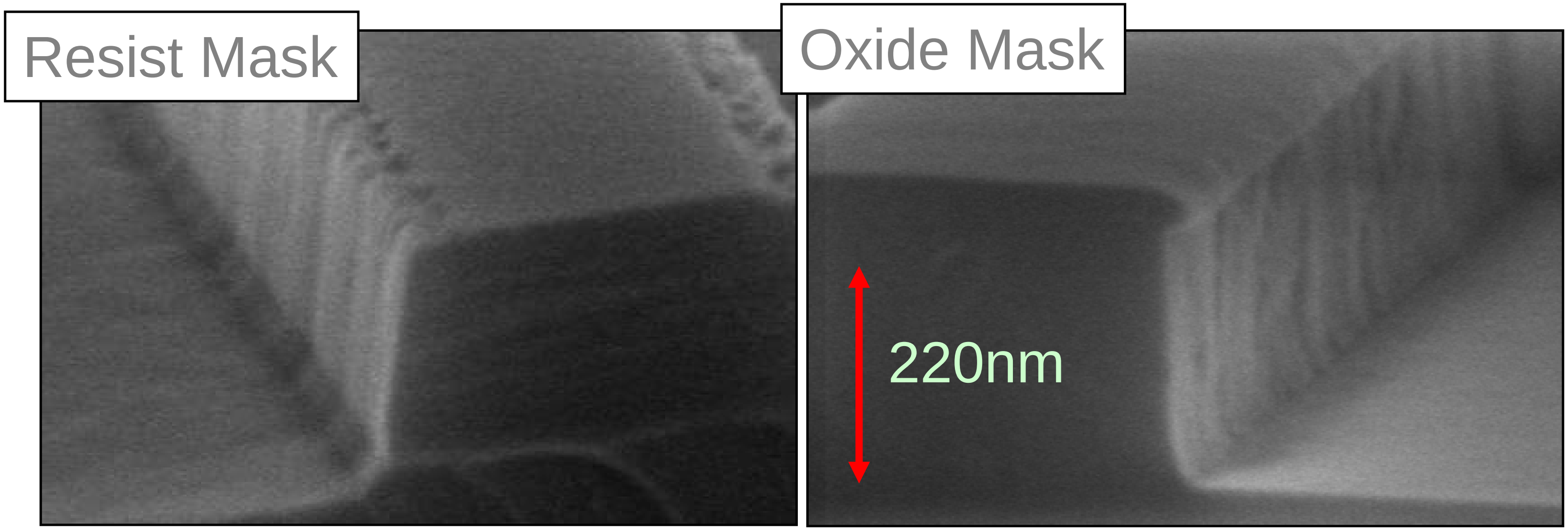
  - Scattering losses at interfaces (approximately):

$$\alpha = \alpha_{scat} \frac{(\Delta n)^2 E_s^2}{P}$$

    with P the optical power and E_s the field on the interface
  - α_{scat} to determine empirically

E.g. see Heebner e.a. Optics Express 15, p 4452 (2007)

Scattering at surface roughness



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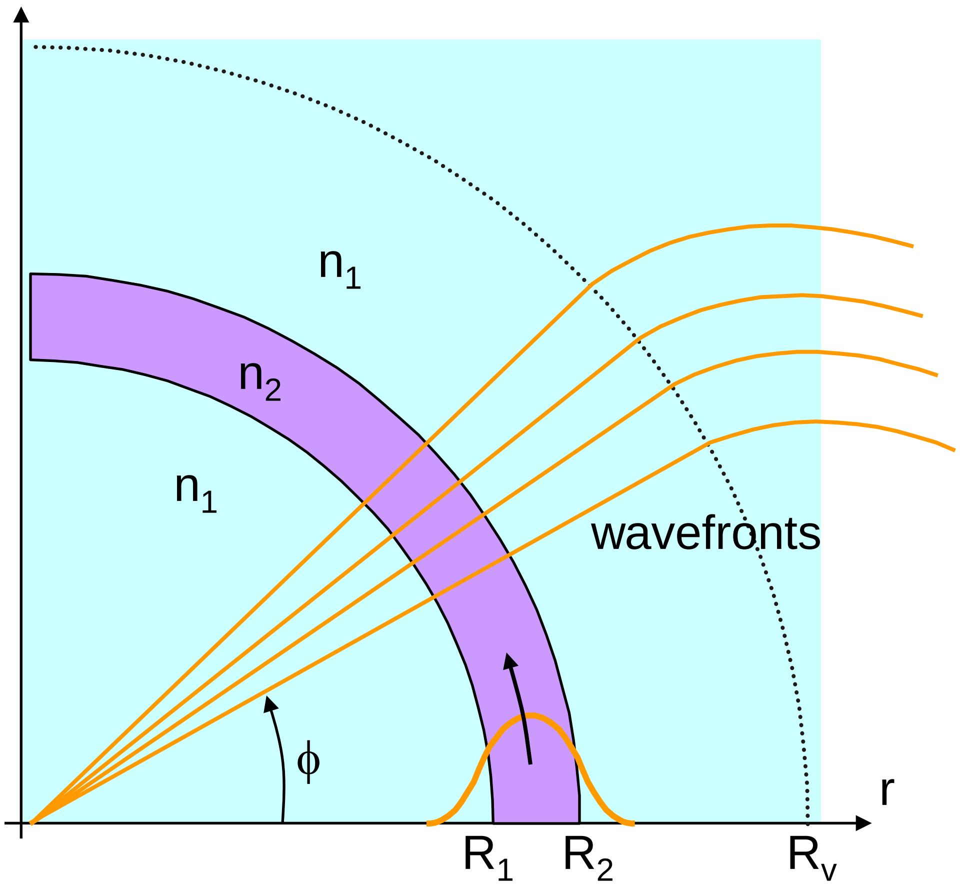
The waveguide bend

- Bend waveguides show a fundamental loss:



- Wavefront revolves around center
- Group velocity of wavefront cannot exceed c/n

→ bending of wavefront

→ radiation

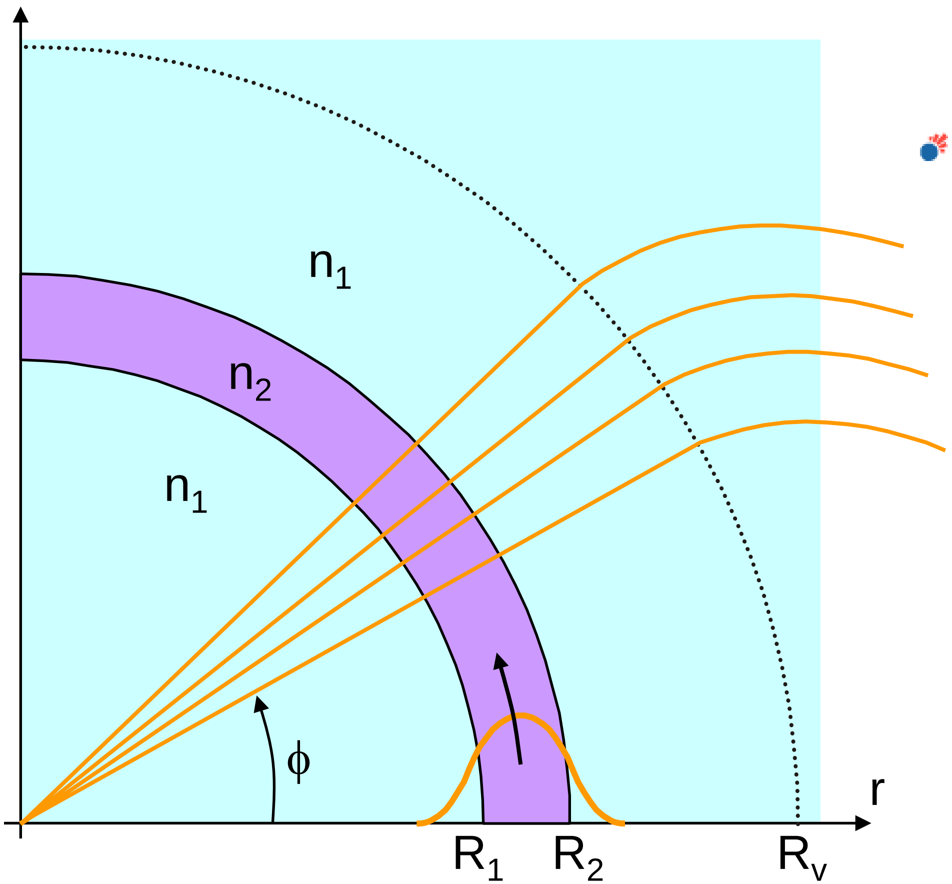
Radiation losses increase with smaller bend radii

↑↓ **tradeoff**

Smaller bend radius needed for larger-scale integration

The waveguide bend

- Calculate propagation losses:



- Two-dimensional waveguide (cylinder coordinates)
- Helmholtz equation:

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial \varphi^2}+k_0^2 n^2(r)\right)\Psi(r,\varphi)=0$$

Fill-in solution: $\Psi(r,\varphi)=\psi(r)\Phi(\varphi)$

- $\psi(r)$: mode profile
- $\Phi(\varphi)$: propagation

The waveguide bend

- Wave equation:

$$\left(\frac{r^2}{\psi(r)}\frac{\partial^2}{\partial r^2}+\frac{r}{\psi(r)}\frac{\partial}{\partial r}+r^2k_0^2n^2(r)\right)\psi(r)=-\frac{1}{\Phi(\varphi)}\frac{\partial^2\Phi(\varphi)}{\partial\varphi^2} \longrightarrow = \text{cst}$$

function of r — function of φ

- Right side:

$$\frac{1}{\Phi(\varphi)}\frac{\partial^2\Phi(\varphi)}{\partial\varphi^2}+\beta_\varphi^2=0$$

- Generic solution $\Phi(\varphi)=Ce^{\pm j\beta_\varphi\varphi}$

➔ Phase fronts turn with bend

The waveguide bend

- Left side of the wave equation:

$$\left(\frac{r^2}{\psi(r)}\frac{\partial^2}{\partial r^2}+\frac{r}{\psi(r)}\frac{\partial}{\partial r}+r^2k_0^2n^2(r)\right)\psi(r)-\beta_\varphi^2=0$$

Substitution: $r=R_t e^{u/R_t} \rightarrow u=R_t \ln\frac{r}{R_t}$

$$\left[\frac{\partial^2}{\partial u^2}+\left(k_0^2n_t^2(u)-\beta_t^2\right)\right]\psi(u)=0$$

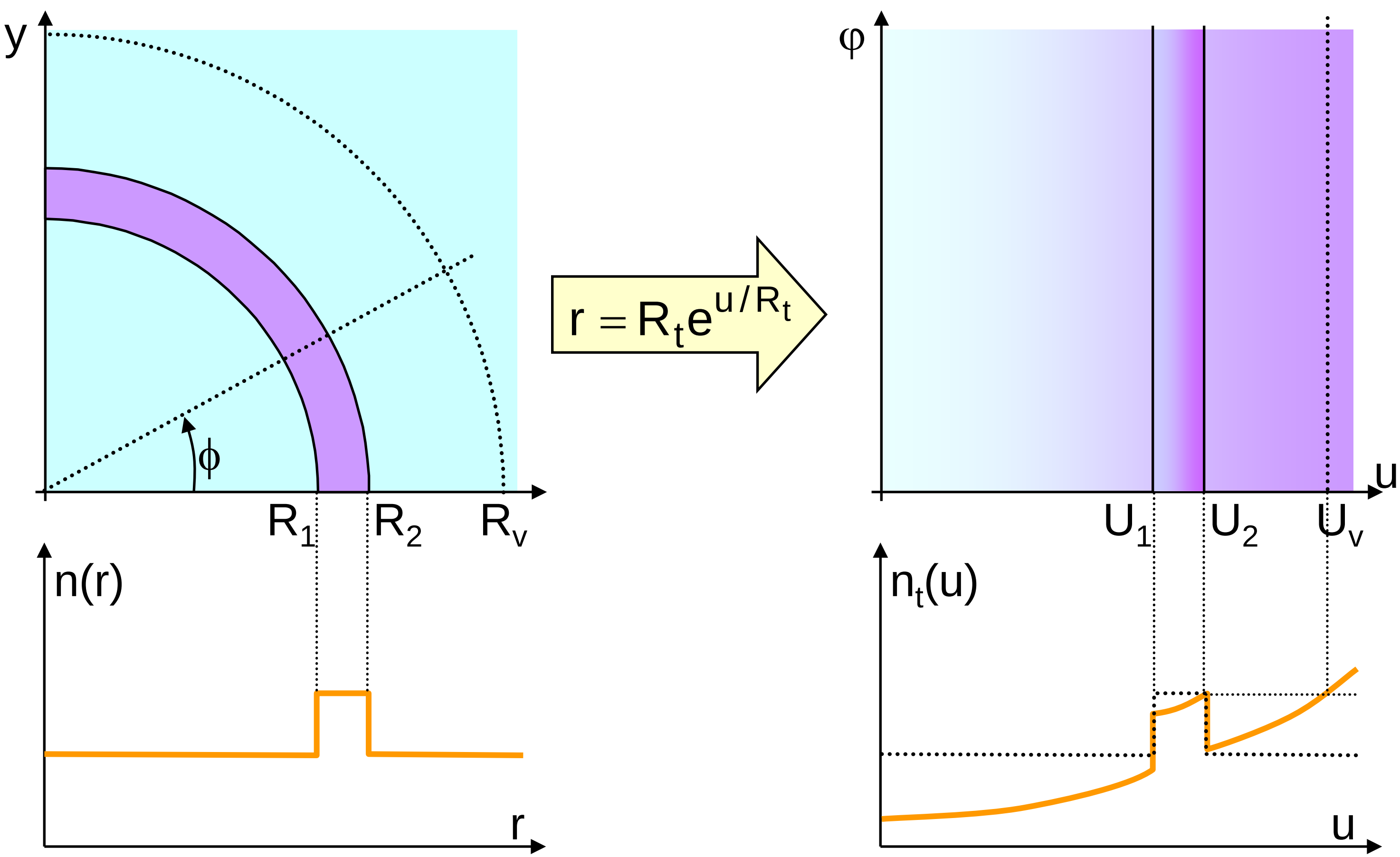
with $n_t(u)=n(u)e^{u/R_t}$ and $\beta_t=\frac{\beta_\varphi}{R_t}$

- Same Helmholtz equation in (u,φ) problem as in cartesian coordinates with a different refractive index profile $n_t(u)$!!!

M. Heiblum and J. H. Harris, "ANALYSIS OF CURVED OPTICAL-WAVEGUIDES BY CONFORMAL TRANSFORMATION," *IEEE Journal of Quantum Electronics, vol. QE11, pp. 75-83, 1975.*

The waveguide bend

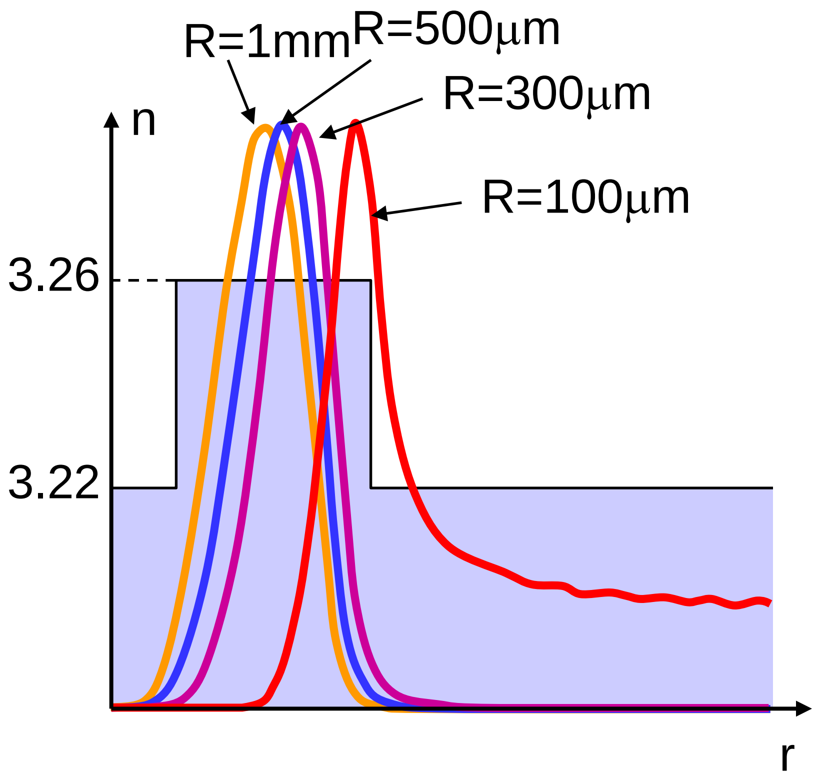
- Coordinates (x,y)
- Coordinates (u,φ)



- Waveguide mode and losses can easily be calculated using standard slab solvers and the modified refractive index profile

The waveguide bend

- Modified index profile learns us a lot already :
  - Mode mostly guided in region with largest index
    → mode shifts outward
    → mismatch losses at transition between straight and bent waveguide
  - "Sharp" bends: mode only on the outside
    → no guiding by inner interface
    "Whispering Gallery" modes
  - Strong field on the outer interface →scattering losses

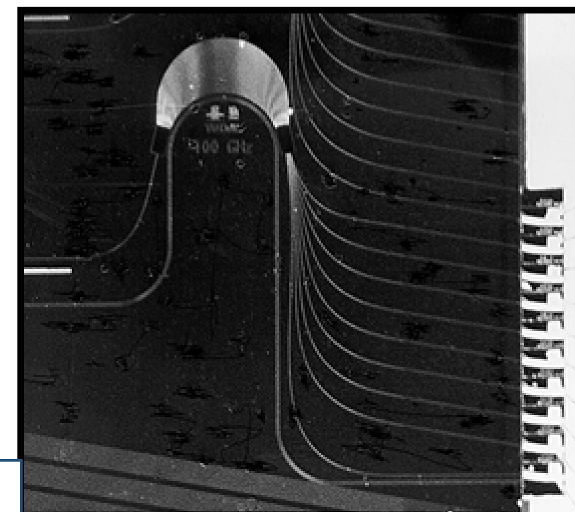


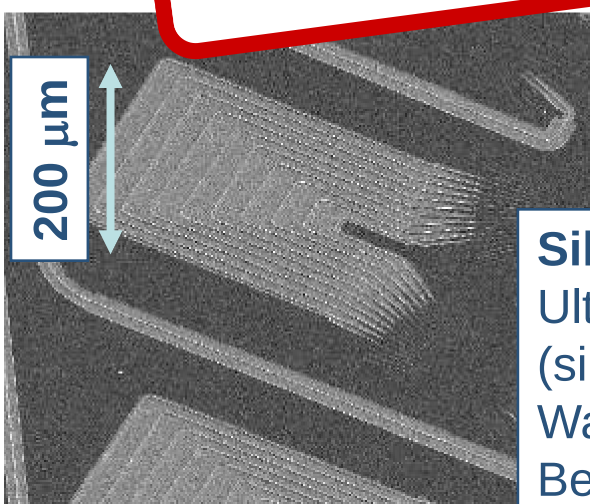
Mode profile calculation using conformal transformation.

The waveguide bend

Glass photonic ICs
Low Contrast - Fiber Matched
(doped silica vs pure silica)
Waveguide: 10x10 μm^2
Bend Radius ~ 5 mm

Density x 10^6



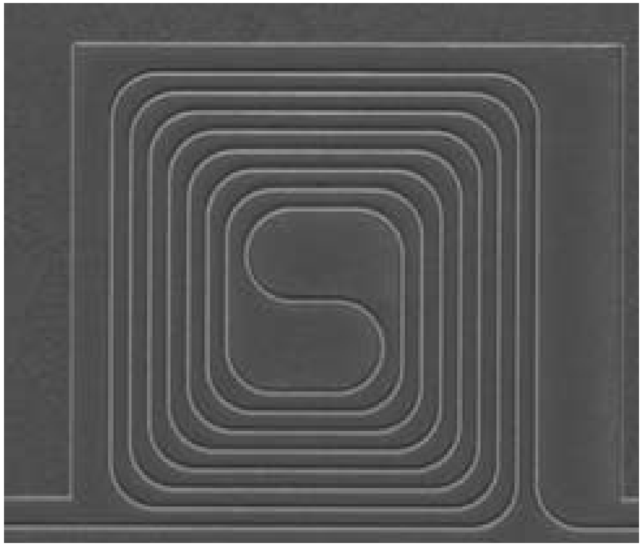


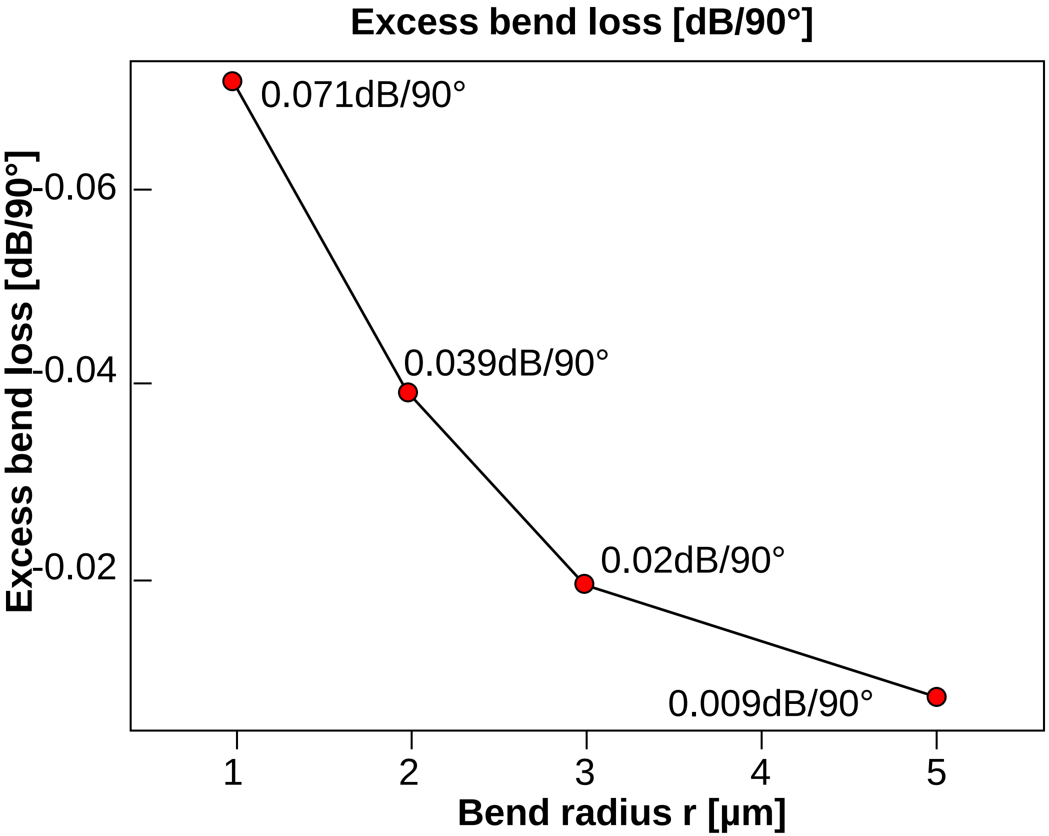
Silicon photonic ICs
Ultra-high Contrast
(silicon vs silica)
Waveguide: 500x200nm^2
Bend Radius < 5μm

III-V photonic ICs
Medium Contrast
(InGaAsP vs InP)
Waveguide: 2x1μm^2
Bend Radius ~ 500μm

The waveguide bend

- Bend losses in silicon wires measured from spirals containing several 100s of bends
- Several groups obtained comparable results



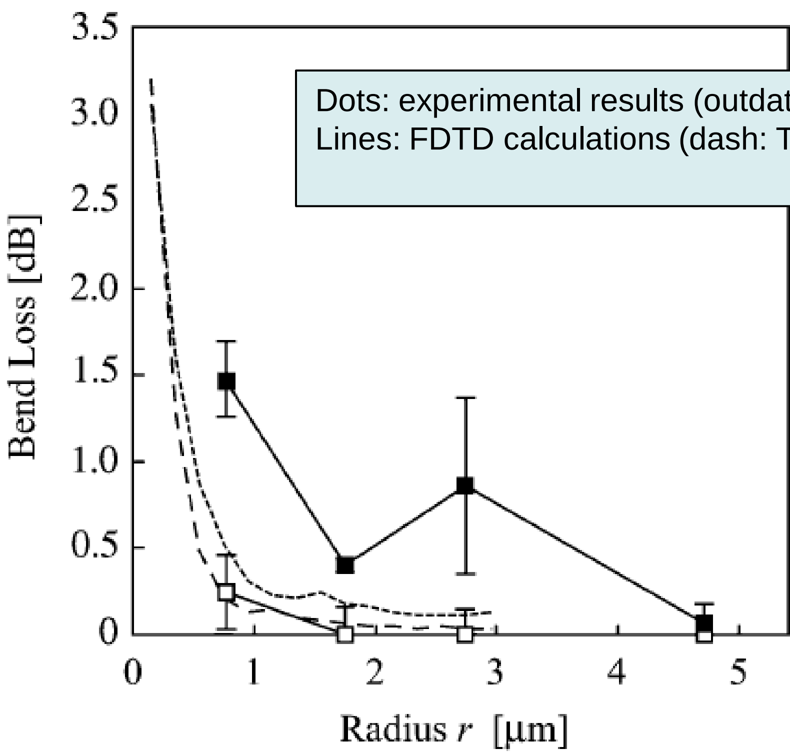


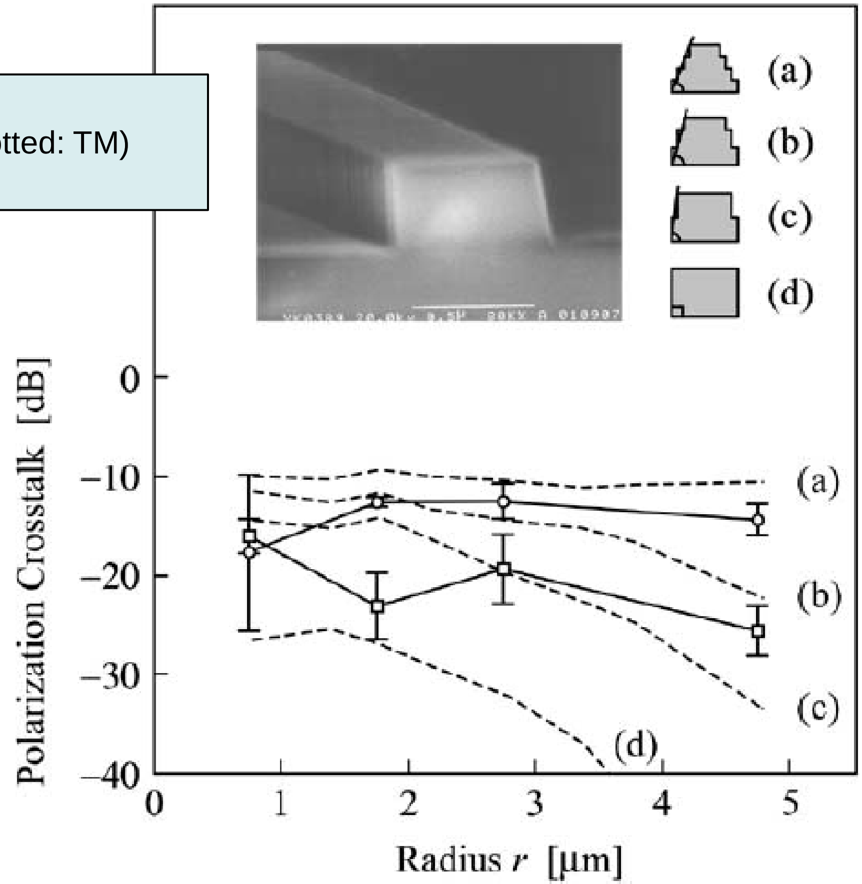
S.K. Selvaraja, JLT 27, p.4070 (2009)
Y. A. Vlasov and S. J. McNab, Optics Express, p. 1622 (2004)

The waveguide bend

- FDTD calulcations in line with recent experimental results
- Bends may introduce unwanted polarization rotation

Dots: experimental results (outdated)
Lines: FDTD calculations (dash: TE, dotted: TM)





A. Sakai, JLT 22, pp 520 (2004)

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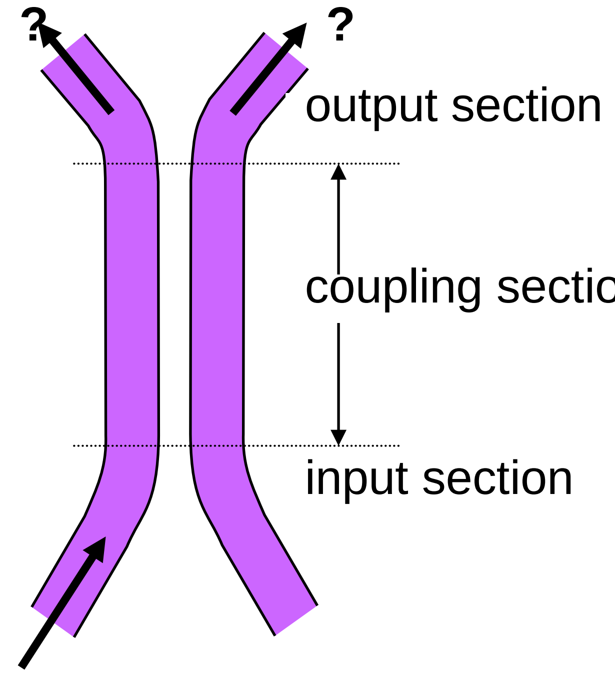
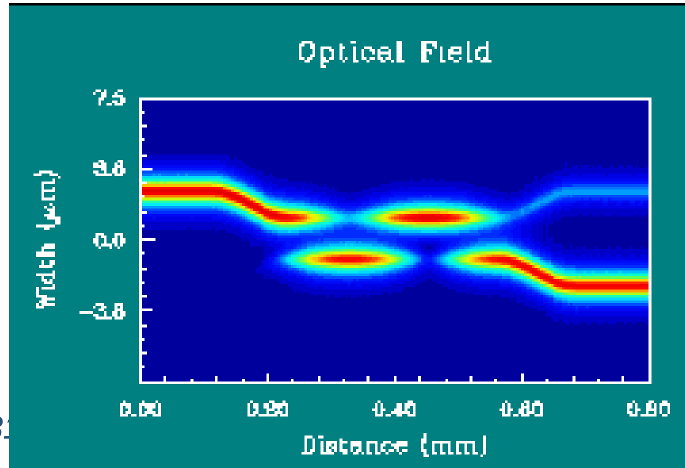
The directional coupler

- Two waveguides close together
  - Evanescent field of first waveguide “feels” second waveguide
  - Gradual coupling of light between both waveguides
- Coupling controlled by length
- Identical waveguides : full coupling
- Otherwise: partial coupling
- Applications: variable splitter, polarization convertor, base component for ring resonator …





The directional coupler

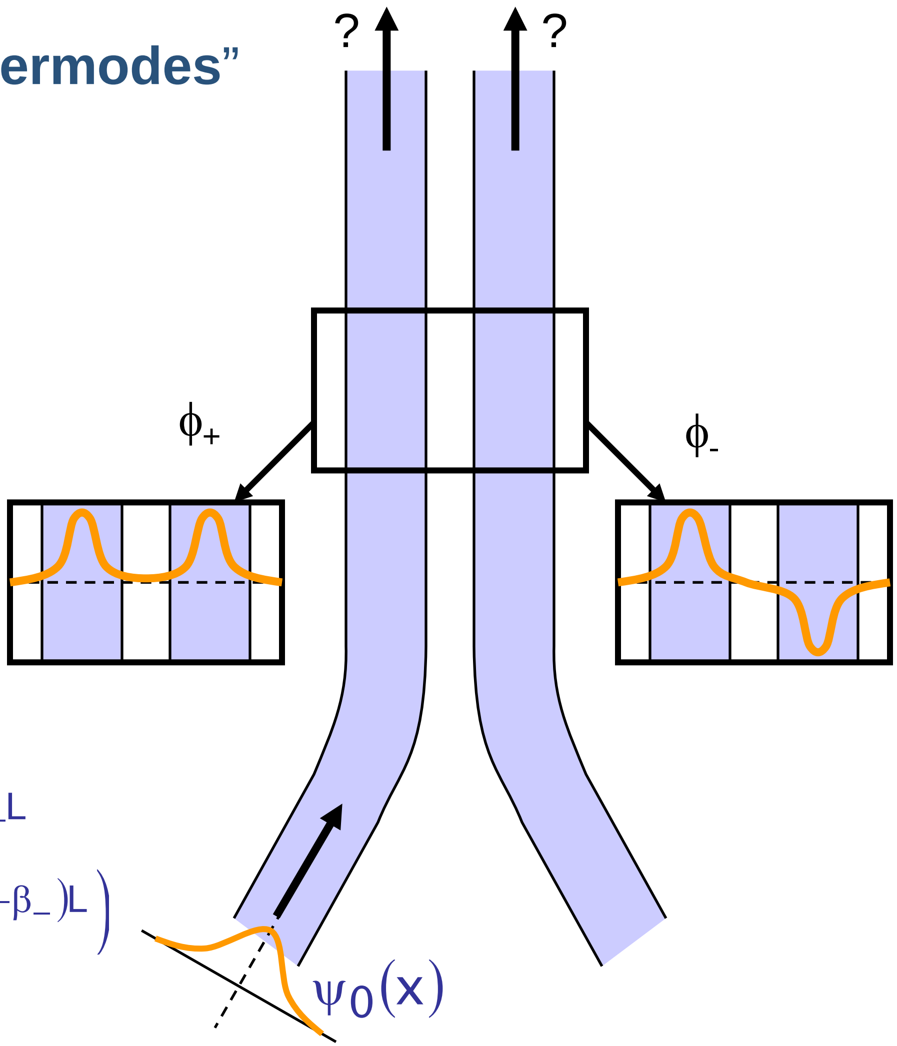
- Coupled waveguides two "**supermodes**"
  - ϕ_+: symmetric
  - ϕ_-: antisymmetric
- Field in z=0:

$$\Psi(x, z=0) = \psi_0(x)$$
$$\approx c_+\phi_+ + c_-\phi_-$$

with $c_+ = c_- = 1/\sqrt{2}$

- After propagation (z=L)

$$\Psi(x, z=L) = c_+\phi_+ e^{-j\beta_+ L} + c_-\phi_- e^{-j\beta_- L}$$
$$= c_+ e^{-j\beta_+ L}\left(\phi_+ + \phi_- e^{+j(\beta_+ - \beta_-)L}\right)$$



The directional coupler

- Total field (z=L)

$$\Psi(x, z = L) = c_+ e^{-j\beta_+ L}\left(\phi_+ + \phi_- e^{+j(\beta_+ - \beta_-)L}\right)$$

- All power in second waveguide when

$$\Psi(x, z = L) = c_+\phi_+ - c_-\phi_-$$

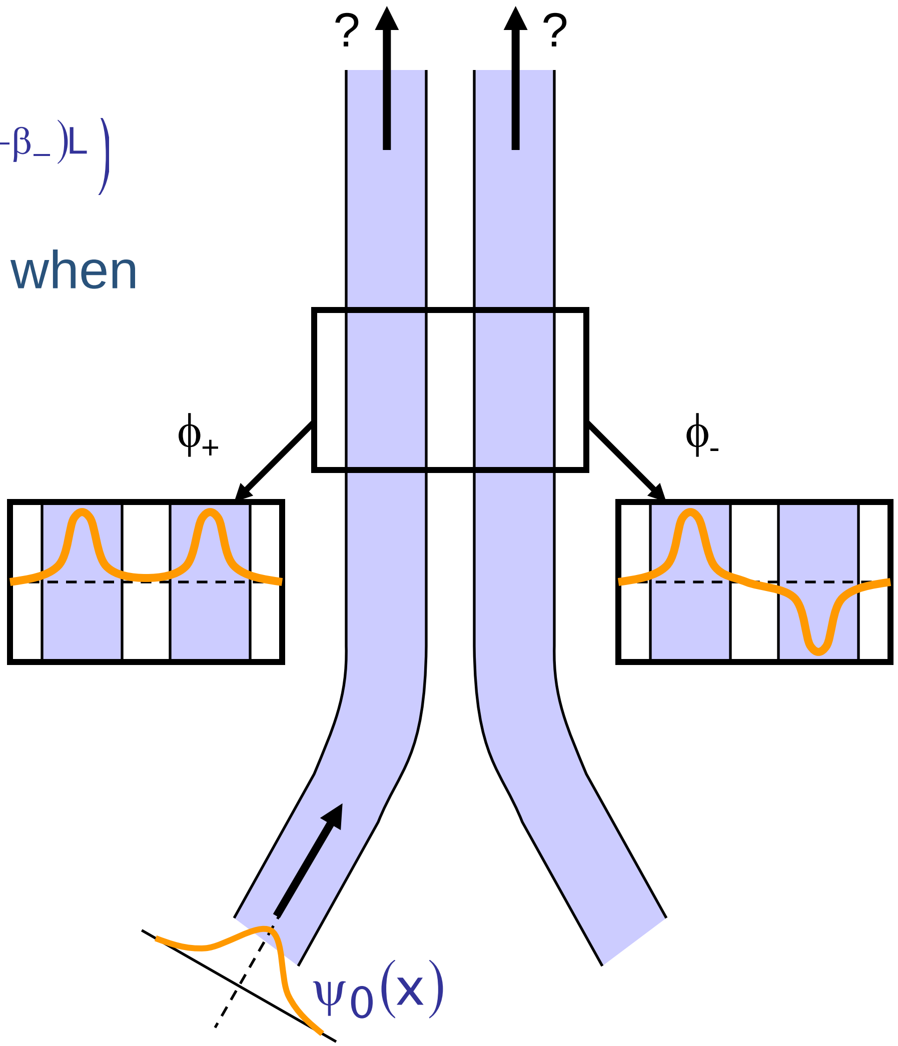
- This is the case when:

$$L = L_c = \frac{\pi}{\beta_+ - \beta_-}$$

(= coupling length)

- Coupling coefficient κ

$$\kappa = \frac{(\beta_+ - \beta_-)}{2}$$



The directional coupler

- **Asymmetric** coupler
  - supermodes no longer perfectly symmetric and antisymmetric
  - $c_+ \neq c_-$
- After propagation (z=L)

$$\Psi(x, z = L) =$$

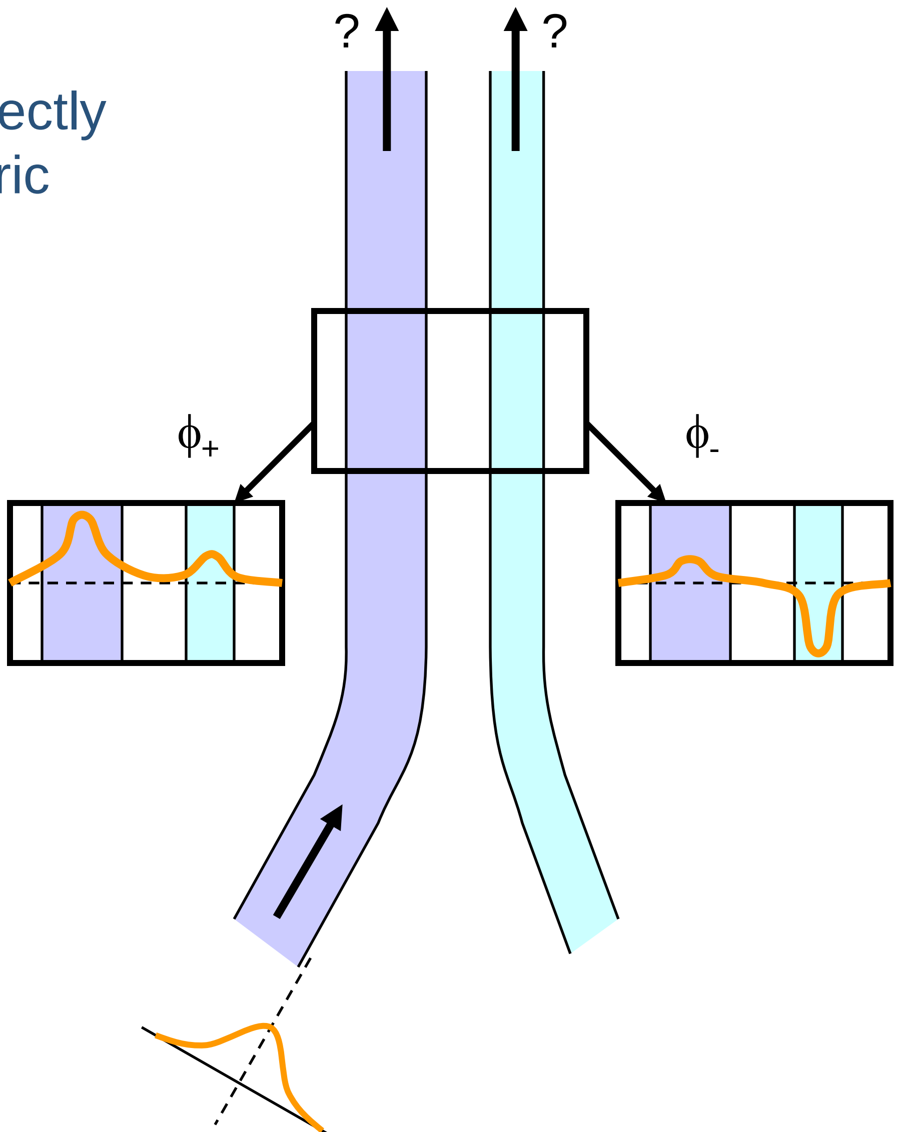
$$c_+ e^{-j\beta_+ L}\left(\phi_+ + \frac{c_-}{c_+}\phi_- e^{+j(\beta_+ - \beta_-)L}\right)$$

- coupling length L_c

$$L_c = \frac{\pi}{\beta_+ - \beta_-}$$

- coupling amplitude = $c_-/c_+ < 1$

(➔ no longer full coupling)

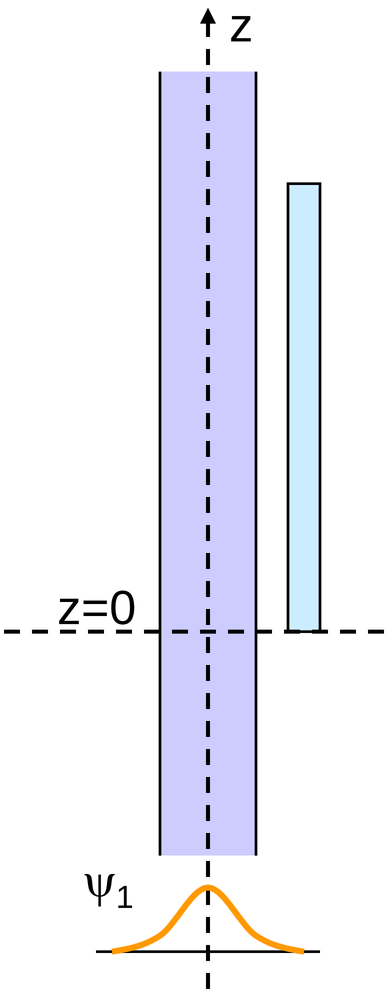


Directional coupler

- From **coupled mode theory** we find the variation of the amplitude in both waveguides:

$$X_1(z) = e^{-j\beta z}\left[\cos(\delta z) - i\frac{\Delta}{\delta}\sin(\delta z)\right]$$

$$X_2(z) = e^{-j\beta z}\left[-i\frac{\kappa_{21}}{\delta}\sin(\delta z)\right]$$



- With:

$$\beta = (\beta_1 + \beta_2 + \kappa_{11} + \kappa_{22})/2$$ ($\beta_{1,2}$=modes of single waveguide)

$$\kappa = \sqrt{\kappa_{12}\kappa_{21}}$$

$$\Delta = (\beta_1 - \beta_2 + \kappa_{11} - \kappa_{22})/2$$ (Δ=Phase mismatch)

$$\delta = \sqrt{\Delta^2 + \kappa^2}$$

- And:

$$\kappa_{12} = \frac{k_0^2}{2}\int\left(n_{12}^2 - n_1^2\right)\psi_1(x)\psi_2(x)dx$$

$$\kappa_{21} = \frac{k_0^2}{2}\int\left(n_{12}^2 - n_2^2\right)\psi_1(x)\psi_2(x)dx$$

Symmetric waveguide: $\kappa_{12} = \kappa_{21} = \kappa$

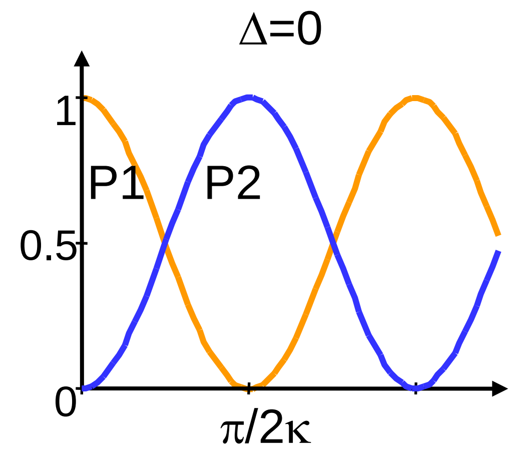
Directional coupler

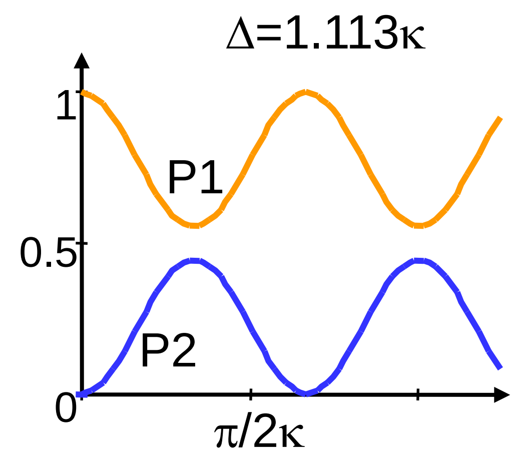
From CMT we find:

- Periodic power exchange:
  - no phase mismatch ($\Delta = 0$)
    $\rightarrow$ full coupling
    = synchronous coupling
  - Increasing phase mismatch ($\Delta < \kappa$)
    $\rightarrow$ less coupling
    $\rightarrow$ shorter period
    = asynchronous coupling
  - Maximal coupled power

    $$= \frac{\kappa^2}{\kappa^2 + \Delta^2}$$

  - Large phase mismatch ($\Delta >> \kappa$)
    $\rightarrow$ no coupling

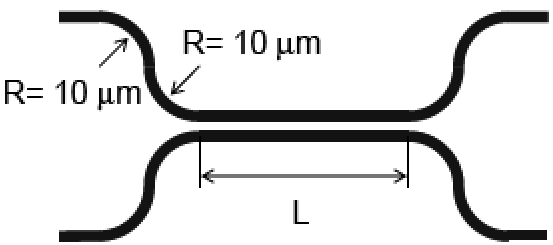


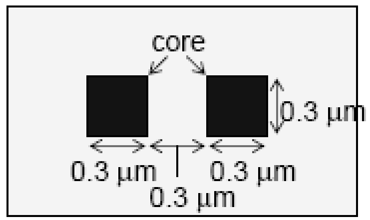


Directional coupler

H. Yamada e.a., PTL 17, p. 585 (2005)

Experimental results

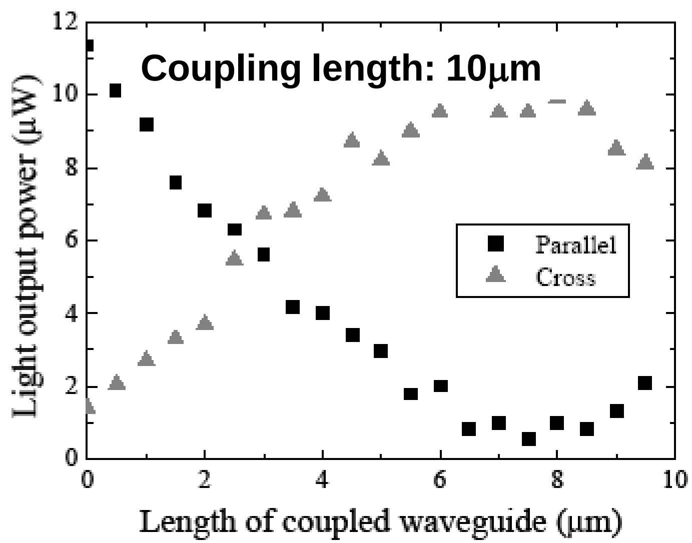




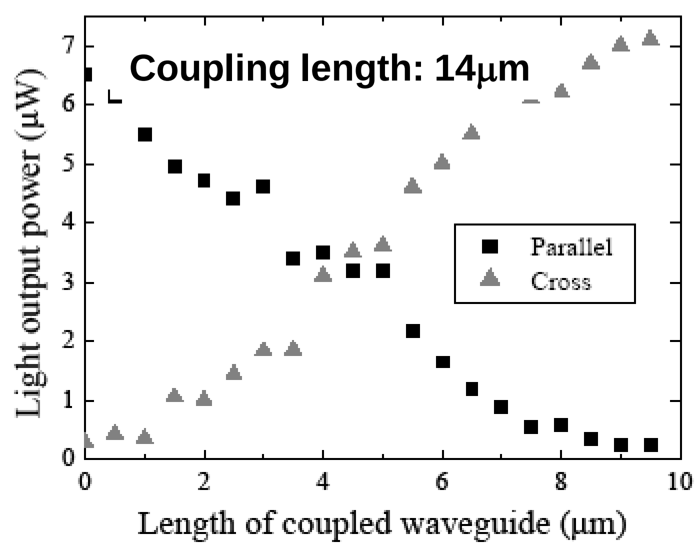
TM mode less confined

→ stronger overlap

→ shorter coupling length !



E □Substrate

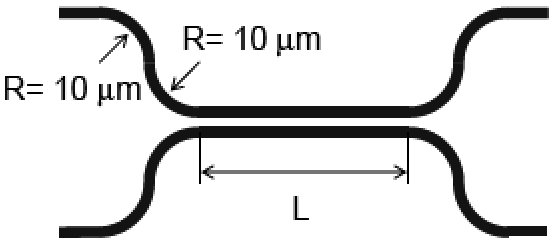


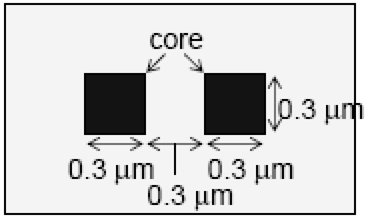
E □Substrate

Directional coupler

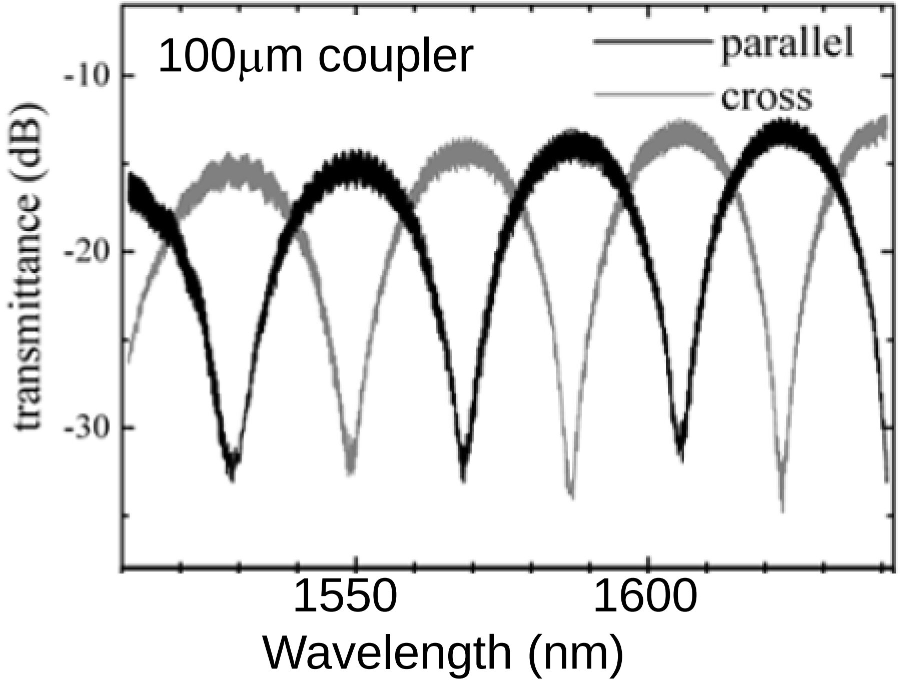
H. Yamada e.a., PTL 17, p. 585 (2005)

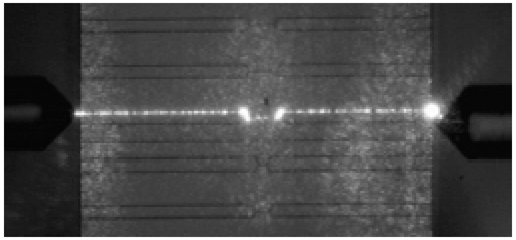
- Experimental results



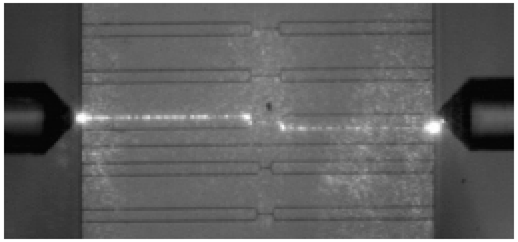


Long couplers or strongly wavelength dependent !





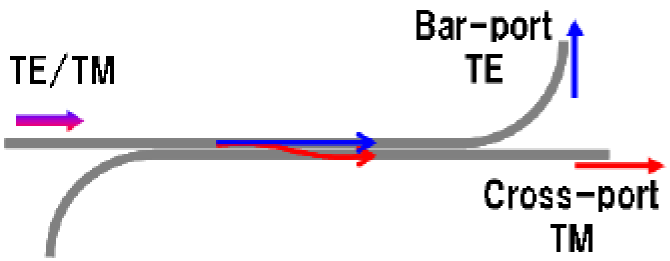
λ= 1534 nm



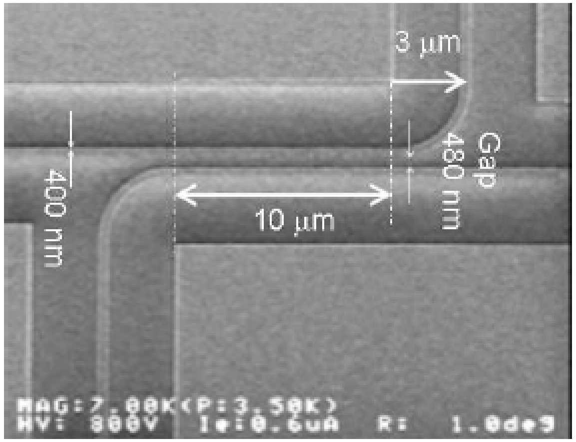
λ= 1563 nm

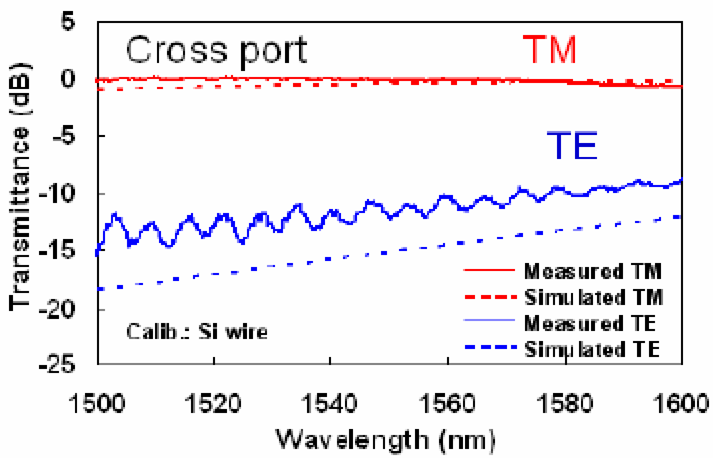
Fukuda e.a., OE 14(25), p. 12401 (2006)

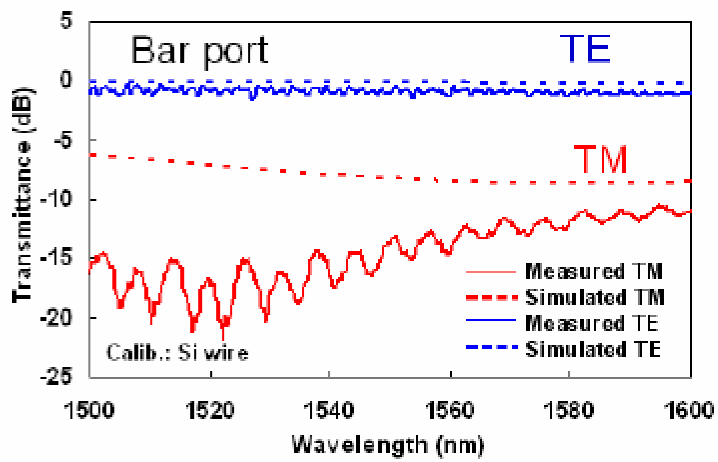
- Use as polarization splitter



Coupling length TM << TE

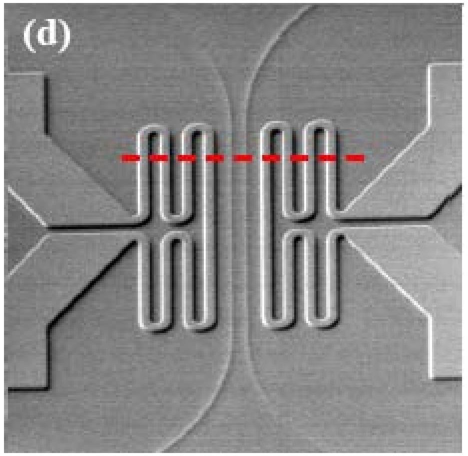






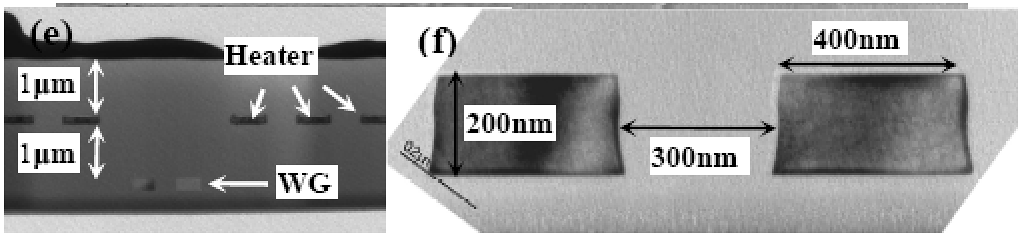
Song e.a., OE 16(26), p. 21481(2008)

- Fine tuning



Heaters can be used to fine tuning the coupling ratio by making coupler asymmetric

Cross-section



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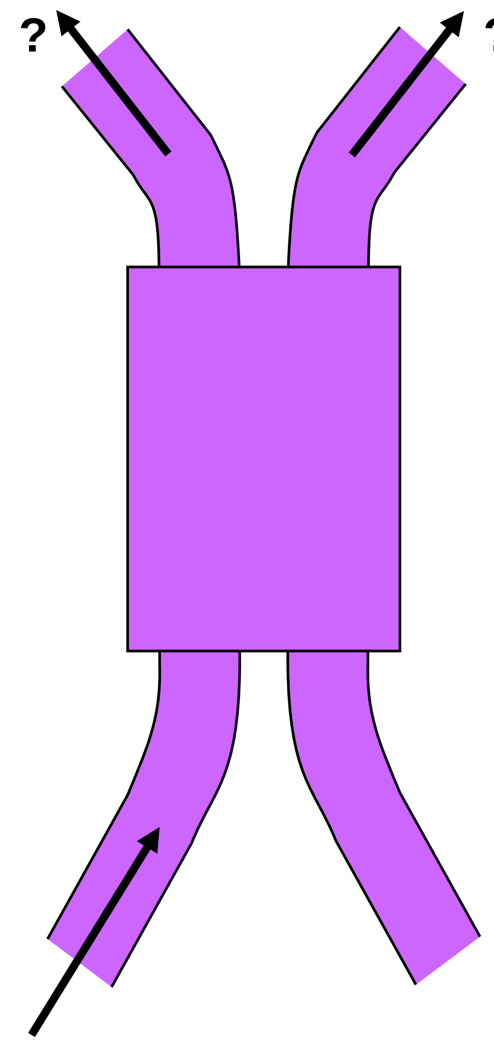
The multimode interference coupler

- Central section = broad waveguide
  - multimodal
  - multiple access waveguides

- Self-Imaging principle:
  In multimodal waveguides an input field will be periodically reproduced in a single or multiple image.

  → 1 x N couplers possible
  → Cross-couplers possible
  → Arbitrary splitting ratios



The multimode interference coupler

- Decompose incident field in eigenmodes of the MMI:

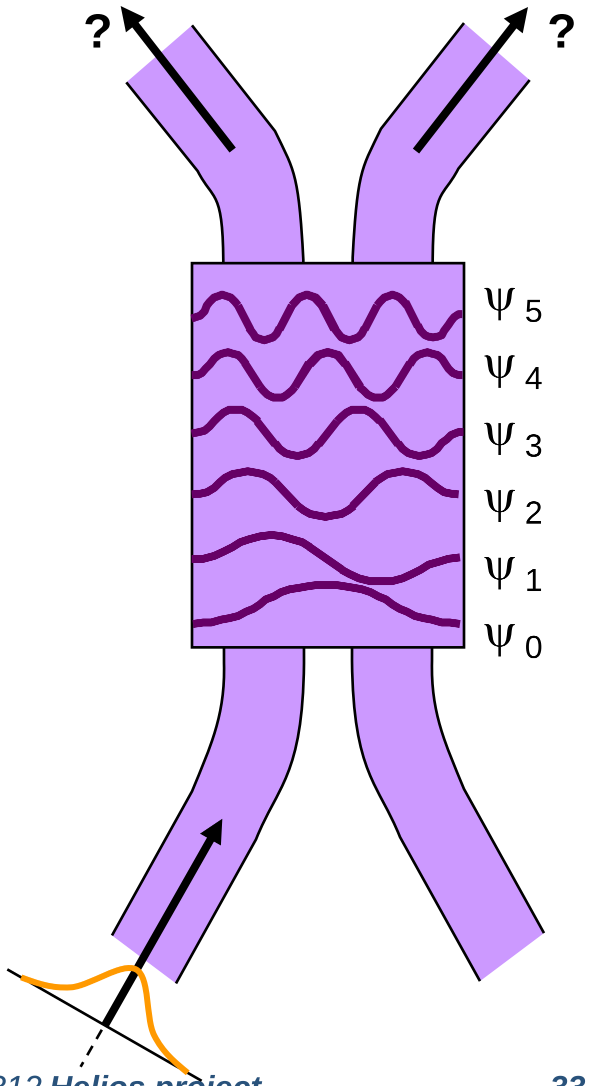
$$\Psi(x,0) = \sum_{i=0}^{N-1} c_i \psi_i(x) \quad \text{with} \quad c_i = \int \Psi(x,0)\psi_i(x)dx$$

(ignore radiative modes if $\Psi(x,0)$ sufficiently narrow compared to the MMI)

- After propagation over distance z:

$$\Psi(x,z) = \sum_{i=0}^{N-1} c_i \psi_i(x) e^{-j\beta_i z}$$

$$= e^{-j\beta_0 z} \sum_{i=0}^{N-1} c_i \psi_i(x) e^{j(\beta_0 - \beta_i)z}$$



The multimode interference coupler

- Approximate MMI modes by the modes for an infinite refractive index contrast:

$$\psi_i(x) = \cos(k_{x,i}x) \quad \text{for i even}$$

$$\psi_i(x) = \sin(k_{x,i}x) \quad \text{for i odd}$$

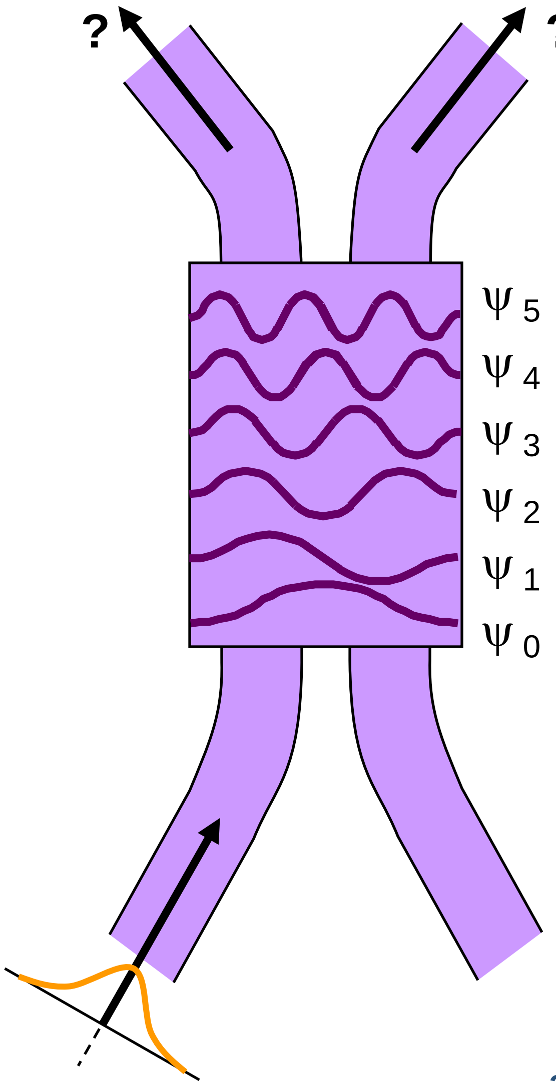
with $k_{x,i} = \frac{(i+1)\pi}{W}$

(good for high contrast waveguides)

- Propagation constant β_i

$$k_{x,i}^2 + \beta_i^2 = k_0^2 n_r^2$$

therefore $\beta_i \approx k_0 n_r - \frac{(i+1)^2 \pi \lambda_0}{4 n_r W^2}$



The multimode interference coupler

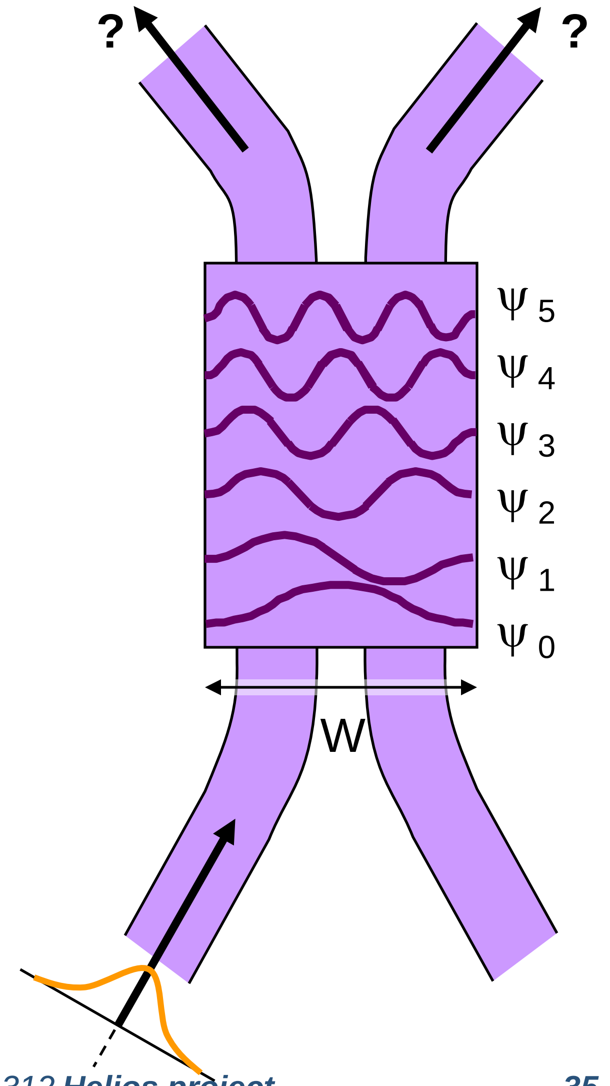
- Difference in propagation constants:

$$(\beta_0 - \beta_i) = i(i+2)\frac{\pi\lambda_0}{4n_r W^2} = \frac{i(i+2)\pi}{3L_\pi}$$

with $L_\pi = \frac{\pi}{\beta_0 - \beta_1} = \frac{4n_r W^2}{3\lambda_0}$

- The Ψ after propagation length L

$$\Psi(x,L) = \sum_{i=0}^{N-1} c_i \psi_i(x) e^{j\frac{i(i+2)\pi}{3L_\pi}L}$$



The multimode interference coupler

- The field Ψ in z=L

$$\Psi(x,L) = \sum_{i=0}^{N-1} c_i \psi_i(x) e^{j\frac{i(i+2)\pi}{3L_\pi}L}$$

- For $L = 6L_\pi$

$$\Psi(x,6L_\pi) = \Psi(x,o)$$

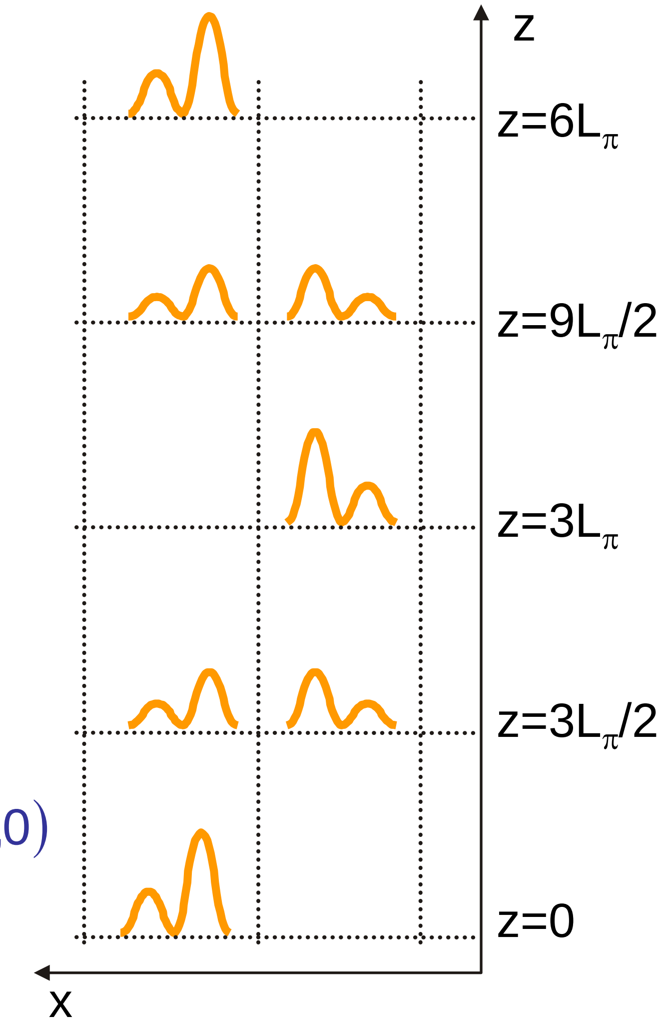
- For $L = 3L_\pi$

$$\Psi(x,3L_\pi) = \Psi(-x,o)$$

- For $L = 3p/2\ L_\pi$ with p odd

$$\Psi\left(x,\frac{p}{2}3L_\pi\right) = \frac{1+(-j)^p}{2}\Psi(x,0) + \frac{1-(-j)^p}{2}\Psi(-x,0)$$

$\rightarrow$ two images (3dB coupling)



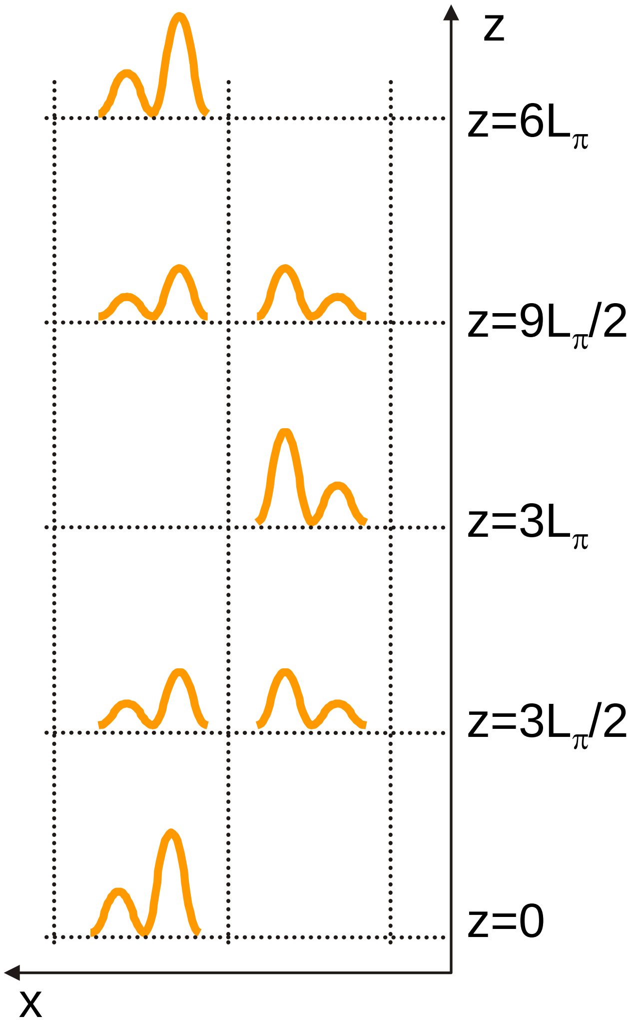
The multimode interference coupler

- The field Ψ in z=L

$$\Psi(x,L)=\sum_{i=0}^{N-1} c_i\psi_i(x)e^{j\frac{i(i+2)\pi}{3L_\pi}L}$$

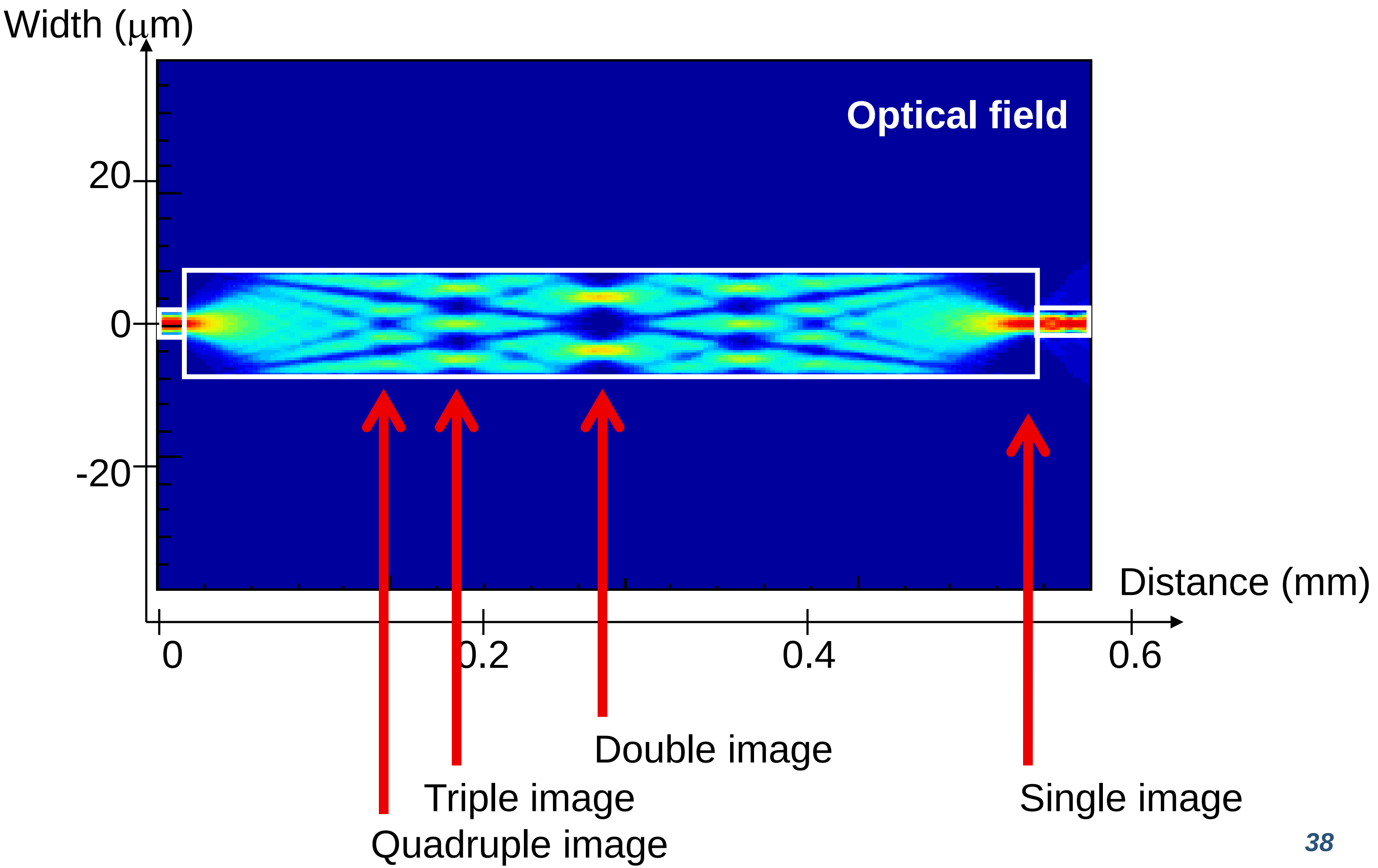
- Multiple images:
  N-fold image at distance $L=3p/N\ L_\pi$
  with p and N whole numbers without common divisors

$\rightarrow$ amplitude = $1/\sqrt{N}$



The multimode interference coupler

- BPM simulation of an MMI (15 x 520 μm)



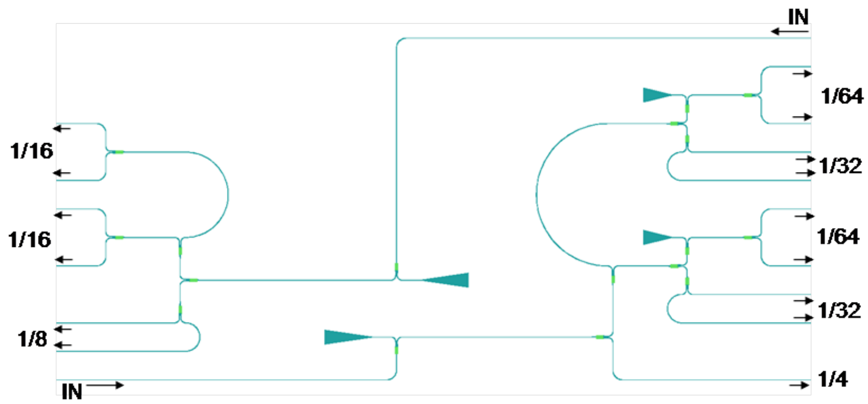
The multimode interference coupler

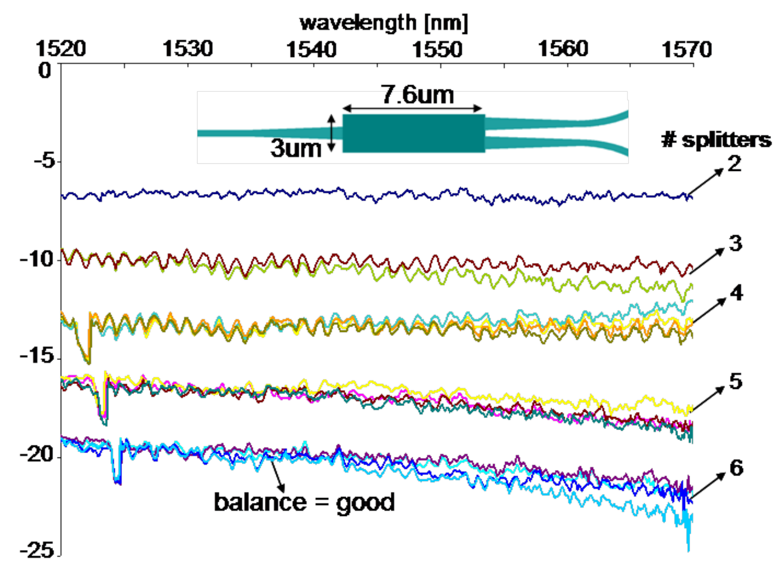
- Other
  - Variable coupling ratio possible but more comples design
  - (Anti-)Symmetric excitation allows for shorter couplers
  - In real devices: replace W by W_{eff}

The multimode interference coupler

- Experimental results
  - Standard coupler (3μm x 7.6μm)

(<0.3dB excess loss)



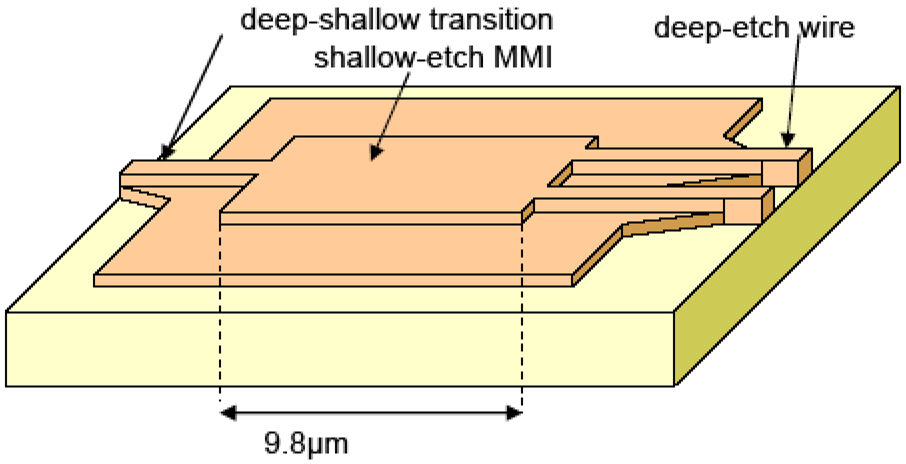


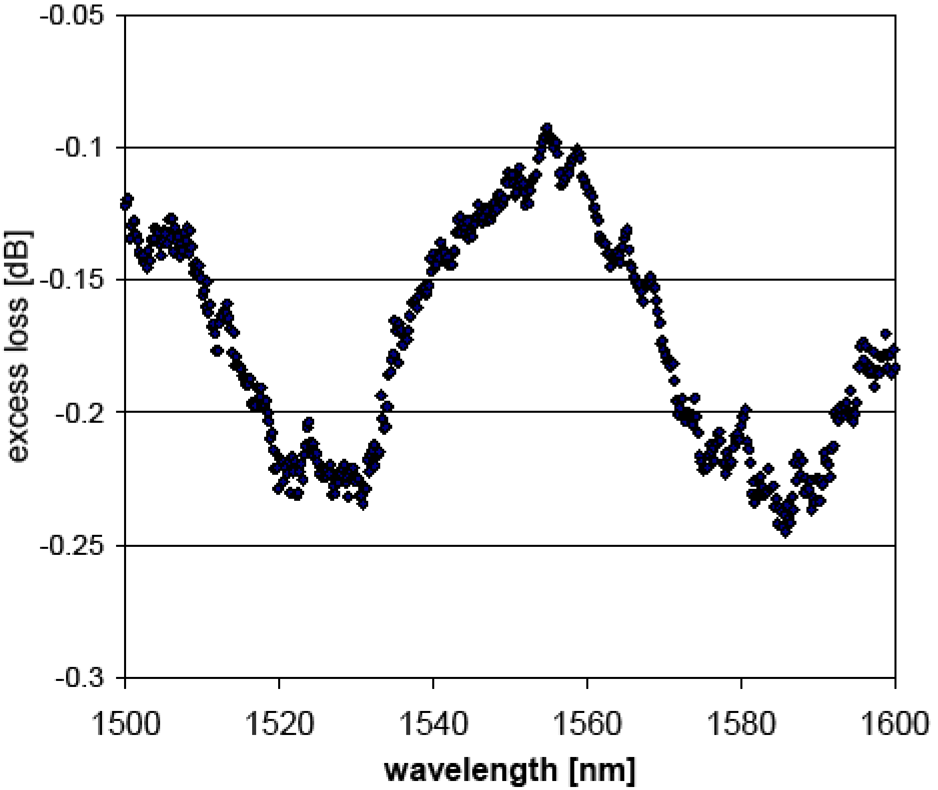
The multimode interference coupler

Bogaerts e.a. , JSTQE 2010

- Experimental results
  - Shallowly etched coupler (3µm x 7.6µm)

(<0.2dB excess loss)

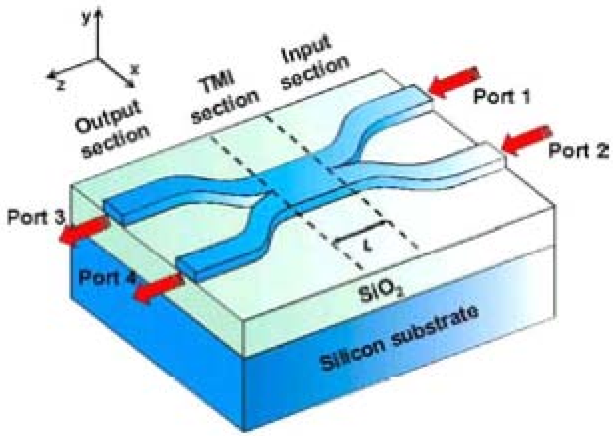


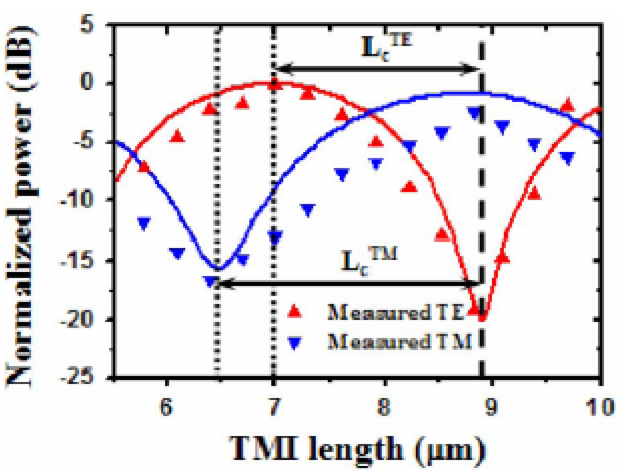


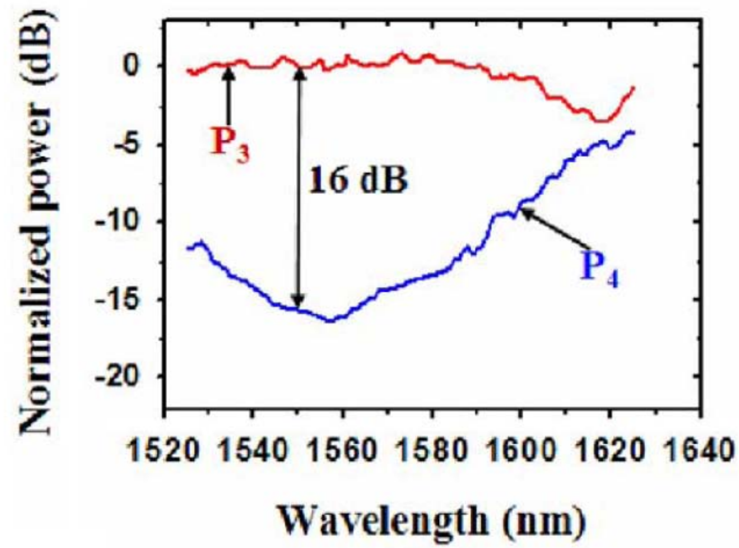
The multimode interference coupler

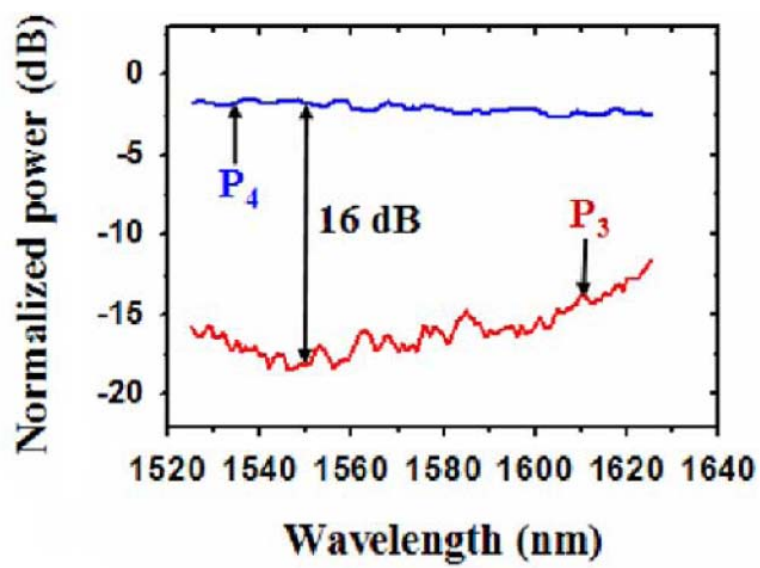
B-K Yang e.a. , PTL 21 (7), p 432 (2010)

- Use as polarization splitter
  - Two mode interference (TMI)









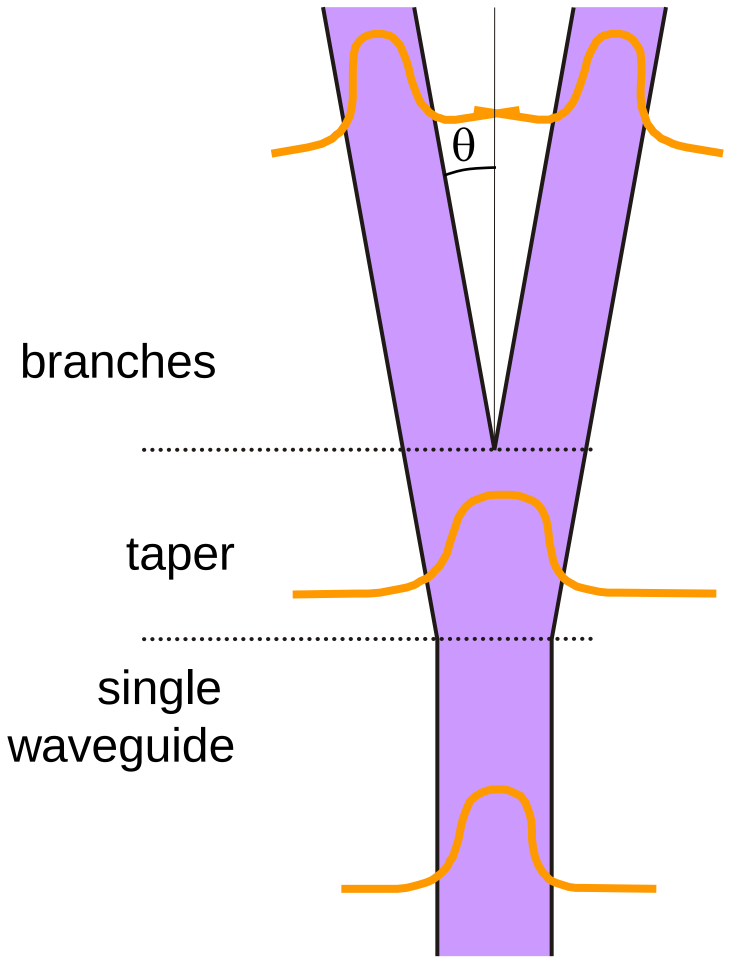
Outline

- The Straight Waveguide
- The Waveguide Bend
- The Directional Coupler
- Star coupler
- The Multimode Interference Coupler
- **The Y-junction**
- The Mach–Zehnder Interferometer
- The AWG

The Y-junction

- **Y-junction** =

  straight waveguide
  +
  taper
  +
  two branches



- Aperture angle θ:
  should be sufficiently small
- Then: no splitting loss
  = adiabatic Y-junction

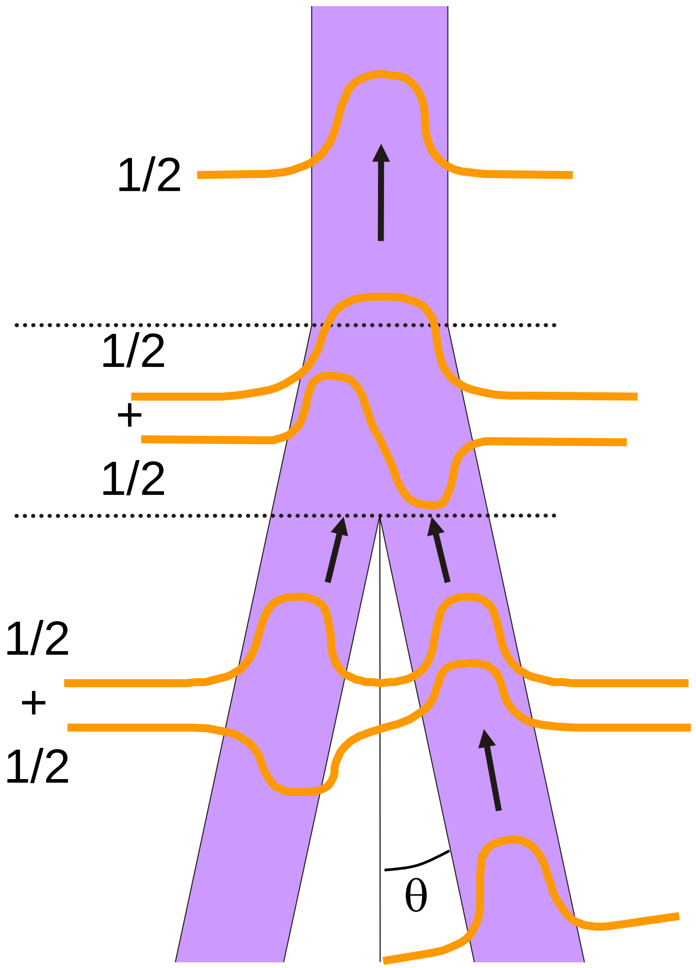
The Y-junction

- Reversed junction:
  a mode in only 1 branch

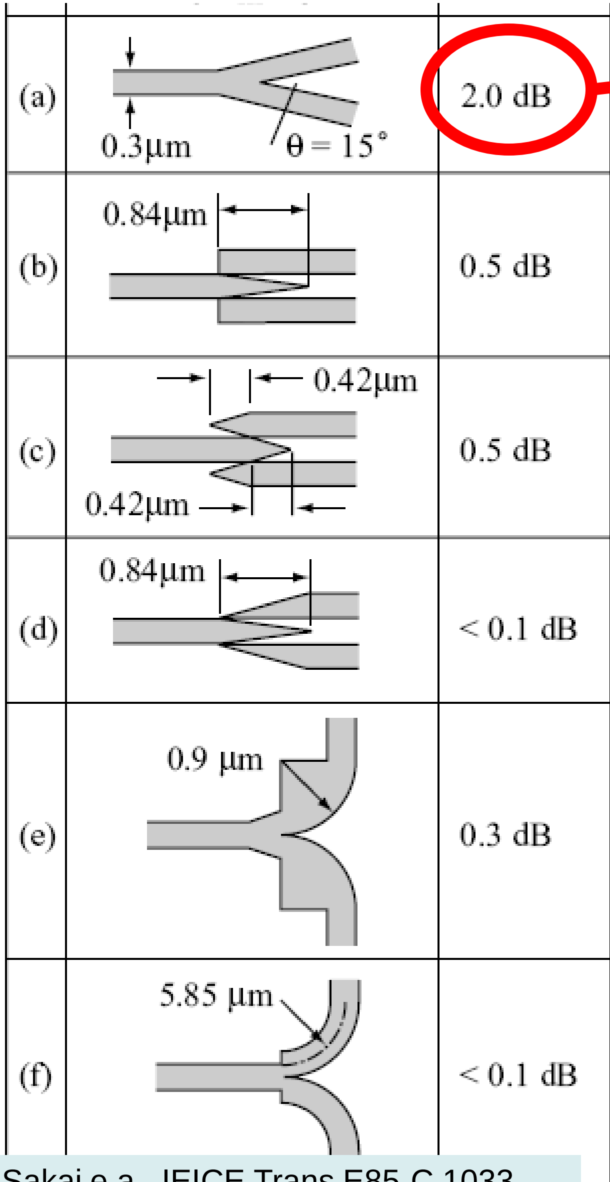
- Decompose into local supermodes
  - symmetric supermode is squeezed into the ground mode
  - Anti-symmetric supermode is squeezed into the first-order mode

  → first-order mode is not guided in a single-mode waveguide

→ **half of the power is lost !!!**



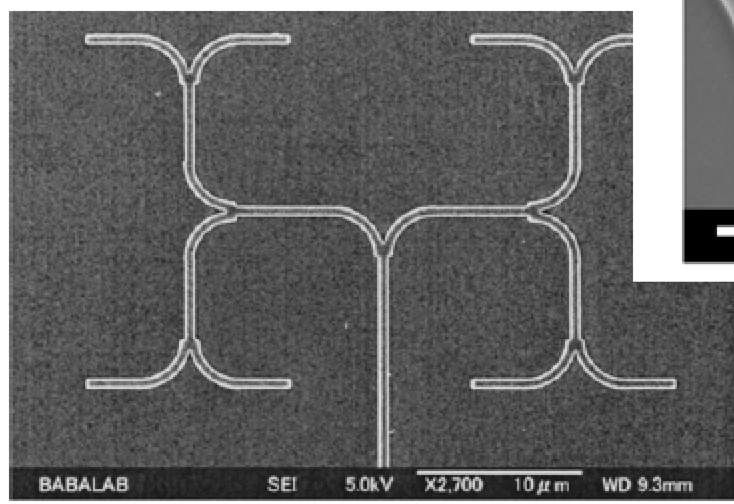
The Y-junction

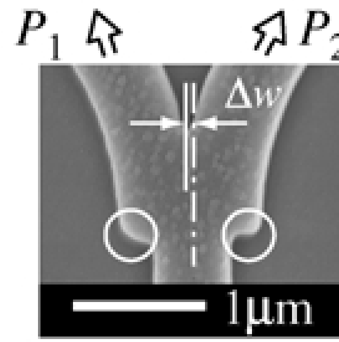


Sakai e.a., IEICE Trans E85-C 1033 (2002)

Large **losses** for standard Y-junction
Need **improved** design !!!

- Example



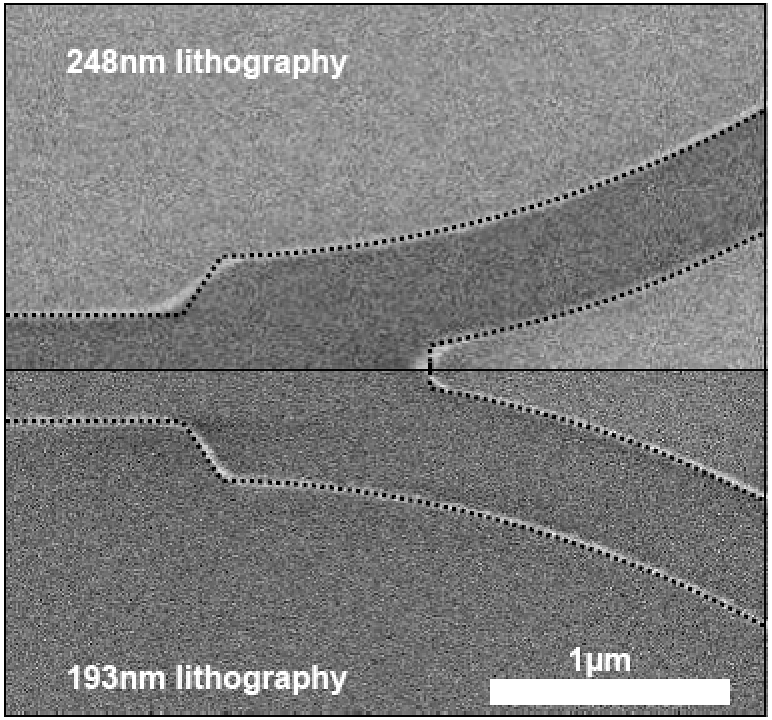


- Simulation: <0.1dB excess loss
  - Experiment: 0.3dB excess loss
  - Some imbalance due to opt. Prox.

Fukazawa e.a. Jpn JAP 41, p L1461 (2002)

The Y-junction

- Need very high lithographic resolution

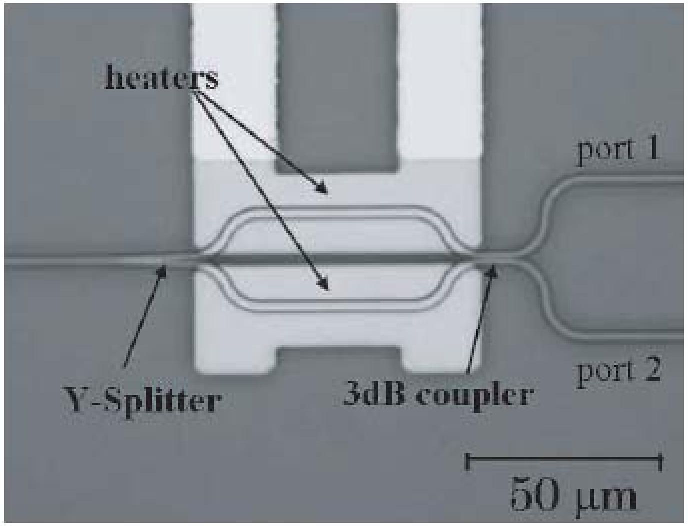


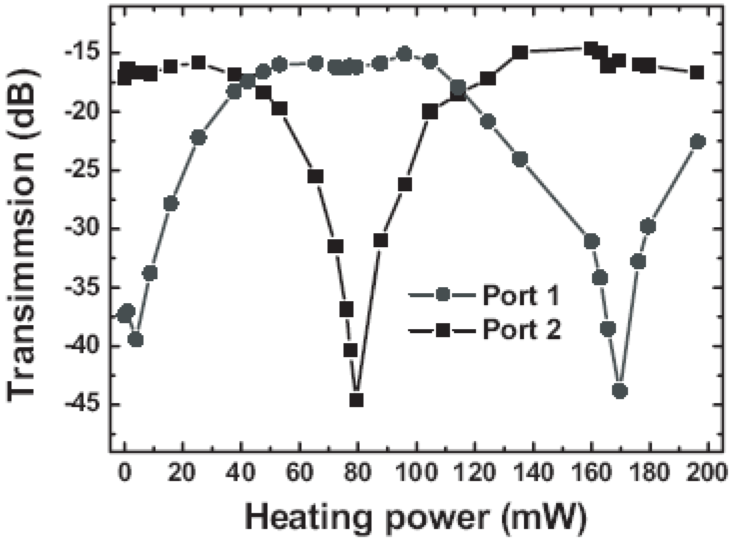
Picture: Bogaerts e.a. JSTQE, 2010

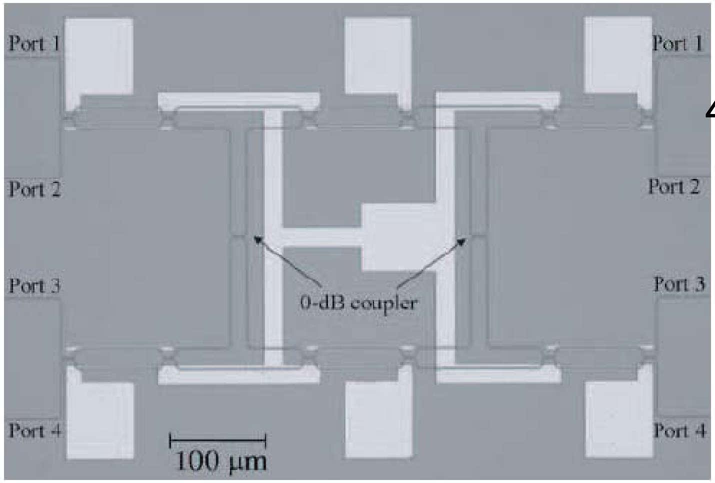
Theory: Fukazawa e.a. Jpn JAP 41, p L1461 (2002)

The Y-junction

- Use Y-junctions to fabricate TO-switches







4 x 4 switch

Yamada e.a., PIERS proc., Beijing, p. 22 (2009)

Outline

- The Straight Waveguide
- The Waveguide Bend
- The Directional Coupler
- Star coupler
- The Multimode Interference Coupler
- The Y-junction
- **The Mach–Zehnder Interferometer**
- The AWG

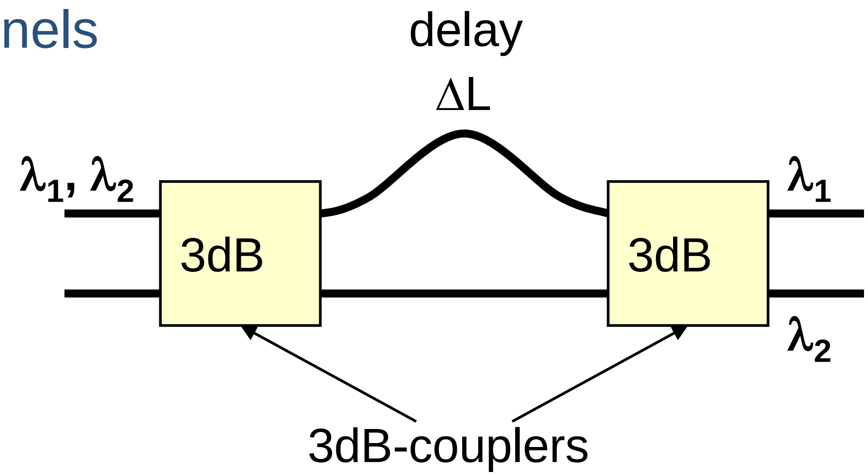
The MZI demultiplexer

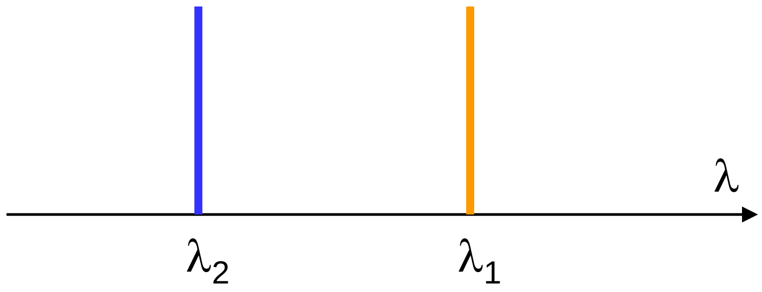
- Mach-Zehnder interferometer:

→ Splitting of two wavelength channels when

$$\frac{\lambda_1 - \lambda_2}{\lambda_c} = \frac{\lambda_c}{2n\Delta L}$$

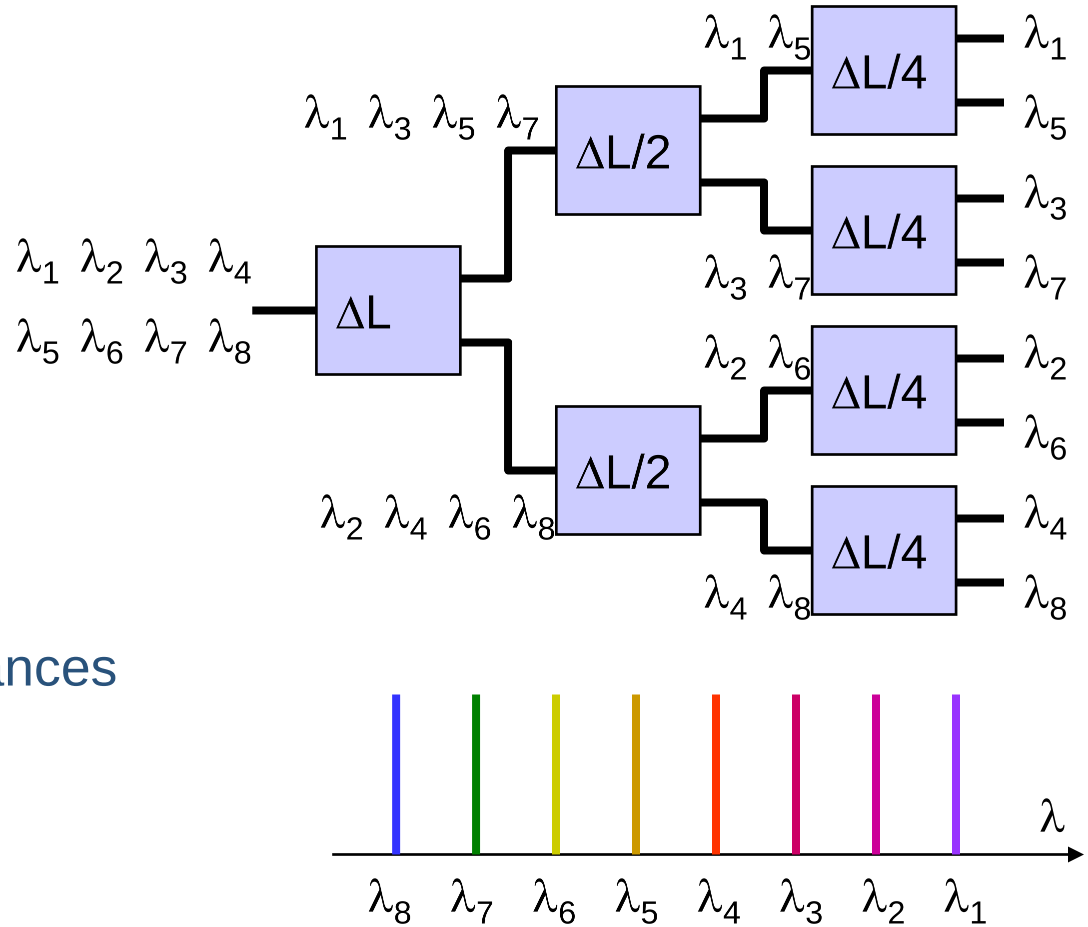
with $\lambda_c = \frac{1}{2}(\lambda_1 + \lambda_2)$





The MZI demultiplexer

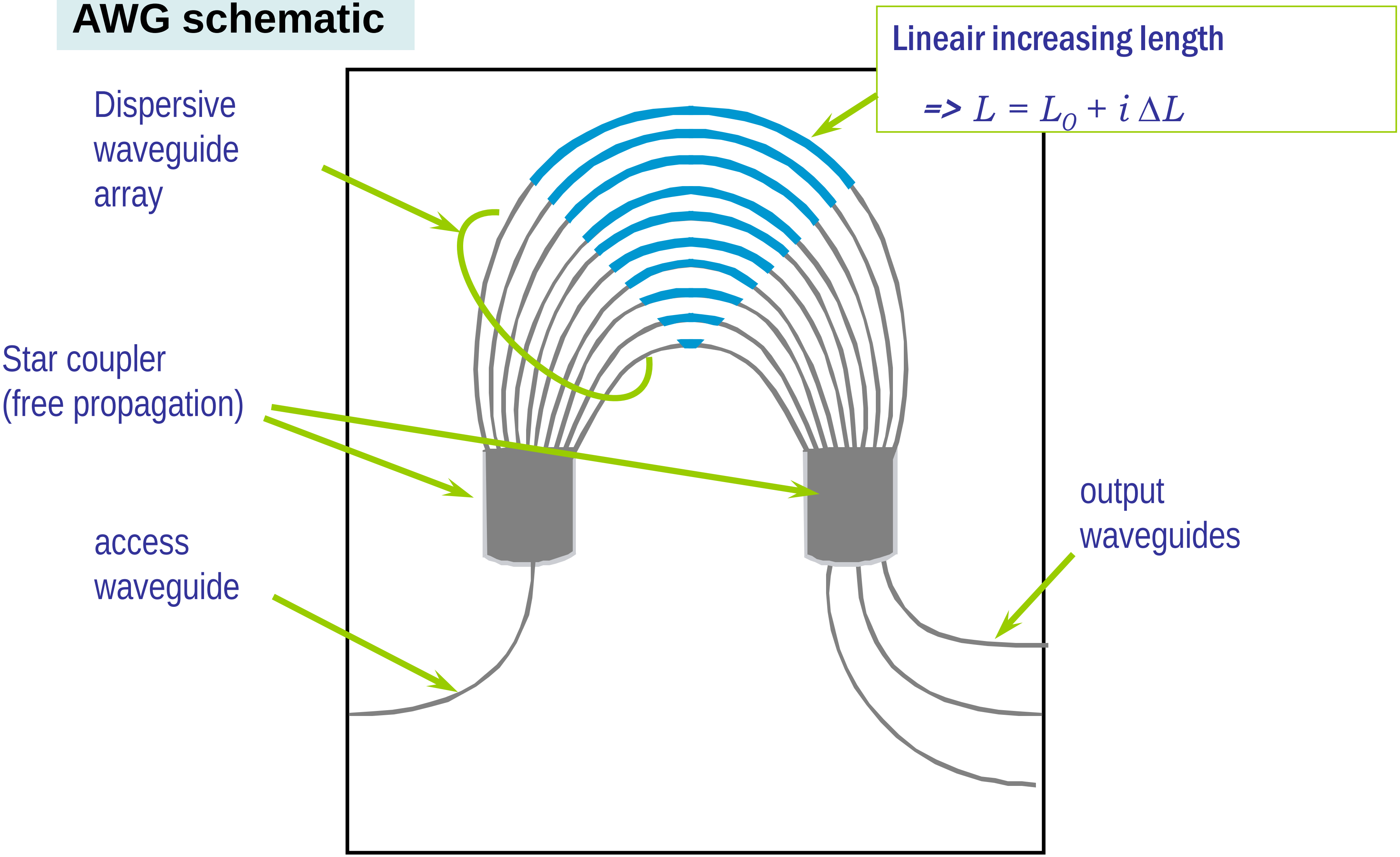
- MZI demultiplexer = cascade of MZI's with smaller delay lengths



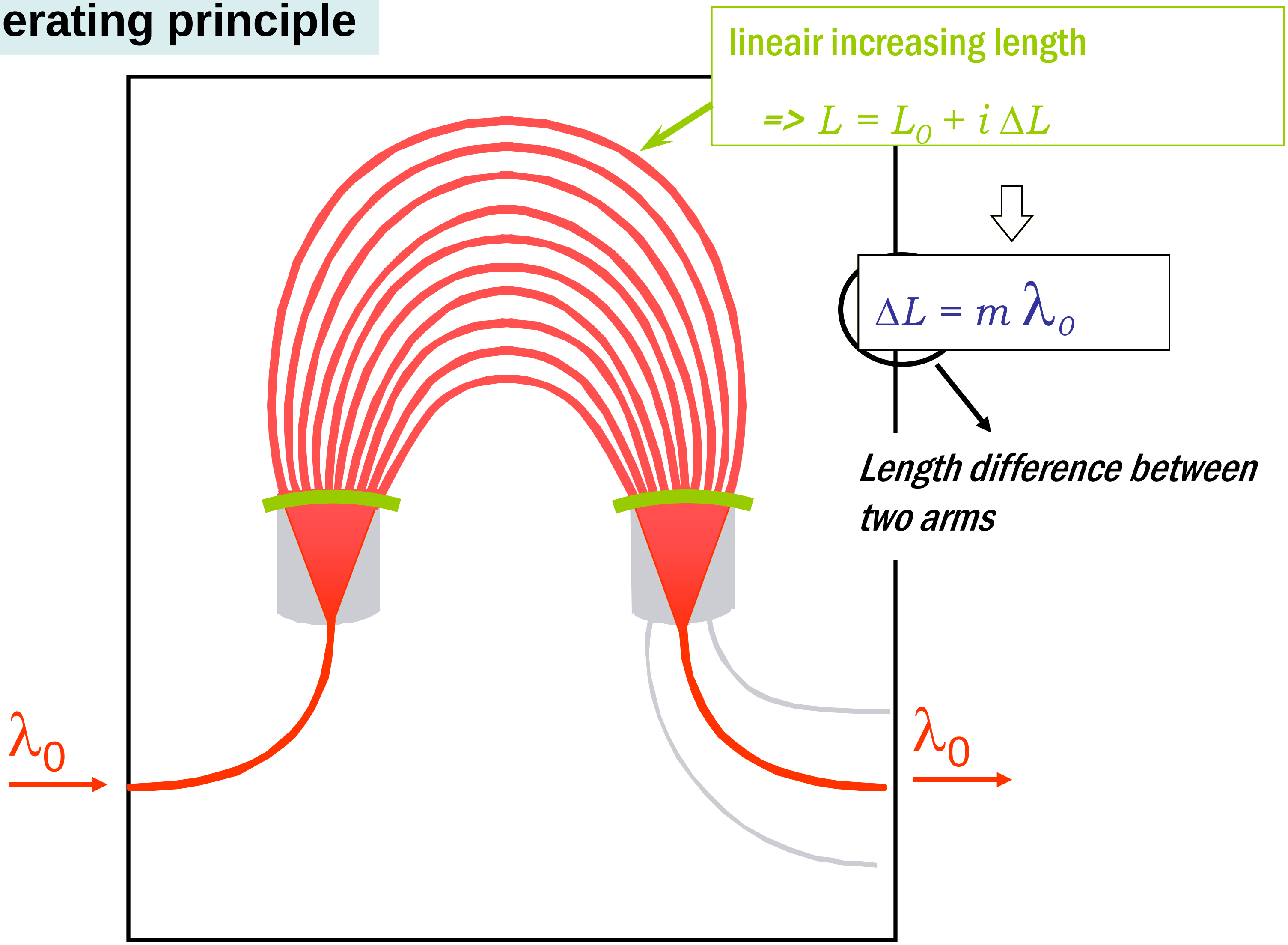
- Very high resolution
- Strict fabrication tolerances

- Outline
  - The Straight Waveguide
  - The Waveguide Bend
  - The Directional Coupler
  - Star coupler
  - The Multimode Interference Coupler
  - The Y-junction
  - The Mach–Zehnder Interferometer
  - **The AWG**

AWG schematic



AWG operating principle



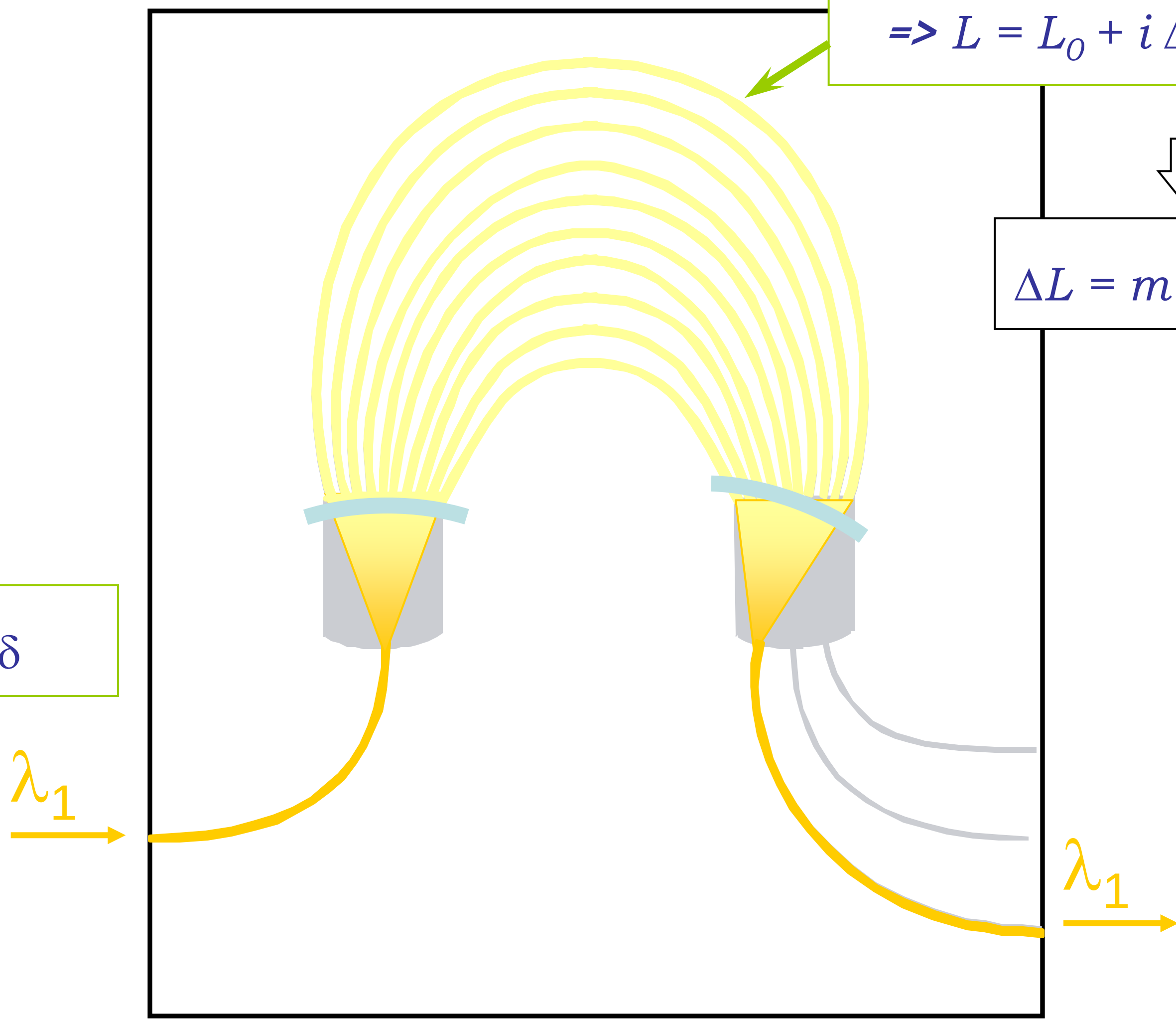
AWG operating principle

Lineair increasing length

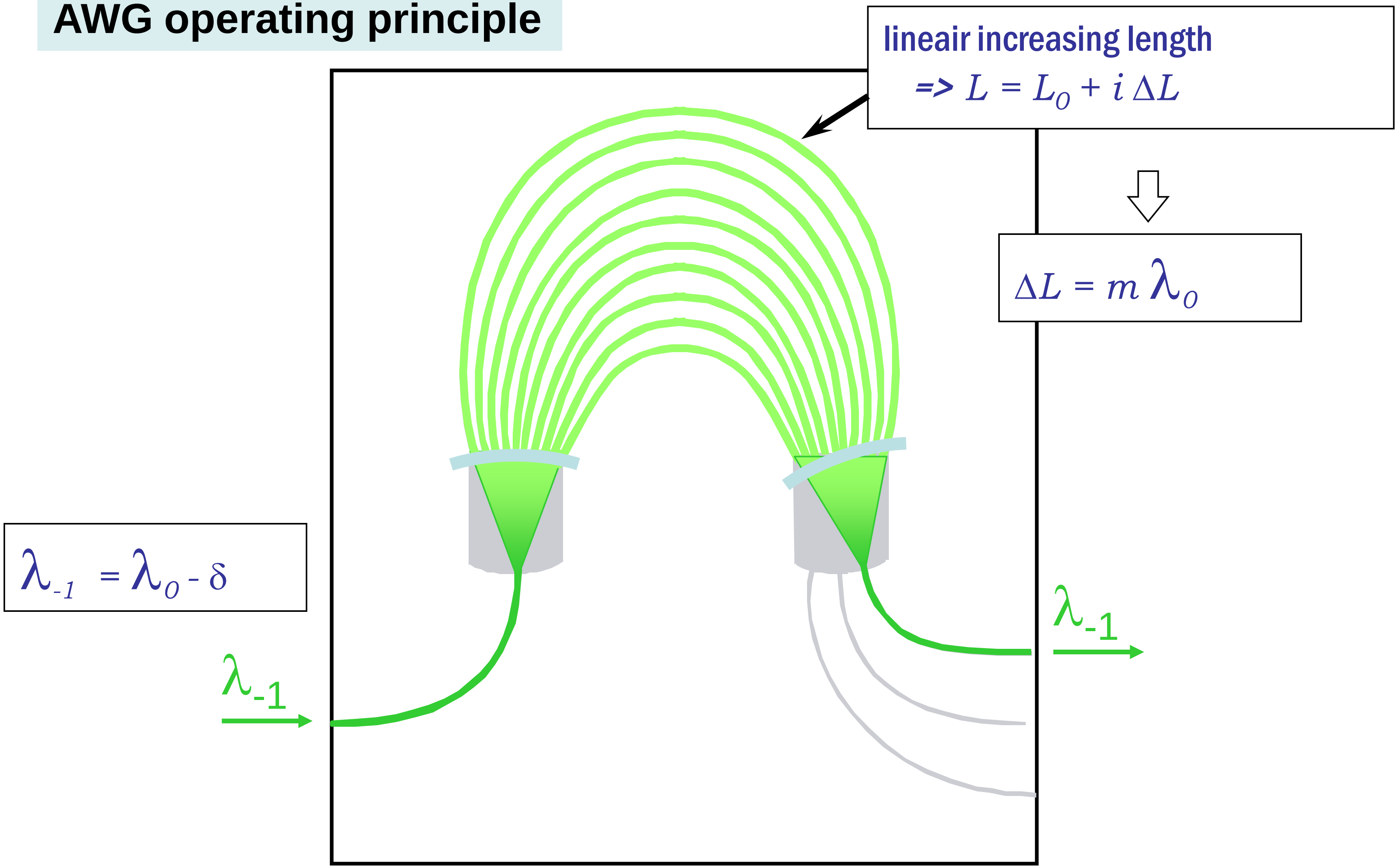
=> $L = L_0 + i\,\Delta L$

$$\Delta L = m\,\lambda_0$$

$$\lambda_1 = \lambda_0 + \delta$$



AWG operating principle



AWG operating principle

Lineair increasing length

=> $L = L_0 + i\,\Delta L$

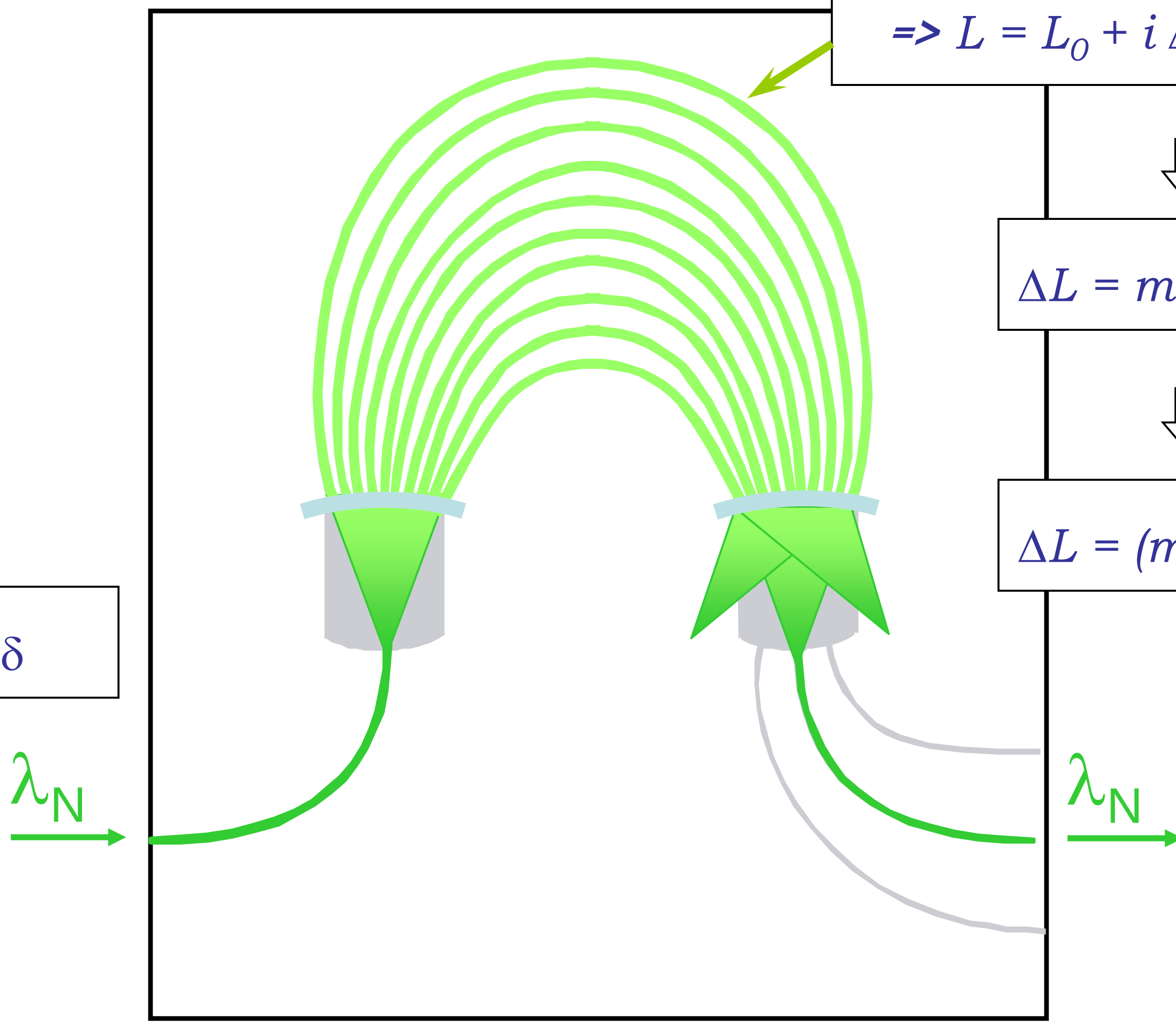
$\Delta L = m\,\lambda_0$

$\delta = \lambda_0 / m$

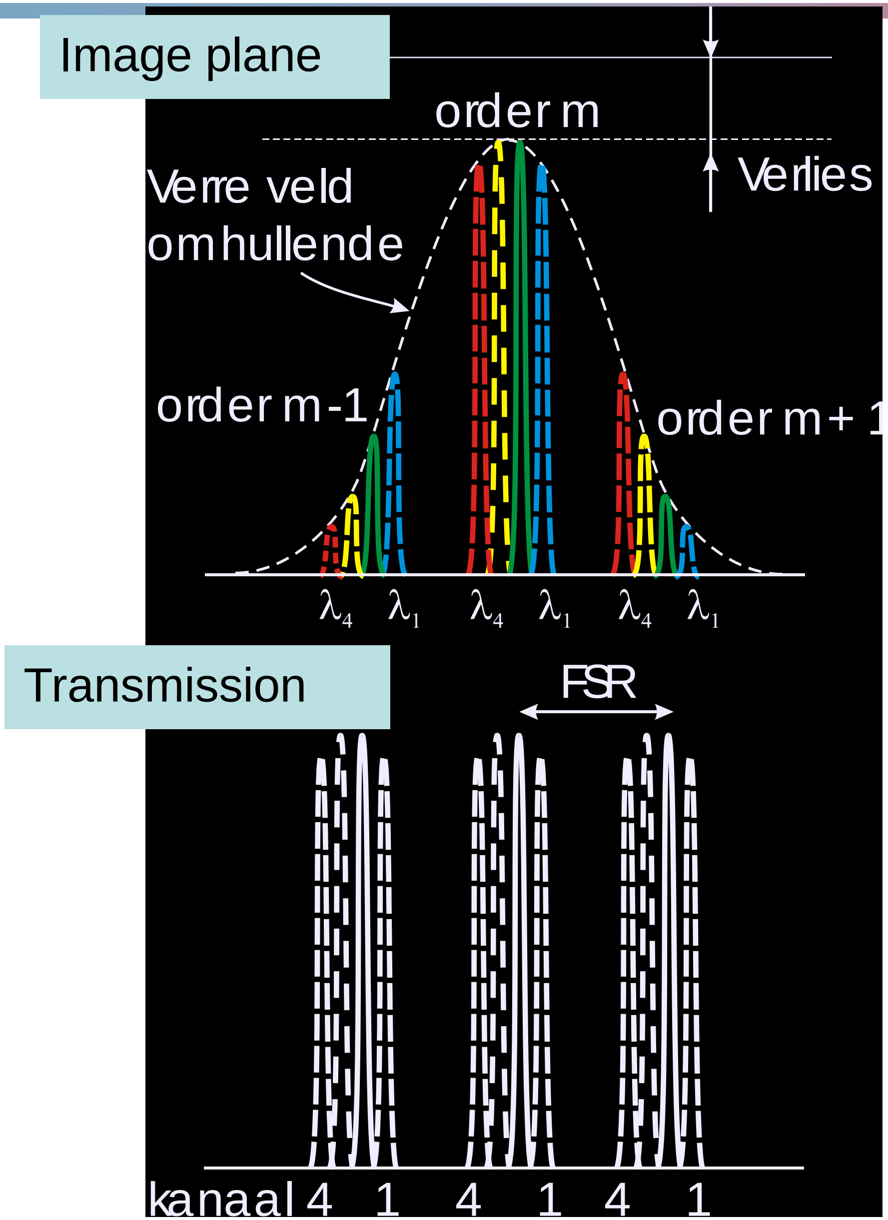
$\Delta L = (m-1)\,\lambda_N$

FSR

$\lambda_N = \lambda_0 + \delta$



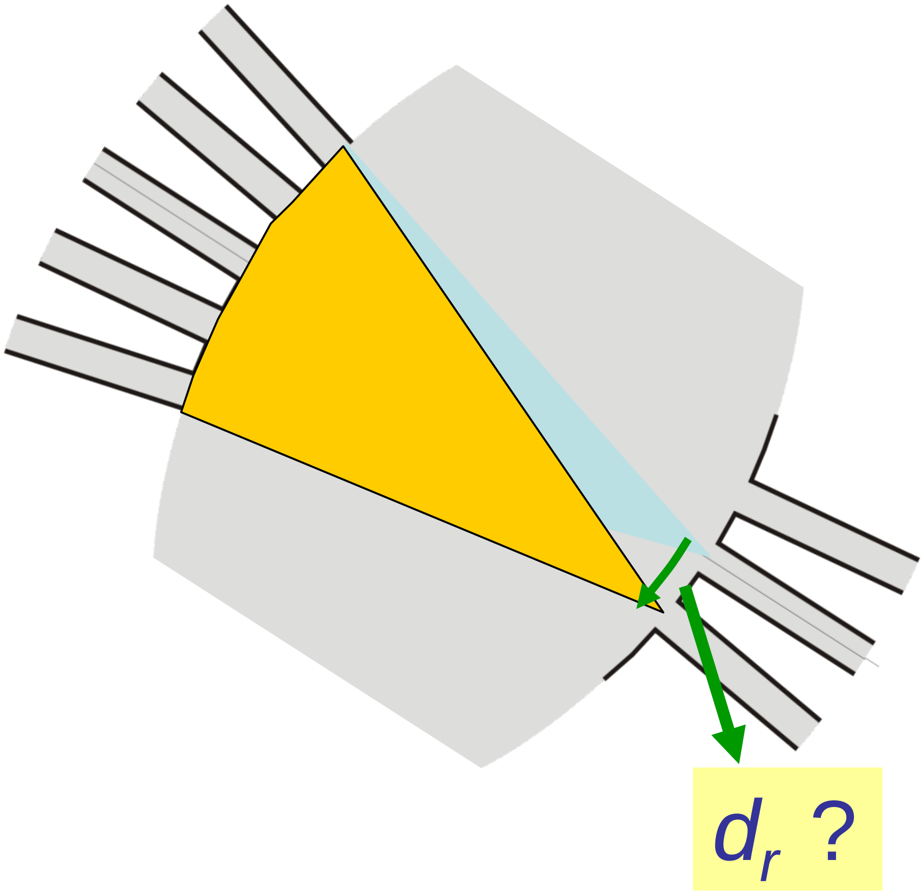
Phased-Array demultiplexer



- AWG is characterised by:
  - Periodicity $\Delta\lambda_{FSR}$
  - Channel spacing $\Delta\lambda_{ch}$
  - Bandwidth
  - Loss
  - Crosstalk

Channel spacing

- What is displacement in focal plane for given $\Delta\nu$?

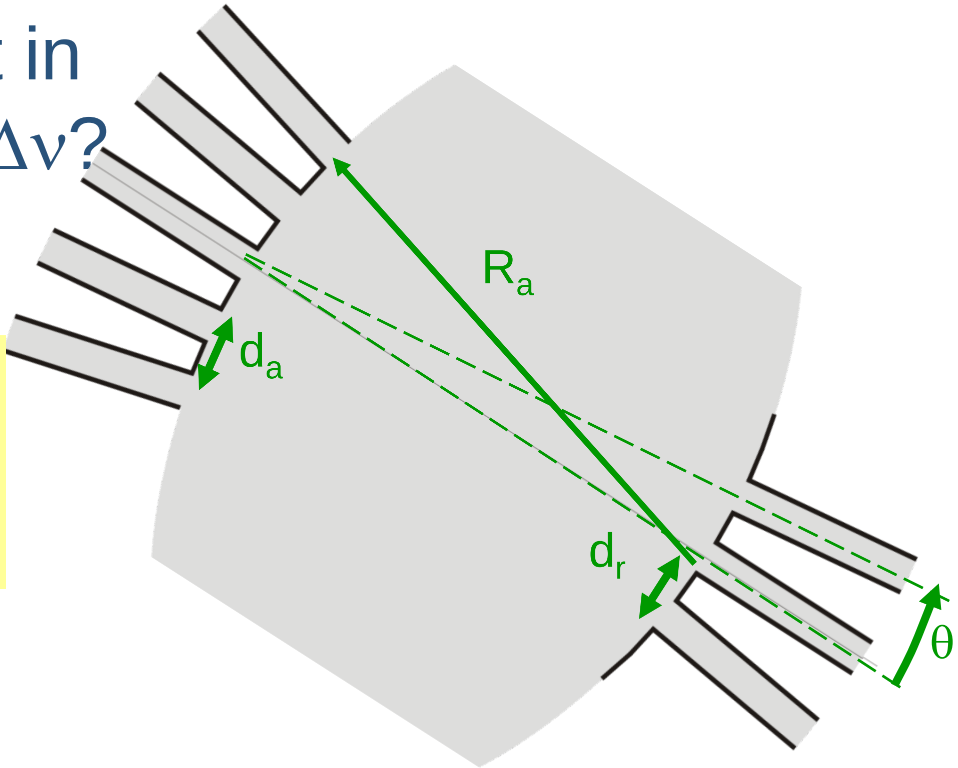


Channel spacing

- What is displacement in focal plane for given $\Delta\nu$?

Determined by dispersion: $D = \frac{ds}{d\nu}$

$$\frac{ds}{d\nu} = R_a \frac{d\theta}{d\nu}$$



Channel spacing

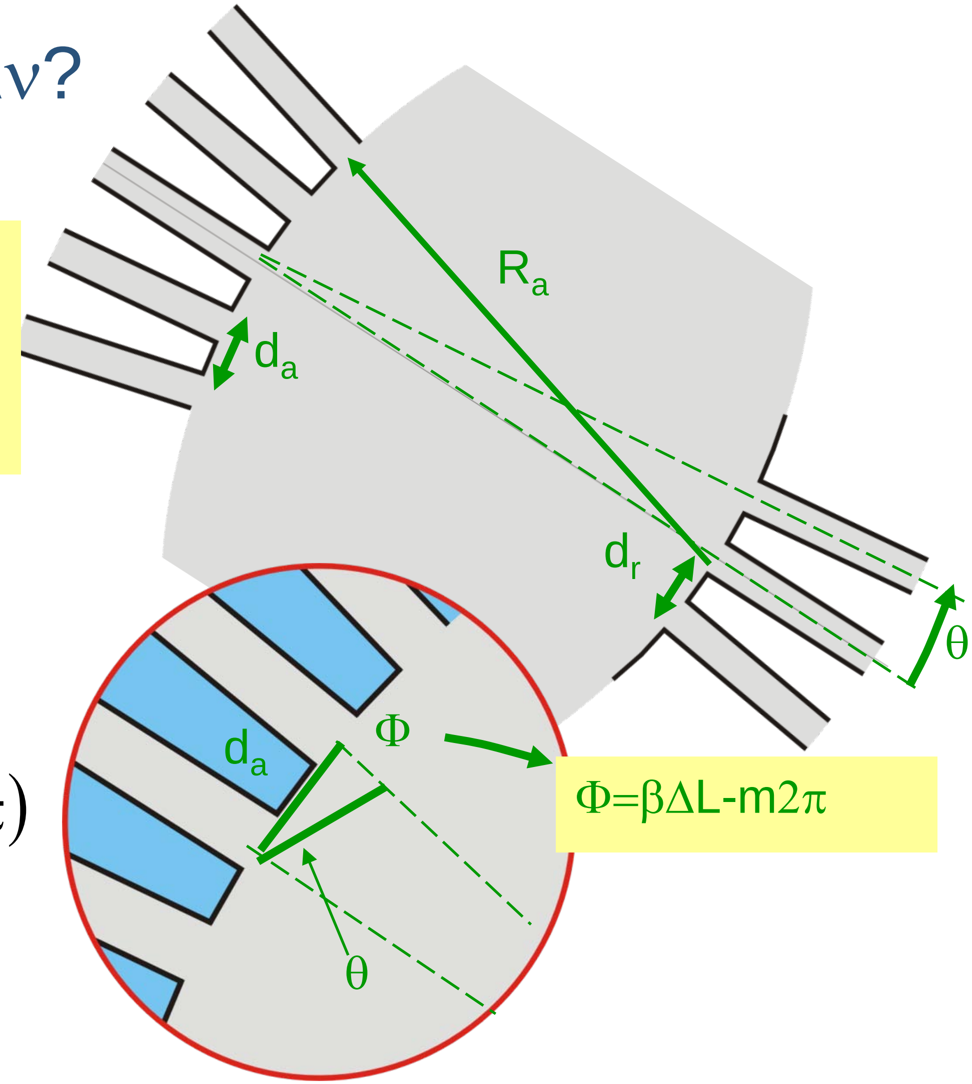
- What is d_r for given $\Delta\nu$?

Determined by dispersion: $D = \frac{ds}{d\nu}$

$$\frac{ds}{d\nu} = R_a \frac{d\theta}{d\nu}$$

$$d\theta = \frac{\lambda}{2\pi} d\Phi = \frac{\lambda_0}{2\pi n_s} d(\beta\Delta L - 2m\pi)$$

$$\frac{ds}{d\nu} = R_a \frac{\Delta L}{\nu_c d_a}$$



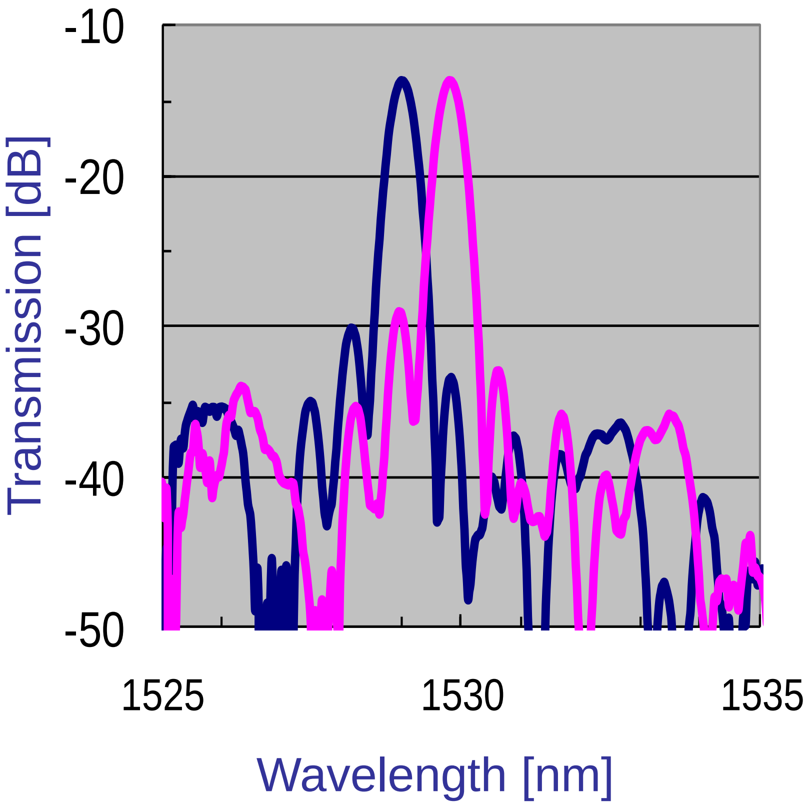
How to design a demultiplexer

- Design parameters
  - →channel spacing, bandwidth FSR
- Practical boundary conditions
  - →waveguide dimensions, minimum waveguide spacing…

↓

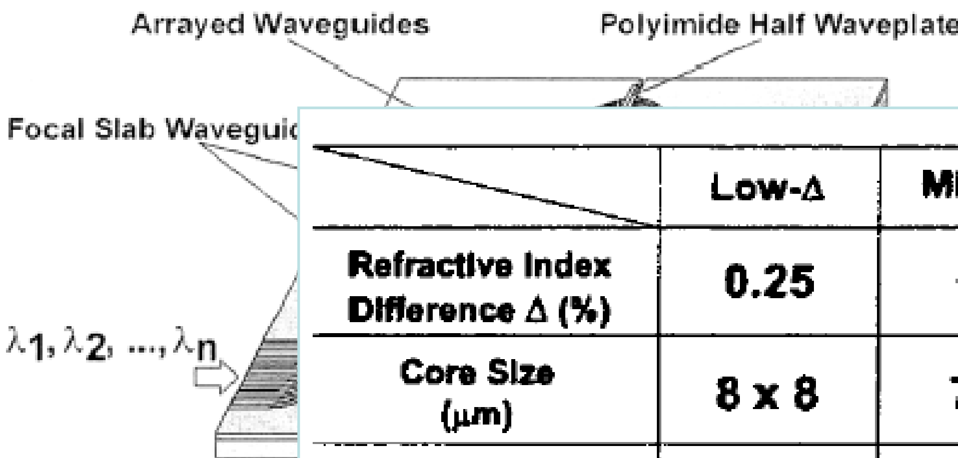
- From this: determine ΔL, dispersion, focal length

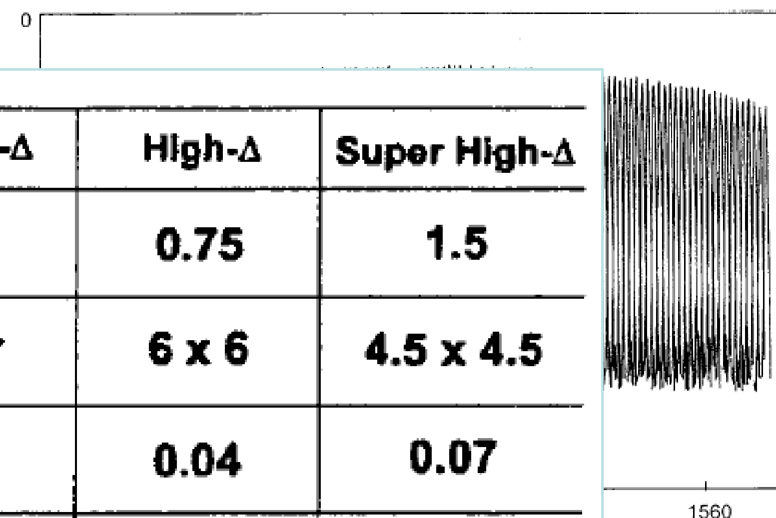
AWG



- Loss
  - Waveguide losses
  - Imperfect star coupler
  - Finite aperture
- Crosstalk
  - Finite aperture
  - Overlapping fields in access waveguides
  - Phase noise on length array waveguides

Reference: Silica-on-silicon devices



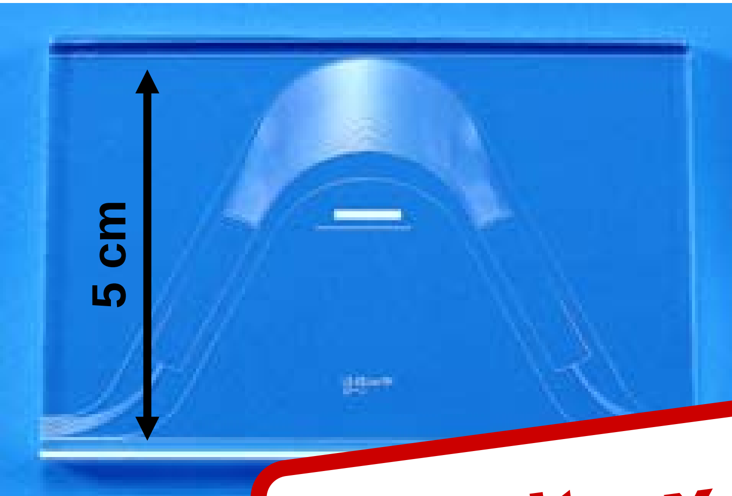


	Low-Δ	Middle-Δ	High-Δ	Super High-Δ
Refractive Index Difference Δ (%)	0.25	0.45	0.75	1.5
Core Size (μm)	8 x 8	7 x 7	6 x 6	4.5 x 4.5
Propagation Loss (dB/cm)	< 0.01	0.02	0.04	0.07
Fiber Coupling Loss (dB/point)	< 0.1	0.1	0.5	2.0 (SMF) 0.4 (DSF)
Minimum Bending Radius (mm)	25	10	5	2
Application Field	Small-Scale PLC	Medium-Scale PLC	Large-Scale PLC	Very Large-Scale & High-Density PLC

Size: Several square centimeter

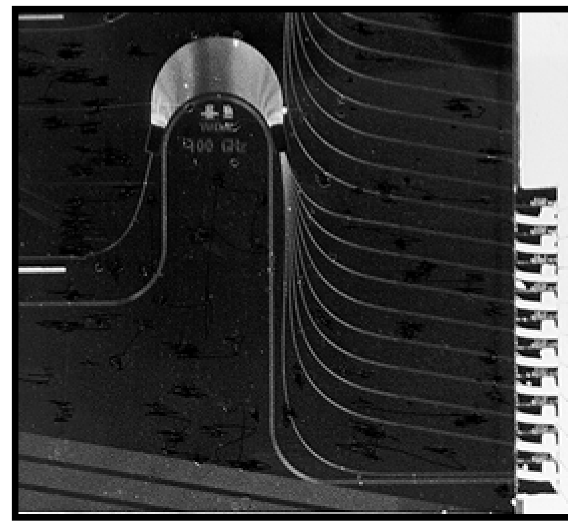
NTT (e.g. Miya e.a., IEEE STQE ’00 pp.38)

AWG



Low Contrast - Fiber Matched
(silica or polymer based)
Bend Radius ~ 5 mm
Size ~ several cm^2

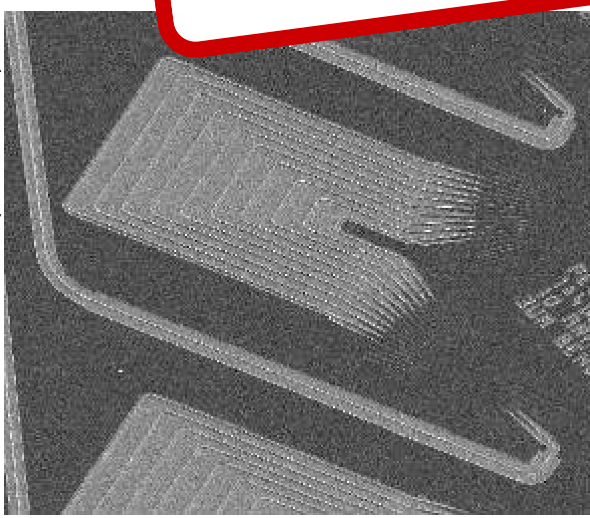
Density x 10^6



5 mm

Medium Contrast
(InP-InGaAsP)
Bend Radius ~ 500µm

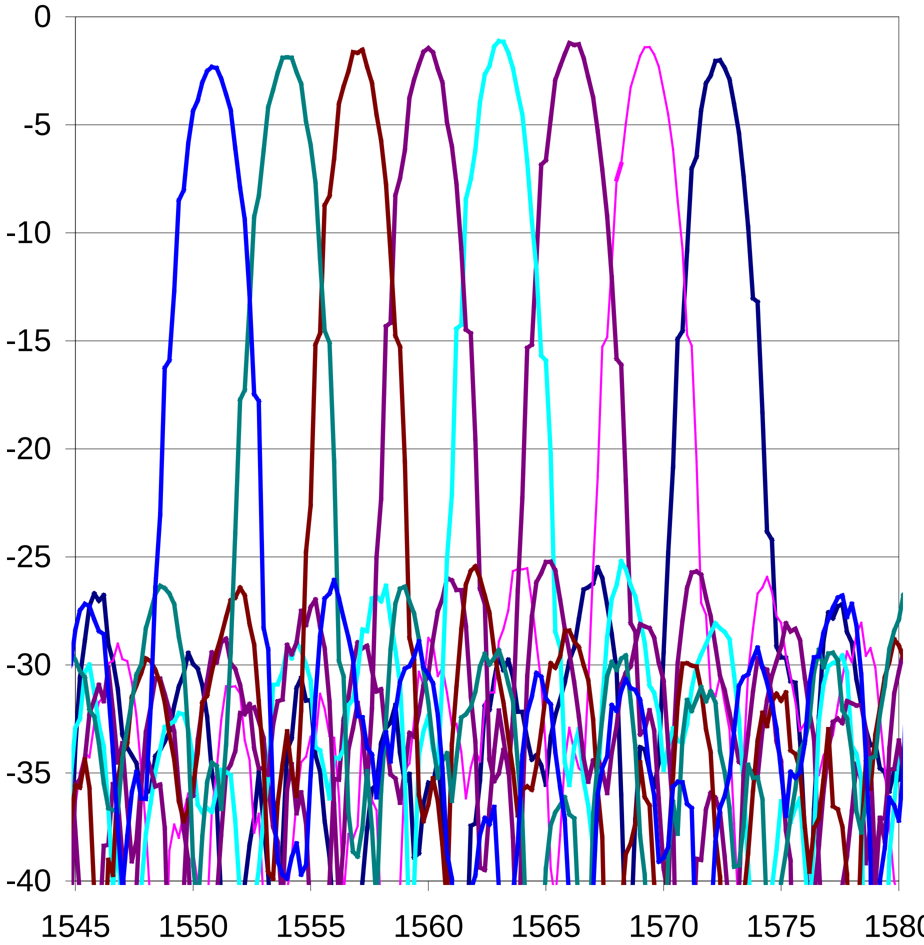
50 µm

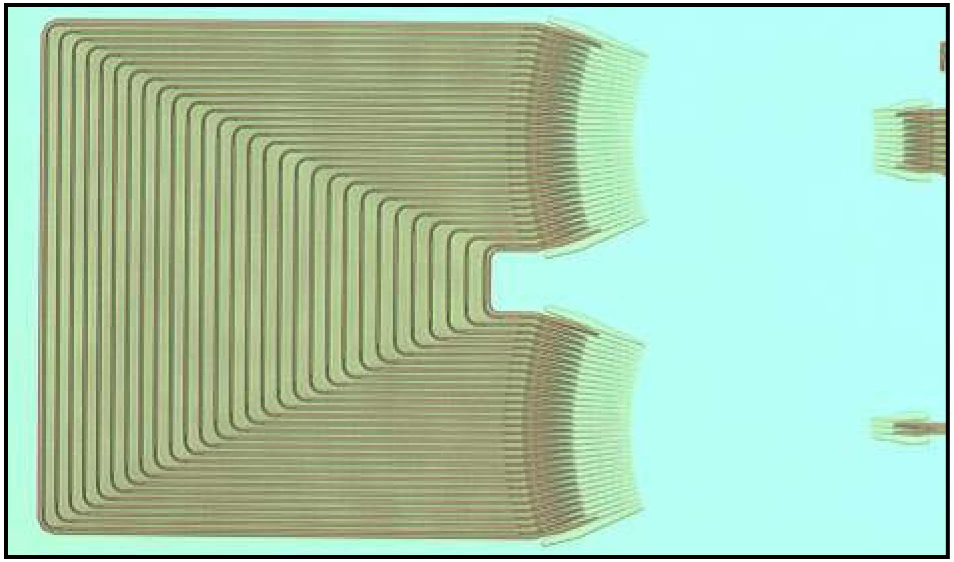


Ultra-high Contrast
(Silicon on Insulator)
Bend Radius < 5µm

Arrayed Waveguide Grating

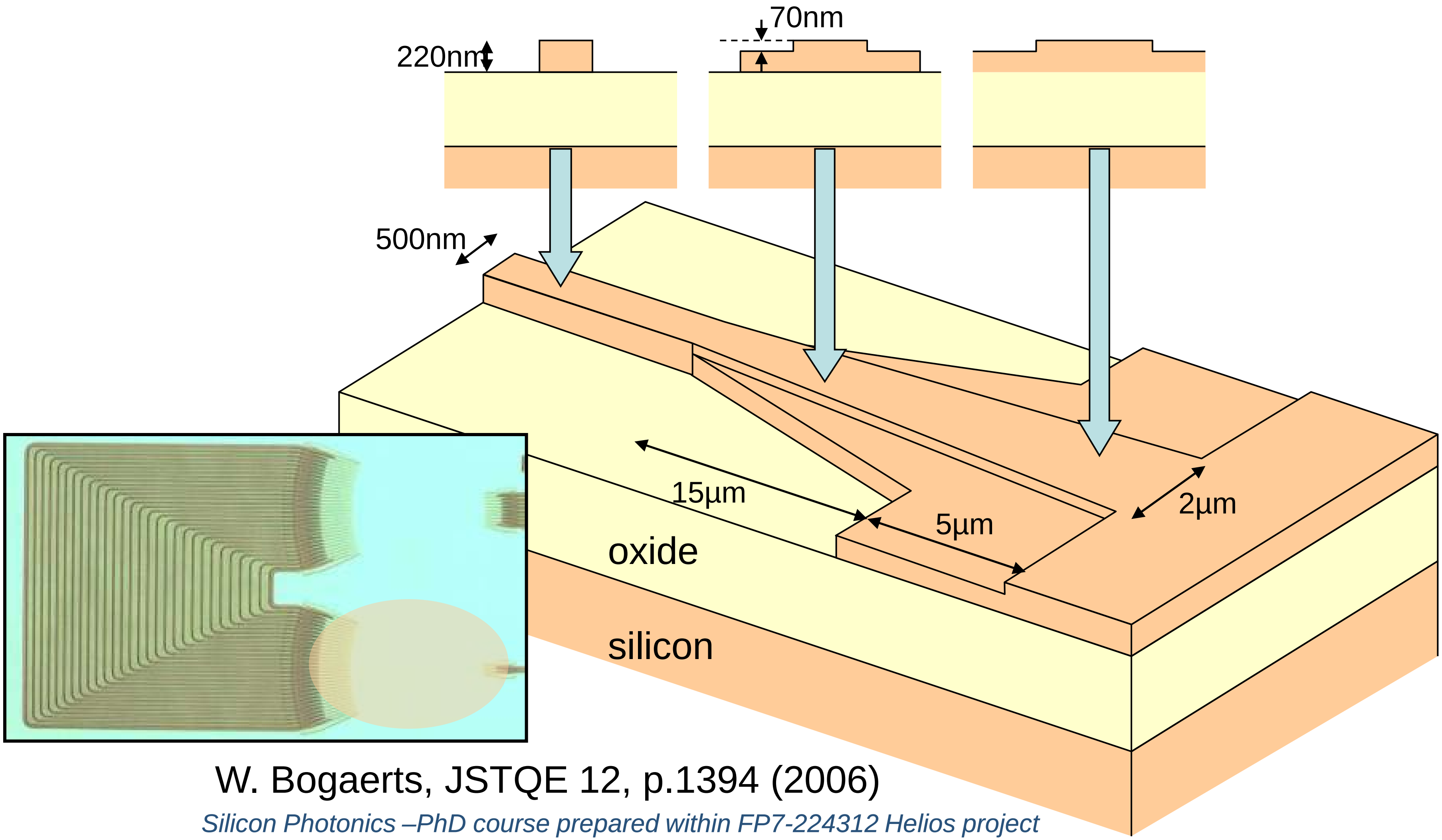
- 8-channel, 400GHz
- FSR = 30nm
- footprint = 200 x 350 μm^2
  - -25 dB crosstalk level
  - -1 dB insertion loss (center channel)
  - 1.5 dB non-uniformity





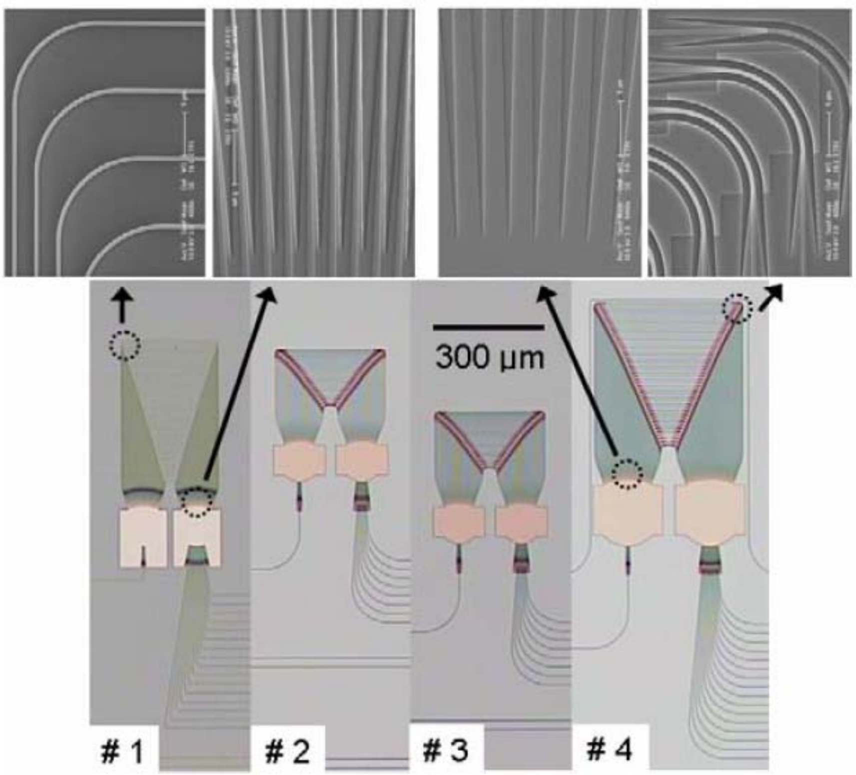
W. Bogaerts e.a. JSTQE, 2010

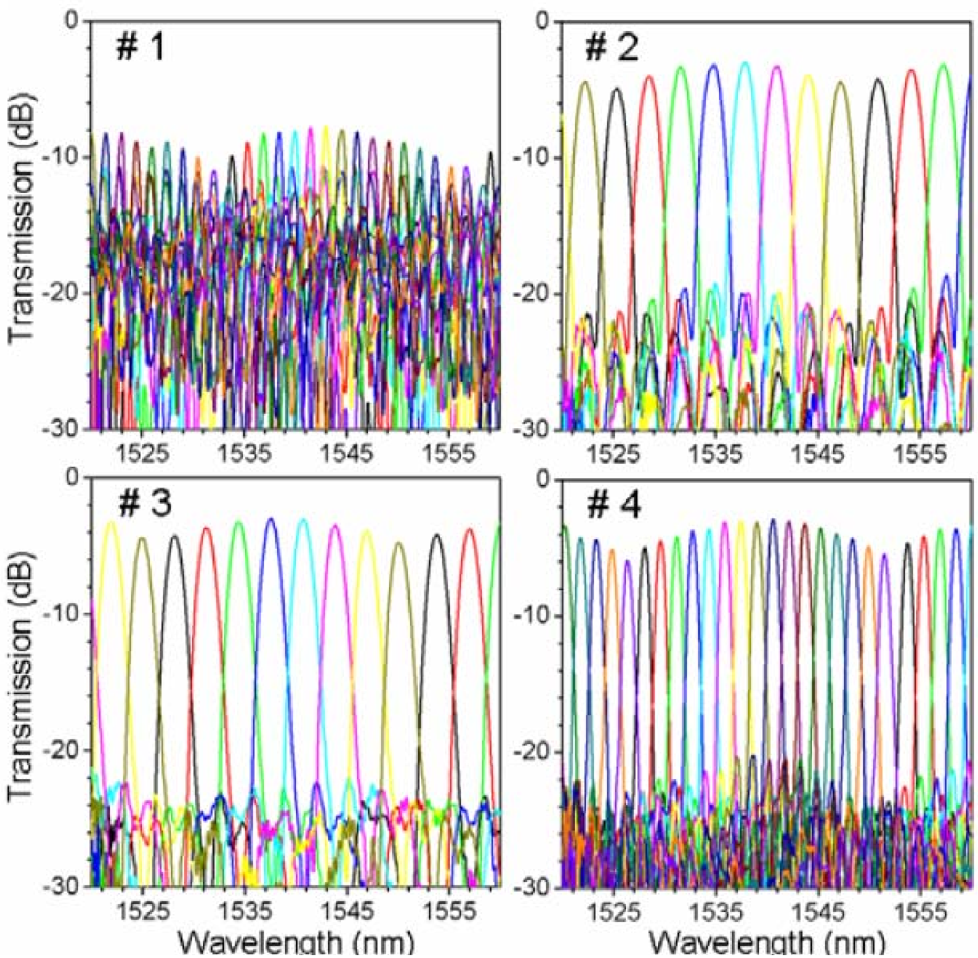
- Star coupler:
  - shallow etch for less contrast



W. Bogaerts, JSTQE 12, p.1394 (2006)

Use of shallowly etched waveguides for crosstalk reduction





DJ Kim e.a. PTL 20 (17-20) p 1615 (2008)

Outline

- The Straight Waveguide

Basic components with high performance have been demonstrated using silicon wire waveguides The next step is to combine them to realise more complex circuits

- The Mach–Zehnder Interferometer
- The AWG