# Nonlinear Optics in Silicon Photonics


Klaus Petermann

E-Mail: petermann@tu-berlin.de

Fachgebiet Hochfrequenztechnik

# Acknowledgement


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## PHOTLINE

H. Porte

# Photonic BiCMOS

## Introduction to Photonic BiCMOS

## Nonlinear Optical Signal Processing using Photonic BiCMOS Devices

# BiCMOS

**Integrated Circuit** **Photonic Integrated Circuit**

**IC** **PIC**

**EPIC**

**Electronic Photonic Integrated Circuit**

# Joint Lab Silicon Photonics

Head: Dr. Lars Zimmermann

IC technology

JointLab
Silicon Photonics

Photonics


Prof. Bernd Tillack


Prof. Klaus Petermann

# IHP location

**Frankfurt (Oder)**


# Pilot line 0.25µm/0.13µm SiGe BiCMOS

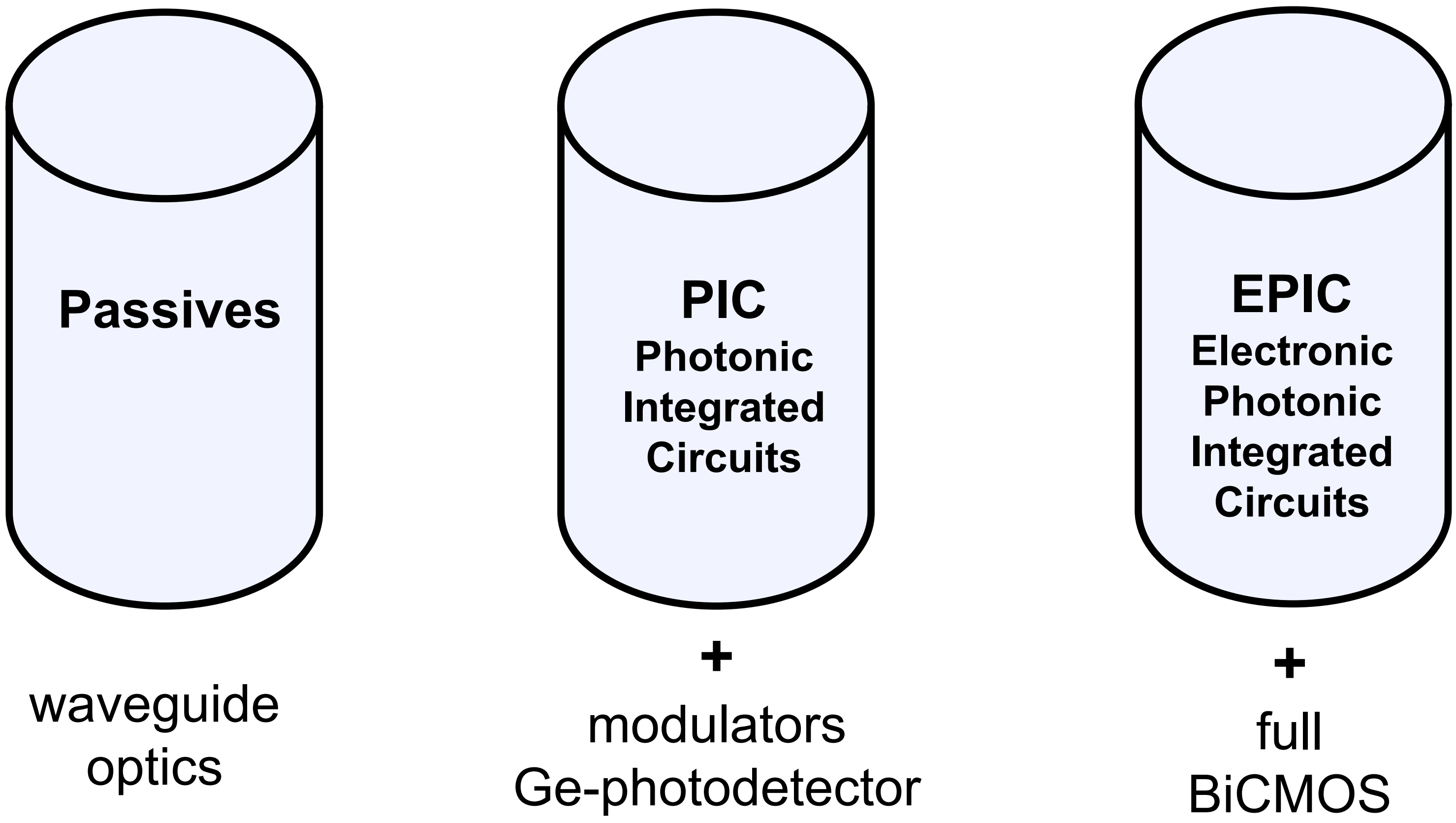
**SG25H1** npn-HBTs up to
$f_t/f_{max}$=180/220GHz

**SG25H3** npn-HBTs up to
$f_t/f_{max}$=110/180GHz
$V_{breakdown}$ up to 7V

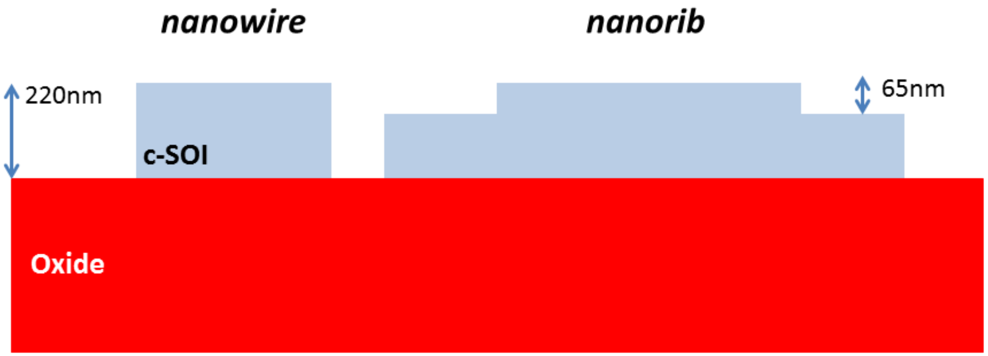
**SG13S** npn-HBTs up to
$f_t/f_{max}$=250/300GHz
3.3V I/O CMOS
1.2V logic CMOS

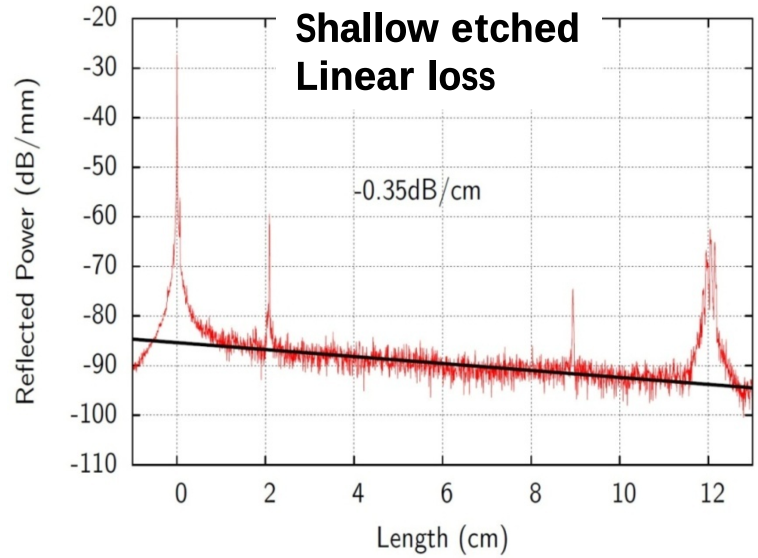
**SG13G2** $f_t/f_{max}$=300/500GHz

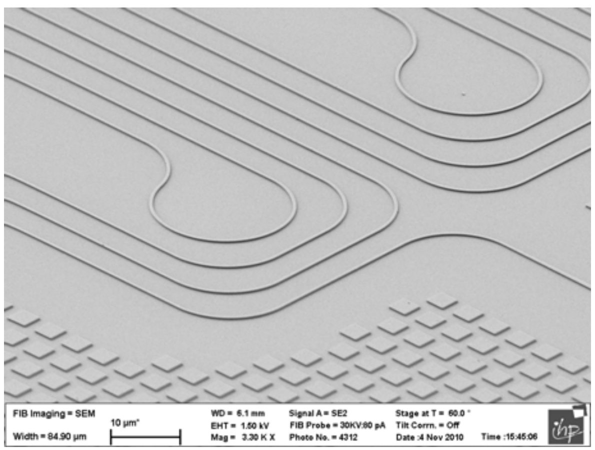
# Si - Photonics Development Lines

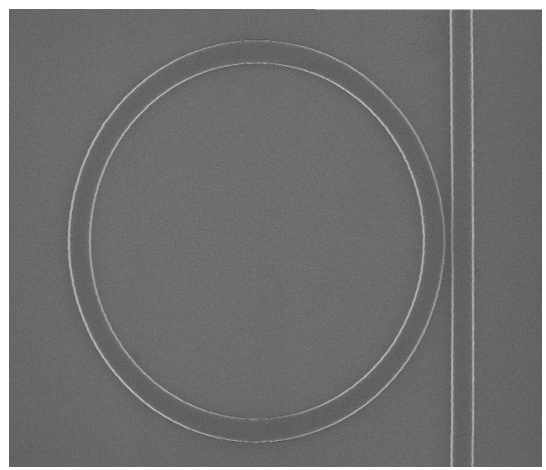


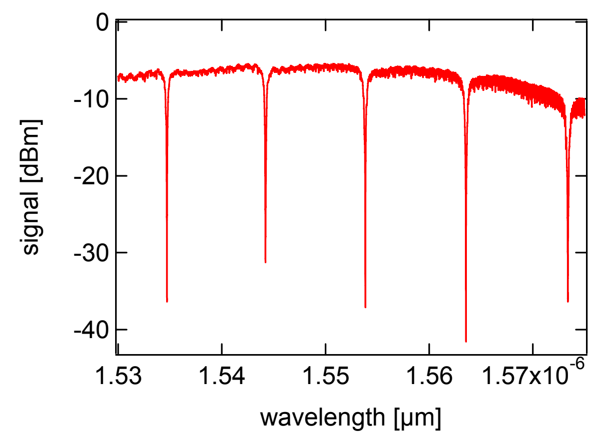
# IHP Si-Photonics technology



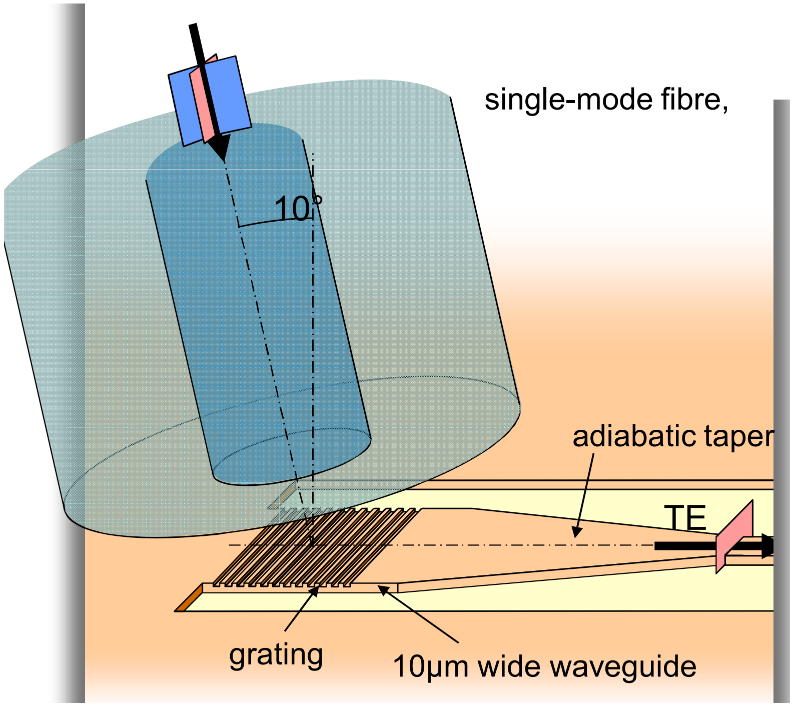







# Coupling via Grating



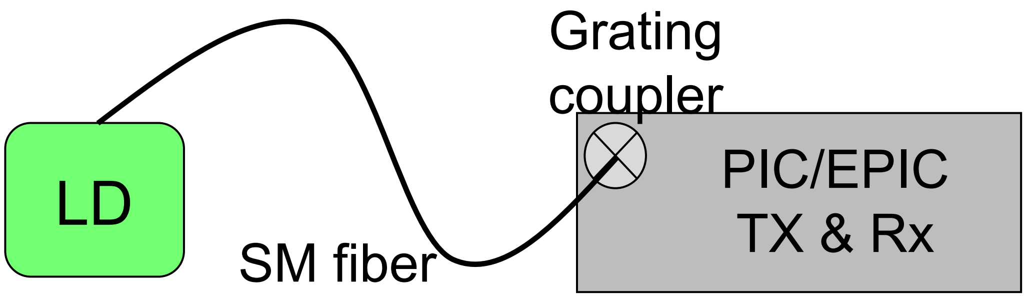

**Grating coupler:**

- **No need for a polished facet**
- **Wafer scale testing**
- **Wafer-level packaging**
- **Compatible with SMF**
- **Flexible and cheap**

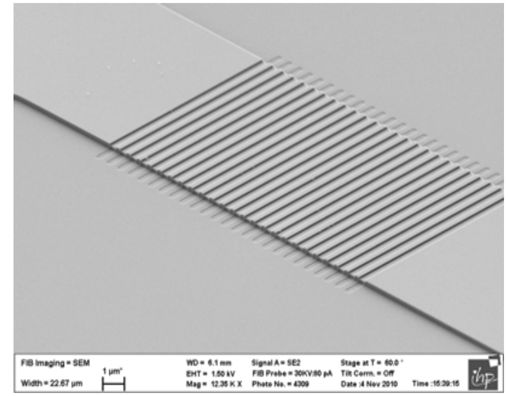
**D. Taillaert et. al., IEEE J. Quantum Electron., vol. QE38 (2002), pp. 949 - 955**

# Present optical i/o

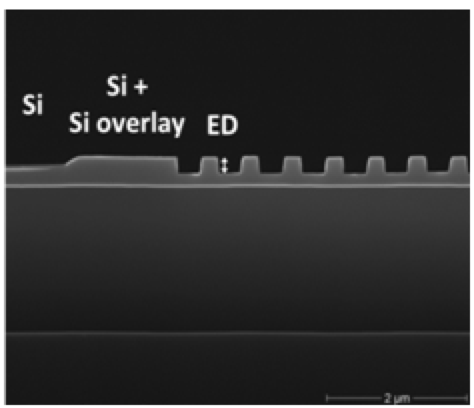
1550nm



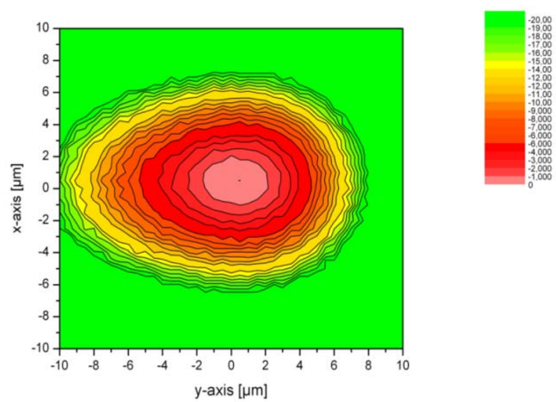

Standard linear

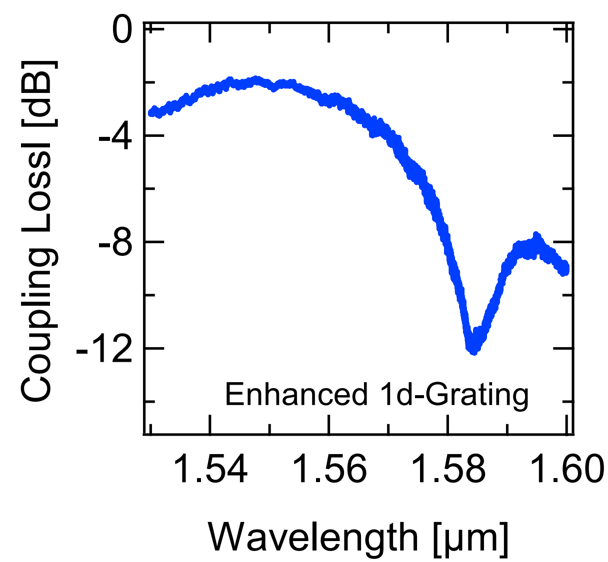


Linear enhanced



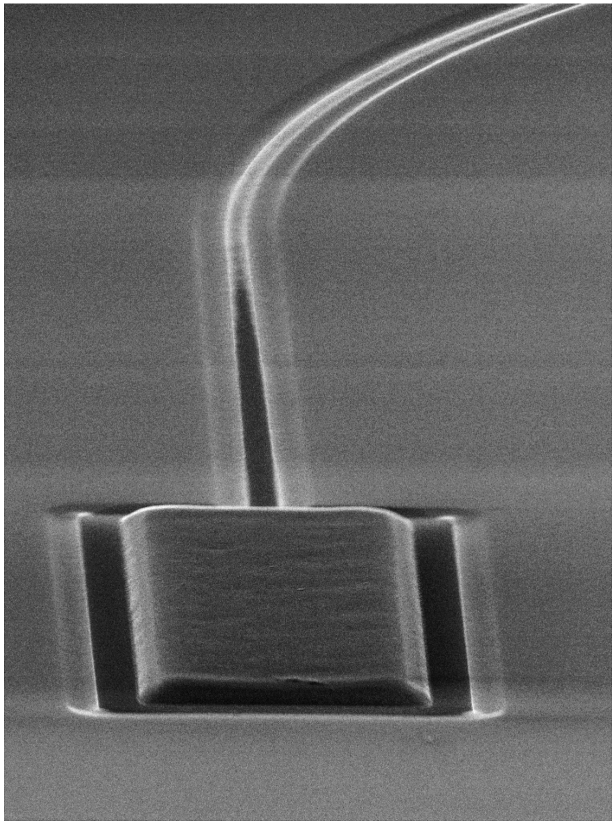

~10µm spot



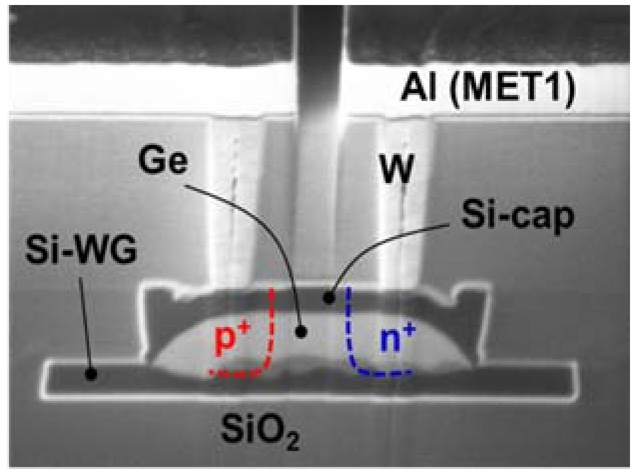



# Germanium photodetectors

## Ge waveguide photodiode

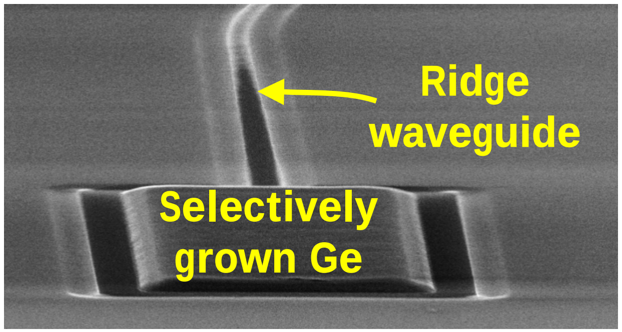


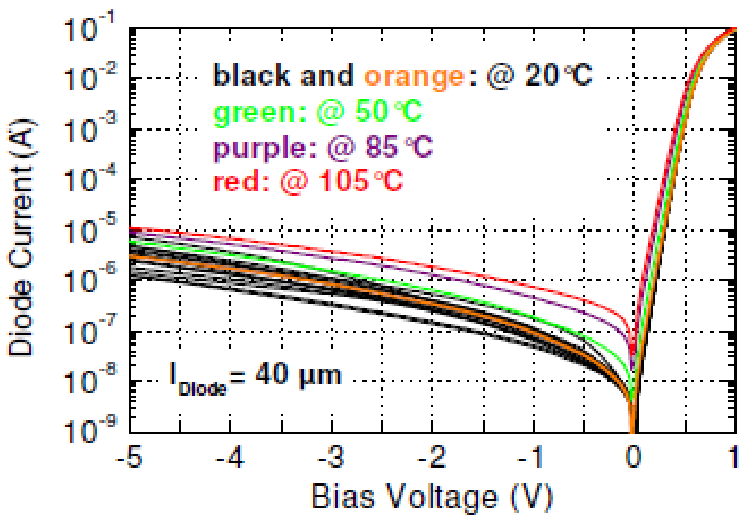
Cross section

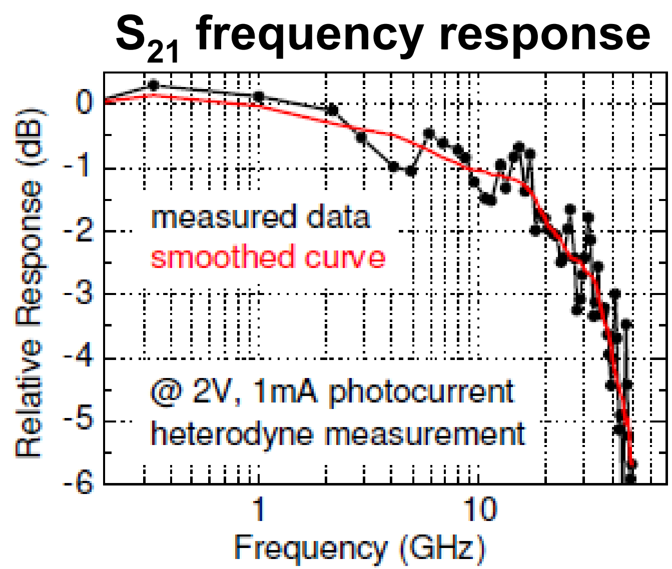



S. Lischke
IEEE Phot. Conf., San Francisco, 2012

# WG-coupled Ge lateral PIN PD

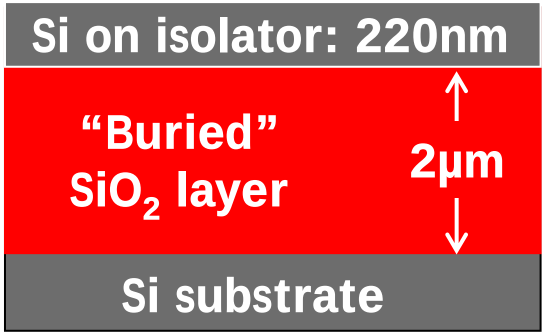



- Nice dark current behavior
- 30(+) GHz **(-3dB)** bandwidth
- 0.6(+) A/W internal respon-sivity @ $\lambda$= 1.55µm

# Photonic BiCMOS substrate issue




Photonic components need SOI for low loss!!

**but "optimum for photonics" SOI dimensions are by far not optimal or even unfit for SOA-CMOS and, fortiori, SOA-BiCMOS!!**

- ***CMOS:*** ***both Si (220nm) and $SiO_2$ layer (2µm) much too thick***
- ***HBT:*** ***Si layer much too thin for a low-$R_C$ collector fabrication; bad head dissipation due to higher $R_{TH}$ of $SiO_2$, compared to Si***

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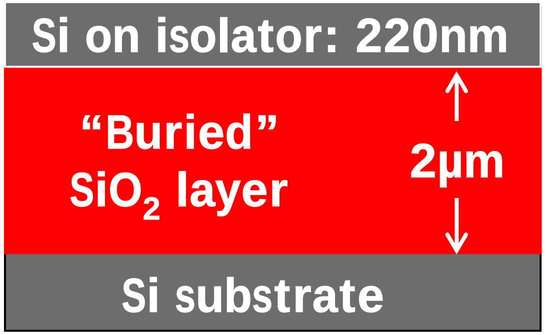


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- ***<u>CMOS:</u>*** ***both Si (220nm) and $SiO_2$ layer (2µm) much too thick***
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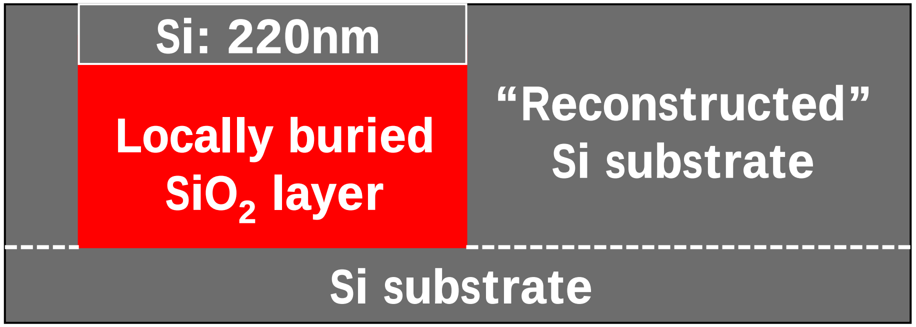
<u>Solution:</u>
"Local-SOI"

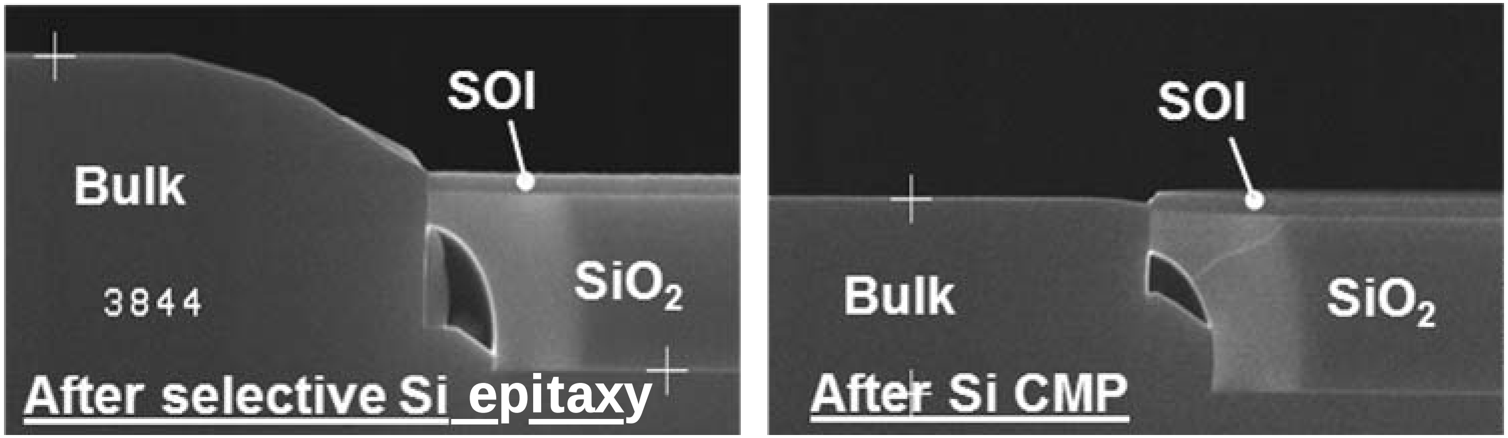
**enables integration of** best of Si-photonics **into** best Bi(CMOS)!!



# Local-SOI fabrication

- **Locally removing SOI structure by RIE / wet etch sequence**
- **Selective Si epitaxy**
- **Planarization by Si-CMP**

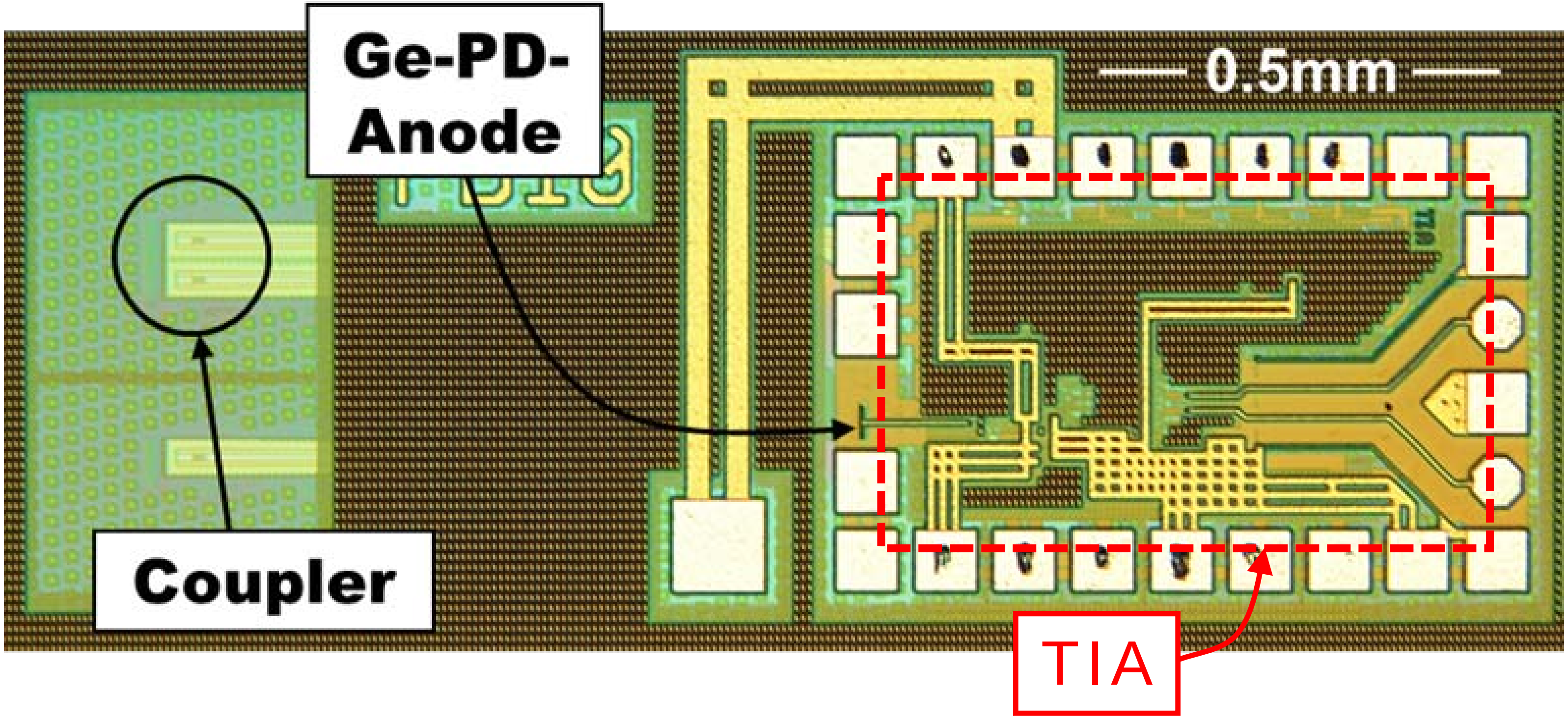
Optimizing to keep usual device yield numbers of parent BiCMOS process!!




**D. Knoll et al., ECS Transactions, 50, 9, pp. 297-303 (2012)**

# Receiver EPIC

Photonic BiCMOS (SG25H1): Receiver (Ge-PD + SiGe-TIA)




D.Knoll et al, OFC 2014

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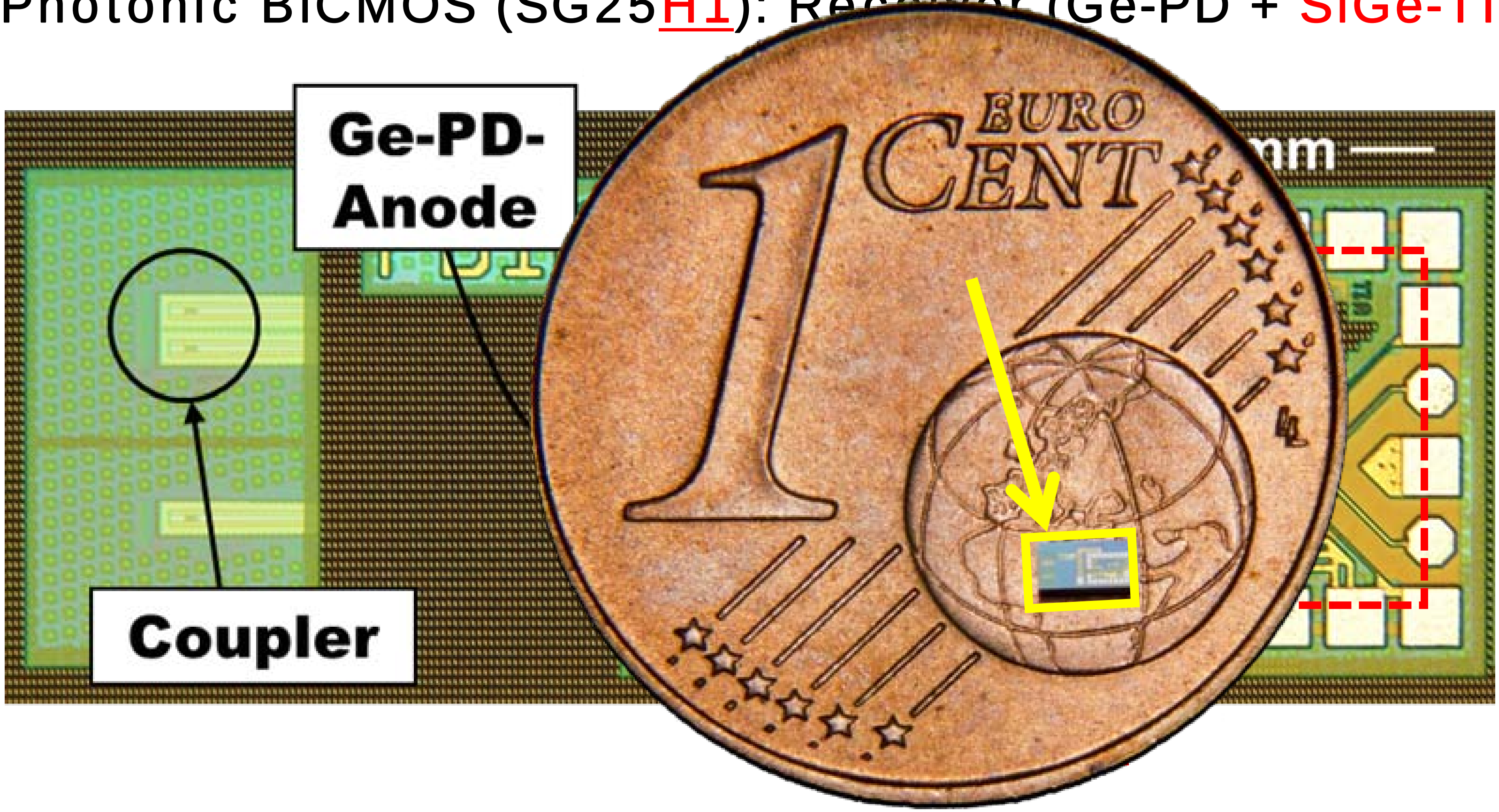
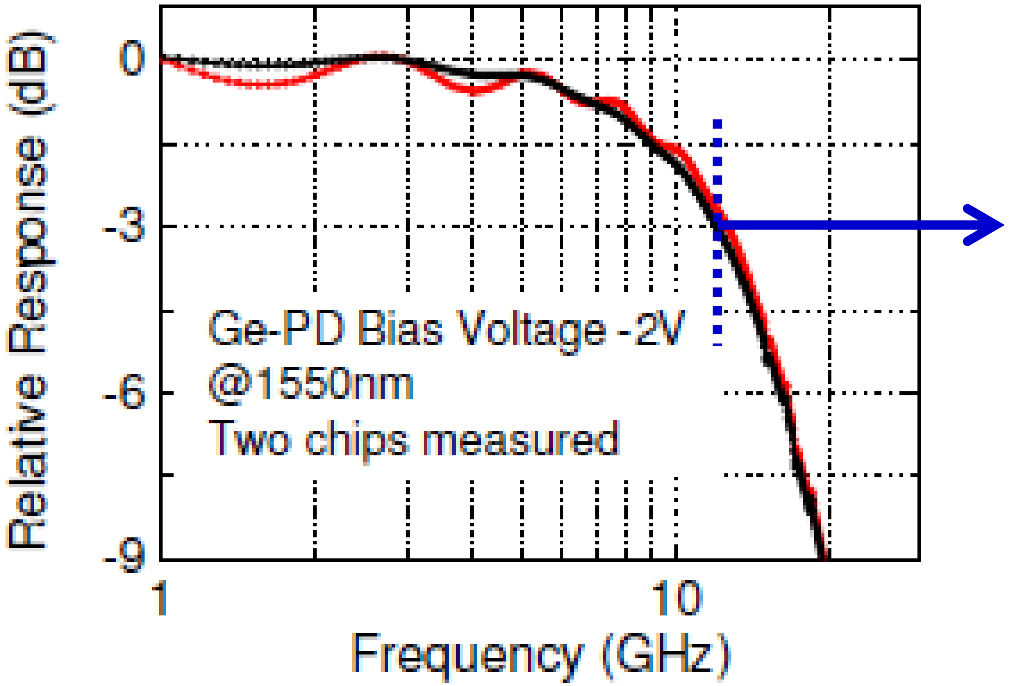



D.Knoll et al, OFC 2014

# Receiver measurement results (I)



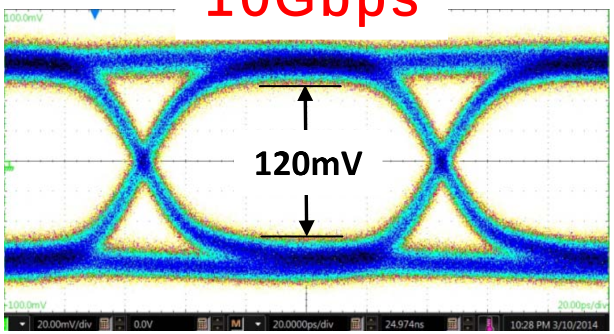

**Normalized receiver frequency response**

- **On wafer characterization**
- **Setup limitations**
  - **Incoupling angle**
  - **Incoupling power**
- **Reduced coupling efficiency**
- **12-15 GHz bandwidth**
- **fits to 20(+) Gbps functionality**

D.Knoll et al, OFC 2014

# Receiver measurement results (II)

10Gbps

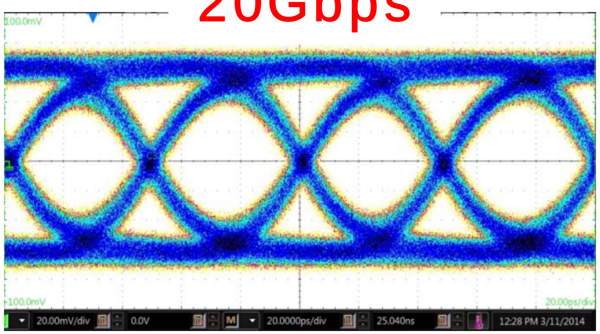



**<u>Eye diagrams for received data</u>**

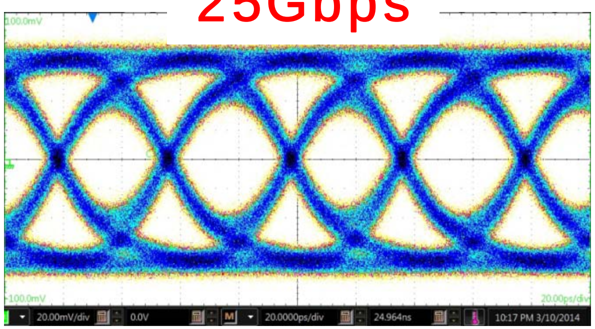
**$2^{31}$-1 PRBS word length**

**Nicely opened eye still at 25Gbps**

20Gbps



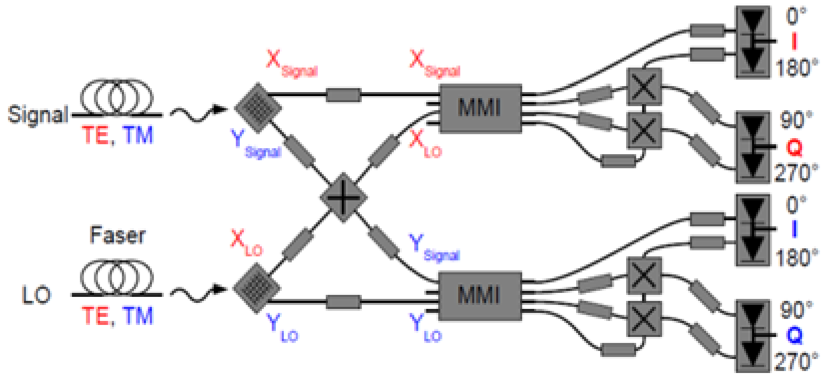
25Gbps

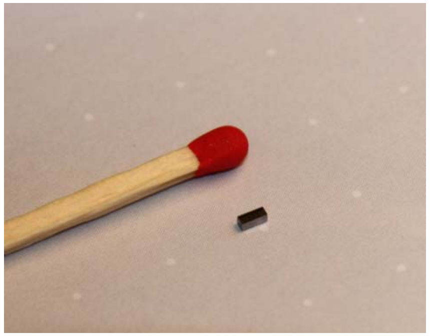


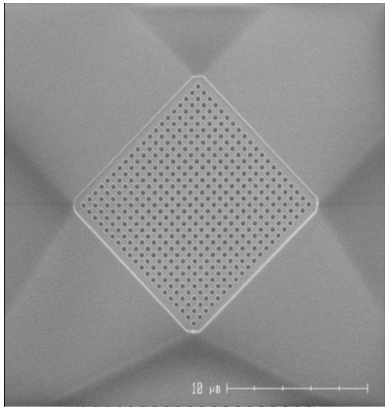
- **Sampling oscilloscope with 70 GHz sampling head**
- **Scale: vertical 20mV/division, horizontal 20ps/div**

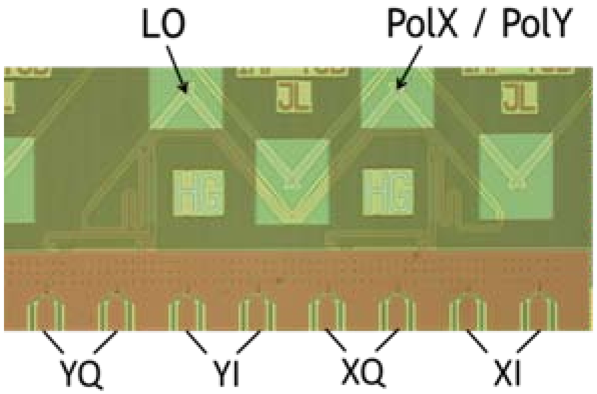
D.Knoll et al, OFC 2014

# Coherent Receiver



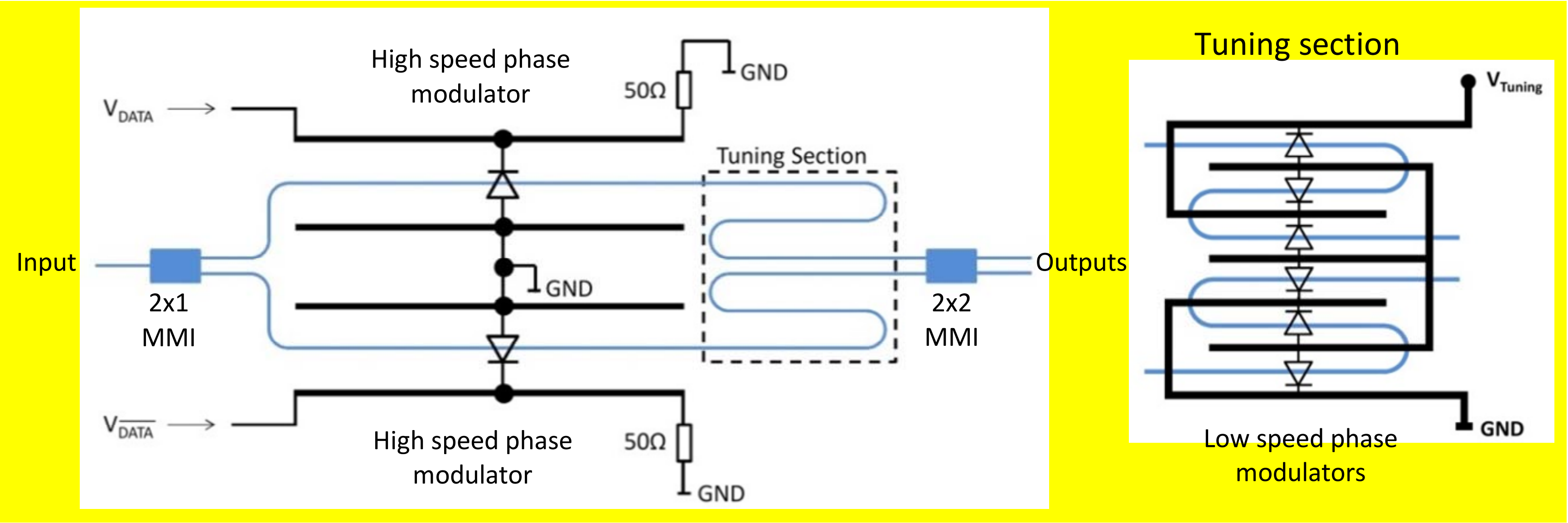





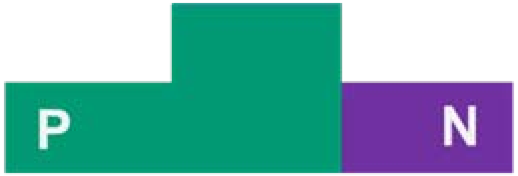



**Coherent receiver with integrated TIAs, see G.Winzer et. al. Paper M3C.4, OFC 2015, 23rd March 2015**

# Modulator with 10Gbit/sec driver



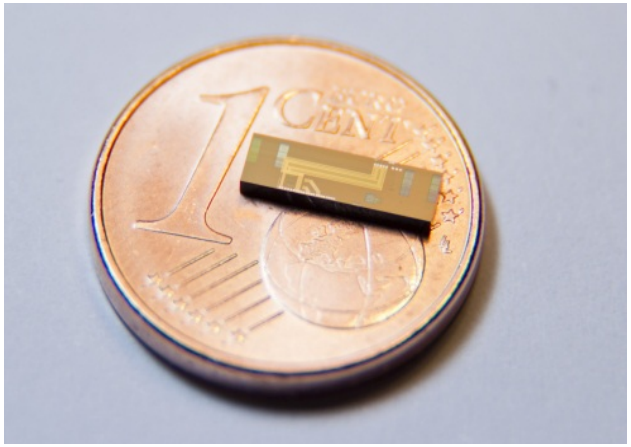

Phase shift + tuning

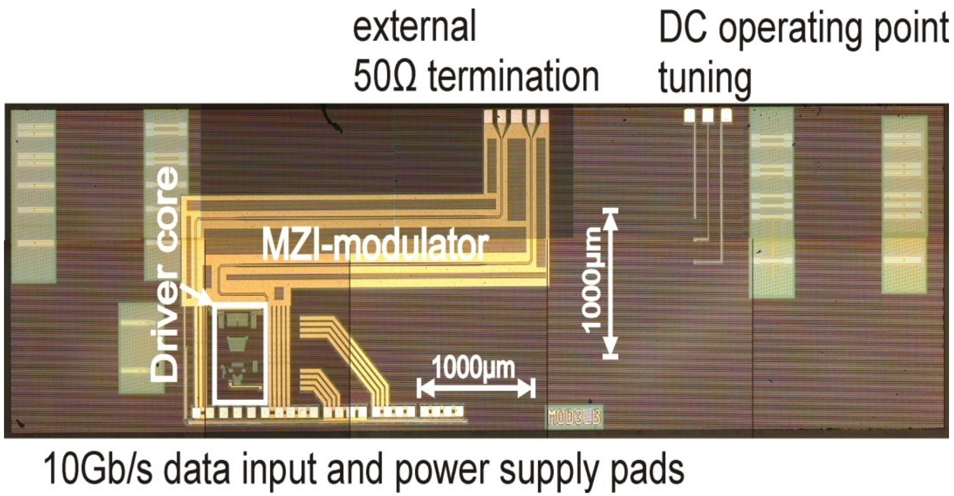


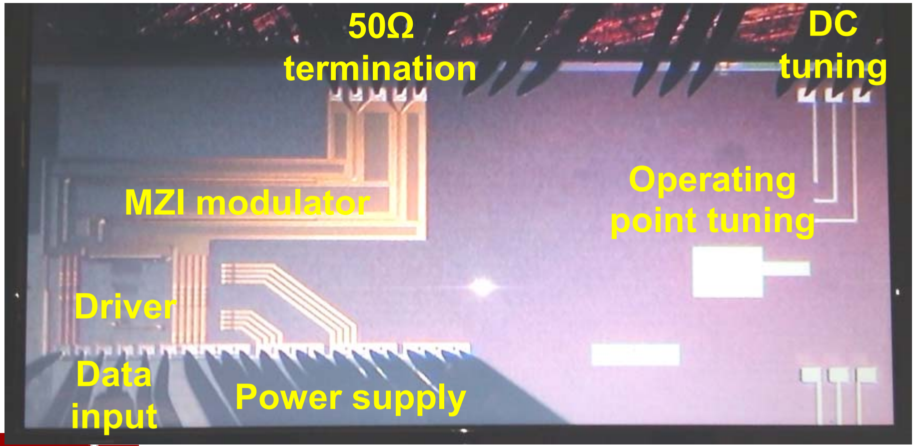

L. Zimmermann et al, ECOC 2013

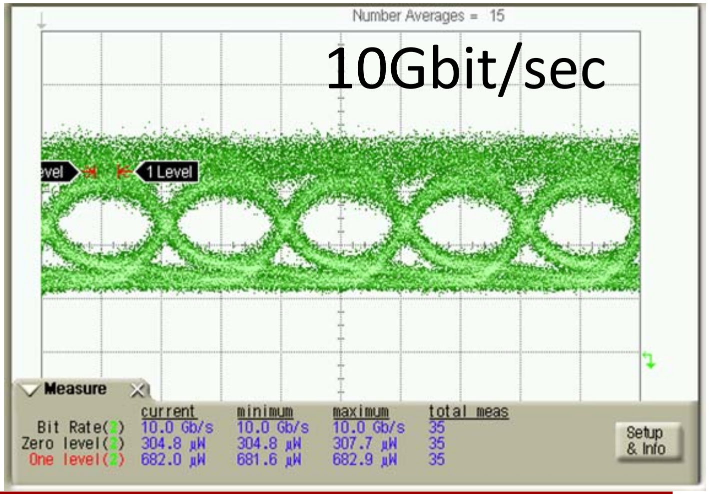
# Photonic BiCMOS: Driver + Mach-Zehnder modulator

L. Zimmermann et al, ECOC 2013





# Photonic BiCMOS

## Nonlinear Optical Signal Processing using Photonic BiCMOS Devices

# Waveguides for Kerr-related nonlinear signal processing

| Material | Nonlinear coefficient $\gamma$ [$W^{-1}m^{-1}$] | |
|---|---|---|
| HNLF | 0.02 | |
| $Si_3N_4$ | 1.4 | D.J. Moss et al.; Nature Photon.,vol.7, pp. 597-607, August 2013 |
| Chalcogenide glass | 10 | R. Neo et al.; Optics Express, vol. 21.,pp. 7926-7933, April 2013 |
| SOH (Silicon-organic-hybrid) | 100 | C. Koos et al.; Nature Photon. Vol. 3, pp. 216–219, April 2009 |
| c-Si-nanowire (crystalline) | 300 | |
| a-Si-nanowire (amorphous) | 1200 | C. Grillet et. al.; Optics Express, vol. 20,pp. 22609-22615. 2012 |

# c-Si for Kerr-related nonlinear optical signal processing

positive

- High nonlinearity $\gamma \sim 300\ W^{-1}m^{-1}$
- Low loss down to $\alpha \sim 0.3$ dB/cm
- 100m HNLF $\longleftrightarrow$ 1cm Si nanowire

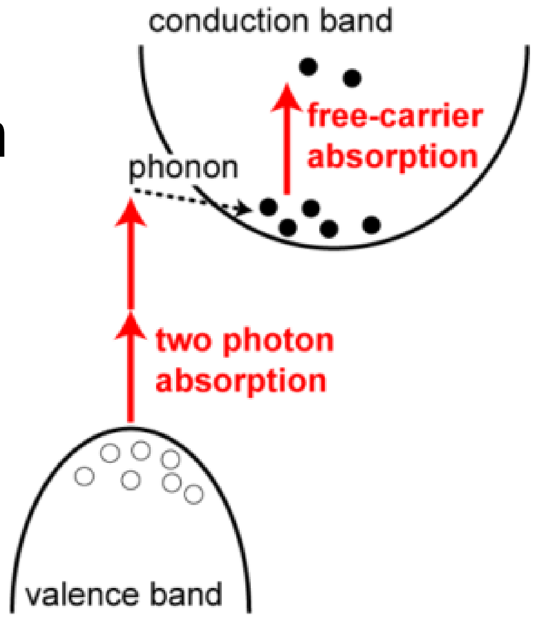
negative

- Two photon absorption $\beta_{TPA} \sim 0.5 \ldots 1\ cmGW^{-1}$
- Free carrier absorption due to TPA

# Nonlinear loss mechanisms in silicon

## Operation at telecom wavelengths ~ 1.55 µm

- Two-photon absorption (TPA), $\lambda < 2.12$ µm
- Free carrier absorption (FCA)
- Free carrier induced index change (FCI)



# Limitations due to Two-Photon-Absorption

For telecom wavelengths @ 1.55 µm

- Absorption $\alpha_{TPA} = \beta_{TPA} P / A_{eff}$ due to $\beta_{TPA}$ negligible up to ~ 100 mW pump power
- Removal of free carriers essential (otherwise only pulsed operation)

Maximum nonlinear phase shift @ 1.55 µm

$$\phi_{NL} = \gamma P L_{eff} < \gamma P / \alpha_{TPA} = \phi_{NL,max}$$

$$\phi_{NL,max} = A_{eff} \gamma / \beta_{TPA} = 2\pi \text{ FOM} \sim 3 \text{ rad}$$

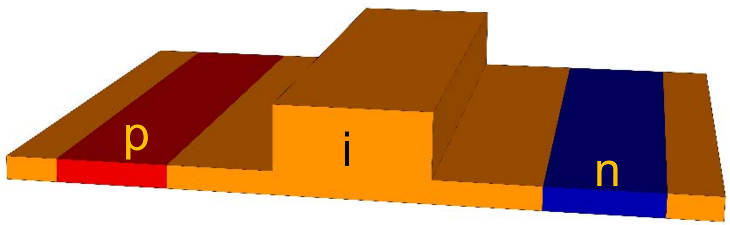
allowing for maximum parametric gain ~ 5 dB

- **<u>Several optical nonlinear effects in SOI waveguides were observed:</u>**
  - Four Wave Mixing (FWM)[1,2,3,4,5]
  - Self Phase Modulation (SPM)[6]
  - Cross Phase Modulation (XPM)[6]
  - Spontaneous and Stimulated Raman Scattering (SRS)[7,8]

- **<u>Applications utilizing nonlinear effects:</u>**
  - Amplification of light
  - Optical signal processing, e.g. wavelength conversion

[1] *Y. H. Kuo et al., Opt. Express 14, 2006*
[2] *W. Mathlouthi et al., Opt. Express 16, 2008*
[3] *M.A.Foster et al., Opt. Express 15, 2007*
[4] *A. C. Turner-Foster et al., Opt. Express 18, 2010*
[5] *J. R. Ong et al., IEEE PTL. 25, 1699-1701 (2013)*
[6] *Q. Lin et al., Opt. Express 15, 2007*
[7] *R. Claps et al., Opt.Express 11, 2003*
[8] *M. Krause et al., Opt. Express.*12, 2004

# Silicon waveguides with reverse biased p-i-n junction



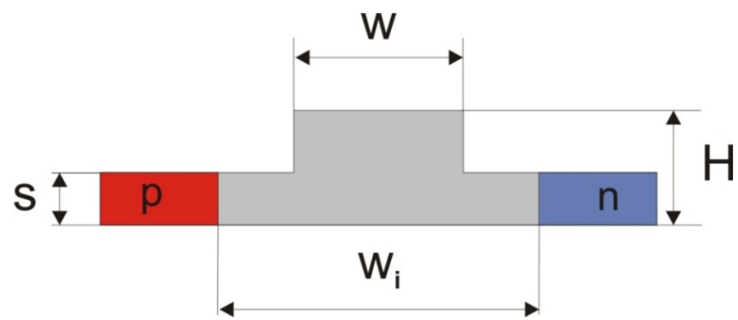

p-i-n junction across the nonlinear silicon waveguide

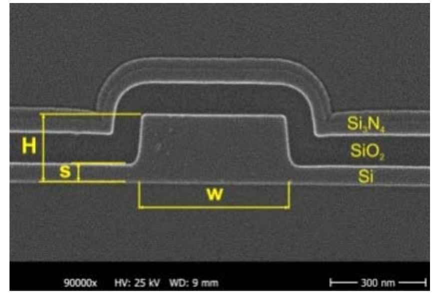
- Sweep the carriers generated by two-photon absorption
- Reduce effective carriers lifetime down to 10... 20 ps

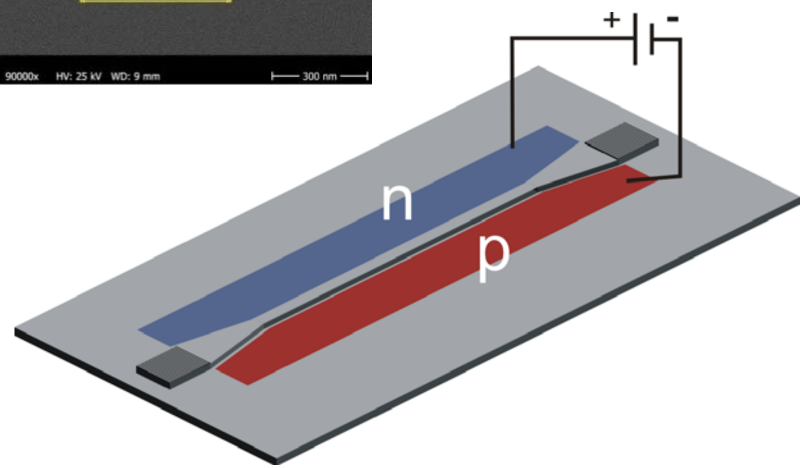
$\Rightarrow$ limits the impact of free-carrier absorption

Y.H. Kuo et. al., Opt. Express 14 (2006) 11721 - 11726.
W. Mathlouthi et al., Opt. Express 18 (2008) 16735 - 16745.
J. R. Ong et al., IEEE Photon. Technol. Lett. 25 (2013) 1699 - 1702.

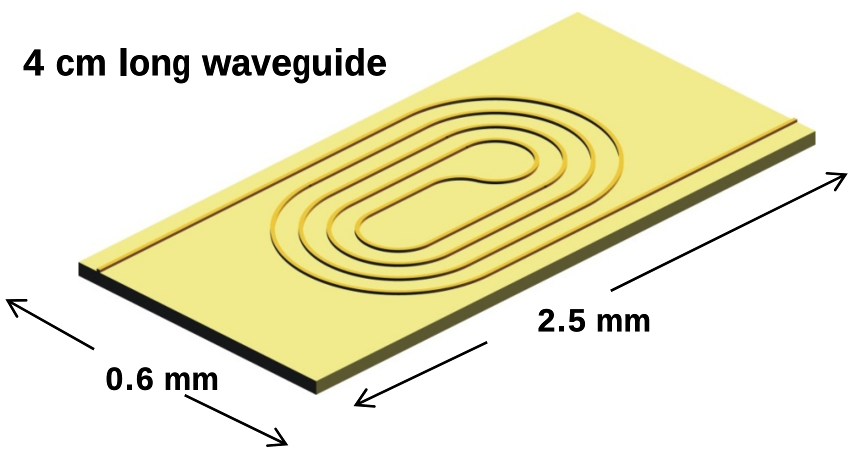
# Structure geometry



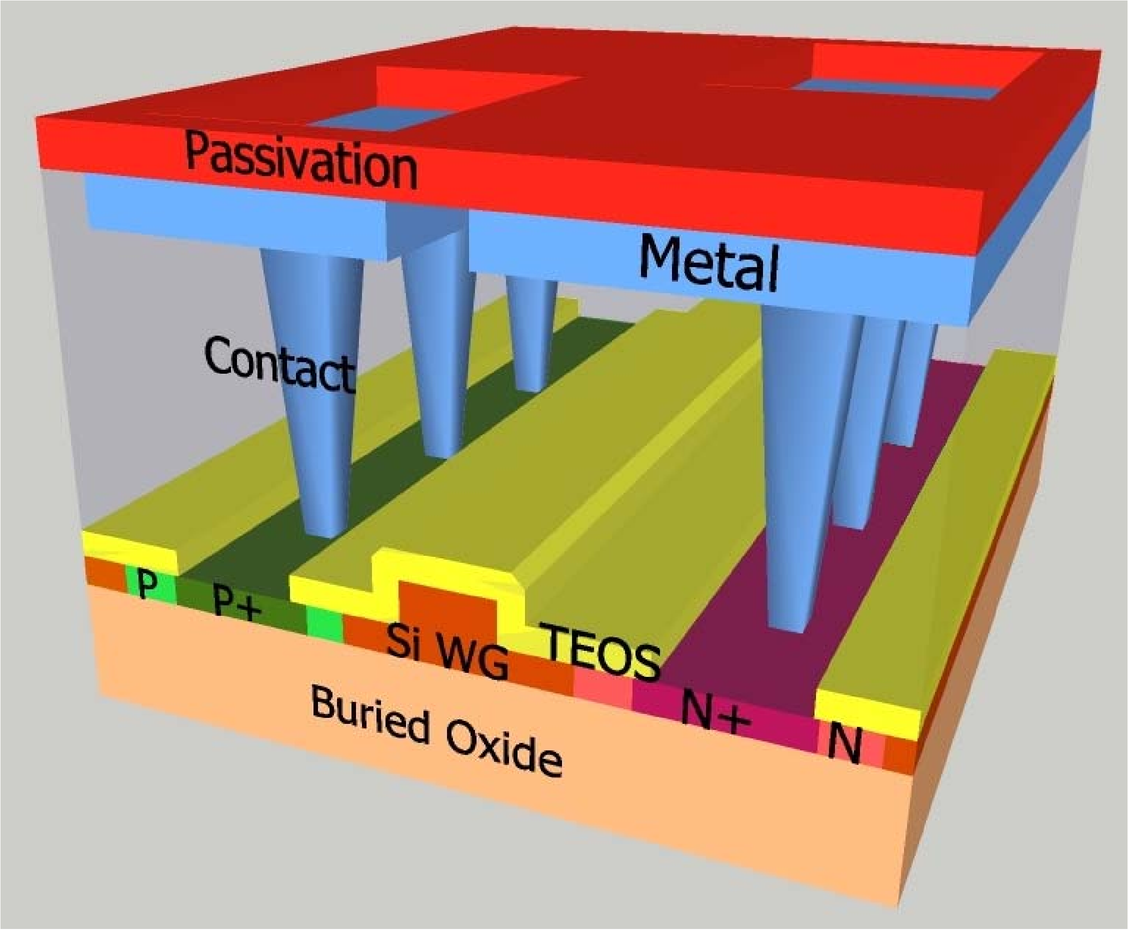




**4 cm long waveguide**



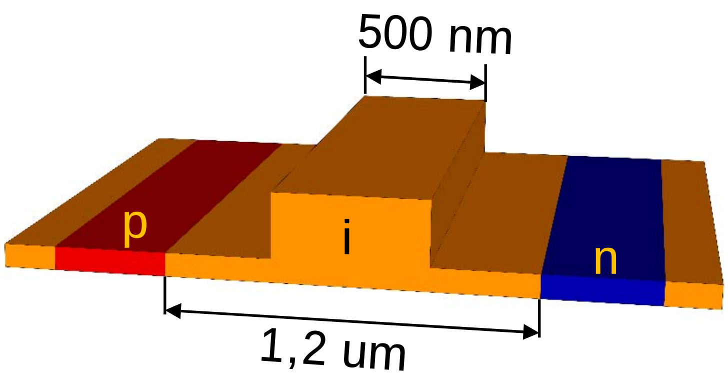

| Parameter | Deep etched waveguide |
|---|---|
| W x H x s [nm] | 500 x 220 x 50 |
| $w_i$ [nm] | 1200 |

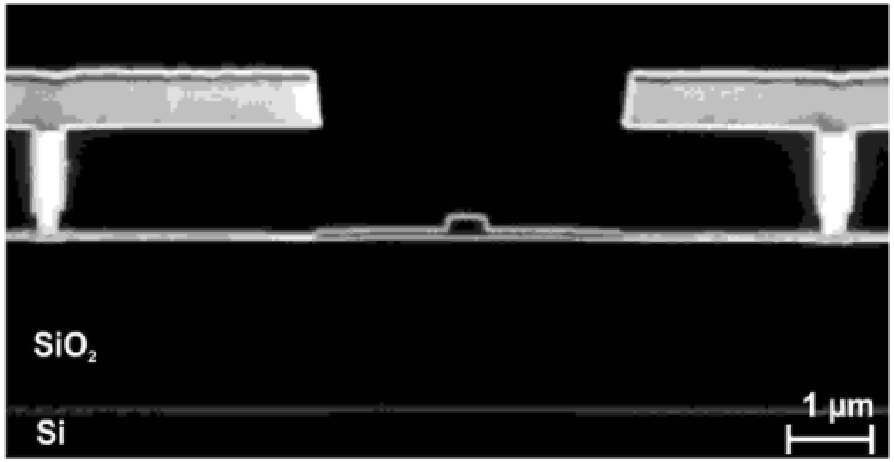
# Waveguide technology cross section



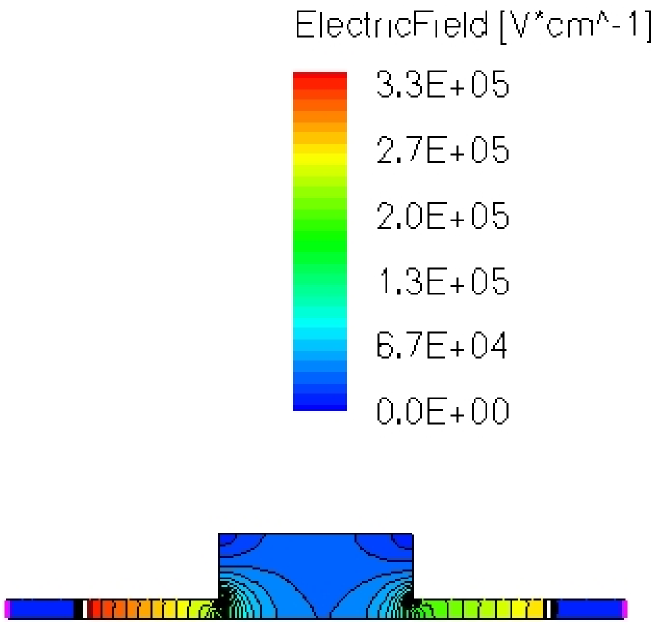
# Fabrication

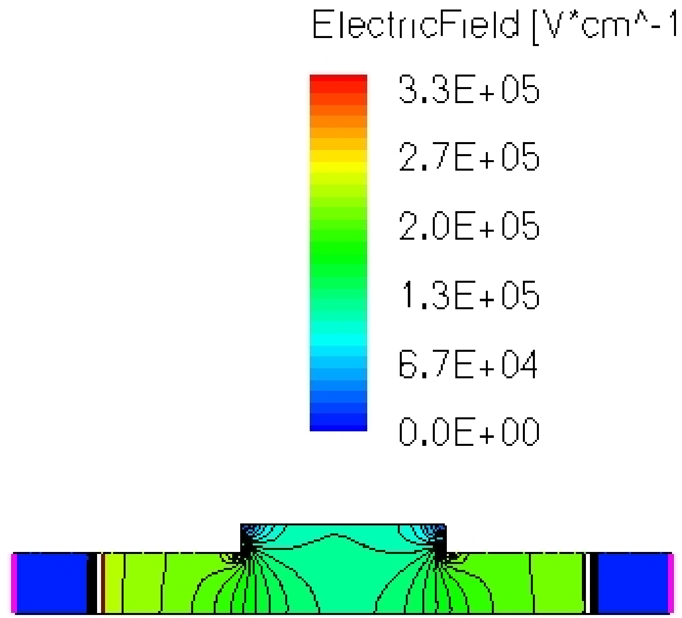
- Used technology : BiCMOS (IHP Frankfurt (Oder))
- 8” SOI wafers, 220 nm top Si layer and 2 μm buried oxide (BOX)
- Linear loss lower than 1 dB/cm for waveguides with 50 nm slab and p-i-n diode
- Doping level in p and n regions of $10^{17}$ $cm^{-3}$



# Electric field distribution

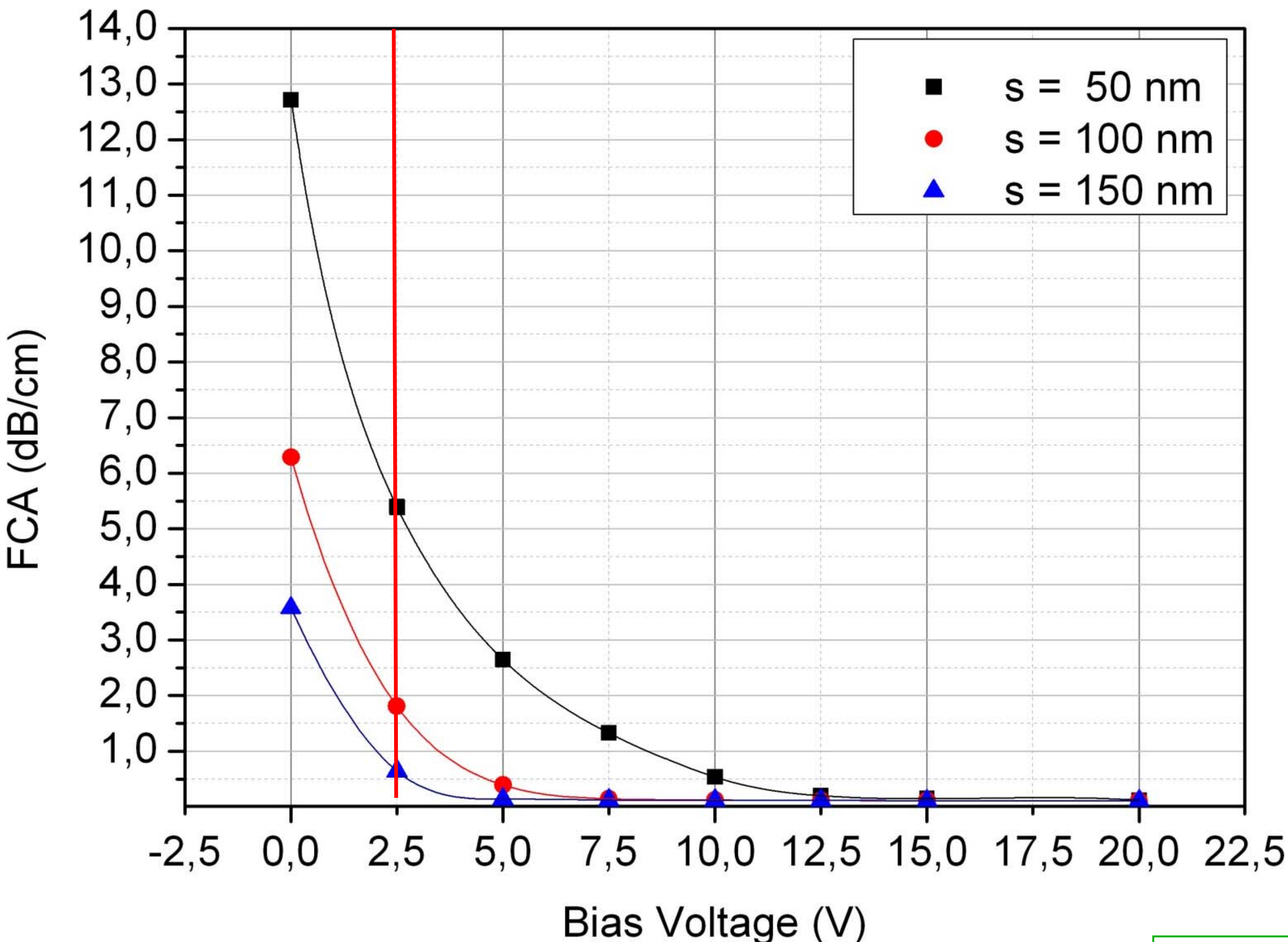



**Shallow rib allows for higher field in the waveguide region**

*A. Gajda et al., Opt. Express, vol. 19, pp. 9915 – 9922, May 2011*

# FCA vs Bias voltage for different slab heights




**Shallower etch**

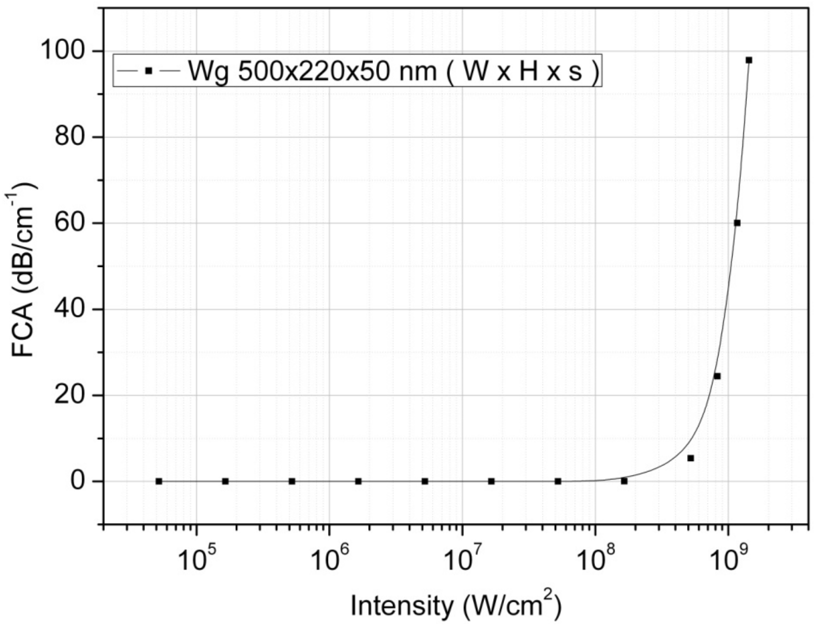
**⇒**

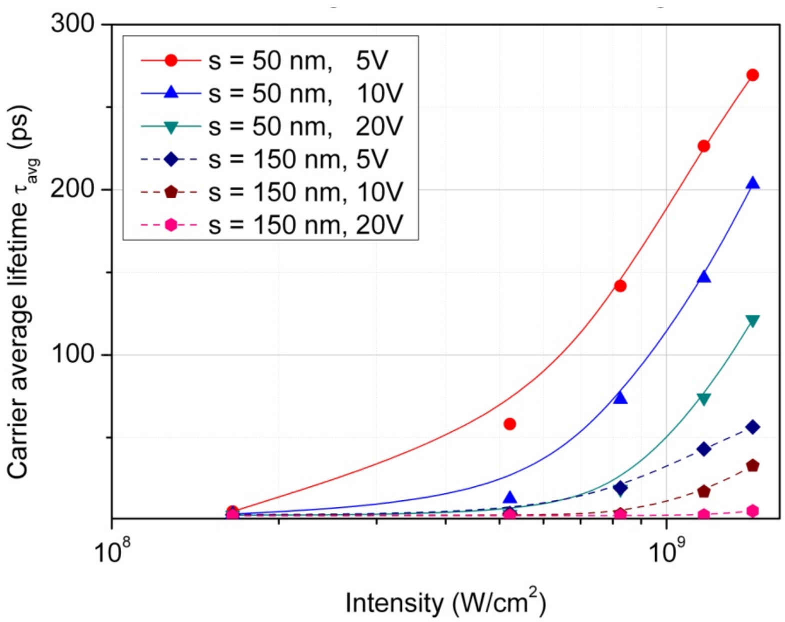
**Lower loss**

*A. Gajda et al., Opt. Express, vol. 19, pp. 9915 – 9922, May 2011*

Intensity 1.65 $10^8$ W/$cm^2$
$w_i$ = 1200 nm

# Carriers screening effect simulation

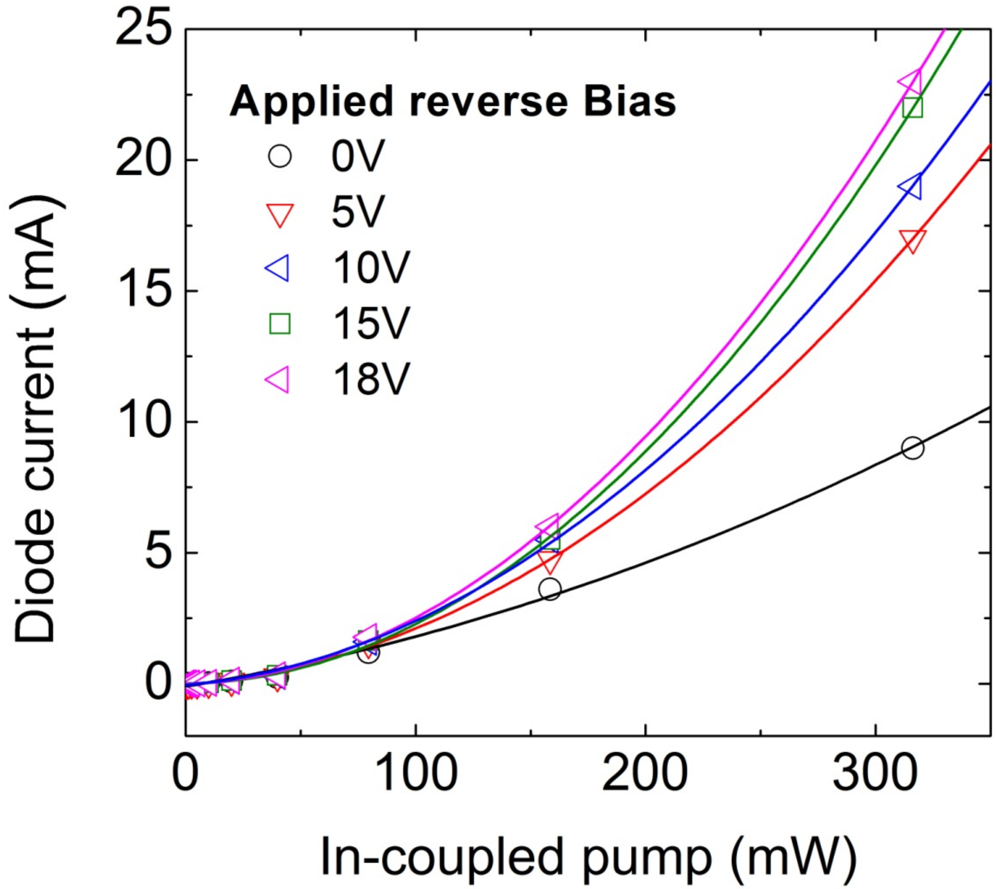



✓ **shallower etch depth ⇒ higher carrier screening threshold**

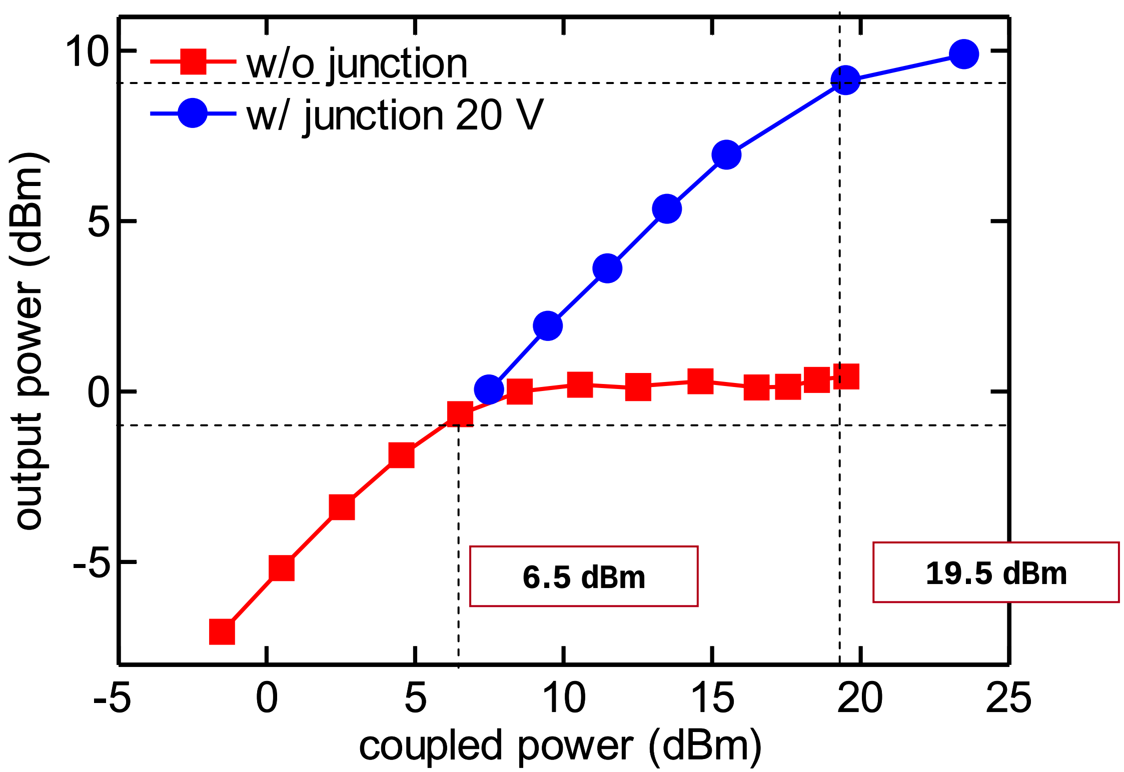
*A. Gajda et al., Opt. Express, vol. 19, pp. 9915 – 9922, May 2011*

# Photo current due to TPA with reversed pin junction

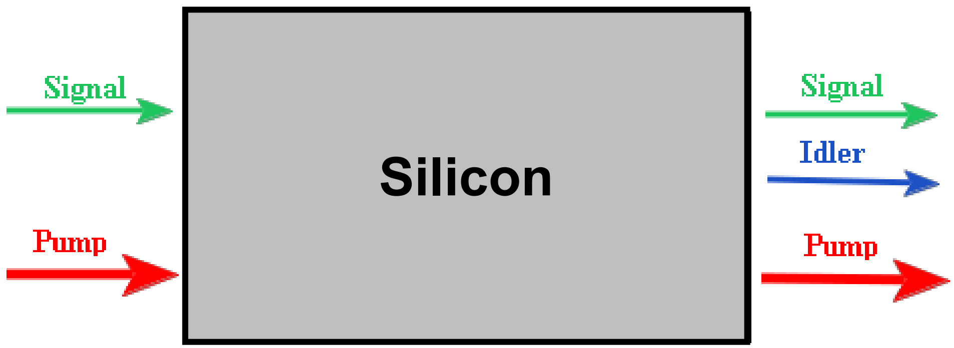


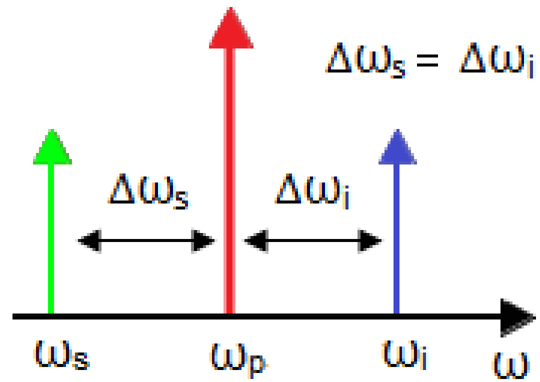

*H. Tian et al., JEOS:RP, Aug. 2012*

# Free carrier absorption threshold



# Four-wave mixing in silicon




$$2\omega_p = \omega_s + \omega_i$$

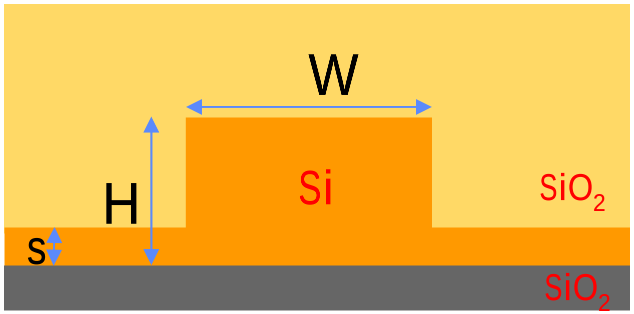
**Phase matching κ=0 required**

⇨ **$\beta_2$ < 0 (anomalous dispersion) corresponds to dτ/dλ > 0**

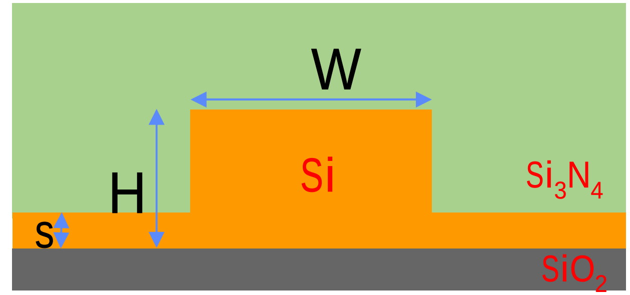
$$\kappa = \Delta k_L + \Delta k_{NL} \approx \beta_2 \left(\omega_s - \omega_p\right)^2 + 2\gamma P_p$$

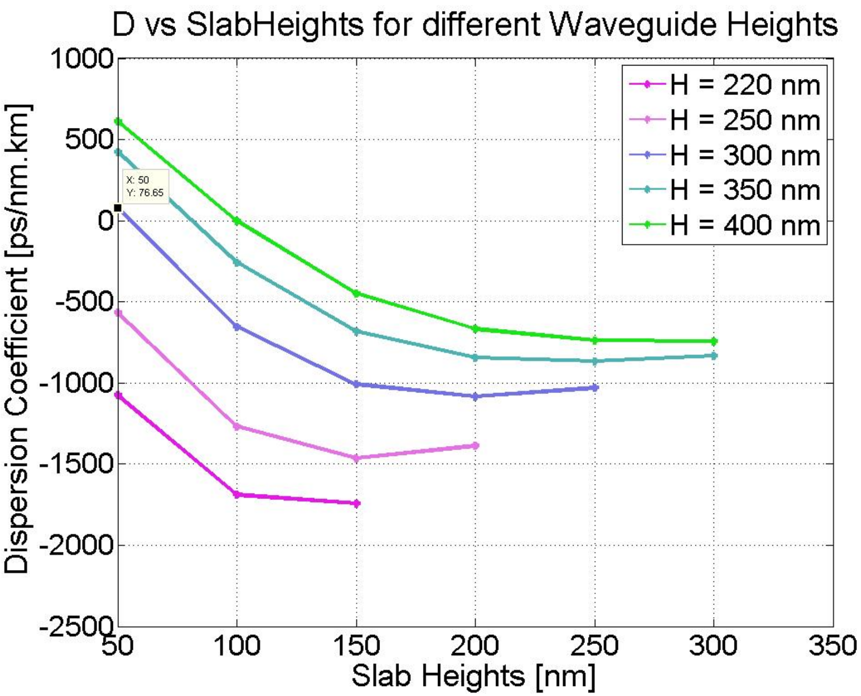
# Chromatic Dispersion

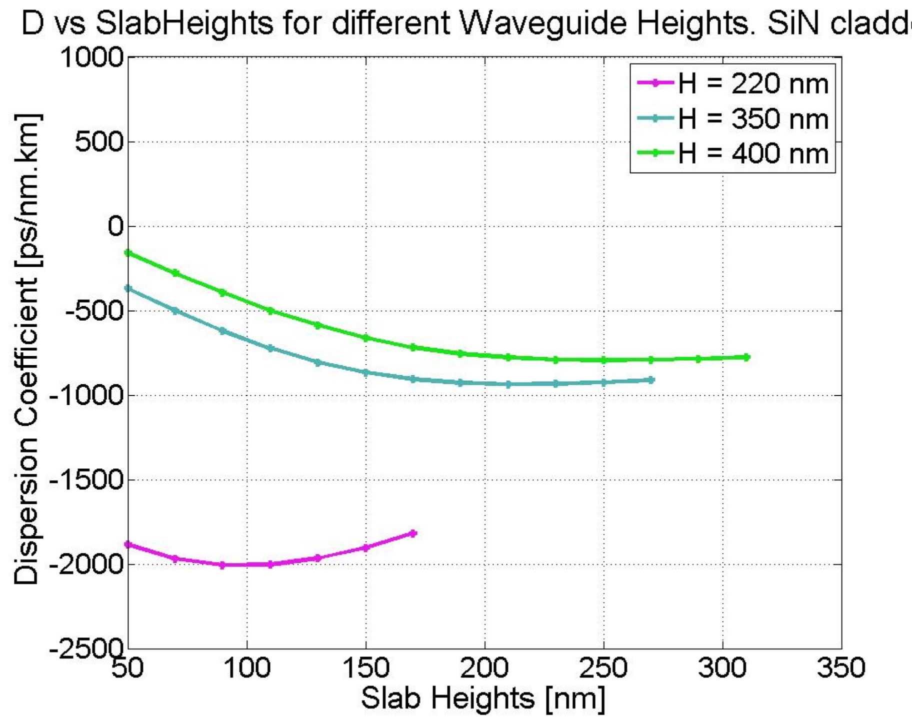
## $SiO_2$ cladding




## $Si_3N_4$ cladding




→ **Anomalous dispersion, requirements: high H, low s, $SiO_2$ cladding**

# Silicon waveguides - optical properties

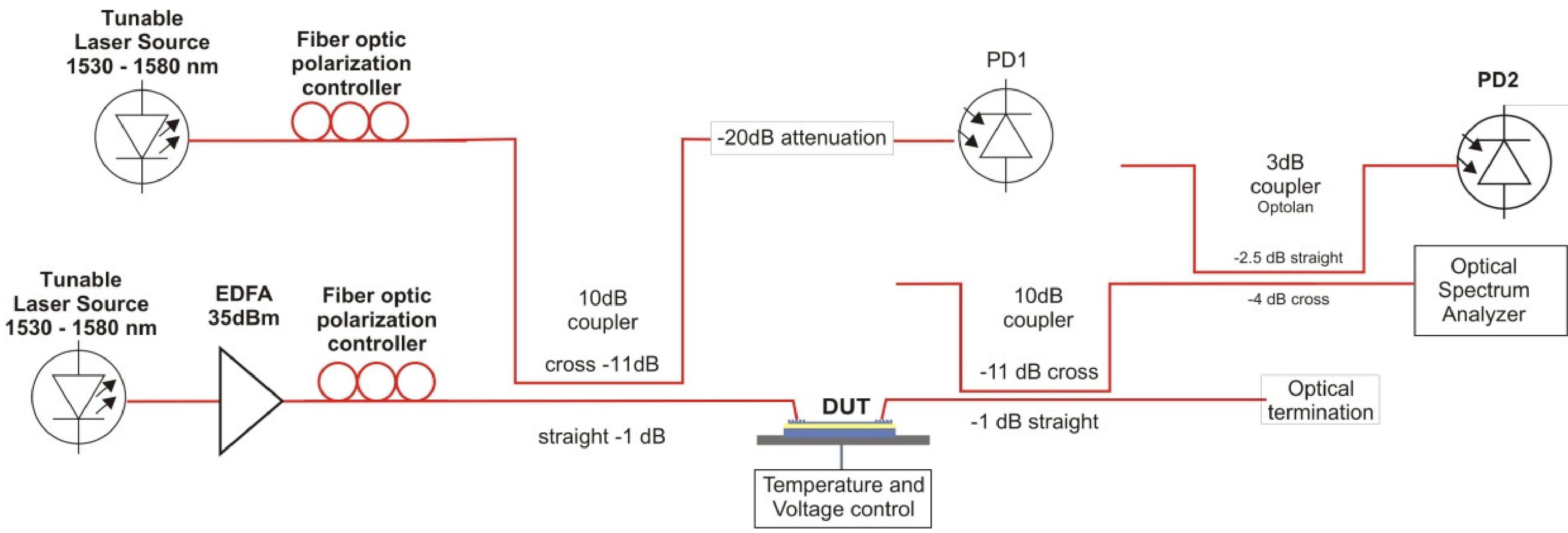
| Quantity | Value | Unit |
|---|---|---|
| Length | 4 | cm |
| Loss | 1 | dB/cm |
| TPA coeff. | 0.5 | cm/GW |
| Nonlinear coeff. | 280 | $W^{-1} \cdot m^{-1}$ |
| Coupling loss* | 4.5 | dB/facet |
| Chromatic dispersion | - 2450 | ps $km^{-1} \cdot nm^{-1}$ |

← **Wrong sign**

*1D grating couplers with 35 nm bandwidth

Waveguide parameters not yet optimum for optical signal processing

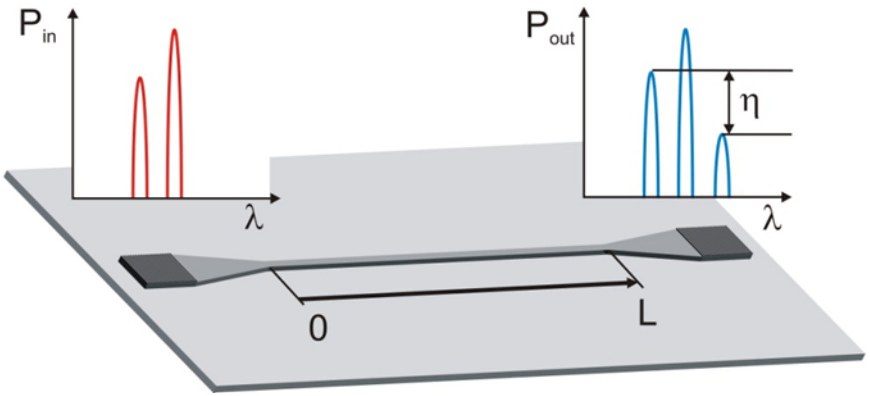
# Four Wave Mixing measurement setup



# Conversion efficiency

- Signal output to Idler output ratio

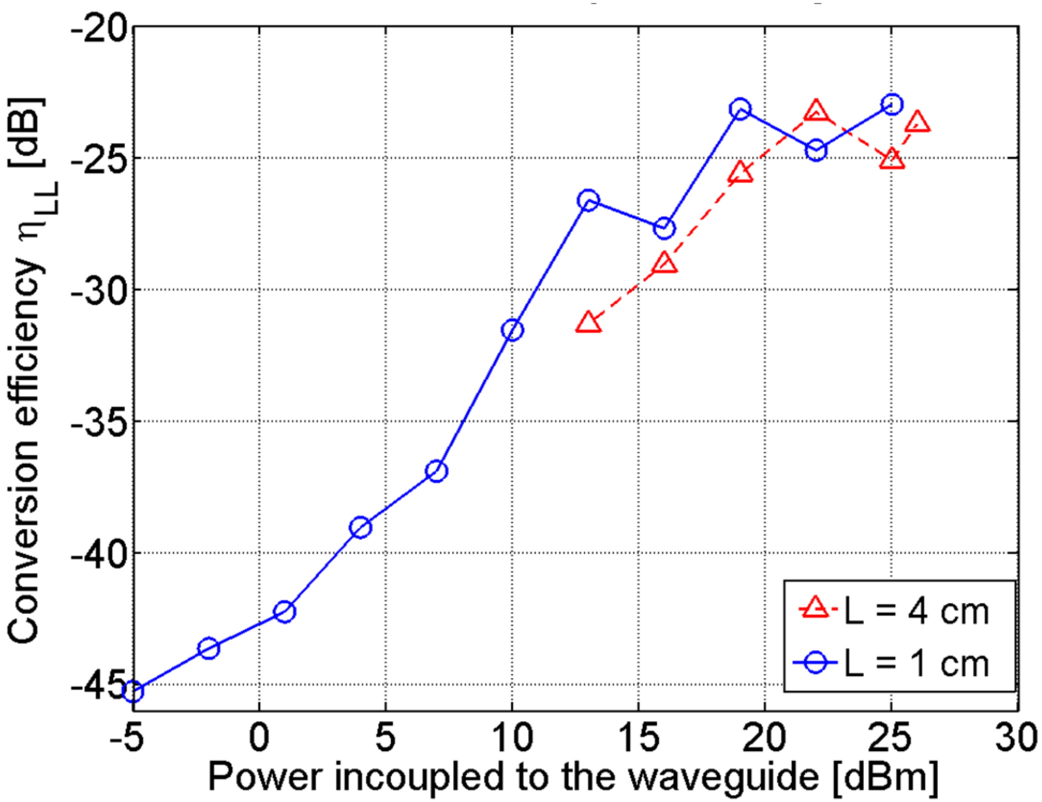
$$\eta = \frac{P_{idler}(L)}{P_{signal}(L)} \quad (**)$$




- used in experimental work (**)
  - easy to measure (using Optical Spectrum Analyzer)

(**) *Y. Kuo et al. Opt. Express 14, 11721-11726 (2006)*

# Waveguides without p-i-n




Pump wavelength $\lambda_{pump}$= 1552.5 nm

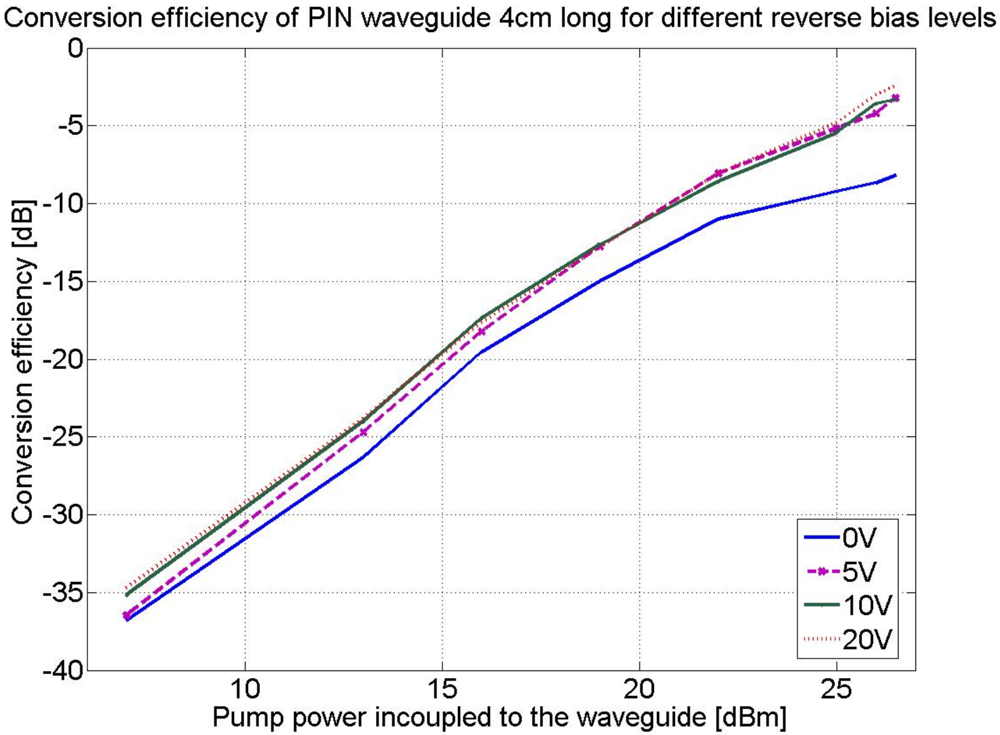
Signal wavelength $\lambda_{signal}$ = 1550.0 nm

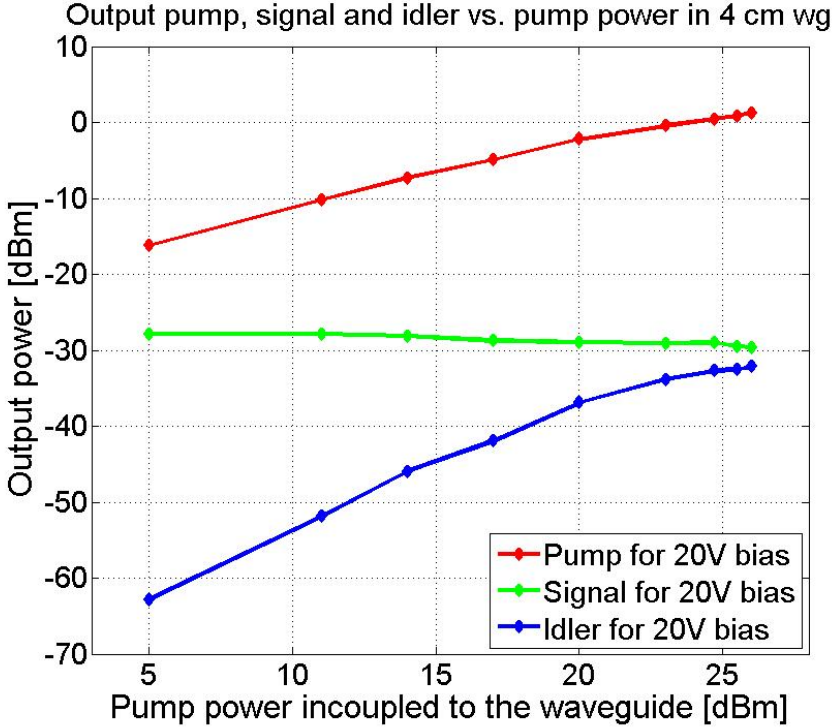
Maximum efficiency -23 dB @ $P_{pump}$ = 26 dBm

Waveguide lengths L = 1cm and L = 4 cm

*A. Gajda et al., Opt. Express, vol. 20, pp. 13100 – 13107, June 2012*

# FWM in p-i-n diode assisted waveguide




Pump wavelength $\lambda_{pump}$= 1552.5 nm

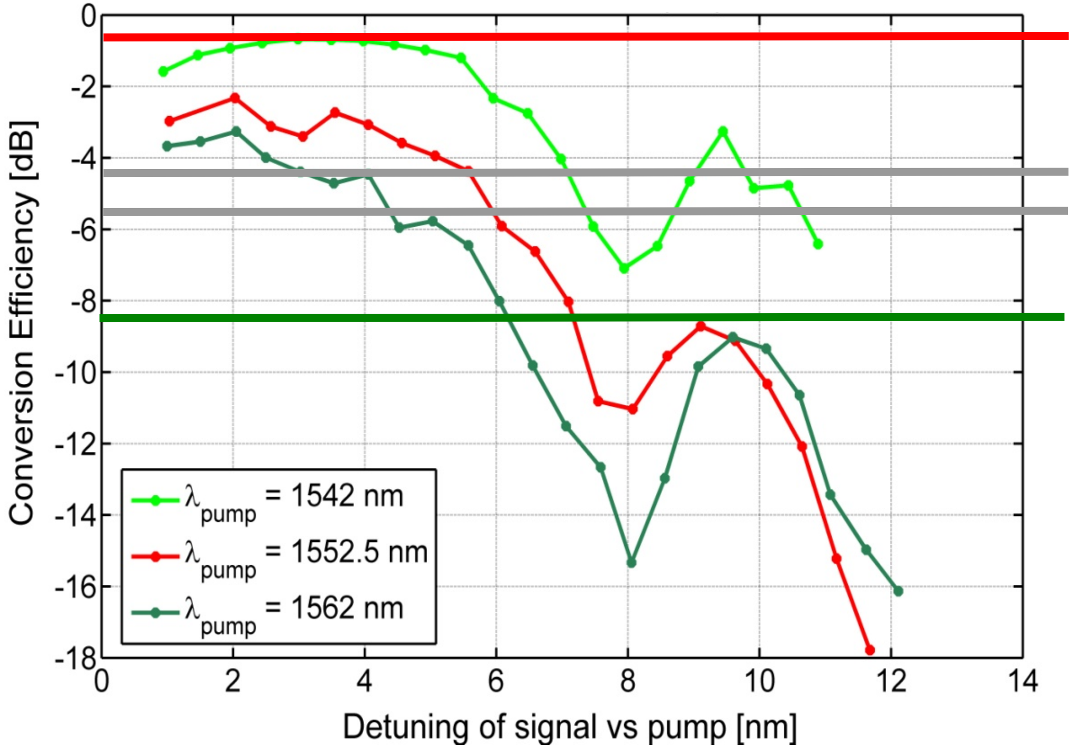
Signal wavelength $\lambda_{signal}$ = 1550.0 nm

Conversion efficiency $\eta_{max}$ ~-2 dB @ $P_{pump}$= 26 dBm

Waveguide length L = 4 cm

*A. Gajda et al., Opt. Express, vol. 20, pp. 13100 – 13107, June 2012*

# Wavelength conversion vs. detuning for different pump wavelengths

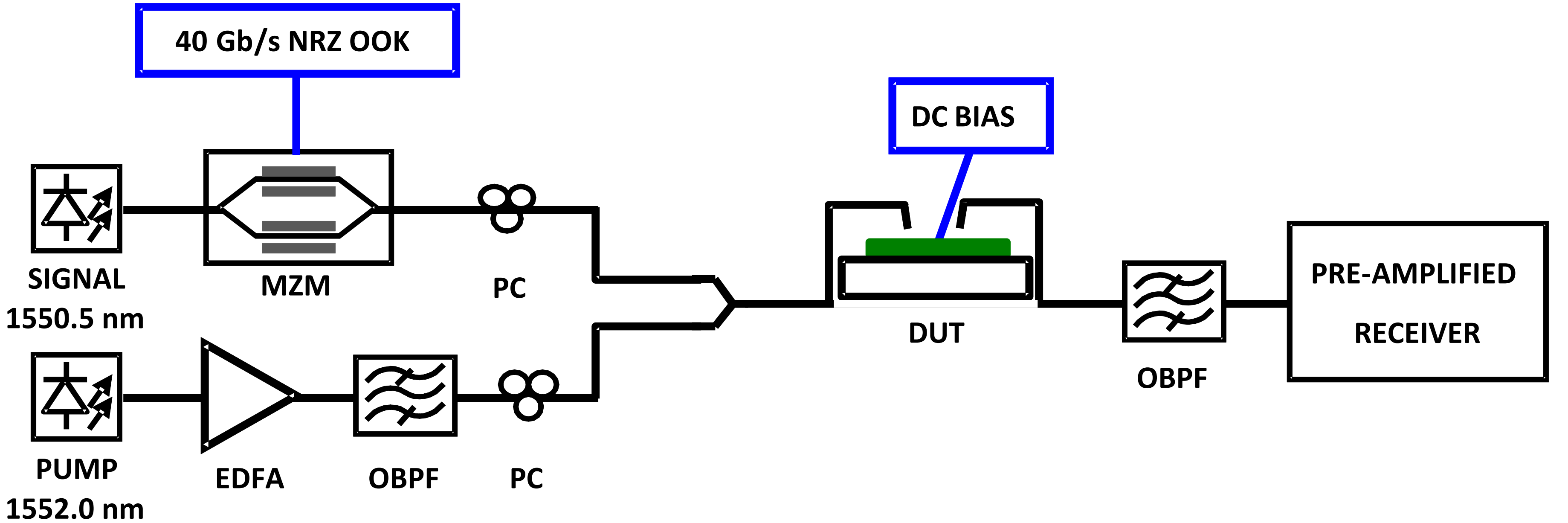



Fraunhofer
Heinrich Hertz Institute

Waveguide length L = 4 cm
Bias voltage: $U_{bias}$ = 20 V
Pump power $P_{pump}$ = 26 dBm
**Maximum efficiency $\eta_{max}(\lambda_{pump}$=1542nm, $\Delta\lambda$=3nm)=-0.7 dB**

*A. Gajda et al., Opt. Express, vol. 20, pp. 13100 – 13107, June 2012*

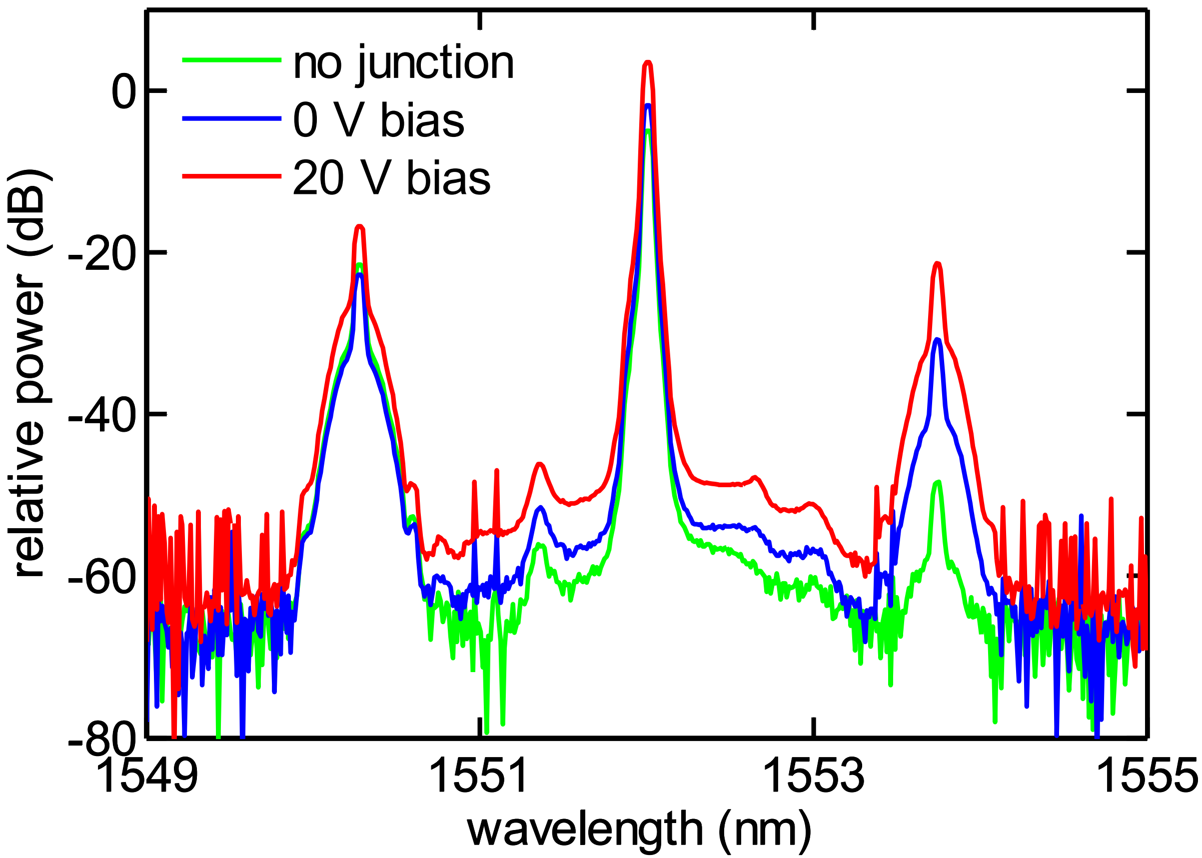
# Bit Error Rate (BER) Measurement setup




Pump power in the waveguide : 20 dBm
Signal power in the waveguide :0 dBm

*A. Gajda et al., Group IV Photonics 2013*

# Wavelength converter output spectra

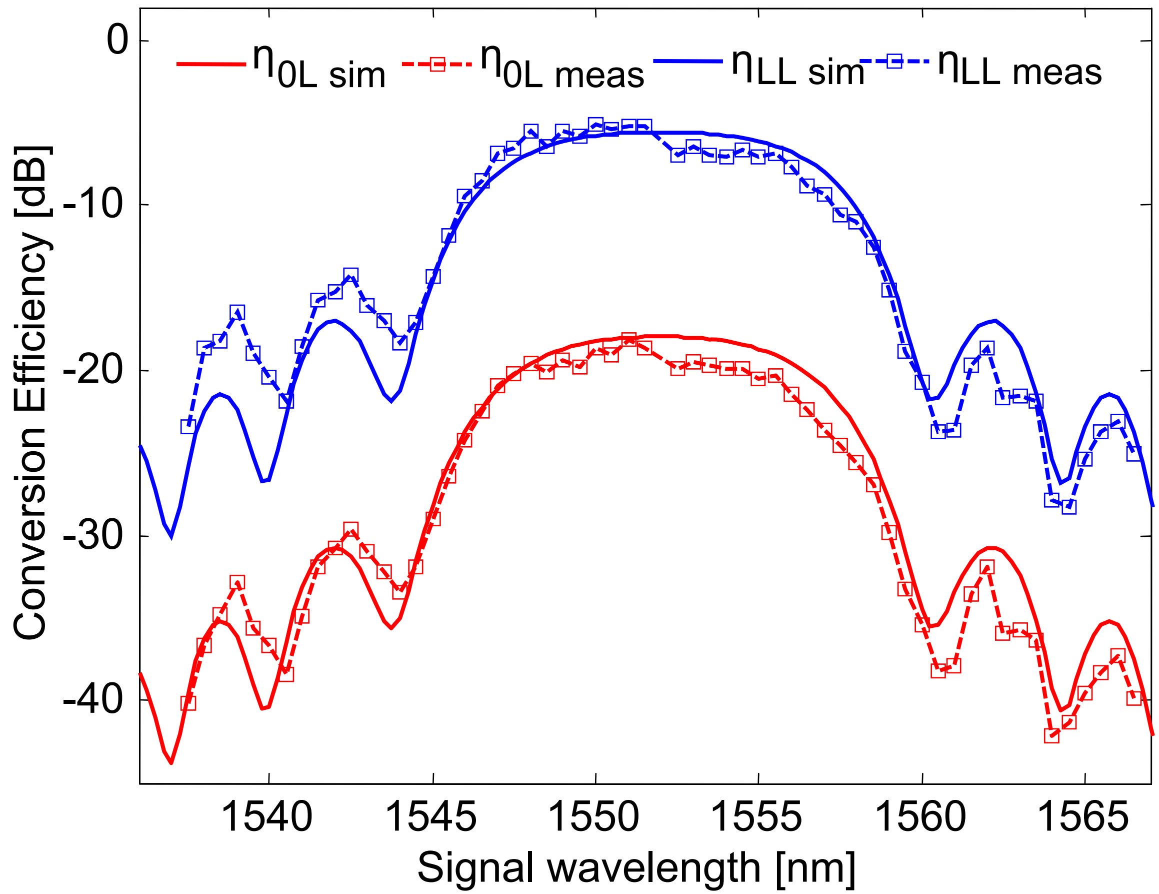



| Bias (V) | CE (dB) |
|---|---|
| no junction | -26.9 |
| 0 | -8 |
| 20 | -4.6 |

*A. Gajda et al., Group IV Photonics 2013*

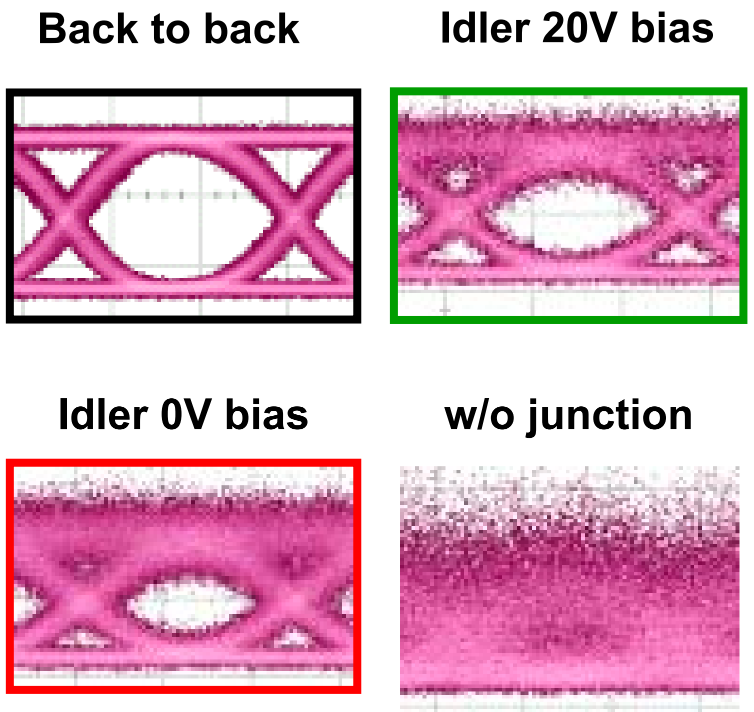
# Measured bandwidth of FWM

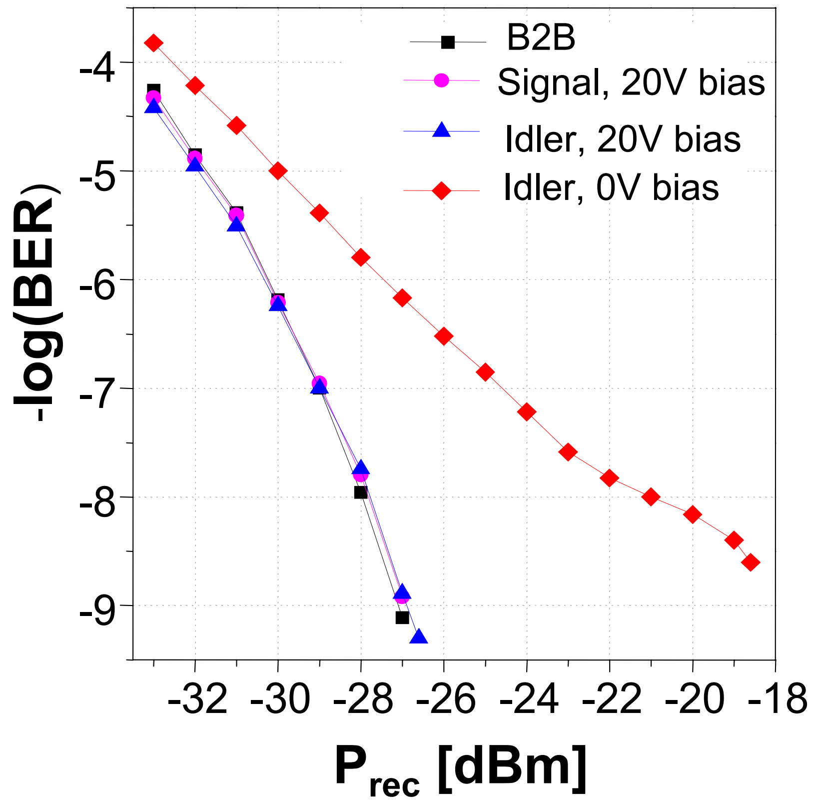
- 3 dB bandwidth of 10 nm
- Estimated dispersion of the waveguide D = -2450 ps/nm·km
- $\eta_{0L}$ contains incoupling loss of 4 dB per coupler




*A. Gajda et al., Group IV Photonics 2013*

# Bit-Error Rate measurement



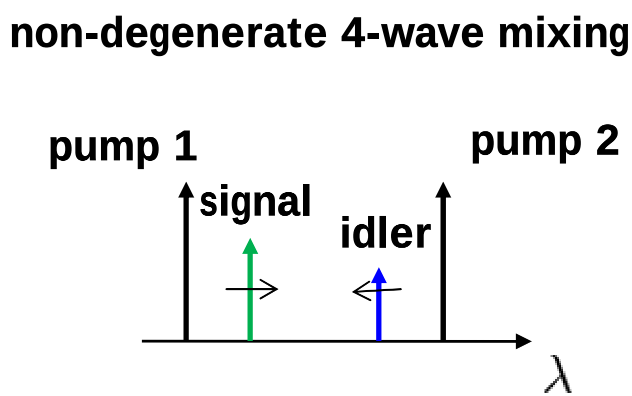

The power penalty of 0.2 dB for idler in the 20V bias case

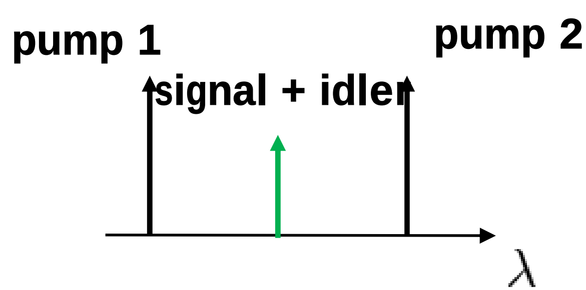
*A. Gajda et al., Group IV Photonics 2013*

# Phase-sensitive Signal Processing

# Four – wave mixing ($\chi^{(3)}$)

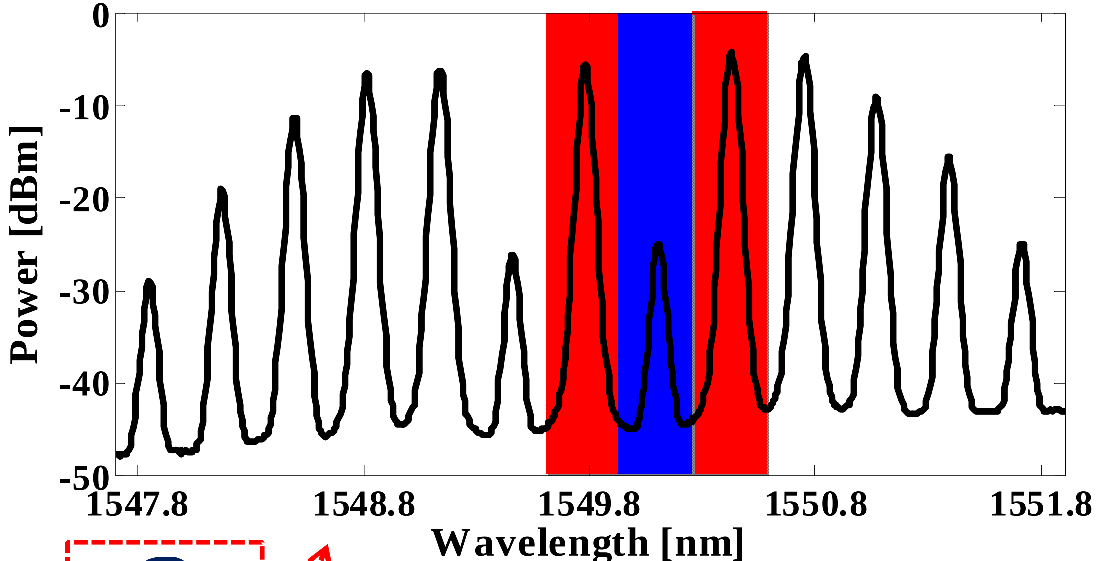
## Phase - sensitive parametric processing (one mode PSA)

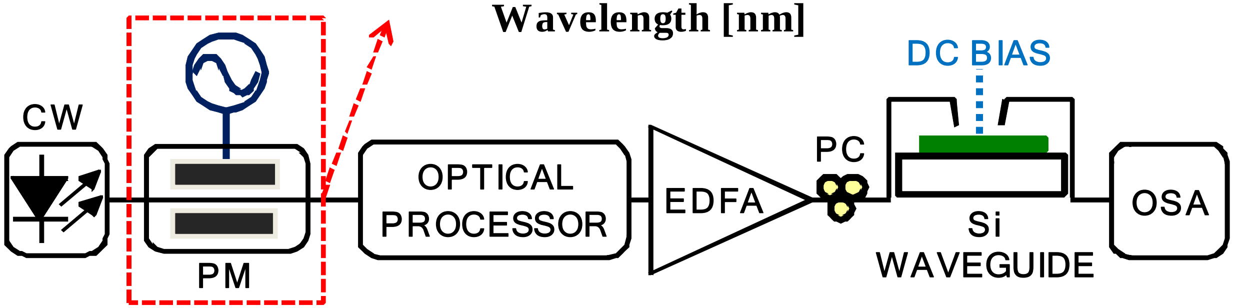



⇨ **Processing of the signal becomes phase - sensitive**

# Phase sensitive amplification - set up

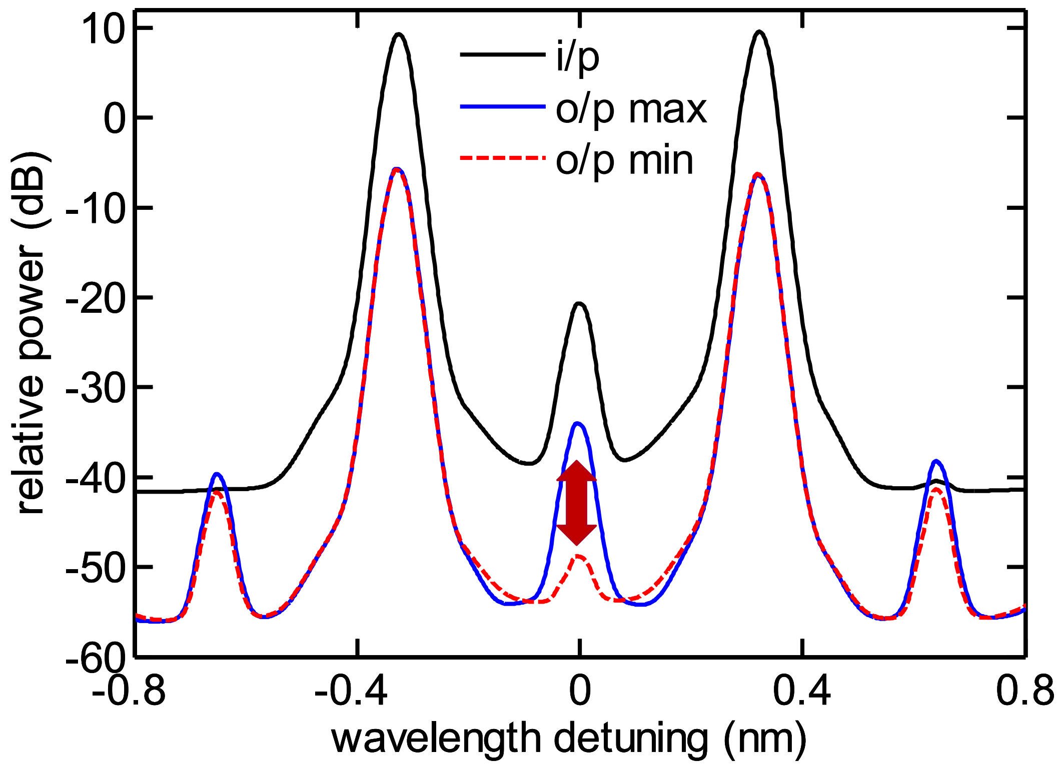



DTU

*F. Da Ros et al., ECOC 2013*

# Evidence of phase-sensitivity in Si




- 28 dBm total power
- pump-to-signal power ratio: 30 dB
- L= 4 cm
- Reverse bias: 25 V
- Signal phase shift:

$$\Phi_s = 30^\circ$$

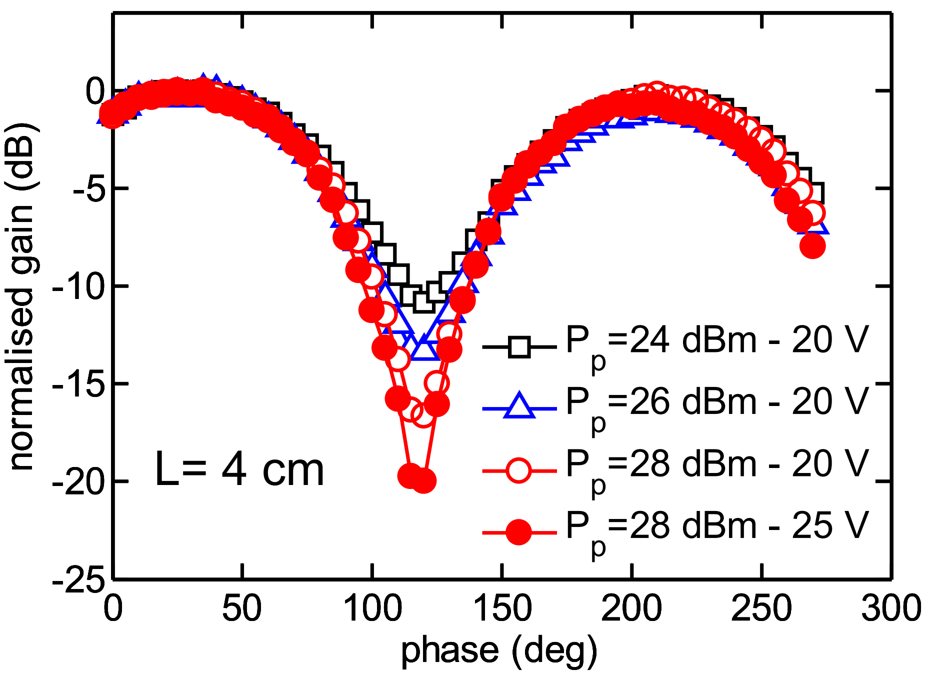
$$\Phi_s = 120^\circ$$

28 dBm total power correspond to 20.5 dBm(110 mW)/pump inside waveguide

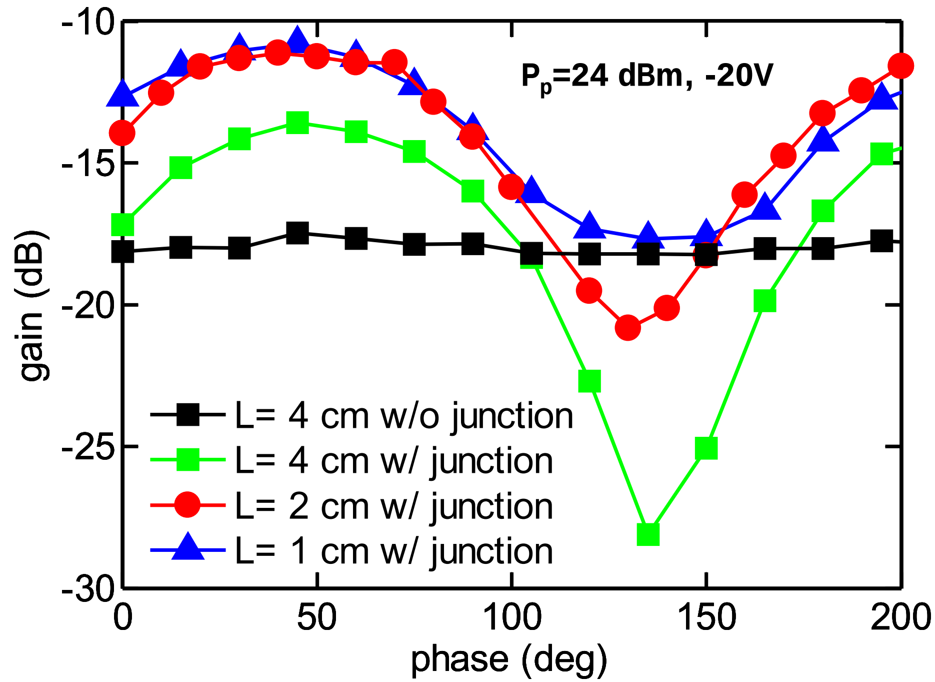
F. Da Ros et al., ECOC (2013) P.2.11.

# Phase sensitive extinction ratio optimisation

pump power



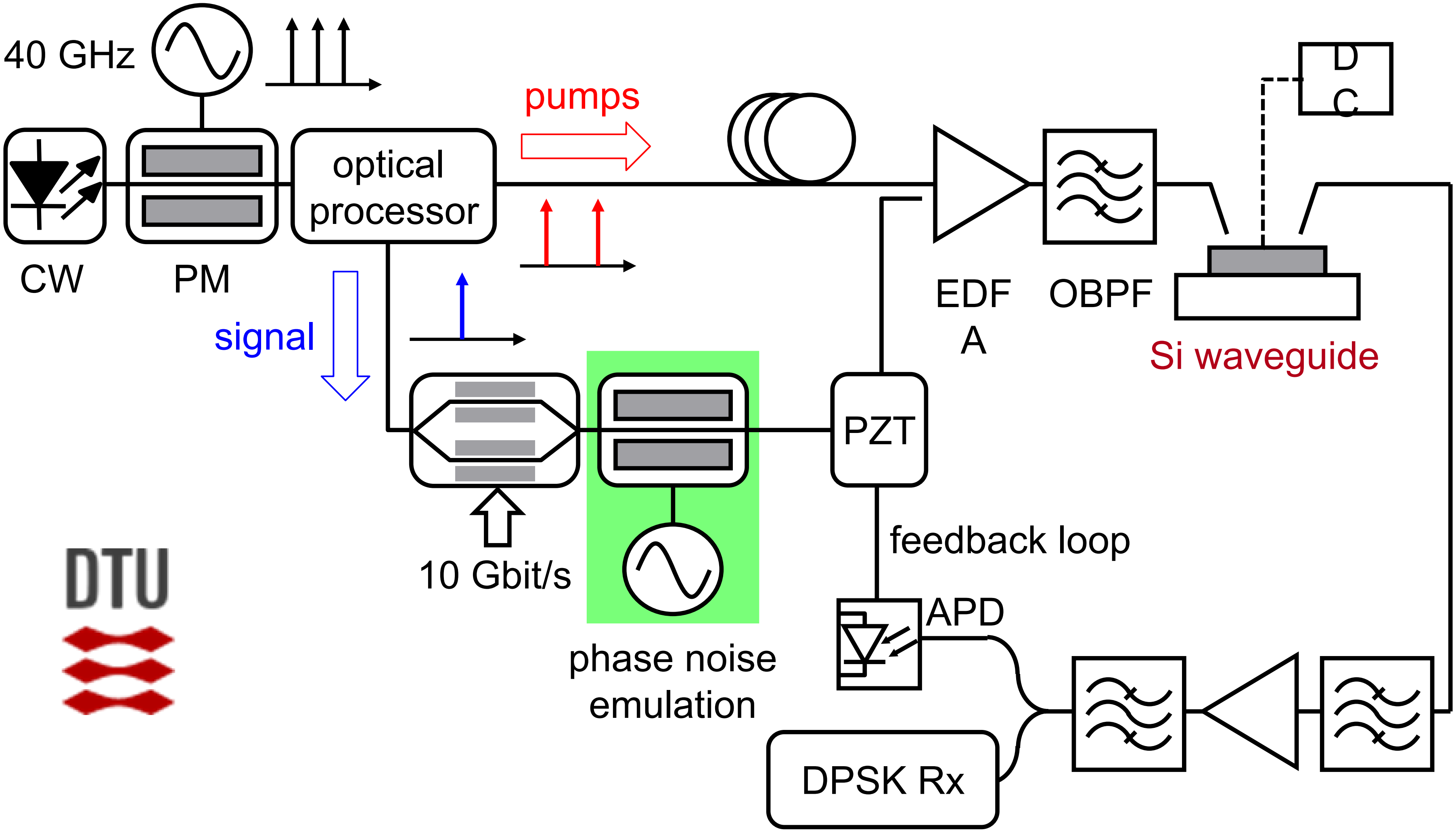

waveguide length




Up to 20 dB phase-sensitive extinction ratio attainable

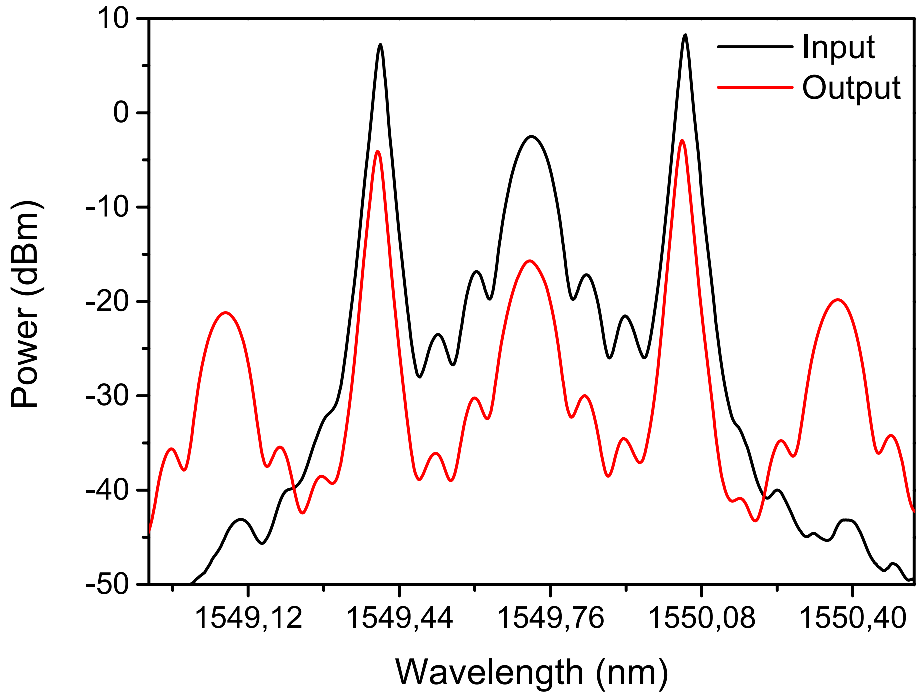
F. Da Ros et al., ECOC (2013) P.2.11.

# Phase regeneration for 10 Gbit/s DPSK




F. Da Ros et al., Opt. Express 22 (2014) 5029.

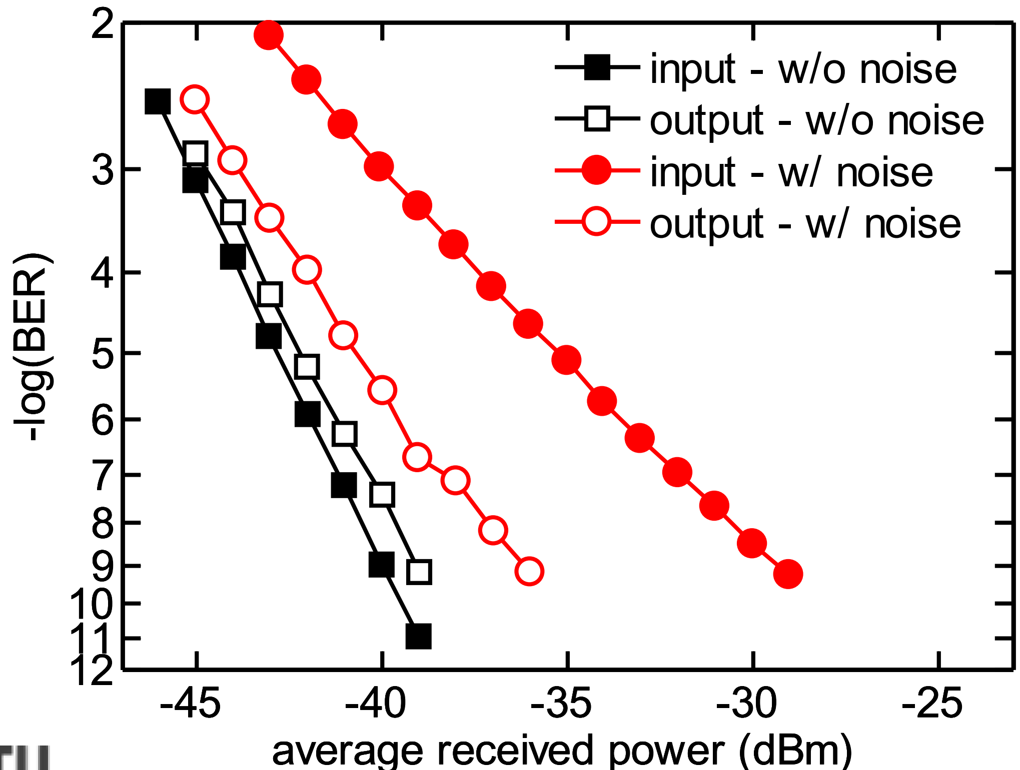
# Phase-sensitive regenerator DPSK output spectrum



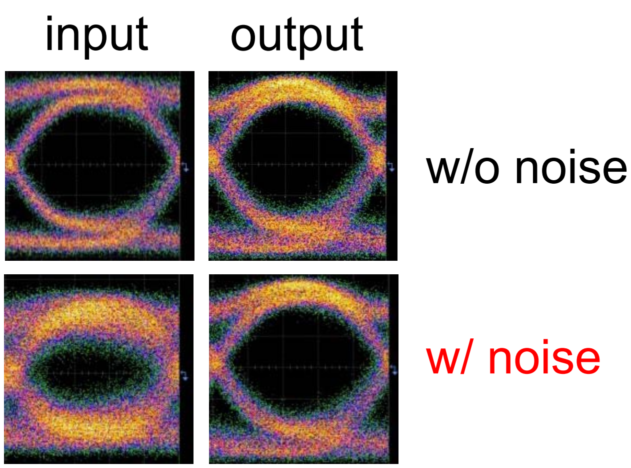

DTU

F. Da Ros et al., Opt. Express 22 (2014) 5029.

# BER evaluation for phase-regeneration




- $2^{15}$-1 PRBS
- 4 GHz phase noise
- 0.57 phase modulation index




Phase-noise penalty reduced from 10 dB to less than 3.5 dB

F. Da Ros et al., Opt. Express 22 (2014) 5029.

# Conclusions

**Successful electronic-photonic BiCMOS co-integrated circuits have been demonstrated**

## FIRST DEMONSTRATIONS

**10Gb/s modulator + driver**

**25Gb/s Germanium PD + TIA**

**Si-nanowaveguides with pin-junctions allow for advanced all-optical signal processing**

**-Highly efficient wavelengh conversion**

**-Phase sensitive parametric amplification**