Parametric Optical Signal Processing in Silicon Waveguides with Reverse-biased p-i-n Junctions

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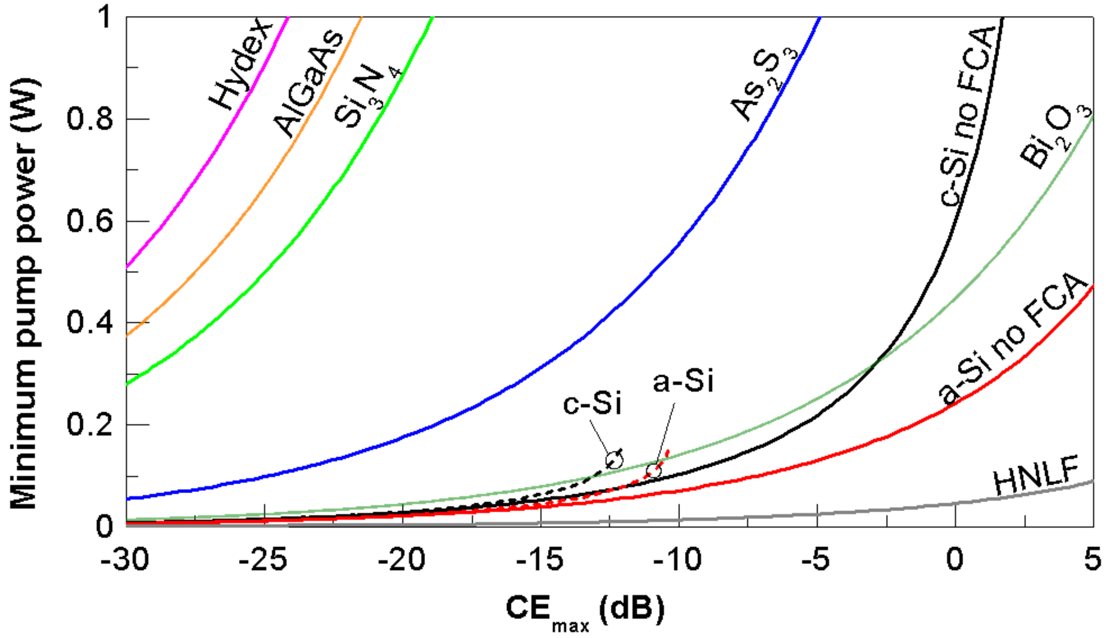
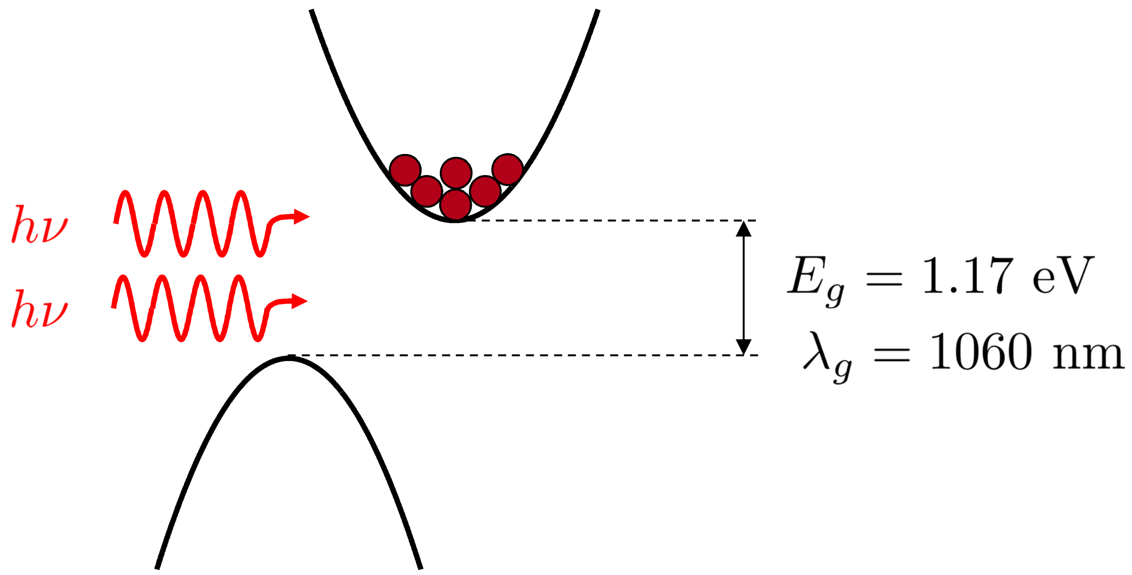
Nonlinear platforms for signal processing



Minimum pump power required for a target conversion efficiency

J. Martínez Díaz et al., IPC (2013) ThG1.5.

Nonlinear loss mechanism in Si waveguides



Two-photon absorption (TPA) if:

$$2h\nu > E_g \quad \Rightarrow \quad \lambda < 2\lambda_g$$

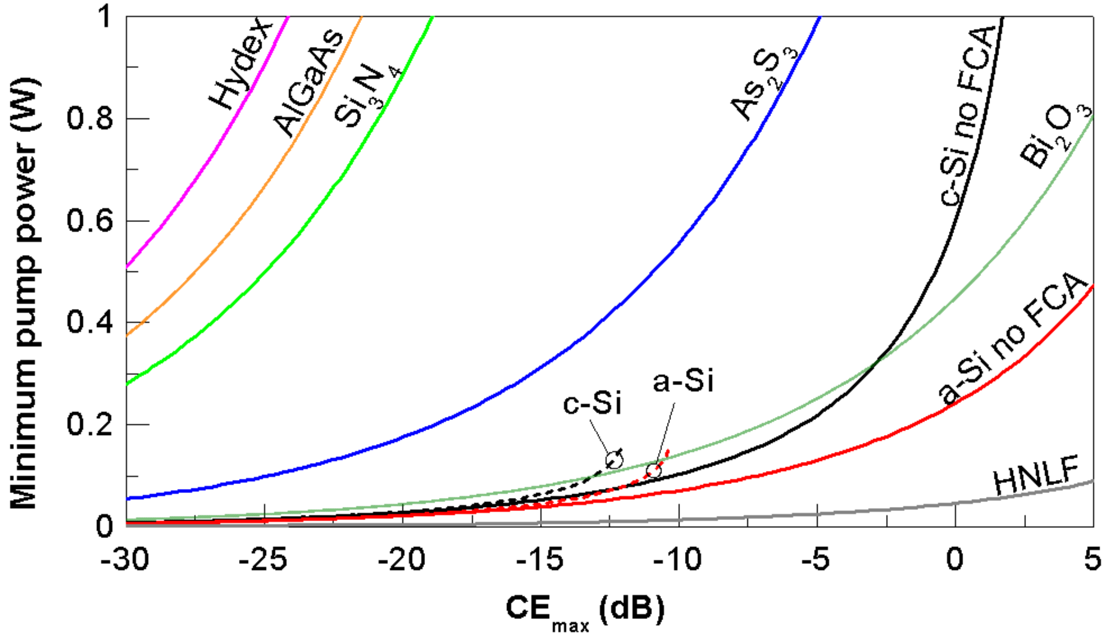
$$\lambda < 2120\ \mathrm{nm}$$

$\Rightarrow$ Generation of free carriers

- Free carrier absorption (FCA)
- Free carrier dispersion (FCD)

can be mitigated using p-i-n junction

Nonlinear platforms for signal processing



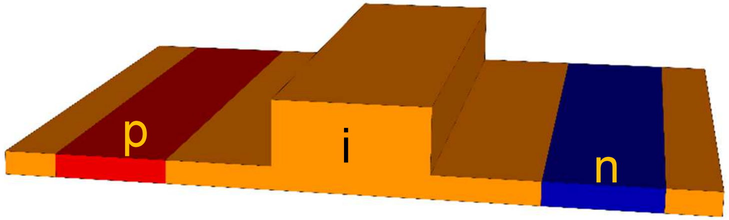
Minimum pump power required for a target conversion efficiency

J. Martínez Díaz et al., IPC (2013) ThG1.5.

Outline

- Motivations
- Silicon waveguides with p-i-n junctions
- Phase insensitive signal processing
  - High-efficiency FWM wavelength conversion
- Phase-sensitive signal processing
  - Regeneration of phase modulated signals
  - Simultaneous wavelength and modulation format conversion
- Summary

Silicon waveguides with p-i-n junction



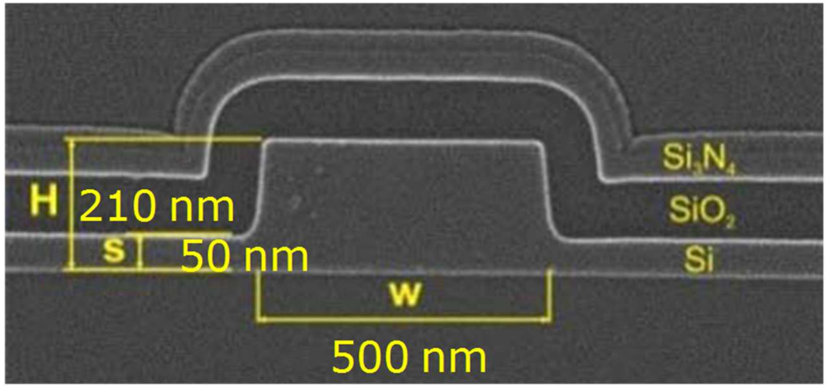
Avoiding nonlinear loss:

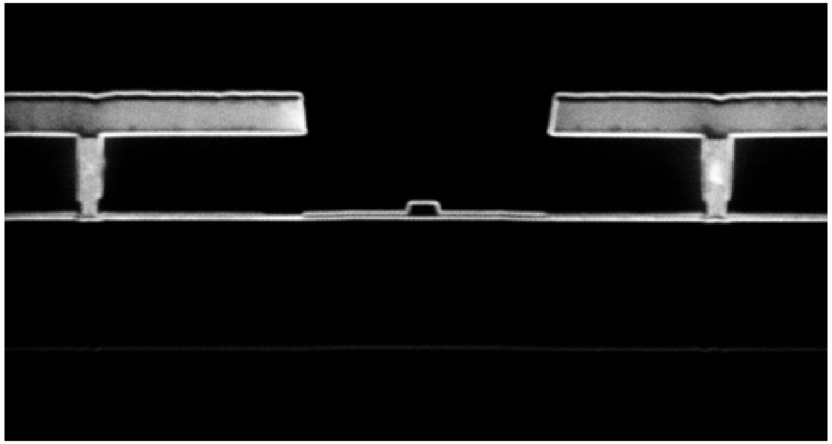
1. Operate at wavelengths above 2120 nm
   - no TPA
   - no telecom band operation
2. Pulsed pump operation with low repetition frequency
   - not compatible with high bit rate operation
3. p-i-n junction across the nonlinear silicon waveguide
   - Sweep the carriers generated by two-photon absorption
   - Reduce effective carriers lifetime

   ⇒ limits the impact of free-carrier absorption

H. Rong et al., Opt. Express 14 (2006) 1182.
A. C. Turner-Foster et al., Opt. Express 18 (2010) 3582.
J. R. Ong et al., IEEE Photon. Technol. Lett. 25 (2013) 1699.

Fabricated silicon waveguide structure





- Waveguide height: H= 210 nm
- Slab height: s= 50 nm
- Rib width: w= 500 nm
- Covered by 100 nm SiO_2 and 90 nm Si_3N_4

- p-doped region: boron
- n-doped region: arsenic

} 10^{18} cm^{-3}

- doped regions spaced 1.2 μm
- higher doped contact regions spaced further away

- Fabricated in a BiCMOS foundry using 258 nm lithography
- 8" wafers with 2 μm buried oxide layer

A. Gajda et al., Opt. Express 19 (2011) 9915.

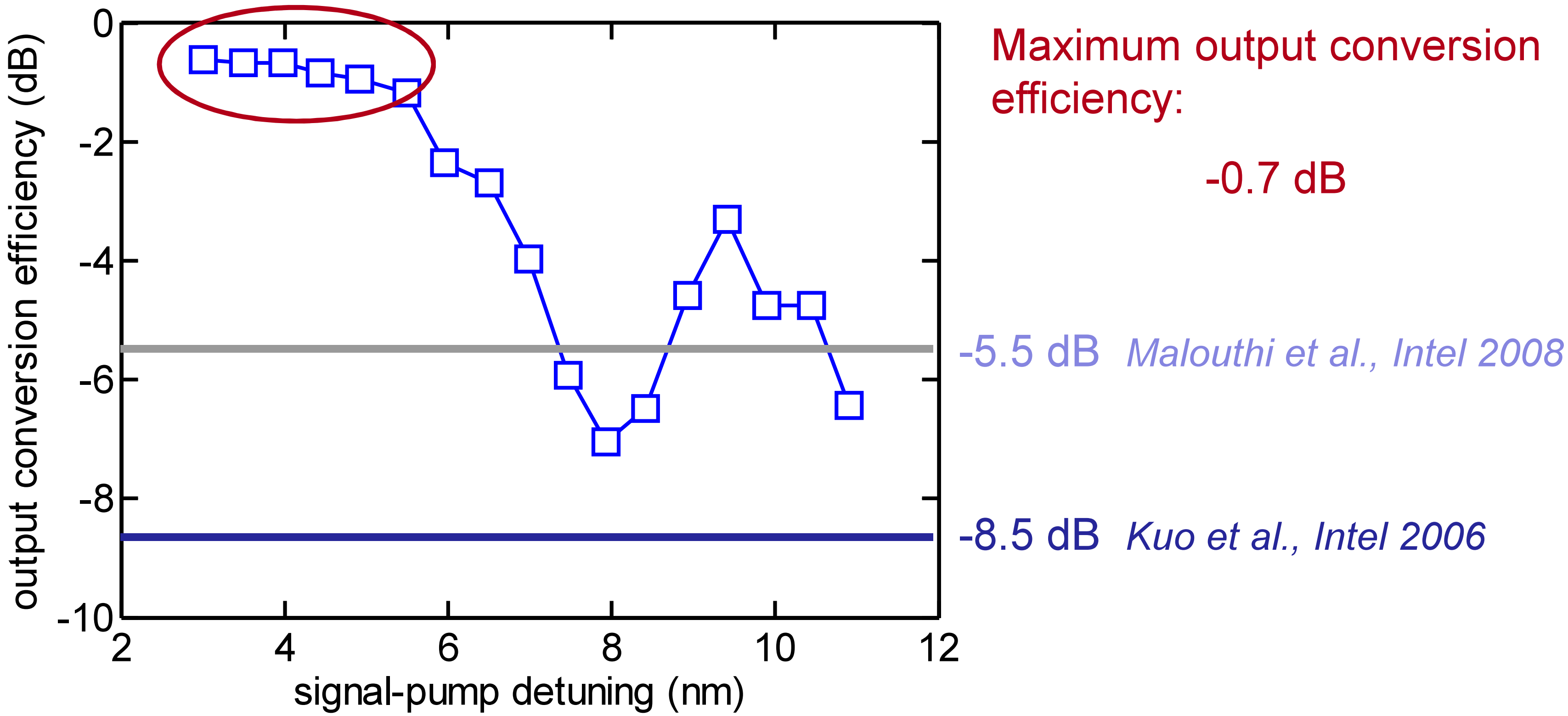
Silicon waveguides optical properties

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

*1D grating couplers with 35 nm bandwidth

Optical properties in line with standard SOI waveguides
+ p-i-n junction

Record (2012) conversion efficiency



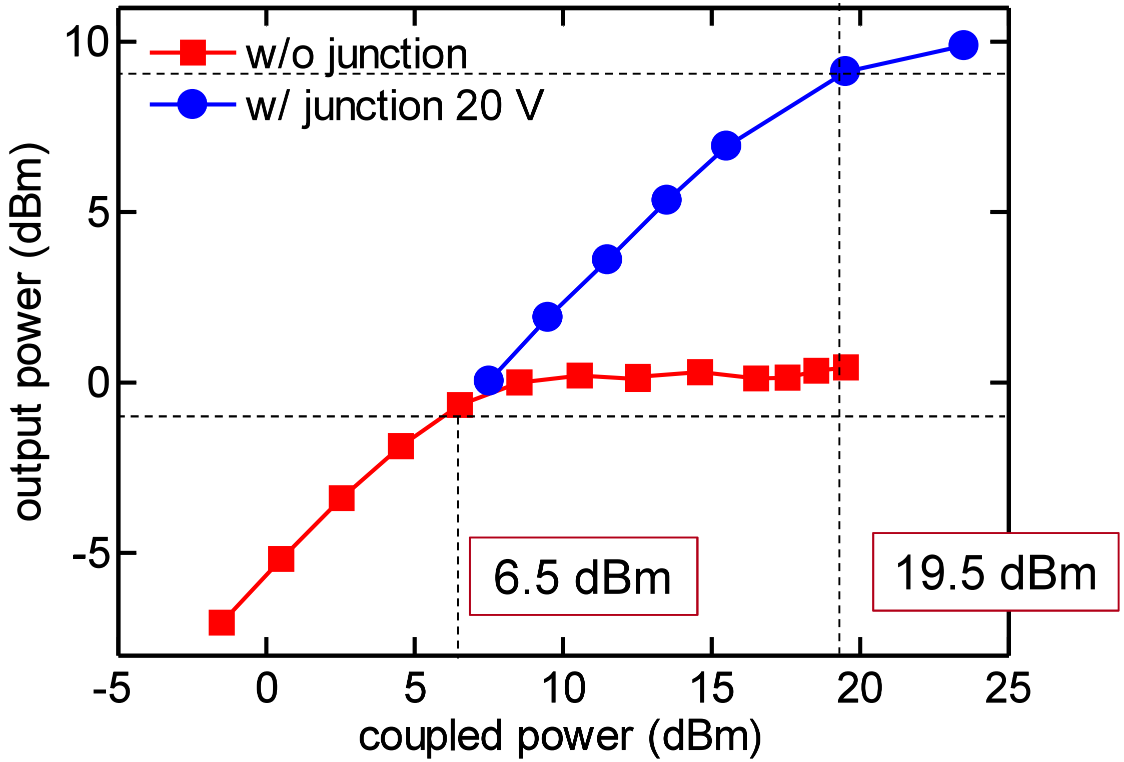
- Pump wavelength λ_p= 1542 nm
- Pump power: 26 dBm
- Reverse bias: 20 V

A. Gajda et al., Opt. Express 20 (2012) 13100.

W. Mathlouthi et al., Opt. Express 16 (2008) 16735.

Y. H. Kuo et al., Opt. Express 14 (2006), 11721.

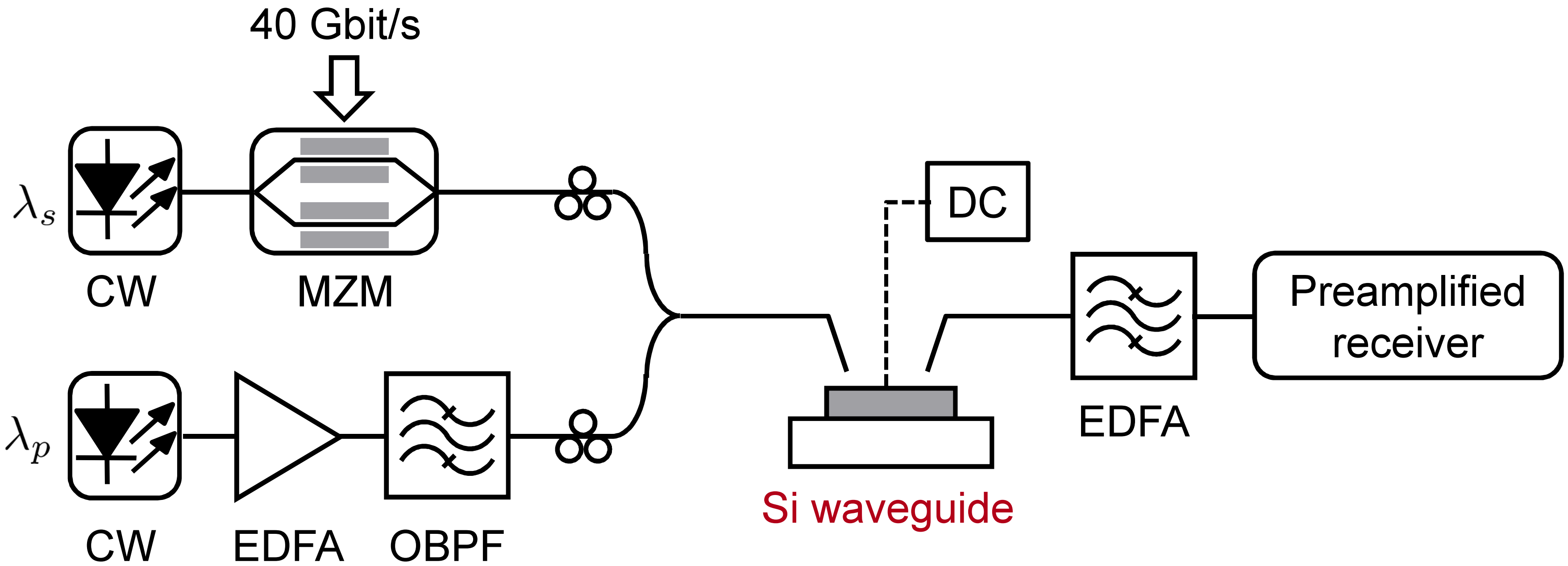
Free carrier absorption threshold



Coupled power before FCA limitation increased by more than 10 dB

Phase-insensitive Signal Processing

Set-up for 40 Gbit/s wavelength conversion

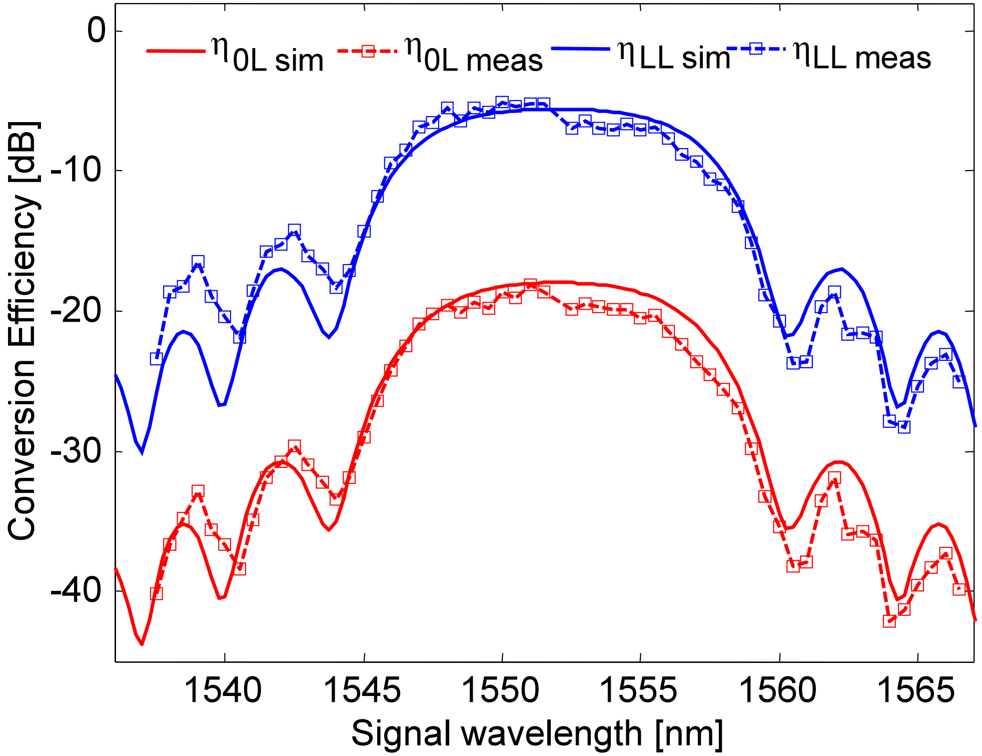


- 40 Gbit/s NRZ-OOK
- PRBS 2^{15}-1
- P_p= 22.5 dBm
- P_s= 2.5 dBm

coupled into Si waveguide

A. Gajda et al., Group IV Photonics (2013) FC3.

Wavelength conversion bandwidth



Conversion efficiency:

output:

$$\eta_{LL} = \frac{P_i(L)}{P_s(L)}$$

input/output:

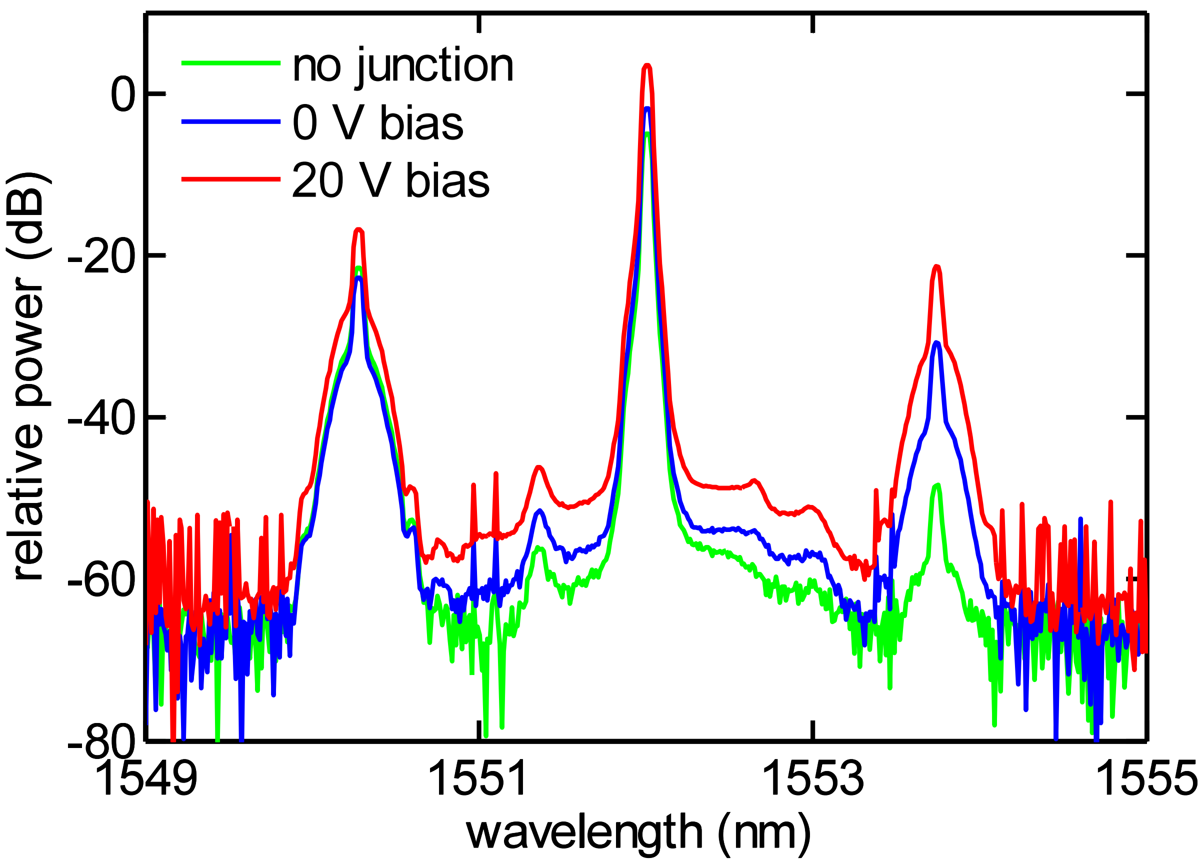
$$\eta_{0L} = \frac{P_i(L)}{P_s(0)}$$

- 20 dBm pump power
- 0 dBm signal power
- 20 V reverse bias
- Good agreement between measurement and theory for D=-2450 ps/(nm·km)

- 3 dB conversion bandwidth of ~10 nm
- Wider bandwidths achievable after dispersion engineering

A. Gajda et al., Group IV Photonics (2013) FC3.

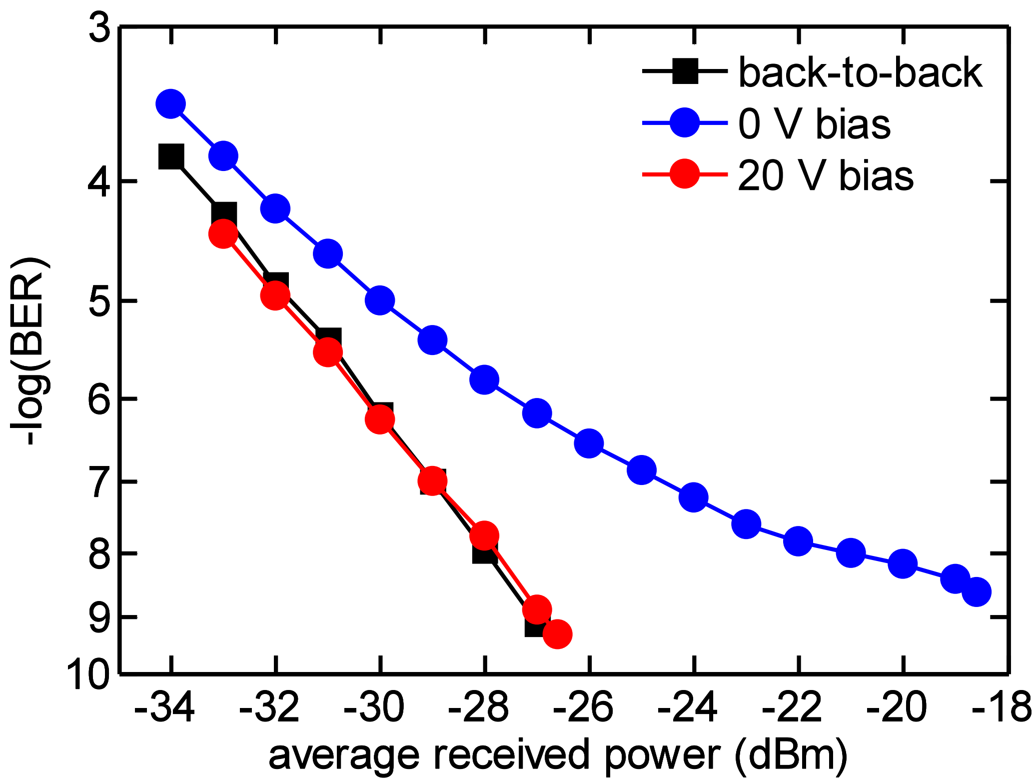
Wavelength converter output spectra

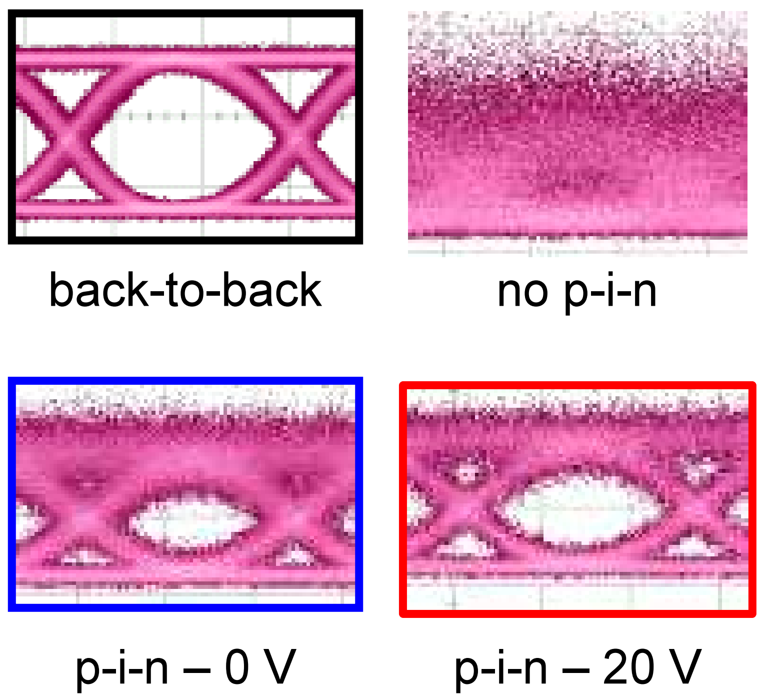


Bias (V)	CE (dB)
no junction	-26.9
0	-8
20	-4.6

- Built-in field of p-i-n junction already significantly improves the conversion efficiency
- Up to -4.6 dB output conversion efficiency for 20 V reverse bias

BER performance for wavelength conversion



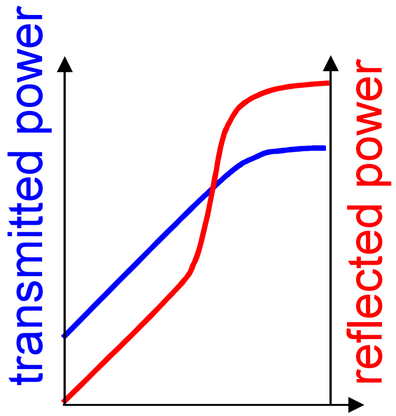


40 Gbit/s wavelength conversion with 0.2 dB power penalty applying 20 V reverse bias

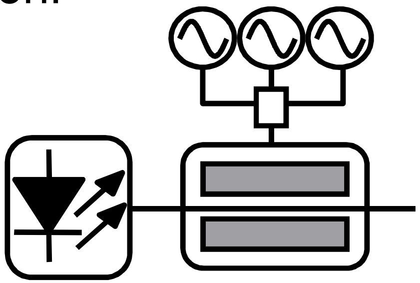
A. Gajda et al., Group IV Photonics (2013) FC3.

Phase-sensitive Signal Processing

Motivations for phase-sensitive processing in waveguides



- Stimulated Brillouin scattering (SBS) limits the amount of pump power that can be coupled in a highly nonlinear fibre (HNLF)
- Classic mitigation technique for parametric amplification:



phase dithering of the pumps

- Not "phase-sensitive friendly" technique
- Other techniques:
  - High-SBS threshold HNLFs $\Rightarrow$ 15 dB/km loss (1st generation)
  - Strained HNLFs $\Rightarrow$ OK as long as dispersion well controlled

Short (but highly nonlinear) waveguides should be relatively immune to SBS

Phase sensitive processing in waveguides

- Periodically-poled lithium niobate waveguides

  K. J. Lee et al., Opt. Express 17 (2009) 20393.

  B. J. Puttnam et al., IEEE Photon. Technol. Lett. 23 (2011) 426.

  T. Umeki, Opt. Express 21 (2013) 12077.

- Chalcogenide waveguide

  R. Neo et al., Opt. Express 21 (2013) 7926.

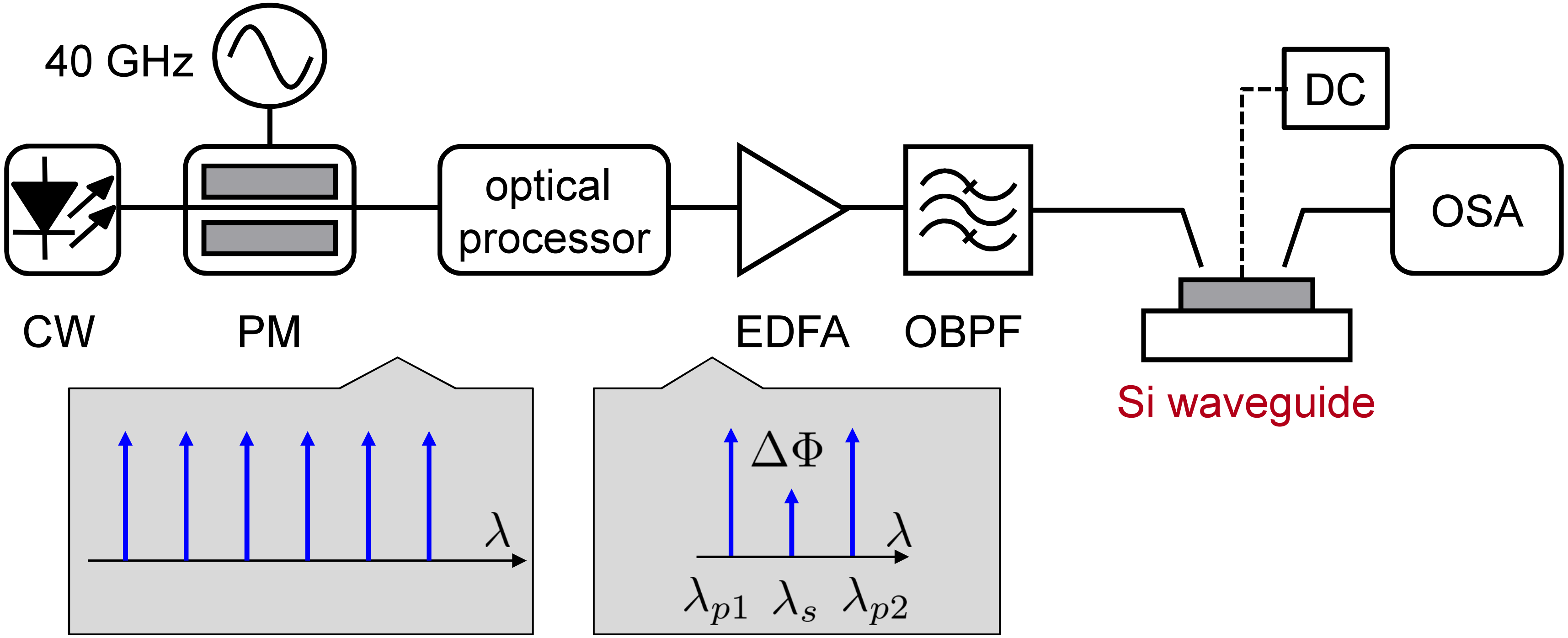
  - Low TPA, no FCA
  - 10 dB phase-sensitive extinction ratio (pulsed pump 38.6 MHz)
  - Limited by damage threshold of the waveguide

- Silicon photonic crystal waveguide

  Y. Zhang et al., Opt. Lett. 39 (2013) 363.

  - 11 dB phase-sensitive extinction ratio (pulsed pump 38.6 MHz)
  - Limited by TPA and FCA

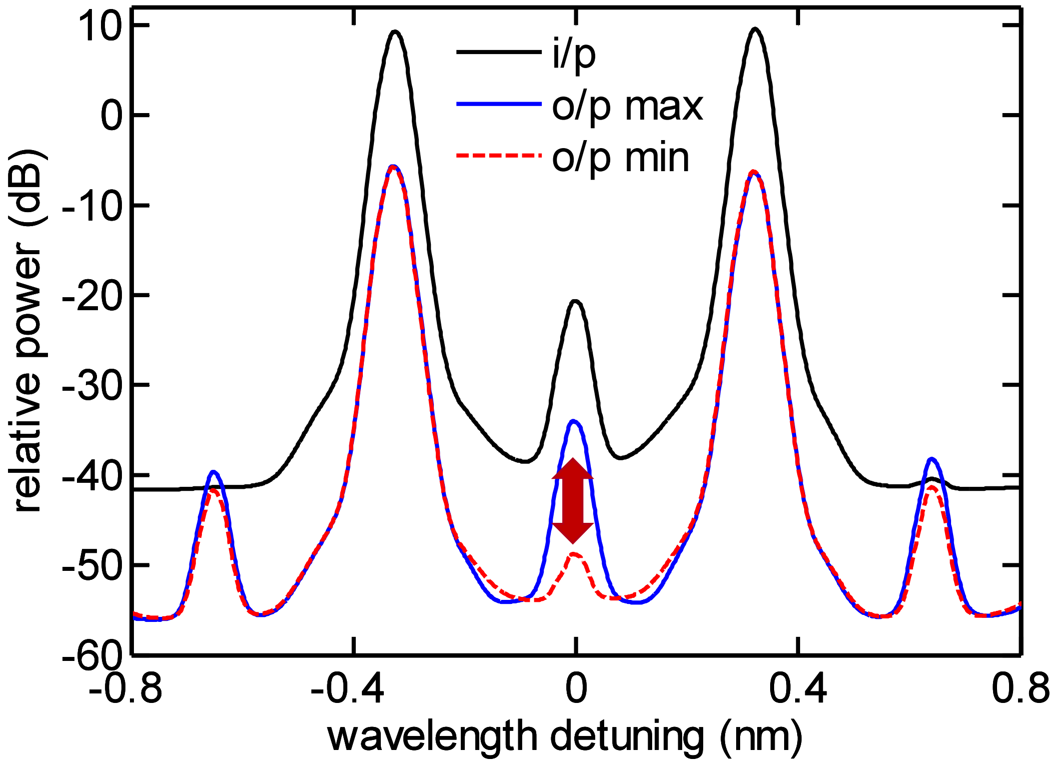
Static phase-sensitive investigation



- Phase coherence between pumps and signal ensured by frequency comb generation
- Frequency spacing of 40 GHz between interacting waves

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

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:

$\Phi_s = 30°$

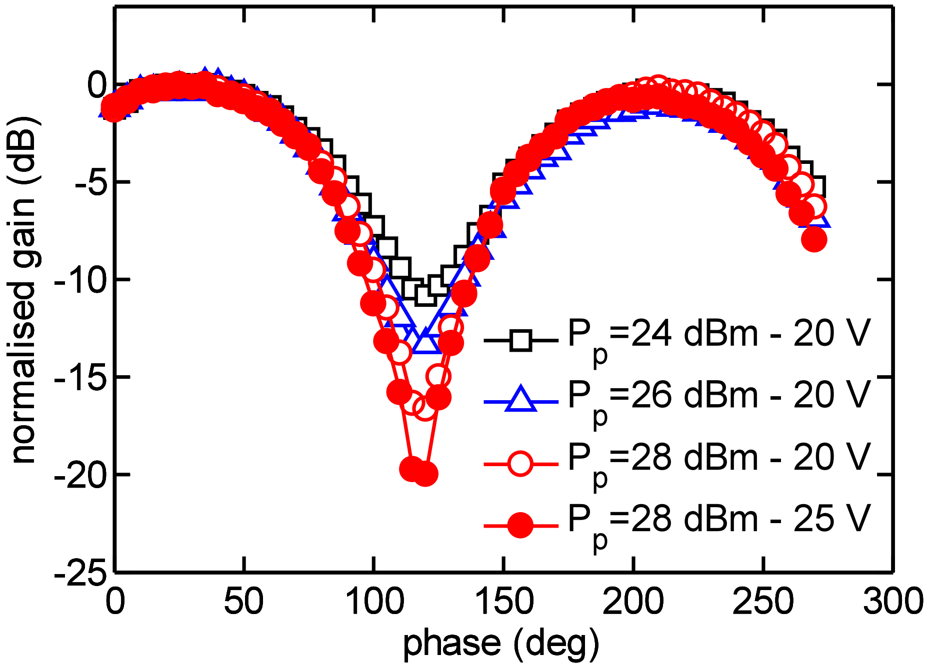
$\Phi_s = 120°$

Power of the degenerate signal/idler depends on the relative phase between signal and pumps

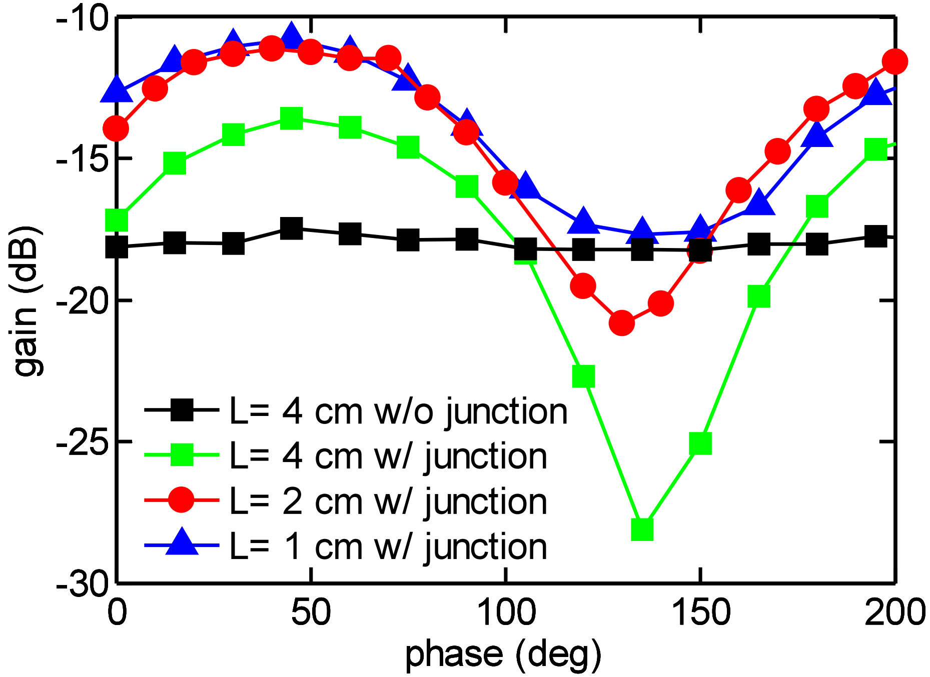
F. Da Ros et al., ECOC (2013) P.2.11.

Phase sensitive extinction ratio optimisation

pump power



waveguide length

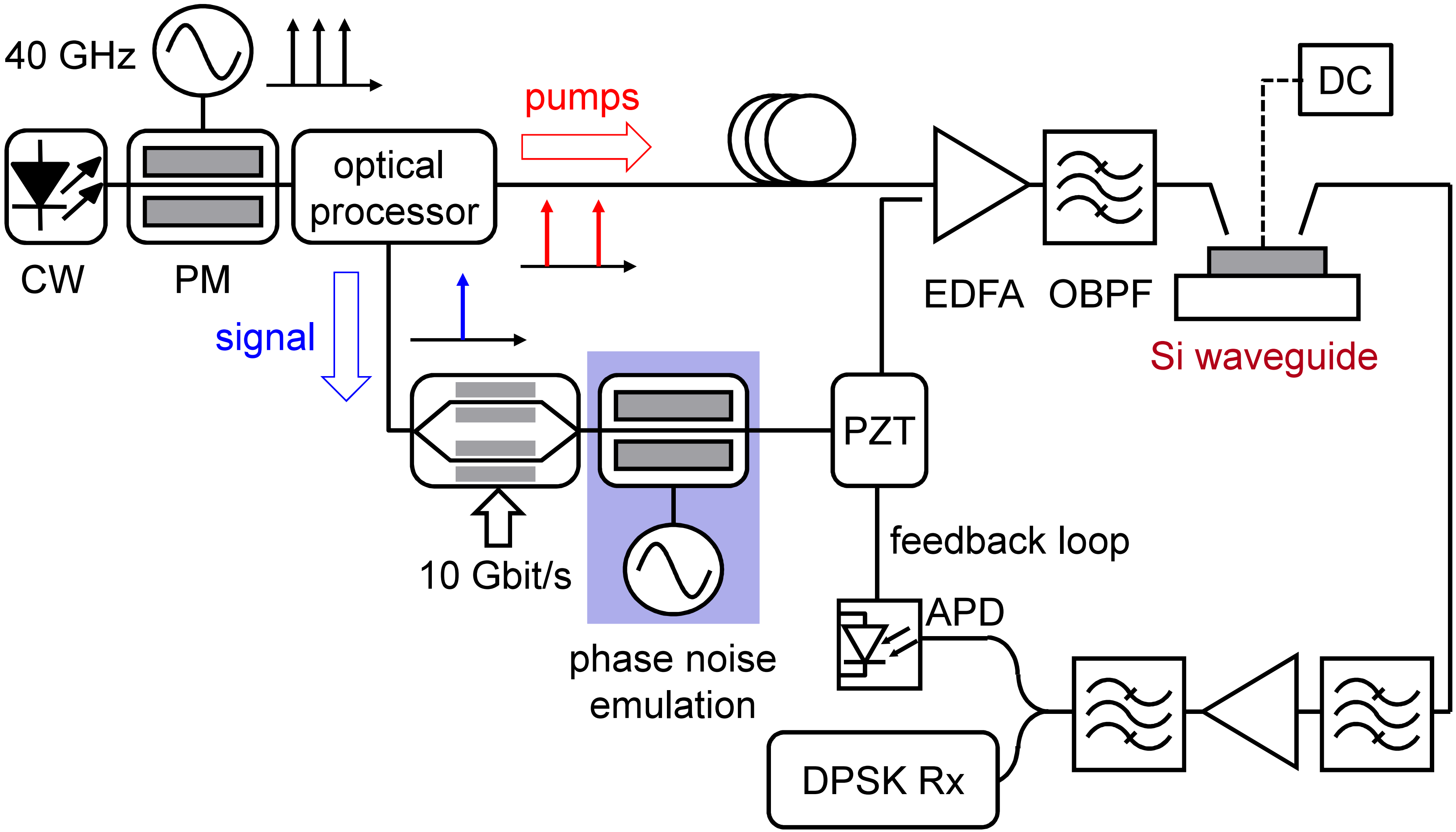


L= 4 cm 7.5 dB coupling loss

Up to 20 dB phase-sensitive extinction ratio attainable

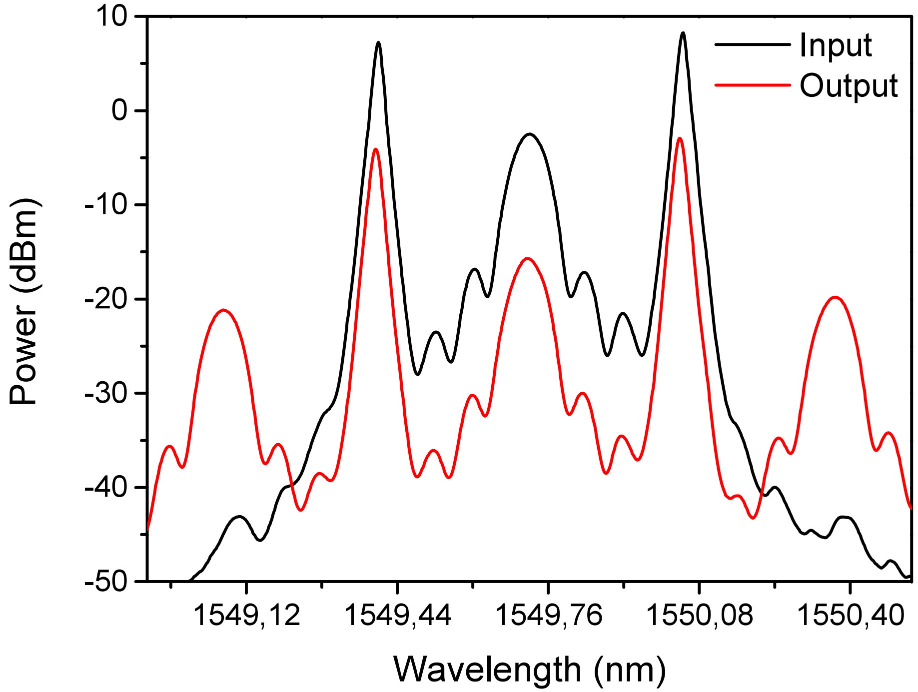
F. Da Ros et al., ECOC (2013) P.2.11.

Setup for phase regeneration



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

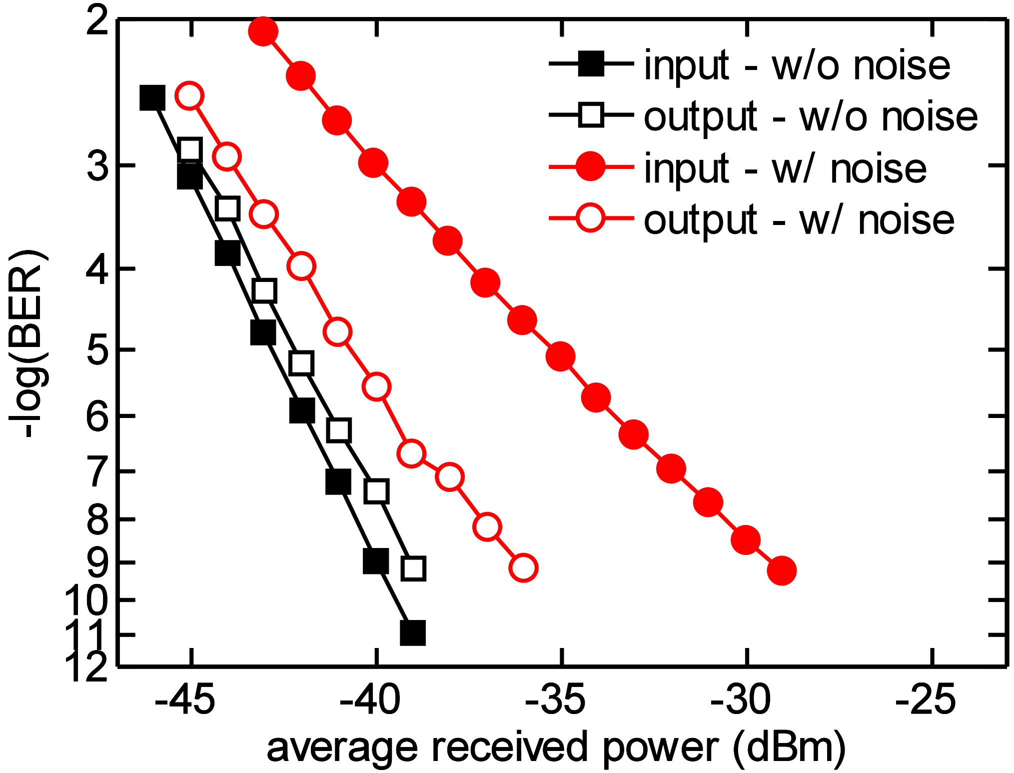
Phase-sensitive regenerator output spectrum



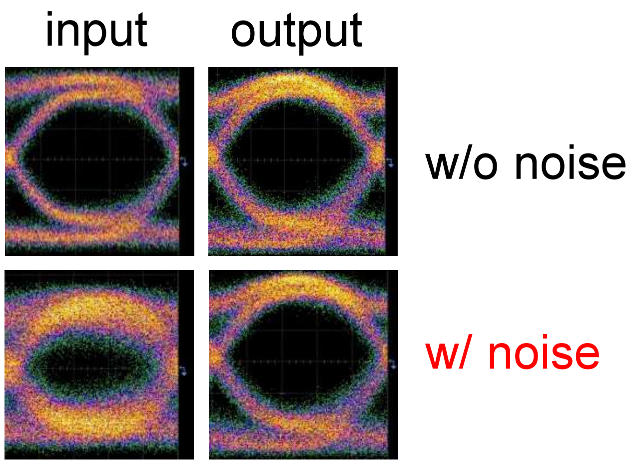
Higher-order sidebands generated

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

BER evaluation for phase-regeneration



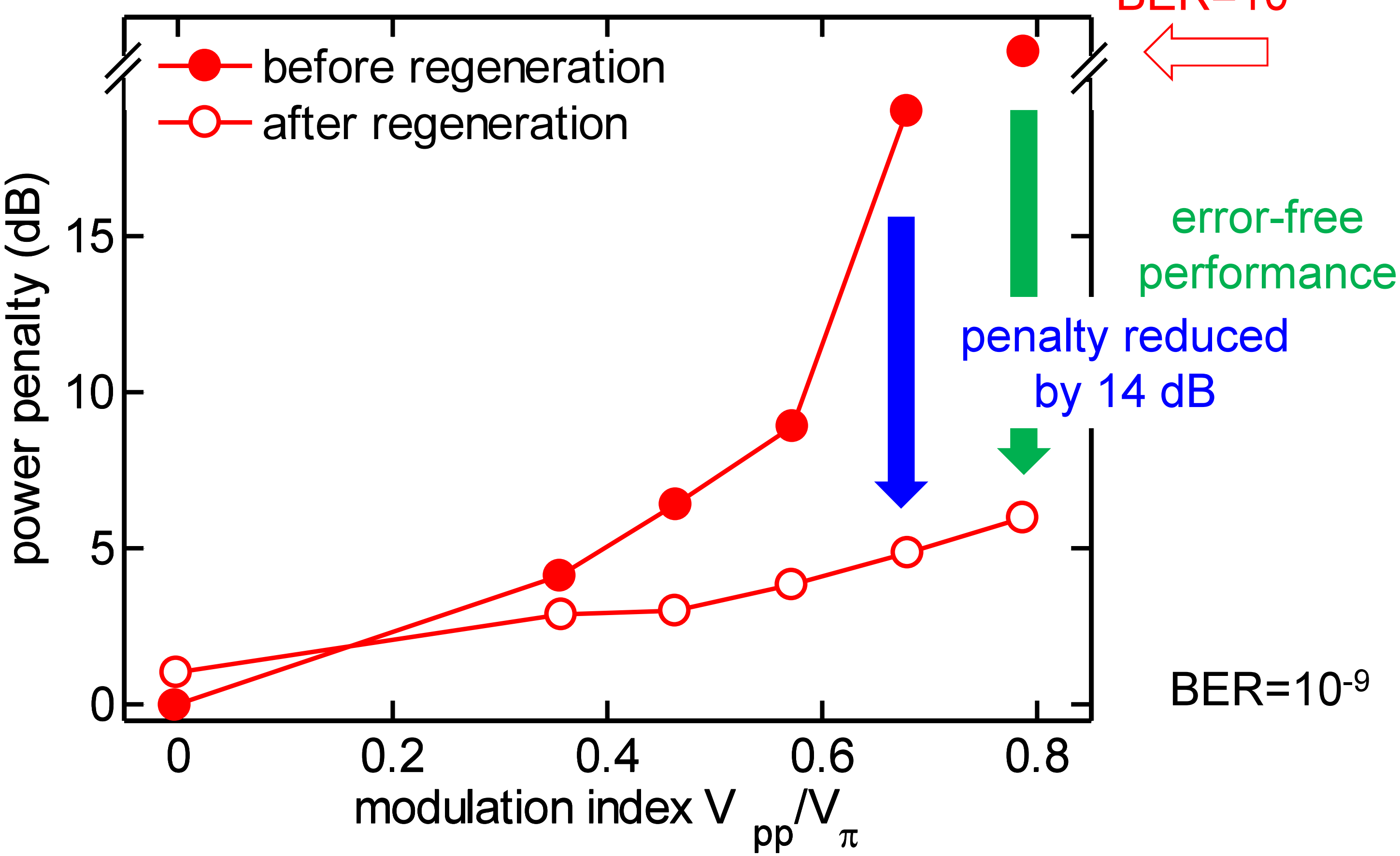
- 2^{15}-1 PRBS
- 4 GHz phase noise
- 0.57 phase modulation index



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

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

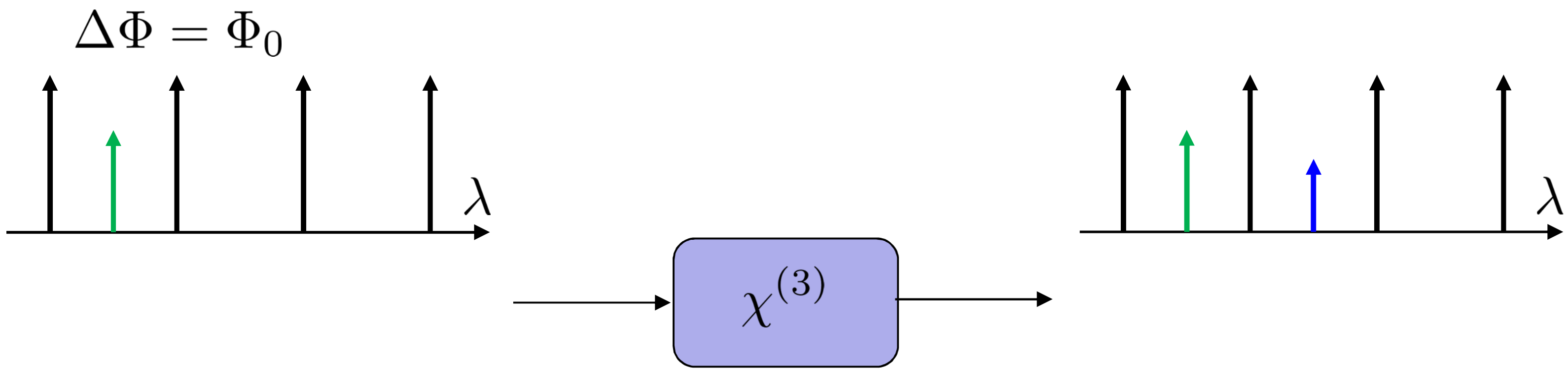
Phase regeneration capability



Increase of the phase noise modulation index slowly increases the power penalty of the regenerated signal

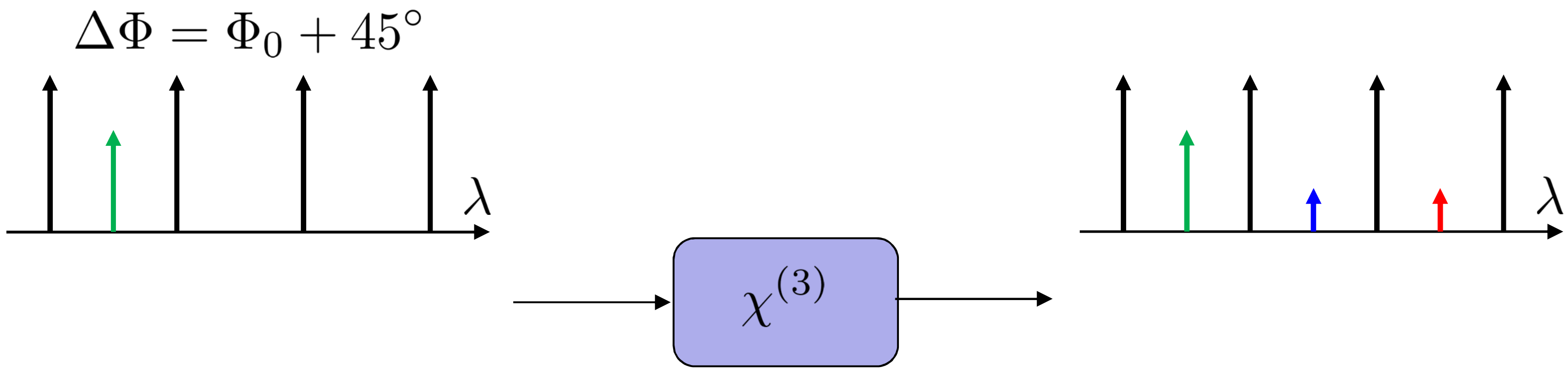
F. Da Ros et al., Opt. Express 22 (2014) 5029.

Phase-sensitive wavelength conversion



R.P. Webb et al., Opt. Express 19 (2012) 20015.

Phase-sensitive wavelength conversion



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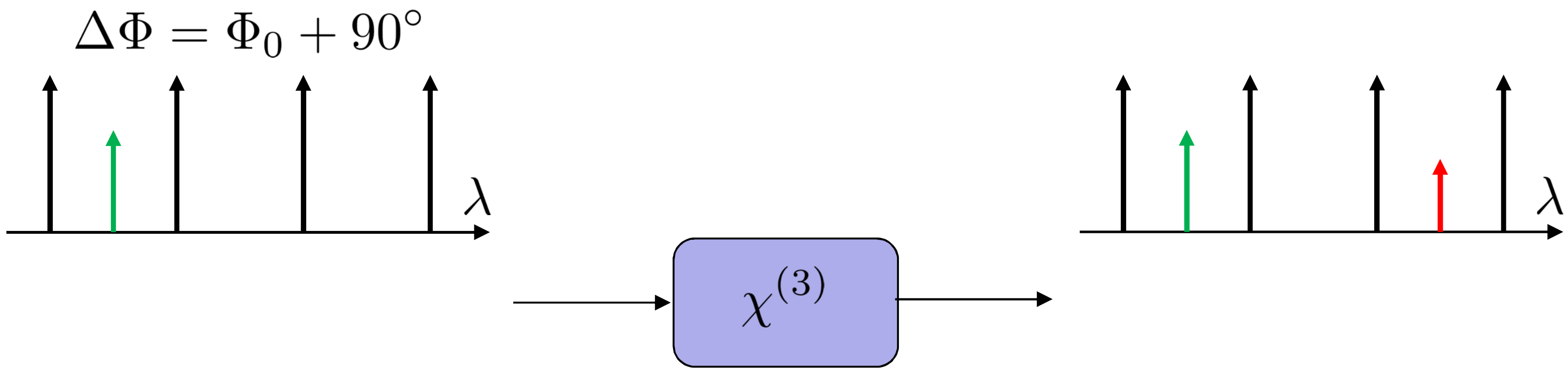

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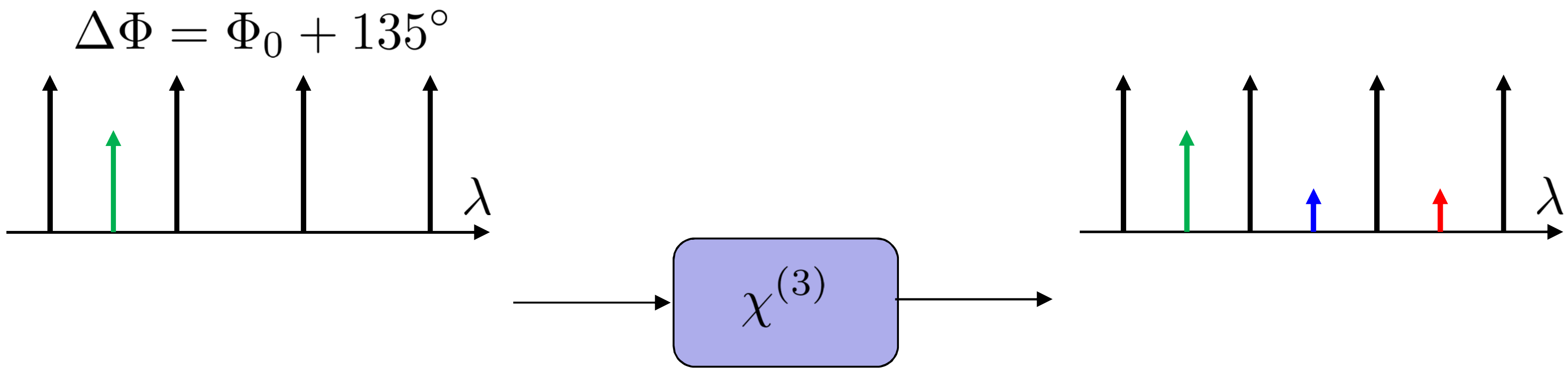

R.P. Webb et al., Opt. Express 19 (2012) 20015.

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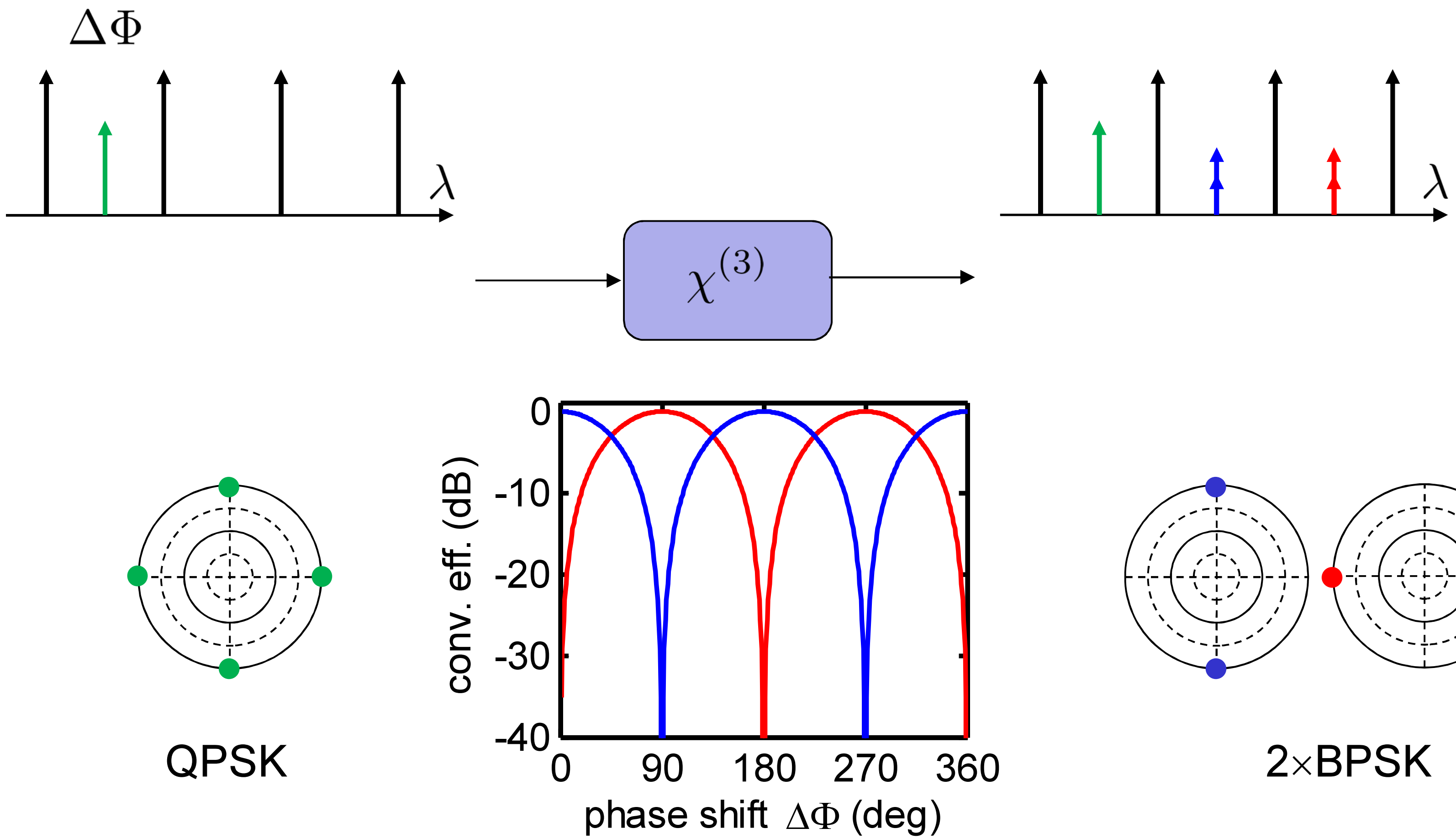
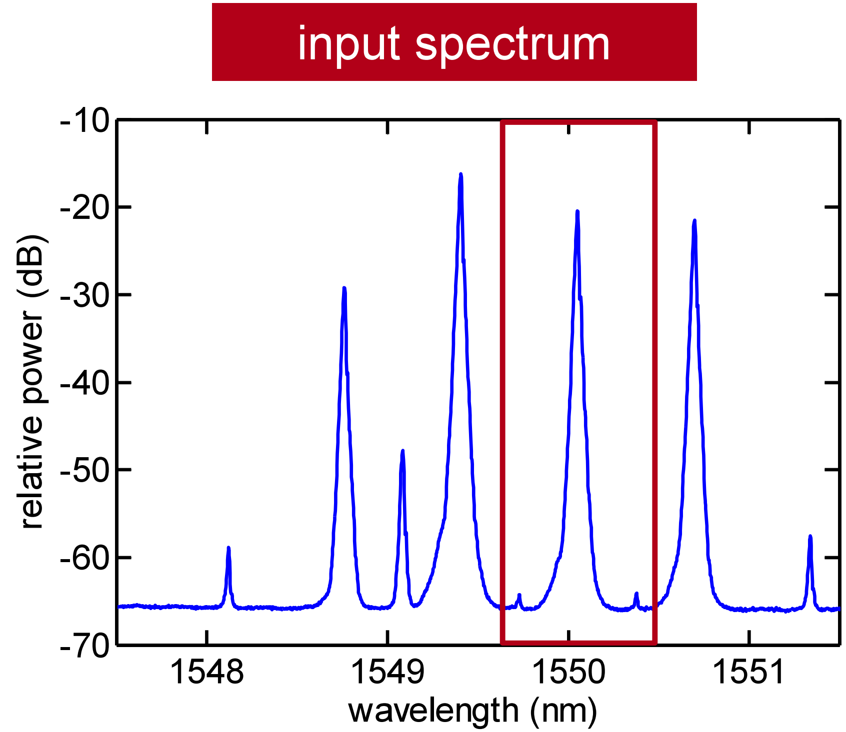
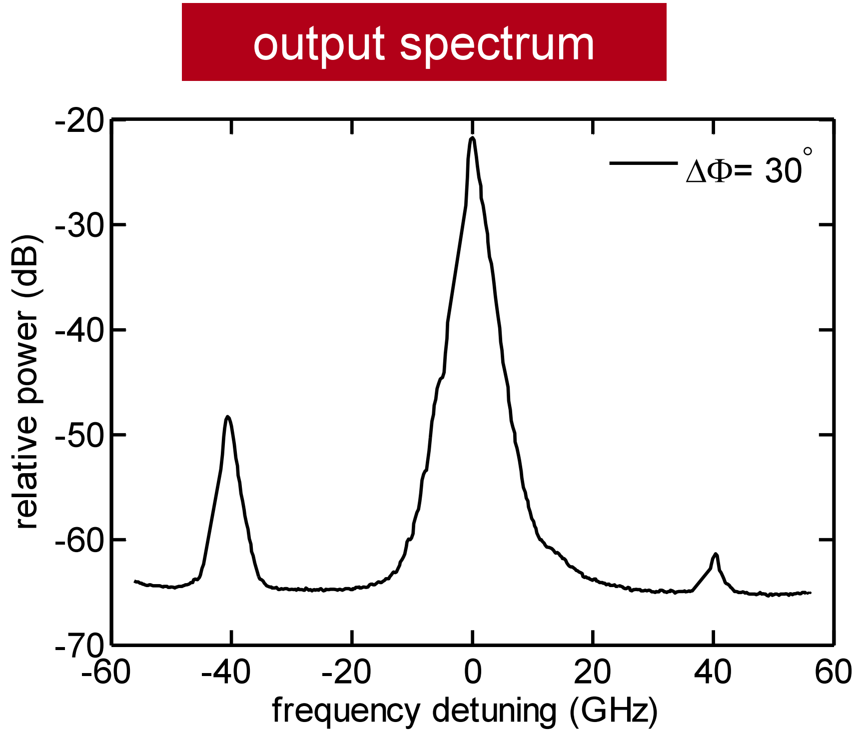


R.P. Webb et al., Opt. Express 19 (2012) 20015.
M. J. Power at al., Opt. Express 21 (2013) 25664.
F. Da Ros et al., Opt. Express 21 (2013) 28743.
F. Da Ros et al., IEEE Photon. Technol. Lett. 26 (2014) 1207.

Phase-sensitive wavelength conversion in Si





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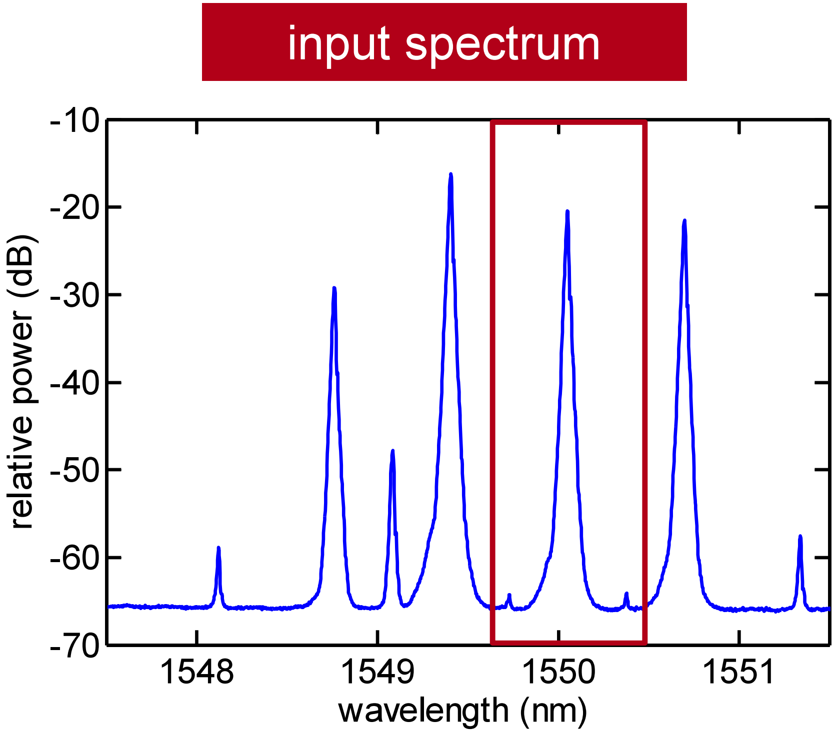
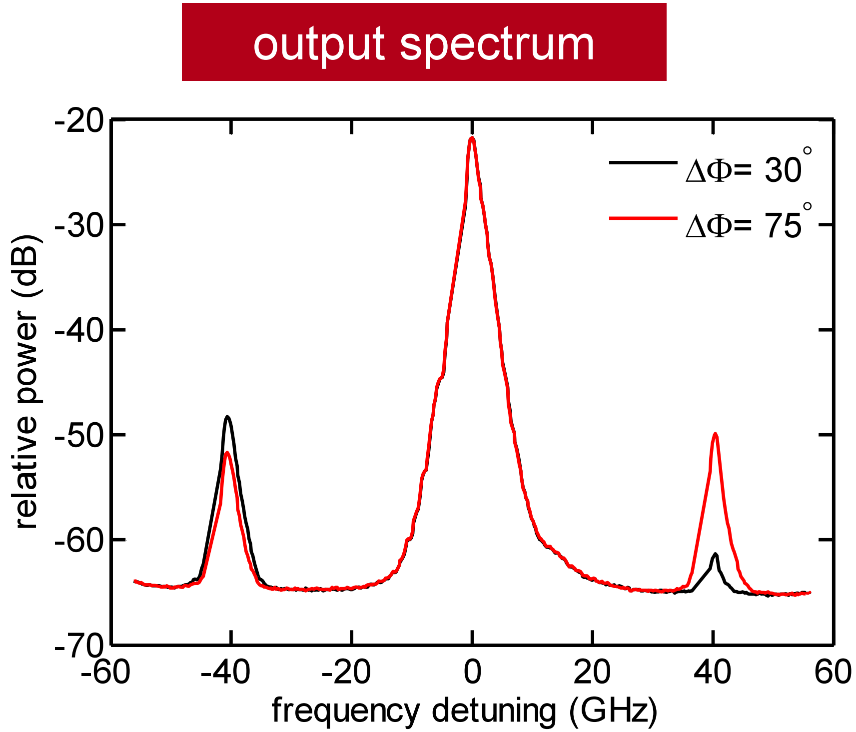
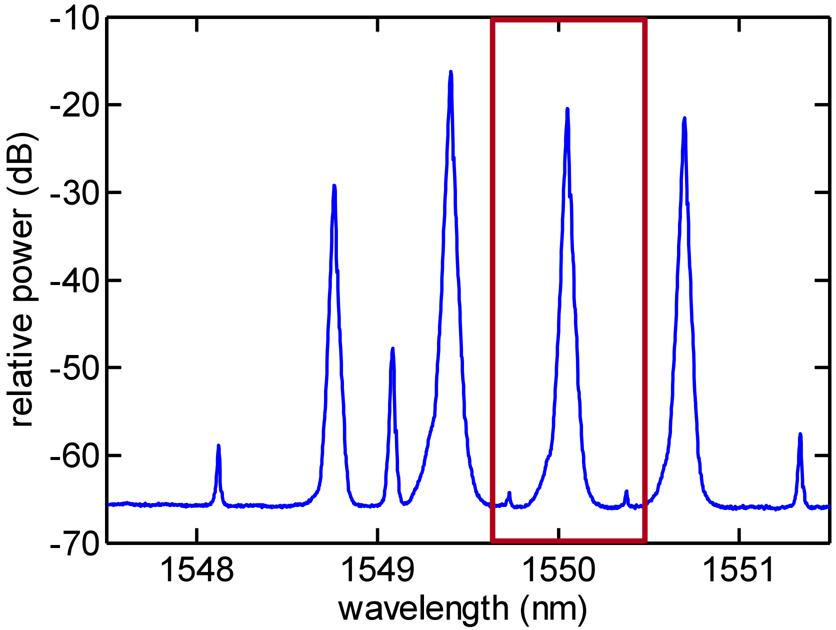


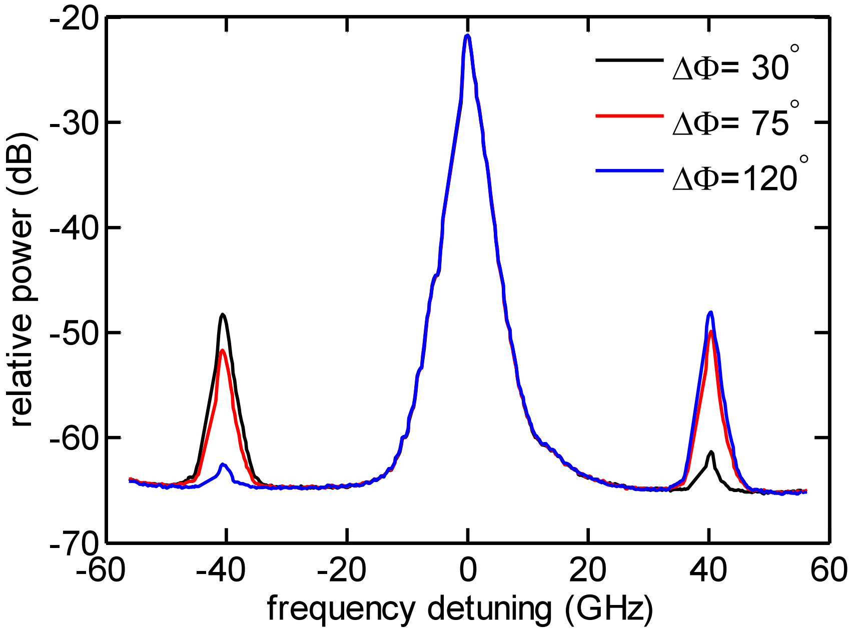


Phase-sensitive wavelength conversion in Si

input spectrum

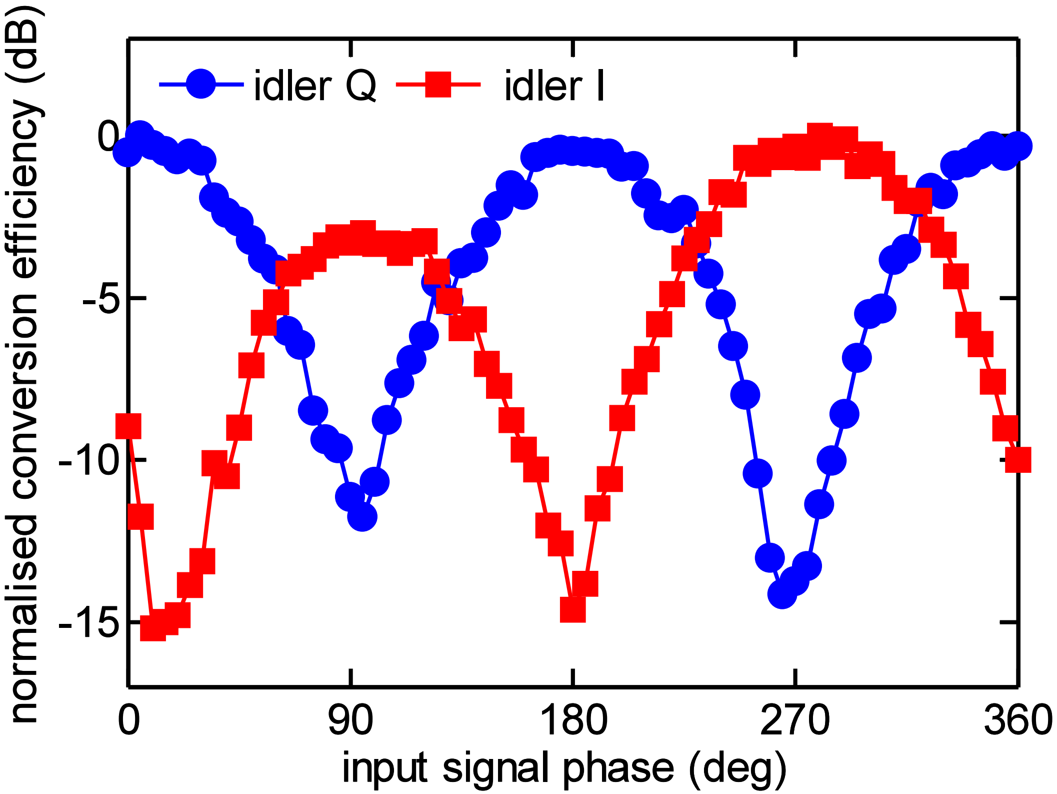


output spectrum



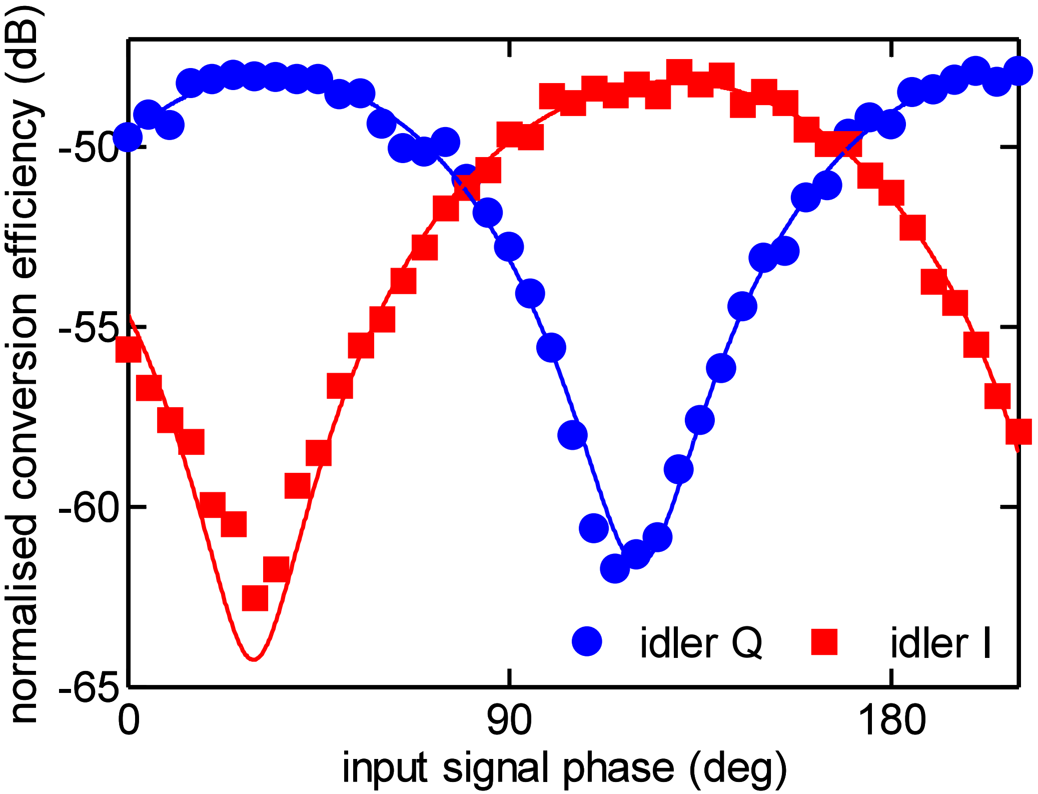
Power evolution of the idlers out of phase

Conversion efficiencies of the idlers



90° phase-shifted dependences of the conversion efficiencies of the idlers on the input signal phase

Conversion efficiencies of the idlers



90° phase-shifted dependences of the conversion efficiencies of the idlers on the input signal phase

Summary

- Silicon waveguides with p-i-n junctions have been designed and fabricated with good optical properties
- High-efficiency FWM wavelength conversion demonstrated at 40 Gbit/s
- First demonstration of phase-sensitive processes on-chip with CW pumping
- Complete phase regeneration demonstrated using 4 cm long waveguide

Trade-off silicon photonics compatibility with increased complexity of active removal of carriers

Acknowledgments

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VILLUM FONDEN