Nonlinear Optical Devices

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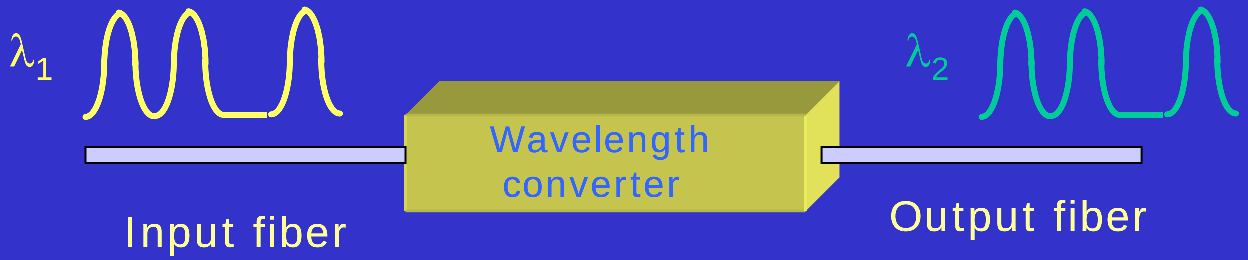
Outline

- Cascaded Wavelength Conversion
- Non-photorefractive crystals
- Compensation of nonlinearity and dispersion in an optical communication link

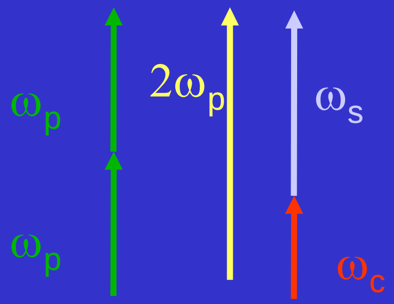
• Silicon Photonics
  - Si-Ge waveguides

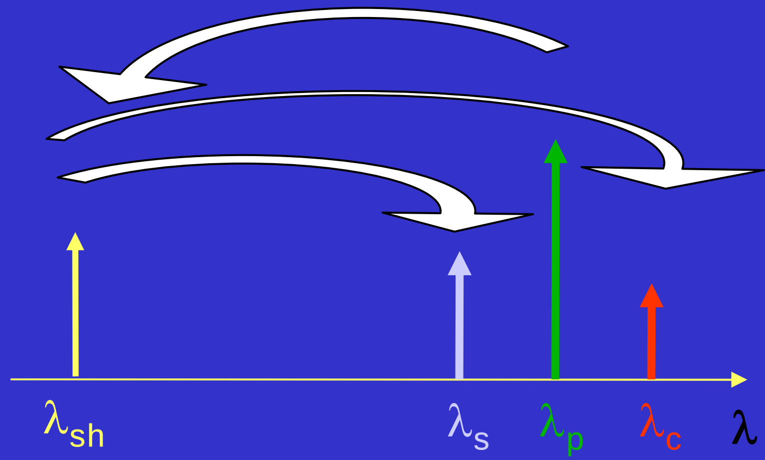
• Other activities that I will not discuss
  - Conical waves (talk by Francesca)
  - Writing by fs pulses (Daniela)
  - Nonlinear propagation in microstructured fibers (L. Tartara)
  - Tunable picosecond pulses (J. Yu, L. Tartara)
  - Biophotonics: a new optical tweezer (I. Cristiani, P. Minzioni)

Wavelength Conversion



Cascading

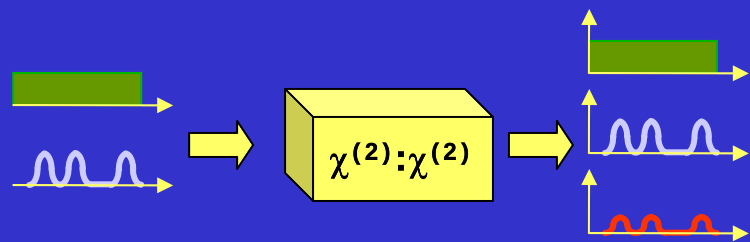




- Cascade of two second order effects

Low conversion regime

$$\chi^{(3)}_{casc} \propto \frac{L}{\lambda_p}\left|\chi^{(2)}\right|^2$$



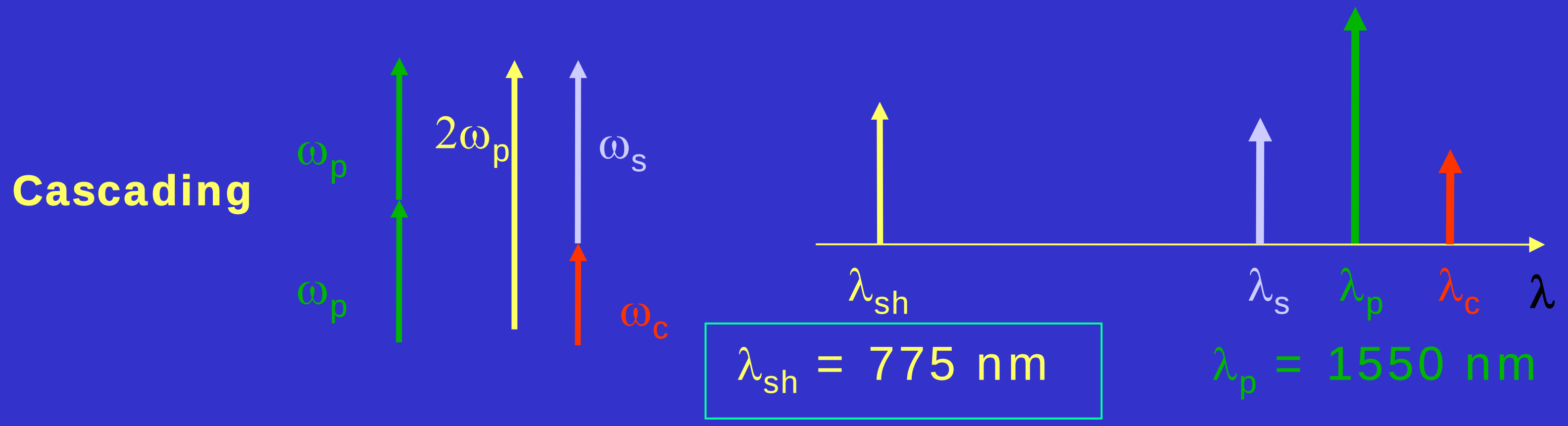
Wavelength Conversion in PPLN Waveguides: Applications to Optical Communications

• Wavelength shifting in WDM systems

• All-optical switching

• Noting that cascaded wavelength conversion is equivalent to an optical phase conjugation process, by inserting the wavelength converter in an optical communication link it is possible to compensate both nonlinearity and dispersion.

Photorefraction



- Photorefractive damage: “permanent” change of refractive indices under illumination with visible or near-infrared light

- Effects: modification of the phase-matching condition, beam distortion

- All the experiments using a CW pump are performed at a temperature higher than 100°C: strong deterrent for applications

Methods to reduce photorefraction

Known solutions :

- **Stoichiometric crystals ([Nb]/([Nb]+[Li])=50 mol%)**
  Reduced number of Lithium vacancies

- **Magnesium-doped crystals (Mg^{2+} @ 5.5 mol%)**
  Increased photoconductivity

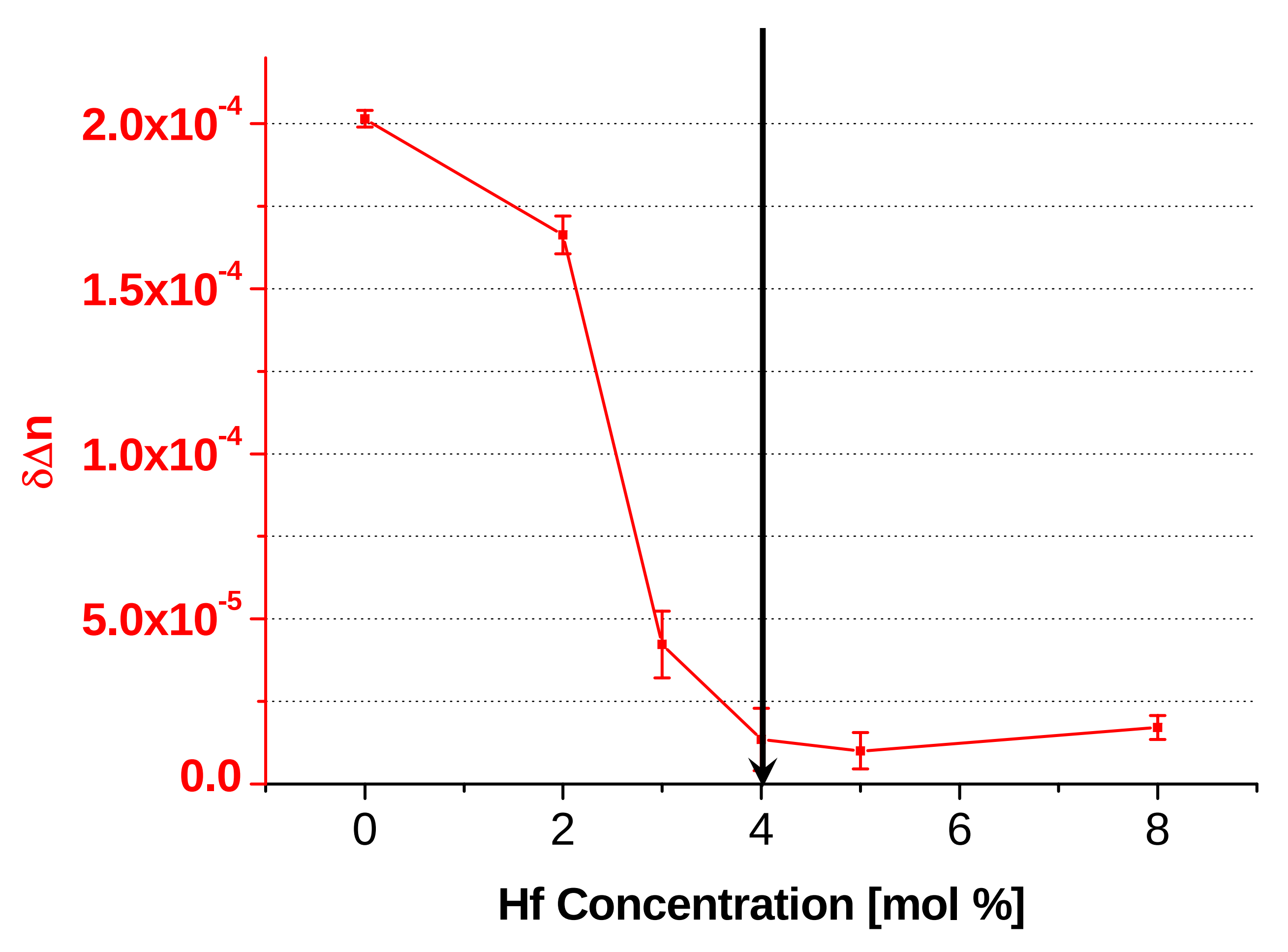
New solution proposed by our group :

- **Hafnium-doped crystals (Hf^{4+}):**
  Required dopant concentration is lower than that for Mg
  *Creation of periodically-poled structures during growth**

A set of congruent Lithium Niobate crystals with increasing concentration of HfO_2 was grown by the Czochralski method at the Institute for Physical Research, National Academy of Sciences of Armenia

Experimental results

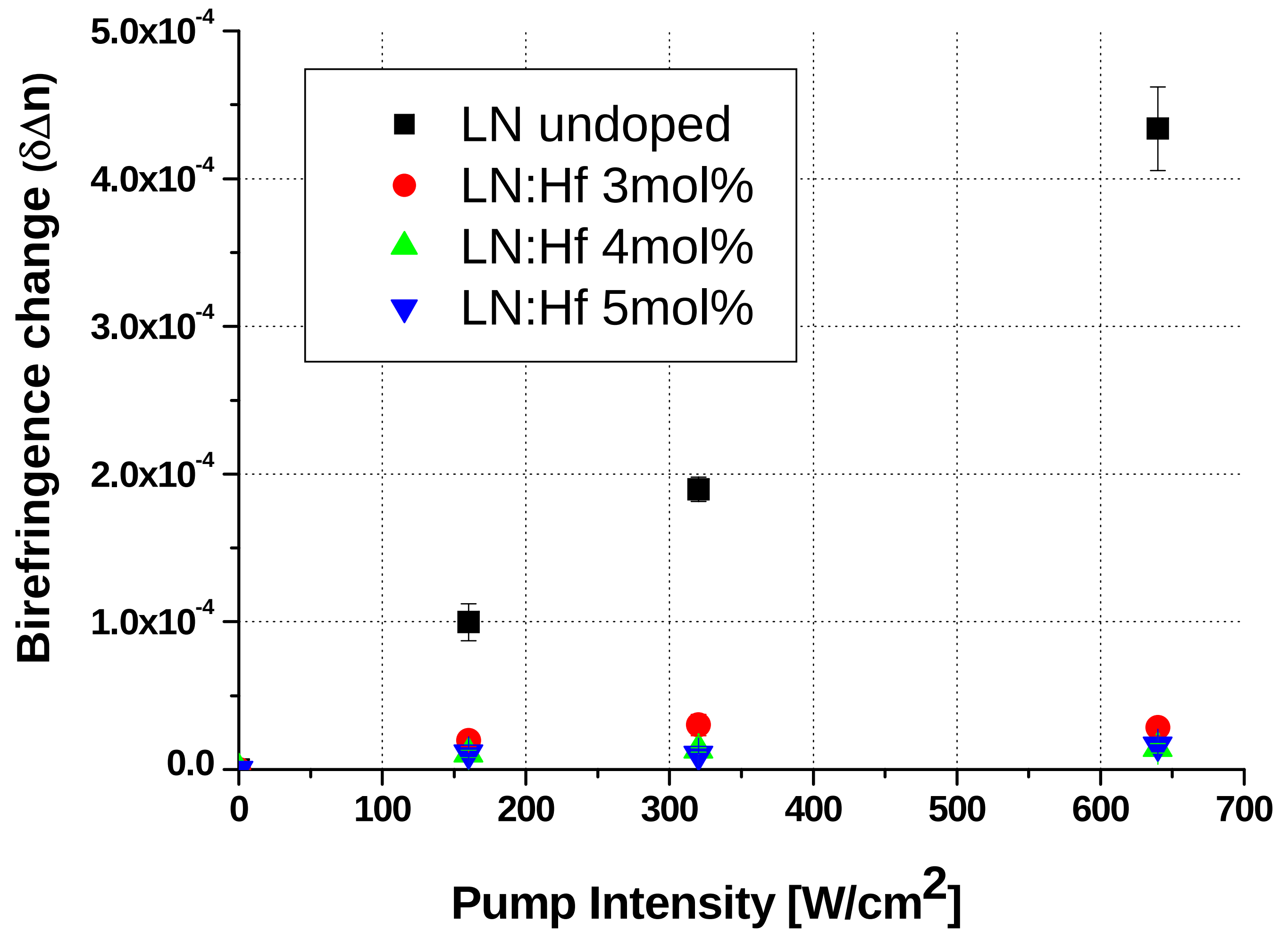
δΔn as a function of Hf concentration



Threshold value is around 4mol%

L. Razzari et al., Appl. Phys. Lett. 86, 131914 (2005)

Photorefractivity vs pump intensity



Properties of Hf-doped LN

- Nonlinear coefficients
- Electrical poling
- Crystal composition
- Crystal homogeneity
- Electro-optical coefficients (D. Grando)

Nonlinearity Cancellation in an Embedded Link with Asymmetrical Power Profiles: Experimental Demonstration of a New Technique based on Optical Phase Conjugation

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1- University of Pavia, It

2- CoreCom Milan

3- University of Stanford, CA

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- **Theory: compensation of the nonlinear effects in High Bit-rate Systems through the Mid-Nonlinearity-Temporal-Inversion (MNTI) technique**

- **Experiment: demonstration of Nonlinearity Compensation in a 600-km-long embedded system**

MNTI

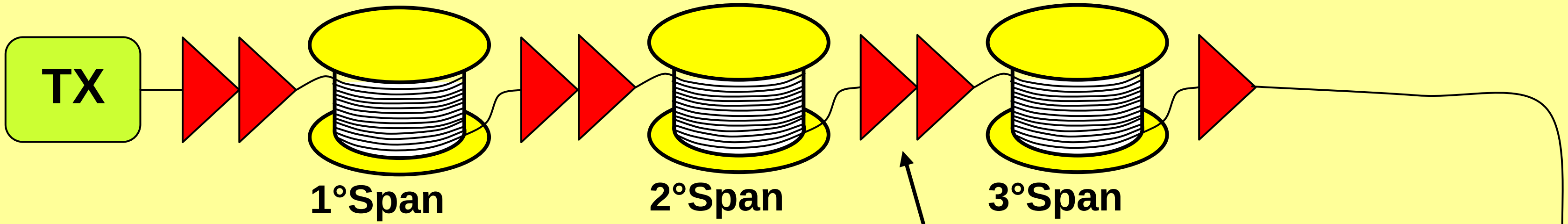
✓*Nonlinearity-compensation through MSSI has been demonstrated only in specifically designed links, with customized dispersion maps and amplification schemes*

✓*Every system proposed in literature and experimentally tested yielding to nonlinearity compensation satisfies the MNTI symmetry-constraint*

✓*The graphical MNTI approach allows easily identifying simple and low cost solutions viable also for already installed communication links*

Theory: Minzioni, Schiffini, Optics Express Vol. 13, 8460-8468 (2005)
Experiment: Minzioni et al., IEEE Photon. Technol. Lett. Vol. 18, 995-997 (2006)

Experimental setup



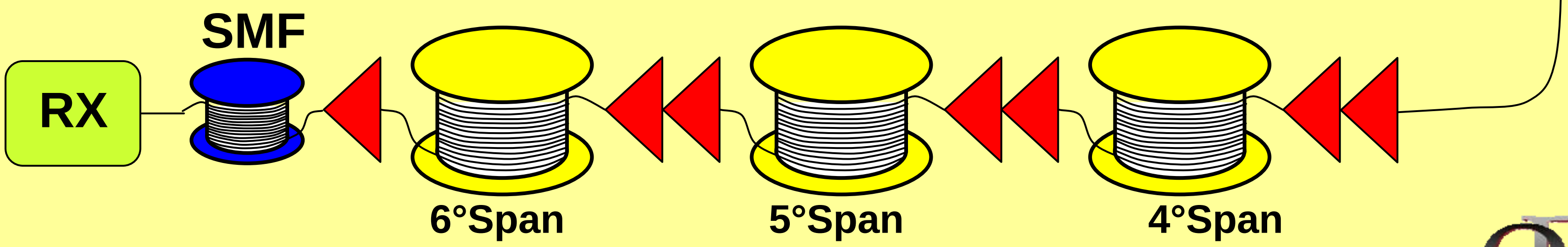
Double stage EDFA

COMMON SYSTEM

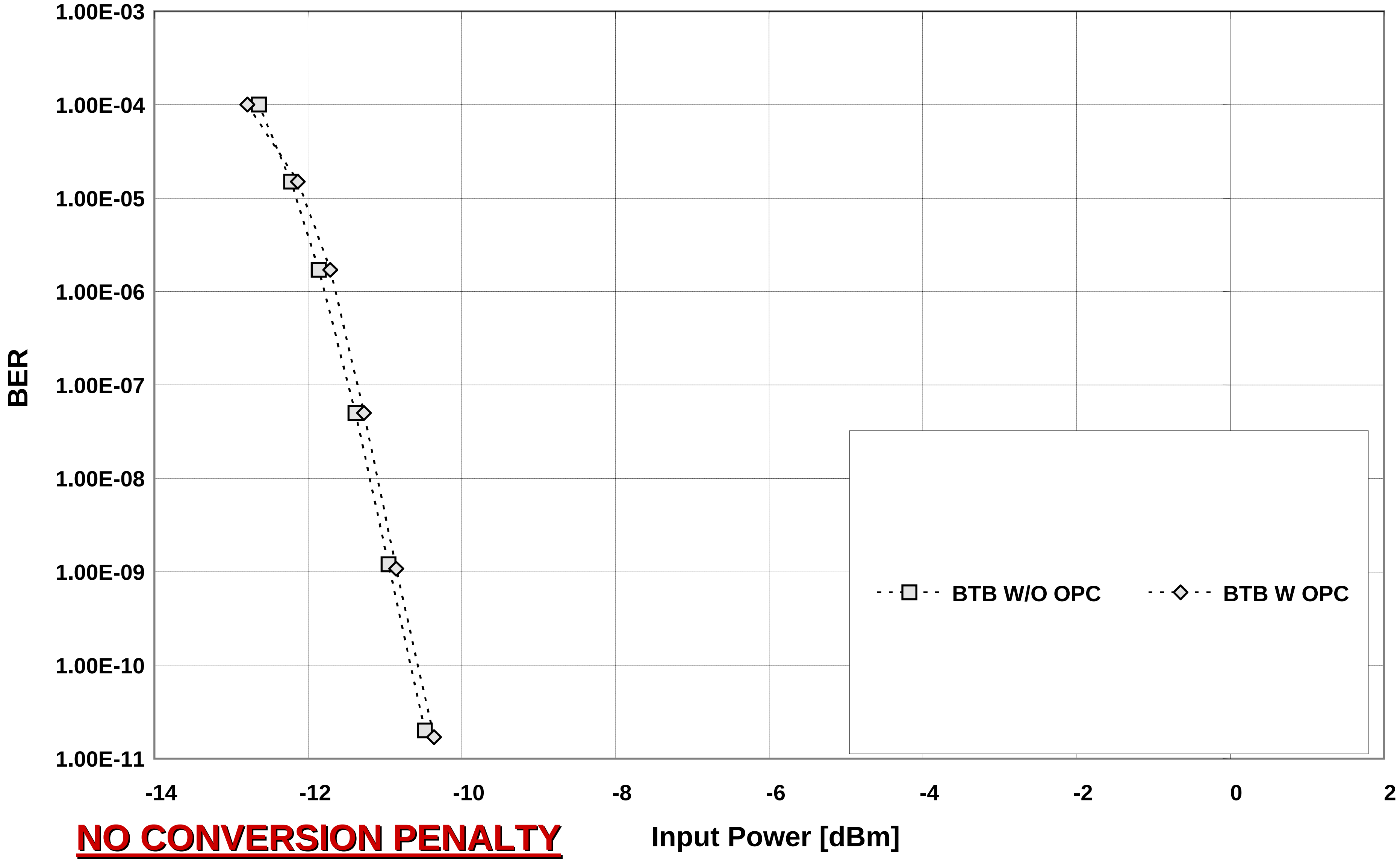
Parameter	Value
Bit-Rate	10Gb/s
Modulation	RZ
T_{FWHM}	45 ps
PRBS	2^{31} bit

Total length: 600 km
Each span length ~ 100 km

Parameter	Name	ITU	A_{eff}	Dispersion	Attenuation
Span	NZDSF	G.655	55 μm^2	-2.9ps nm^{-1} km^{-1}	0.22 dB km^{-1}
Disp. Comp	SMF	G.652	78 μm^2	+16.1 ps nm^{-1} km^{-1}	0.23 dB km^{-1}

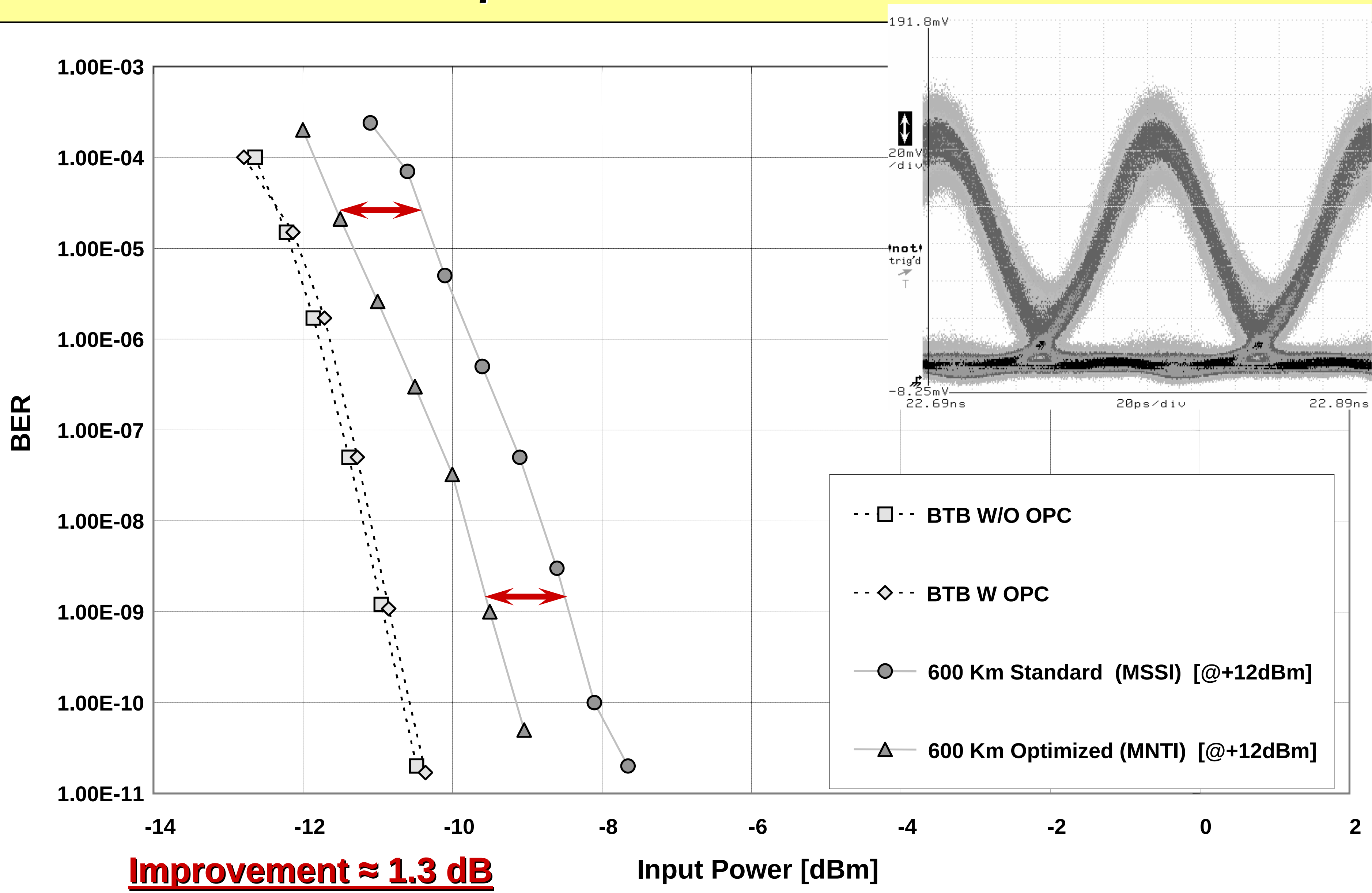


Experimental Results -1



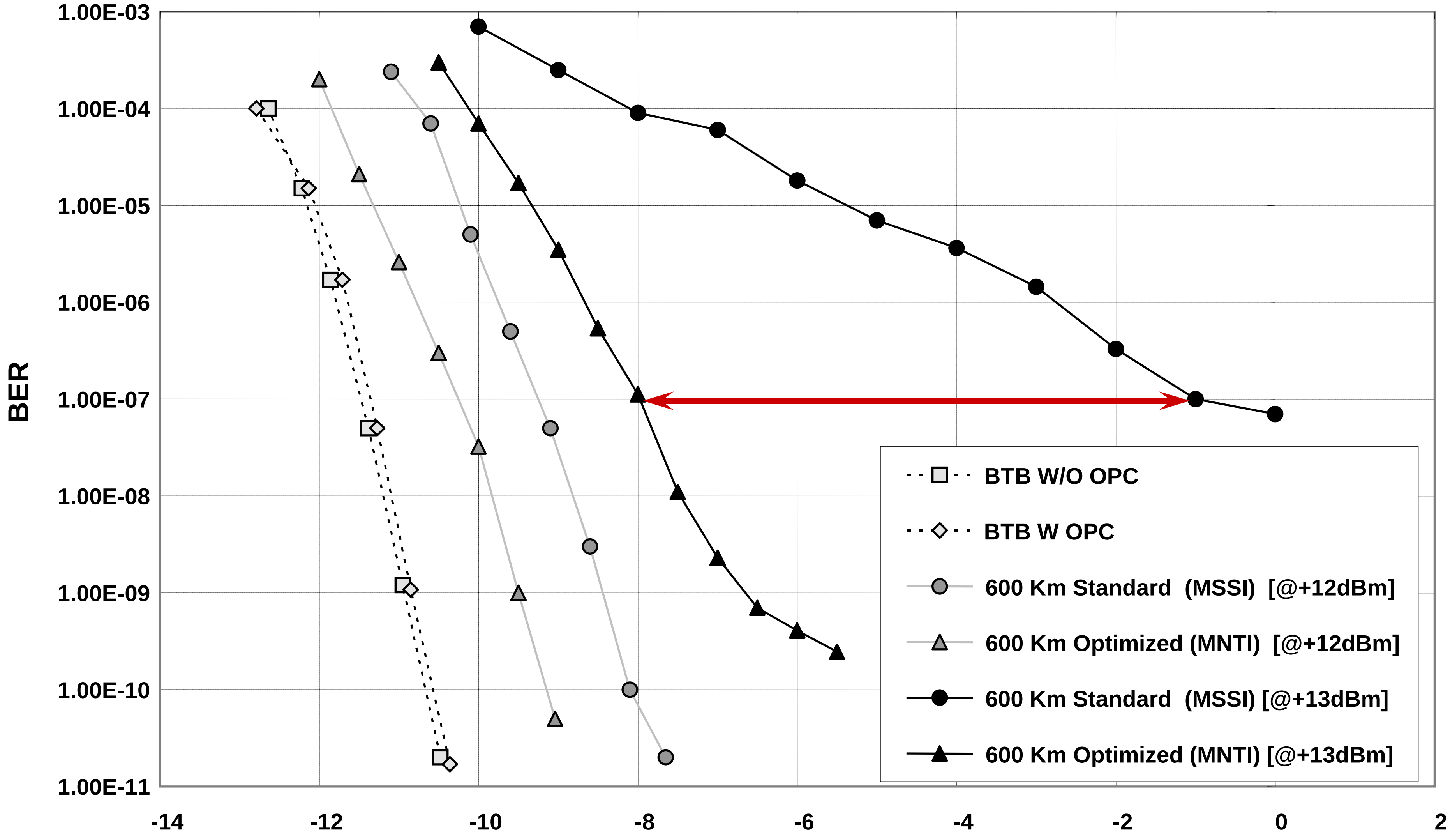
NO CONVERSION PENALTY

Experimental Results -1



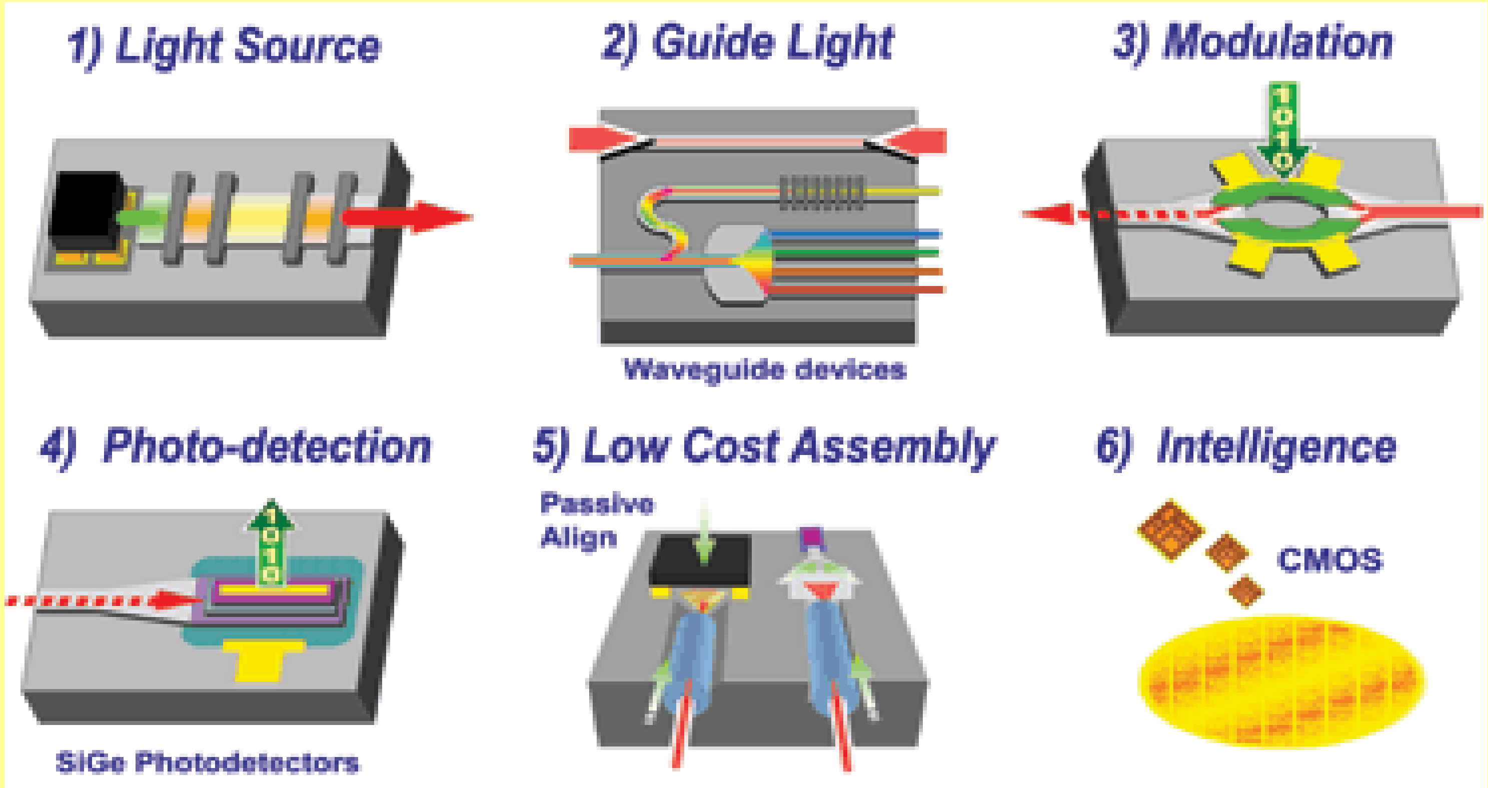
Improvement ≈ 1.3 dB

Experimental Results -1



Improvement > 7 dB @BER = 1 10^{-7}

Silicon Photonics



Optical circuit: Set of optical and electronic functions available as monolithically integrated blocks upon a single substrate.

Active Research Groups: Intel, UCLA, Cornell University

Silicon Photonics

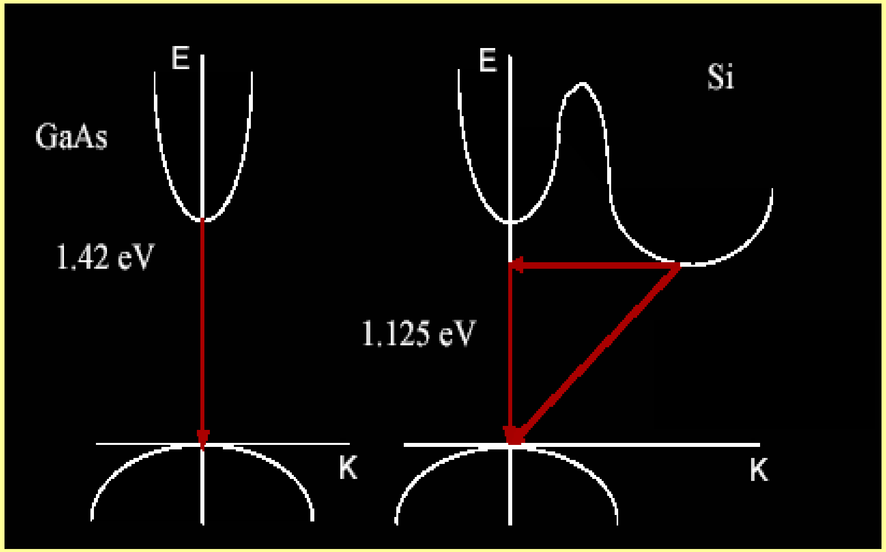
Active devices
based on nonlinear effects

- $\chi^{(2)} \approx 0$
- $\chi^{(3)}$ high:

– Kerr effect
– Raman effect
– Two Photon Absorption
– Free Carrier Absorption

Comparison with fiber:

– Kerr: 100 times higher
– Raman: 1,000-10,000 times higher

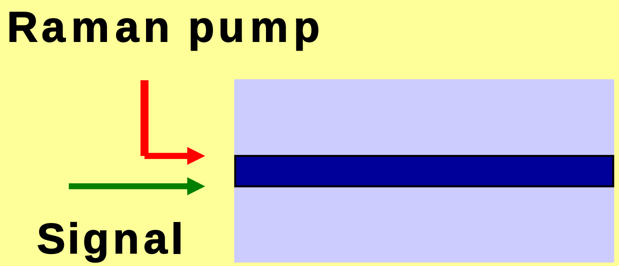


Raman amplification:
light amplification
and lasing action in Silicon

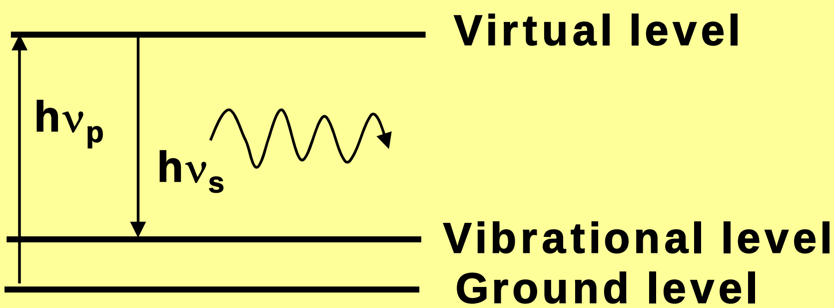
Broadband amplification:
Four Wave Mixing and
Frequency conversion

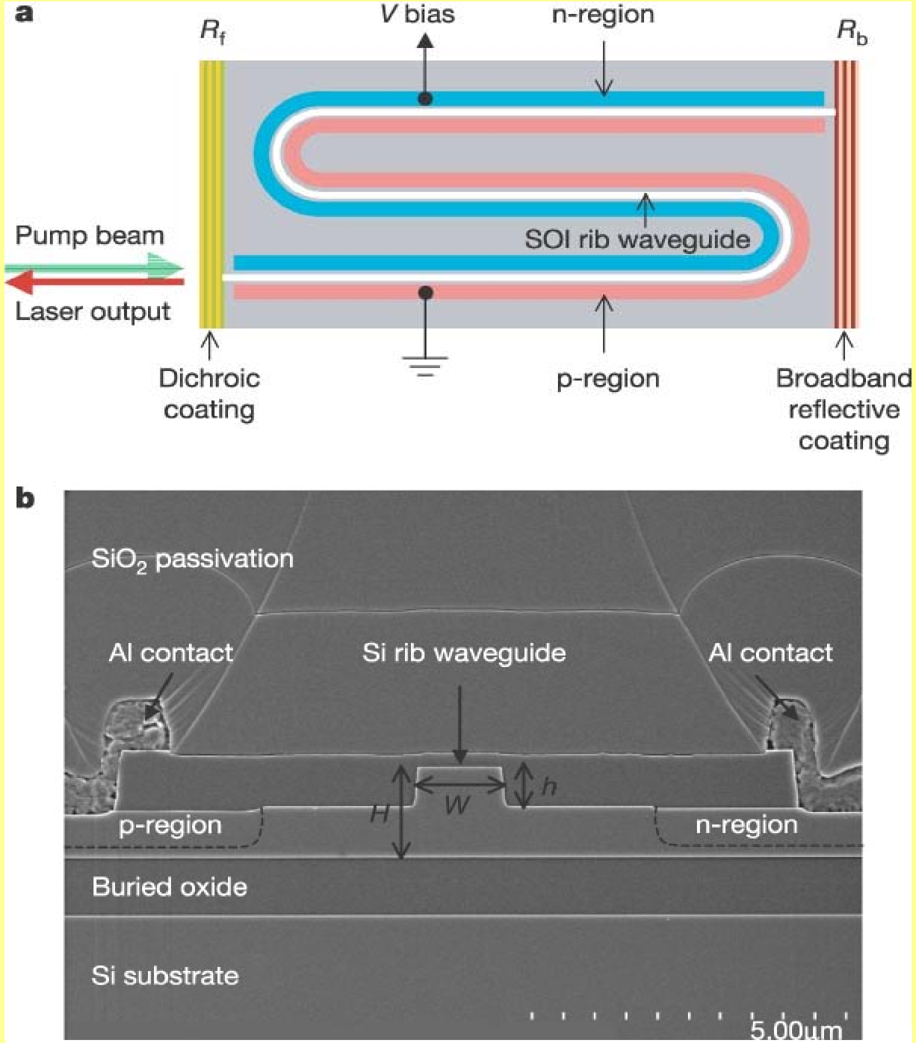
Silicon Photonics

Raman amplification:
light amplification
and lasing action in Silicon



Stokes wave





Intel

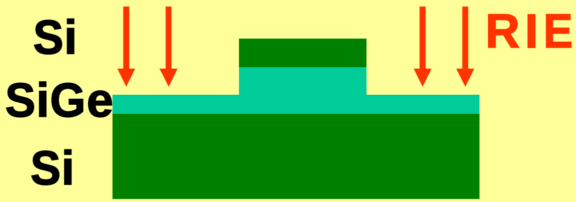
Silicon Photonics

Silicon-Germanium (SiGe): why?

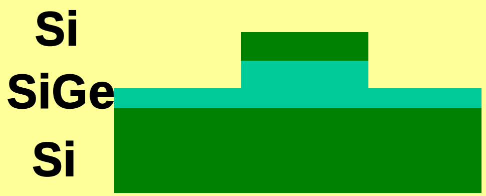
- **tailoring of waveguide properties (by choosing Ge content)**
- **symmetric channel waveguide structure**
- **low propagation losses**
- **high nonlinearity**

Phase 1:
planar waveguide

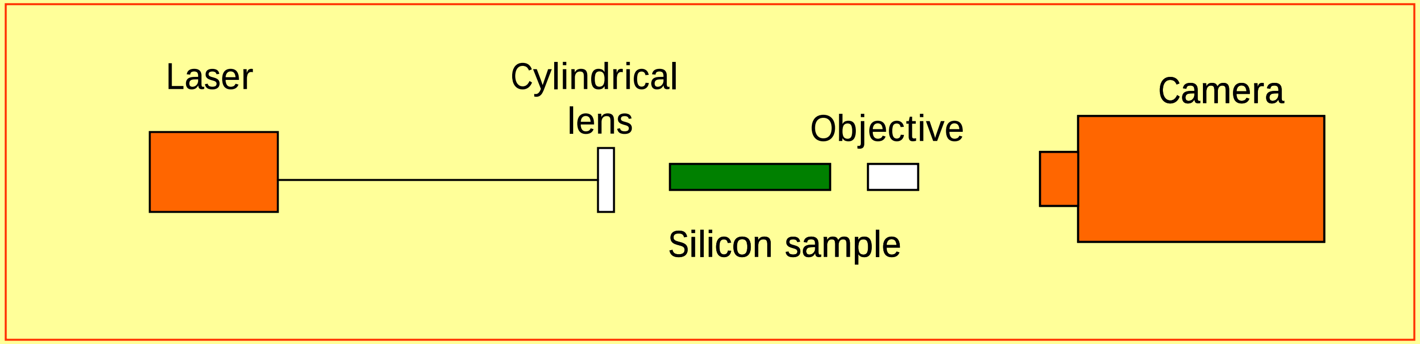
Phase 2:
channel waveguide

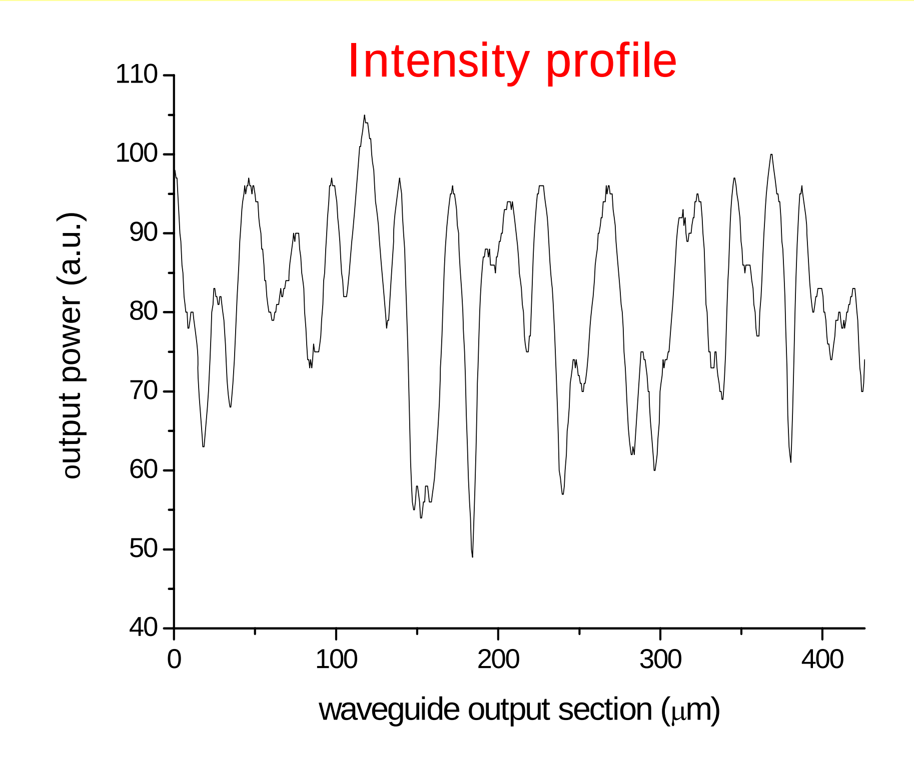


Phase 3:
applications

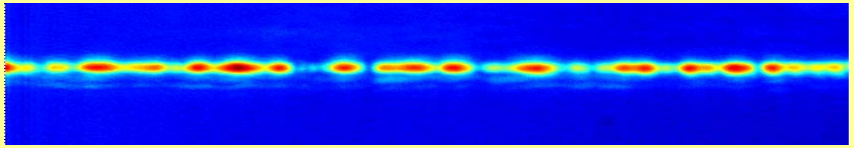


Measurement of the output spatial profile

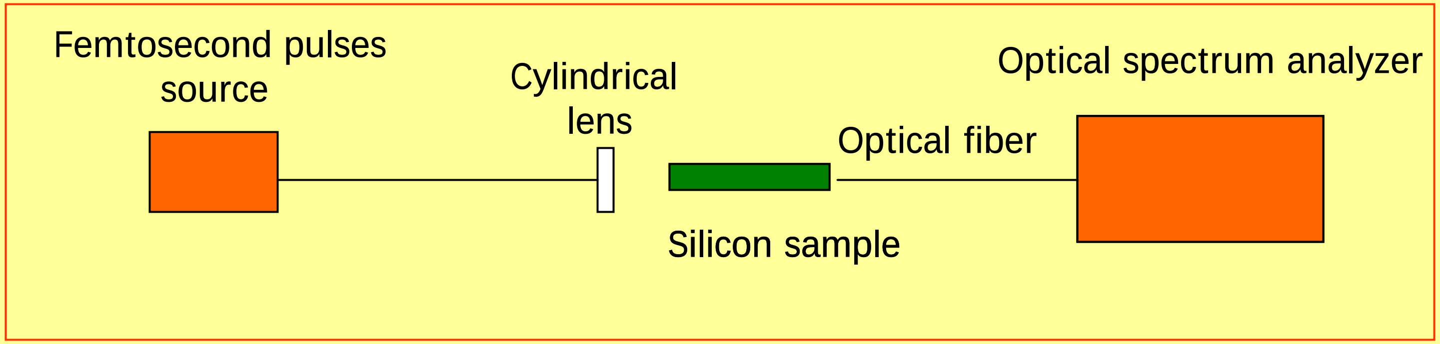




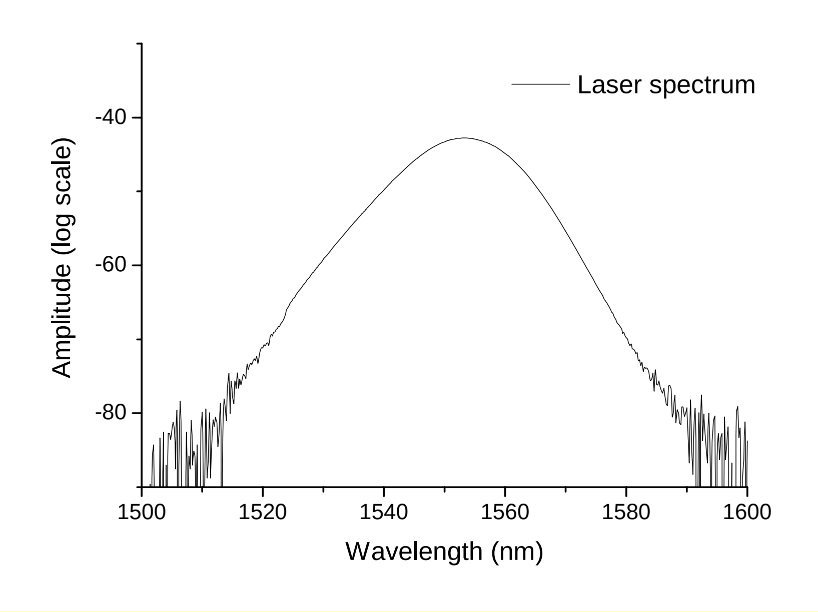
Intensity spatial distribution



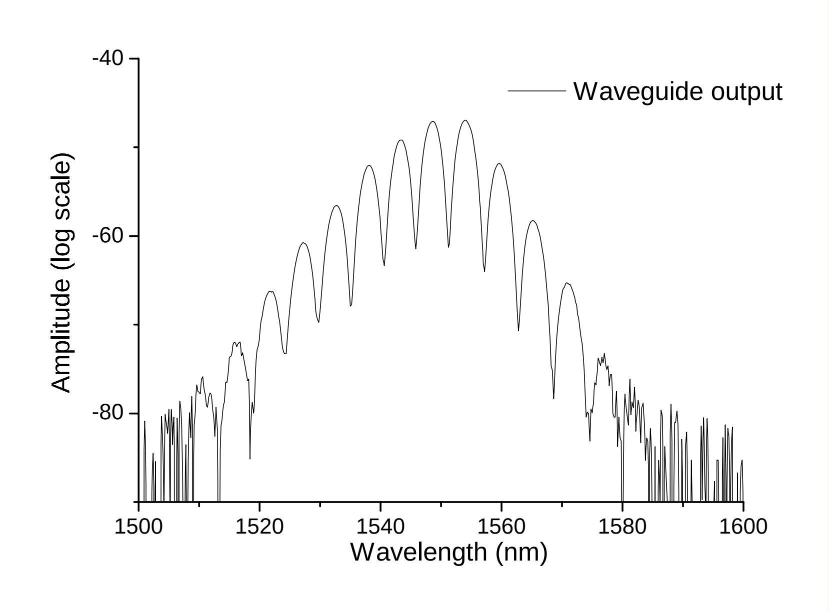
Measurement of the waveguides spectral transmission



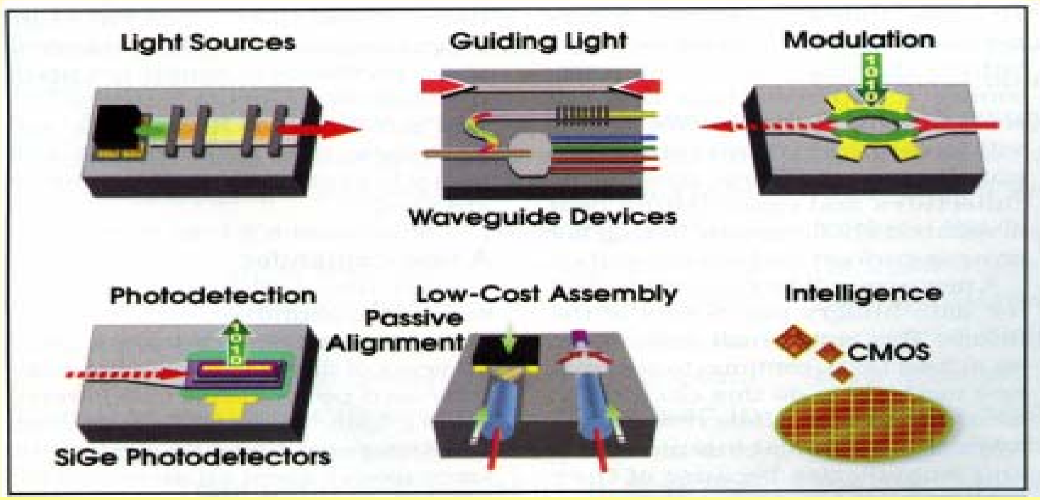
Input spectrum



Output spectrum



Silicon Photonics



Optical circuit:
set of optical and electronic functions available as monolithically integrated blocks upon a single substrate

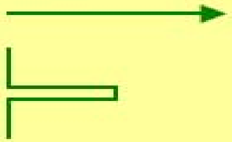
Optical waveguides

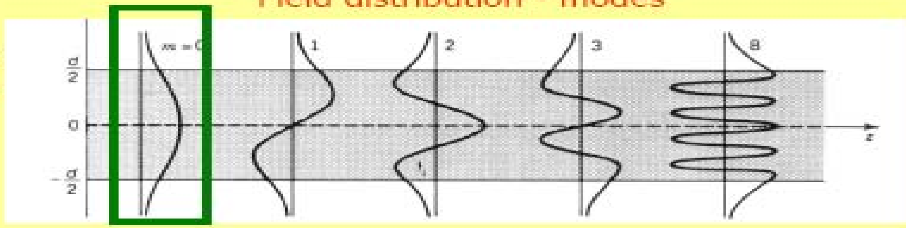
Field distribution - modes

Refractive index

Planar waveguide

light



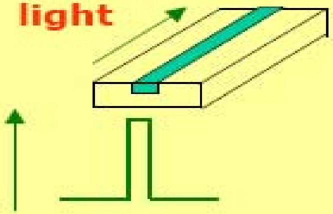


Field distribution - modes

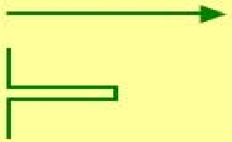
Channel waveguide

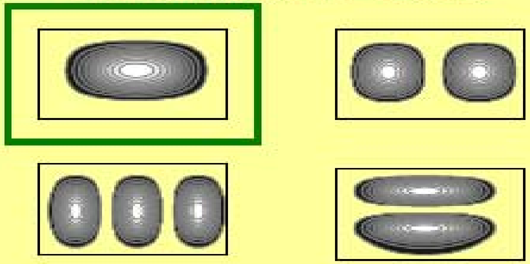
light

Refractive index



Refractive index



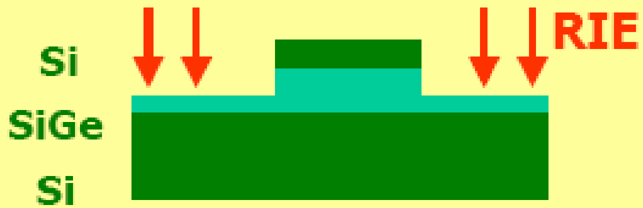


Scheme of the project

Phase 1: planar waveguide

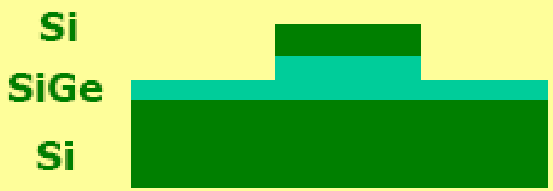
- Fabrication through LEPECVD
- Test the physical and optical quality of the SiGe laye
  - ✓Structure (strain – dislocation formation)
  - ✓Optical uniformity - losses
  - ✓Refractive index
  - ✓Birefringence

Phase 2: channel waveguide



- Fabrication through LEPECVD + RIE
- Low losses (< 0.8 dB/cm), control of the surfaces, appropriate design
- Physical structure of the layer
- Trade-off between small modal area for the nonlinear performance optimisation and light coupling efficiency;
- Reduction of the free carriers induced losses
- Suitable dispersive behaviour

Phase 3: applications



- Light generation and amplification through Raman effect
- Wavelength conversion
- Other interesting applications??