All-Optical Wavelength Conversion in Ultra-High Speed Optical Communication Systems

Paulo Almeida

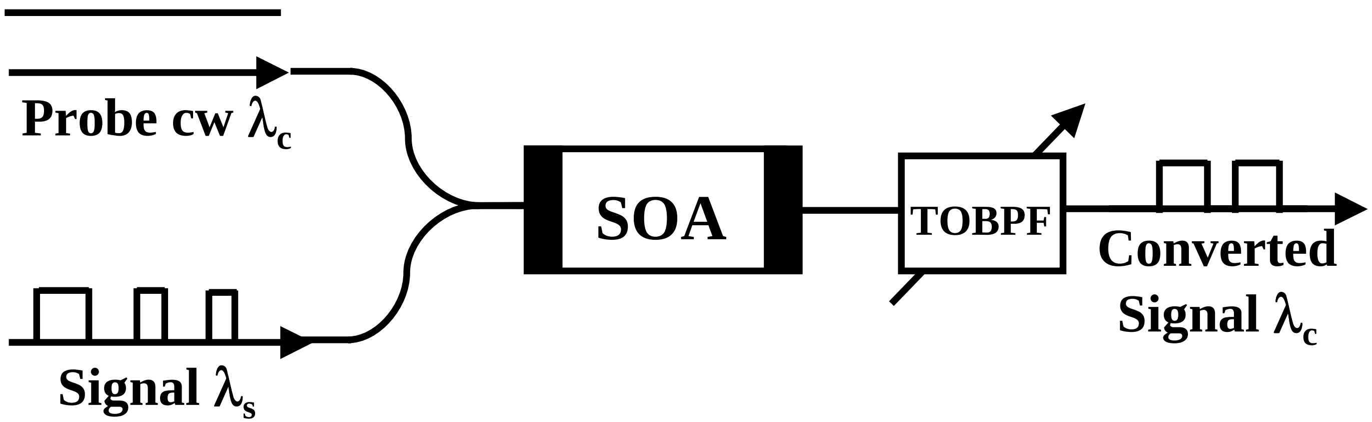
Instituto de Telecomunicações

Wavelength Conversion in the Optical Communication Systems

- All Optical Cross-Connects (OXCs):
  - Wavelength routing networks
  - Simplify the OXC's architecture
  - Increase the number of light paths between two end points
  - Avoids communication's fail due to the wavelength collision
  - Independent wavelengths' management in subnetworks
- Multi-wavelength sources:
  - Integrated optics components are the most promising

How to perform wavelength conversion?

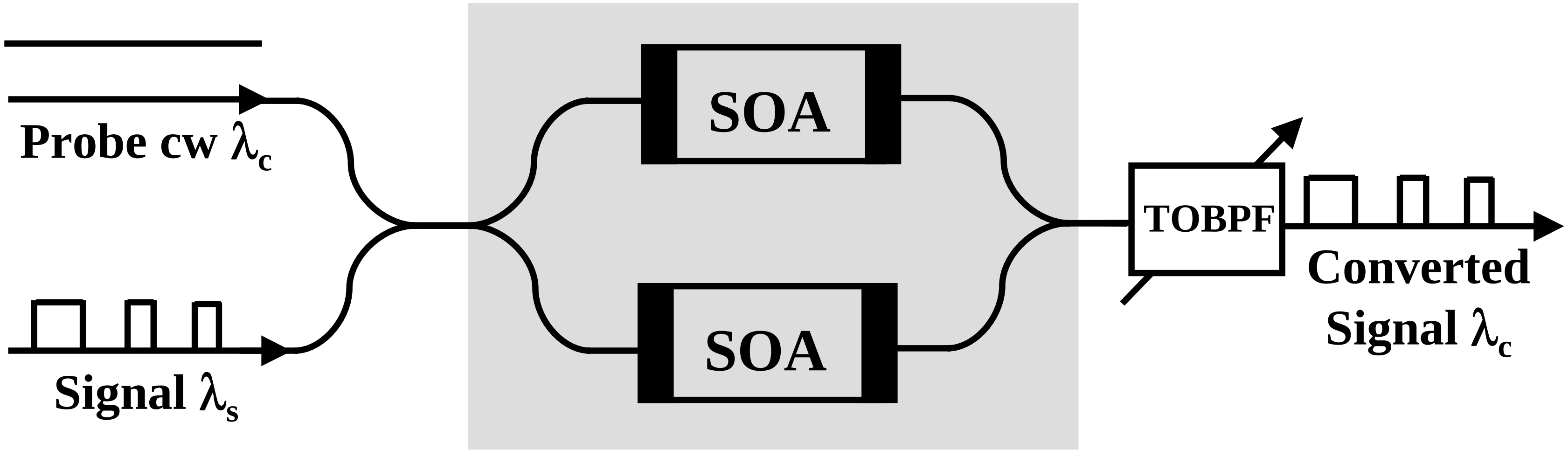
- Cross Gain Modulation (XGM):



- Gain modulation due to the carrier depletion
- Impairments:
  - SNR degradation
  - Extinction ratio degradation
  - Bit stream inversion
  - Phase modulation

How to perform wavelength conversion?

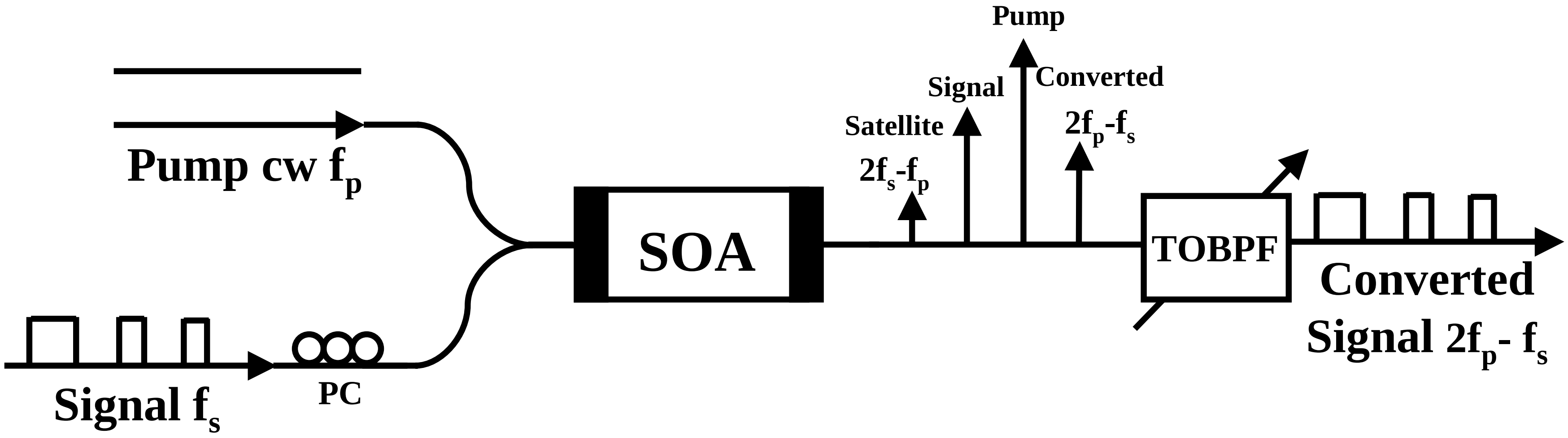
- Cross Phase Modulation (XPM):



- Mach-Zehnder interferometer.
- Phase modulation ⇨ Intensity modulation.
- Reduces greatly the pulses' chirp and distortion.

How to perform wavelength conversion?

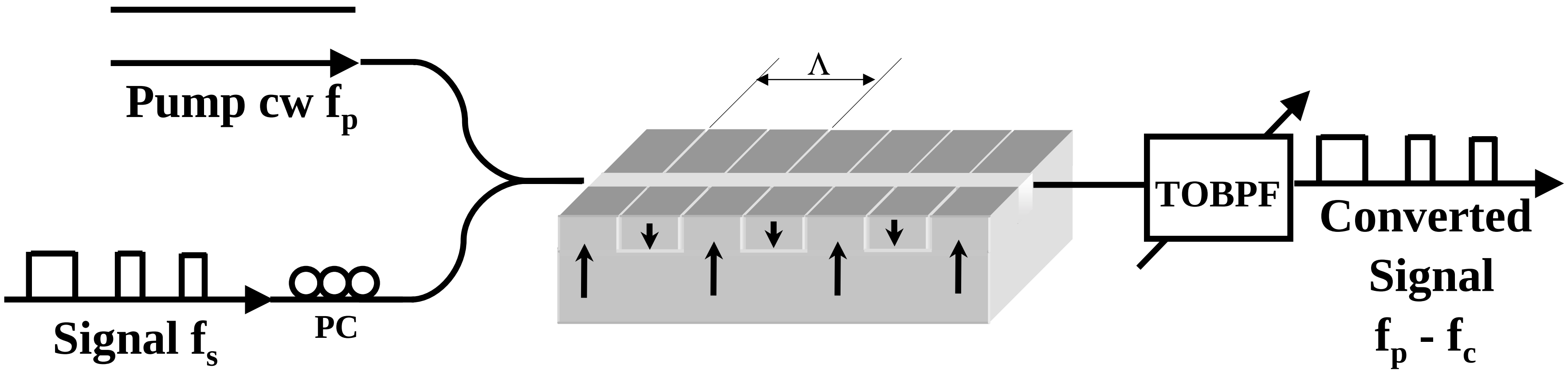
- Four Wave Mixing (FWM):



- Carrier pulsation at the beating frequency causes index-gain grating which scatters the signal and the pump generating new frequencies.

How to perform wavelength conversion?

- Difference Frequency Generation (DFG):



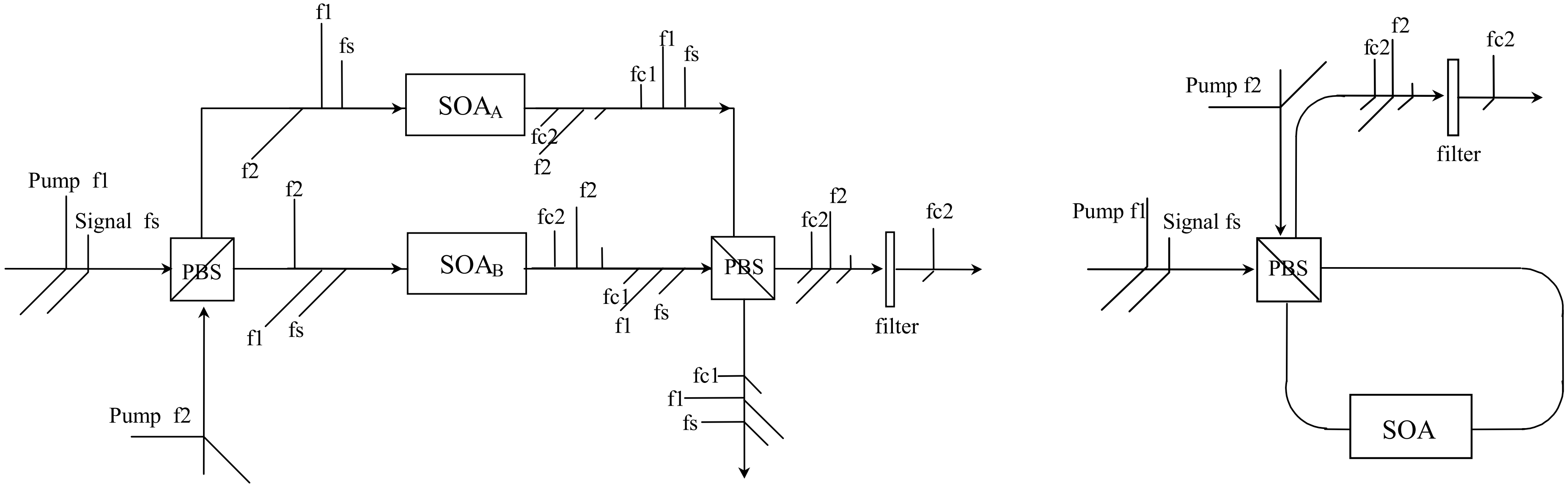
- Periodically poled Lithium niobate (PPLN)
- Quasi-phase matching condition

Wavelength conversion techniques

	XGM in SOA	XPM in SOA	FWM in SOA	DFG in Passive waveguides
Bit-rate limit	10 Gbit/s	10 Gbit/s	>10 Gbit/s	>10 Tbit/s
Transparency	Limited	Limited	Strict	Strict
Polarization sensivity	Insensitive	Insensitive	Sensitive	Sensitive
s/n ratio	NF 7-9 dB	NF 3 dB	NF 7-9 dB	Same as input sinal s/n ratio
Simultaneous conversion	No	No	Yes	Yes
Advantages	•Simple configuration	•Reduced Chirp and distortion	•Transparency •Chirp reversal	•Transparency •No excess noise •Broad bandwidth
Disadvantages	•High chirp, noise figure and distortion. •Bit stream inversion	•Limited transparency	•Large ASE noise	•Crystal poling

Wavelength converter based on FWM

- Insensitivity to the signal polarization and conversion interval

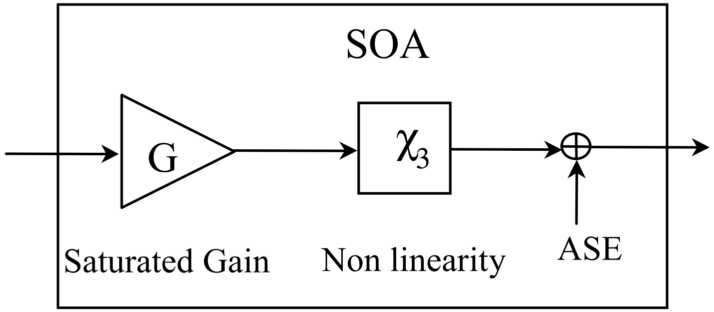


Modelling wavelength converter based on FWM

- Lumped Model

$$\mathbf{E}_{in,soa\,\mathbf{A}} = \sqrt{\alpha P_s}\cos\theta\exp[j(\omega_s t+\phi_s)]\hat{\mathbf{x}} + \sqrt{\frac{\alpha P_1}{2}}\exp[j(\omega_1 t+\phi_1)]\hat{\mathbf{x}} + \sqrt{\frac{\alpha P_2}{2}}\exp[j(\omega_2 t+\phi_2)]\hat{\mathbf{y}}$$

$$\mathbf{E}_{in,soa\,\mathbf{B}} = \sqrt{\alpha P_s}\sin\theta\exp[j(\omega_s t+\phi_s)]\hat{\mathbf{y}} + \sqrt{\frac{\alpha P_1}{2}}\exp[j(\omega_1 t+\phi_1)]\hat{\mathbf{y}} + \sqrt{\frac{\alpha P_2}{2}}\exp[j(\omega_2 t+\phi_2)]\hat{\mathbf{x}}$$



$$\mathbf{E}_{out,soa\,\mathbf{A}} = \sqrt{\frac{P_s P_1 P_2 G^3 \alpha^3}{4}}\cos\theta\, r(\omega_1-\omega_s)\exp\ [j((\omega_1+\omega_2-\omega_s)t+\phi)]\hat{\mathbf{y}}$$

$$\mathbf{E}_{out,soa\,\mathbf{B}} = \sqrt{\frac{P_s P_1 P_2 G^3 \alpha^3}{4}}\sin\theta\, r(\omega_1-\omega_s)\exp\ [j((\omega_1+\omega_2-\omega_s)t+\phi)]\hat{\mathbf{x}}$$

Modelling wavelength converter based on FWM

- Saturated Gain
  - Carrier depletion due to the Spontaneous and Stimulated Emission

$$\frac{P_1 + P_2}{P_{sat}} = \left(\frac{1 - \frac{\gamma_{sc}}{\Gamma g_0}}{\frac{\gamma_{sc}}{\Gamma g_0}} \right) \frac{1 - \left(\frac{G}{G_0} \right)^{\frac{\gamma_{sc}}{\Gamma g_0}}}{G - \left(\frac{G}{G_0} \right)^{\frac{\gamma_{sc}}{\Gamma g_0}}}$$

- Efficiency of the FWM process
  - Carrier pulsation is mainly due to the following Physical phenomena
    - Electron-hole recombination
    - Spectral hole burning
    - Carrier heating

$$R(\omega_1 - \omega_s) = |r(\omega_1 - \omega_s)|^2 = \left| \sum_{m=1}^{3} c_m \frac{1}{1 - i2\pi(f_1 - f_s)\tau_m} \right|^2 \qquad c_m = \frac{g_0 L}{0.46 G \left(1 + \frac{GP(0)}{P_{sat}} \right)} \frac{1 - i\alpha_m}{P_m}$$

Modelling wavelength converter based on FWM

- Performance of the wavelength converter
  - Conversion efficiency

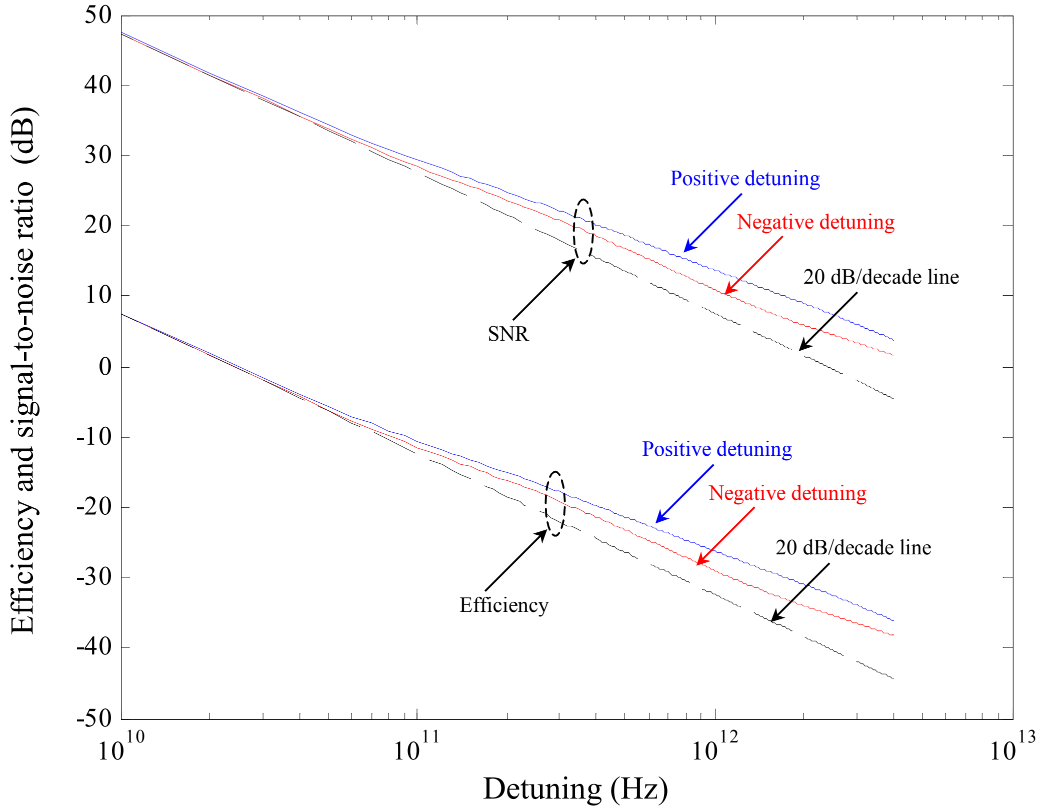
$$\eta \equiv \frac{P_{out}}{P_s} = \frac{\alpha^4 G^3 P_1 P_2}{4} R(\omega_1 - \omega_s)$$

  - Signal-to-noise ratio
    - Considering the beating between signal and ASE noise dominant
    - Considering ASE noise added on the same polarization of the signal

$$SNR = \frac{P_{out}}{2 W_{ASE} B_{signal}} = \frac{\alpha^4 G^3 P_1 P_2 P_s}{8 B_{signal} h f_{conv} (G-1) n_{sp}} R(\omega_1 - \omega_s)$$

Modelling wavelength converter based on FWM

- Wavelength converter performance



- Opto Speed SOA L956

Optical Confinement	0.35
Scattering loss	1000 (1/m)
Saturation power	8.5 (dBm)
Unsaturated Gain	28.8 (dB)
Length	1.5 (mm)
Active zone area	0.72 (μm^2)
Linear index gain coupling coef.	8
CH index gain coupling coef.	4
SHB index gain coupling coef.	0.6 (not given)
Spontaneous lifetime	70 (ps)
CH lifetime	800 (fs)
SHB lifetime	60 (fs)
CH non linear coefficient	2 (1/W)
SHB non linear coefficient	1 (1/W)
Injection current	500 (mA)

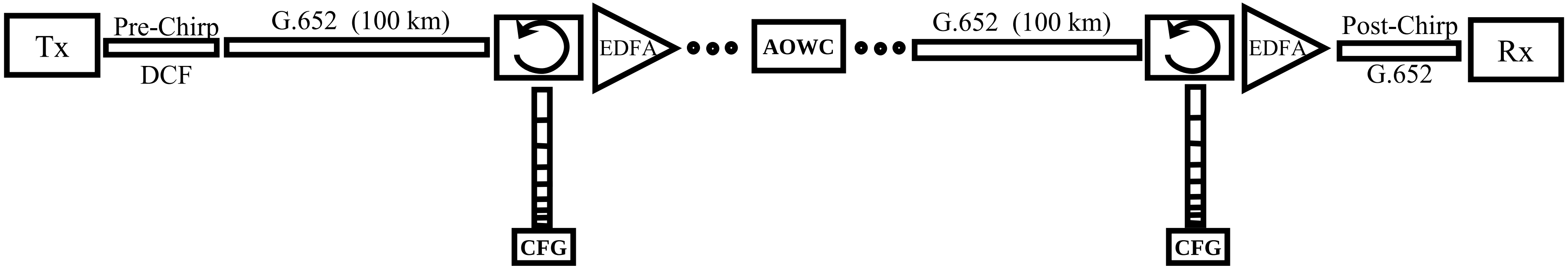
- Measurements from Opto Speed Italia:
  - Down conversion with a frequency detuning of 100 GHz
  - Efficiency –10.2 dB and SNR 29.1 dB

Communication system with wavelength conversion

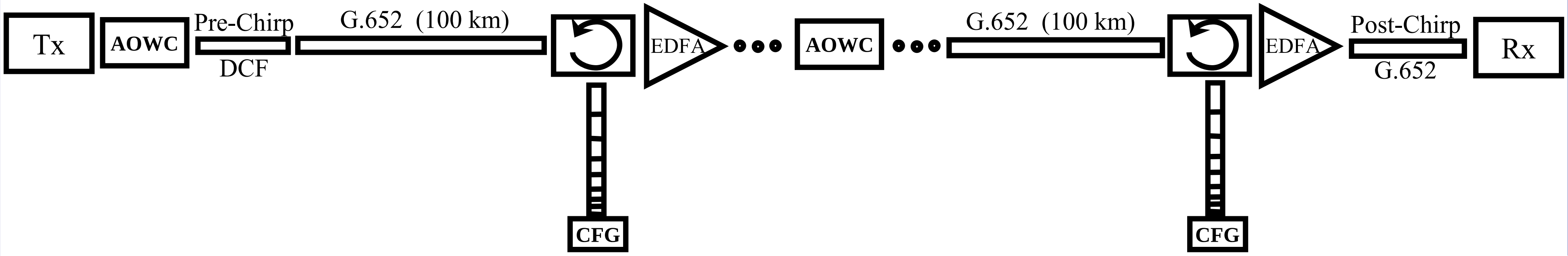
- Transmitter Output:
  - Average optical power 8 dBm
  - Gaussian pulses at 40 Gbit/s
- Transmission over SSMF
- Fibre span of 100 km
- Partial compensation of intra-channel non-linear effects
- Optical amplifiers full compensate the fibre losses [G = 25 dB]
- Wavelength Conversion:
  - Signal-Pump1 detuning 250 GHz
  - Efficiency –18 dB
  - Optical signal-to-noise ratio 22 dB
  - Boost amplification to equalize channels [G = 18 dB]
- Direct detection receptor

Communication system with wavelength conversion

- Optical signal-to-noise ratio at the receptor input



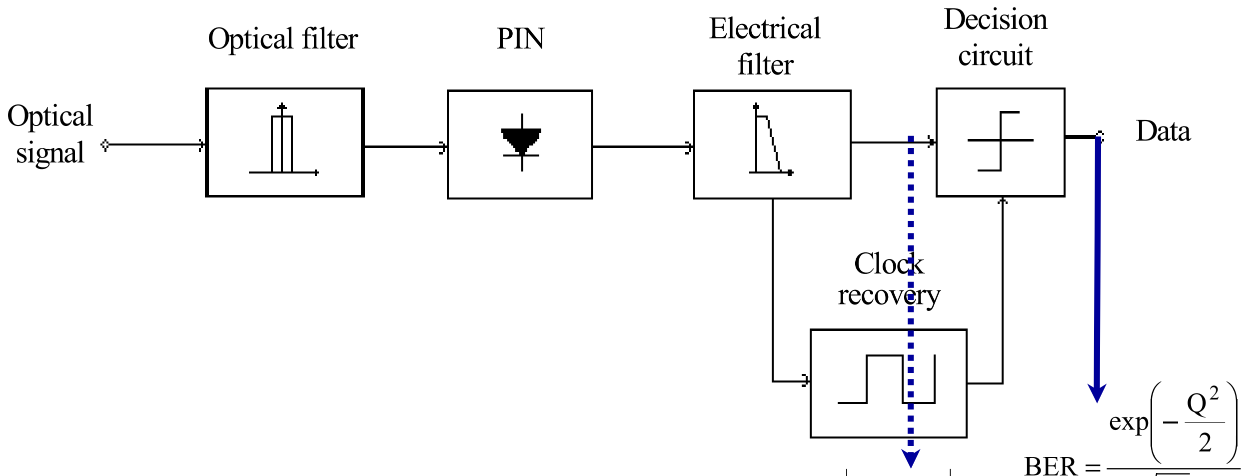
[Scheme 1] OSNR= 16.2 (dB)



[Scheme 2] OSNR= 15.1 (dB)

Communication system with wavelength conversion

- Modelling the direct detection's receptor for BER estimation



$$Q = \frac{|m_1 - m_0|}{\sigma_1 + \sigma_0}$$

$$BER = \frac{\exp\left(-\frac{Q^2}{2}\right)}{\sqrt{2\pi}Q}$$

$$m_0 = p\Re N_0 B_{opt} \int_{-\infty}^{+\infty} h_r(t-\tau)d\tau + \Re \frac{P_p}{(\varepsilon+1)} \int_{-\infty}^{+\infty} h_r(t-\tau)d\tau$$

$$m_1 = p\Re N_0 B_{opt} \int_{-\infty}^{+\infty} h_r(t-\tau)d\tau + \Re \int_{-\infty}^{+\infty} h_p(\tau) h_r(t-\tau)d\tau$$

$$\sigma_0^2 = p\Re^2 N_0^2 B_{opt} \int_{-\infty}^{+\infty} h_r^2(t-\tau)d\tau + \frac{2\Re^2 N_0 P_p}{\varepsilon+1} \int_{-\infty}^{+\infty} h_r^2(t-\tau)d\tau + \sigma_{th}^2$$

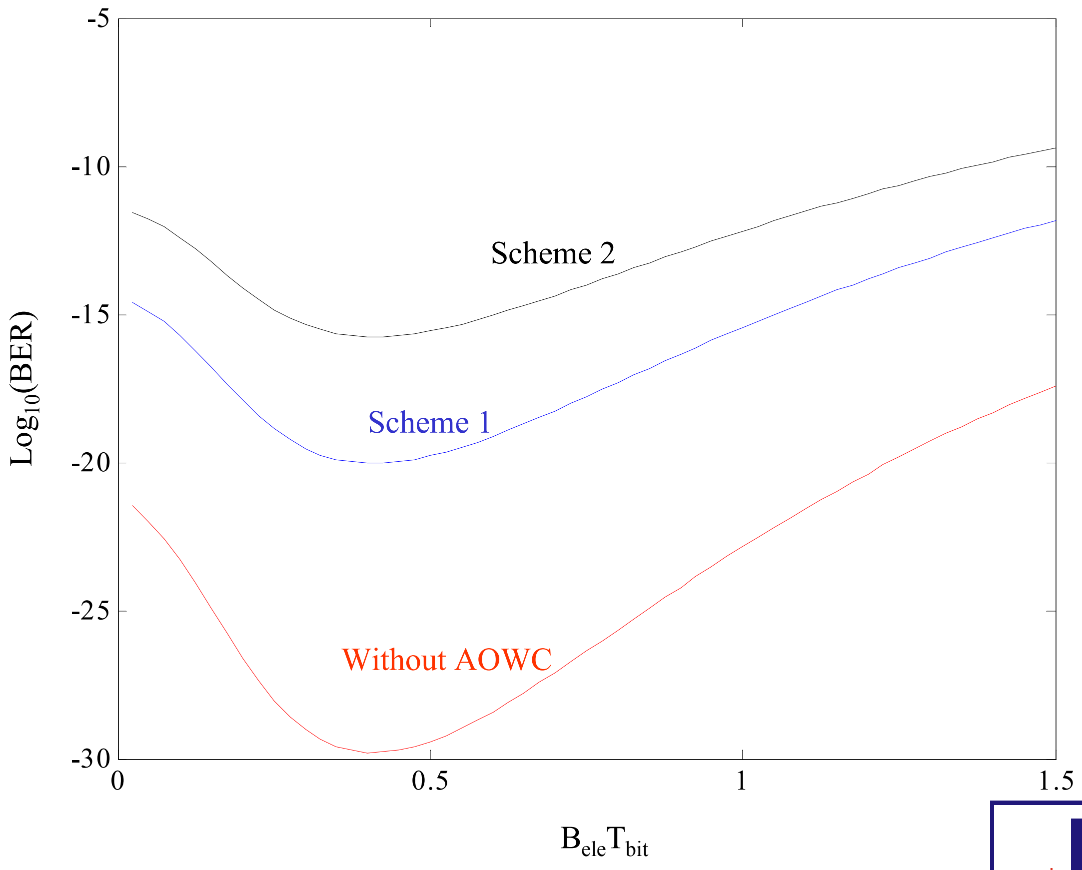
$$\sigma_1^2 = p\Re^2 N_0^2 B_{opt} \int_{-\infty}^{+\infty} h_r^2(t-\tau)d\tau + 2\Re^2 N_0 \int_{-\infty}^{+\infty} h_p(\tau) h_r^2(t-\tau)d\tau + \sigma_{th}^2$$

$$\sigma^2 = \sigma_{ase-ase}^2 + \sigma_{Sig-ase}^2 + \sigma_{th}^2$$

Communication system with wavelength conversion

- BER estimation for a receptor with a gaussian electrical filter

Optical filter bandwidth	100 (GHz)
Responsivity	0.6 (A/W)
Electrical amplifier gain	10 (dB)
Optimum electrical filter bandwidth	16 (GHz)
Extinction ratio	10 (dB)
Input average optical power	2 (dBm)



- Wavelength converting the channel once the BER degrades 10 dB.

- Wavelength converting the channel twice the BER degrades 15 dB

Conclusions

- Four techniques to perform wavelength conversion:
  - Cross gain modulation (simplest configuration)
  - Cross Phase modulation (good quality of the signal)
  - Four wave Mixing (transparency)
  - Difference frequency generation (excellent performance but difficult fabrication)
- FWM Wavelength converter based on a diversity polarization scheme
- Lumped model gives a good approximation to the efficiency and the signal to noise ratio of the FWM converter

Future work

- Model should take into account the pulse distortion due the self-phase modulation effect

Acknowledgements

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Thanks