Optimal Configuration for Doped Fiber

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Hybrid Raman/Erbium-Amplifiers

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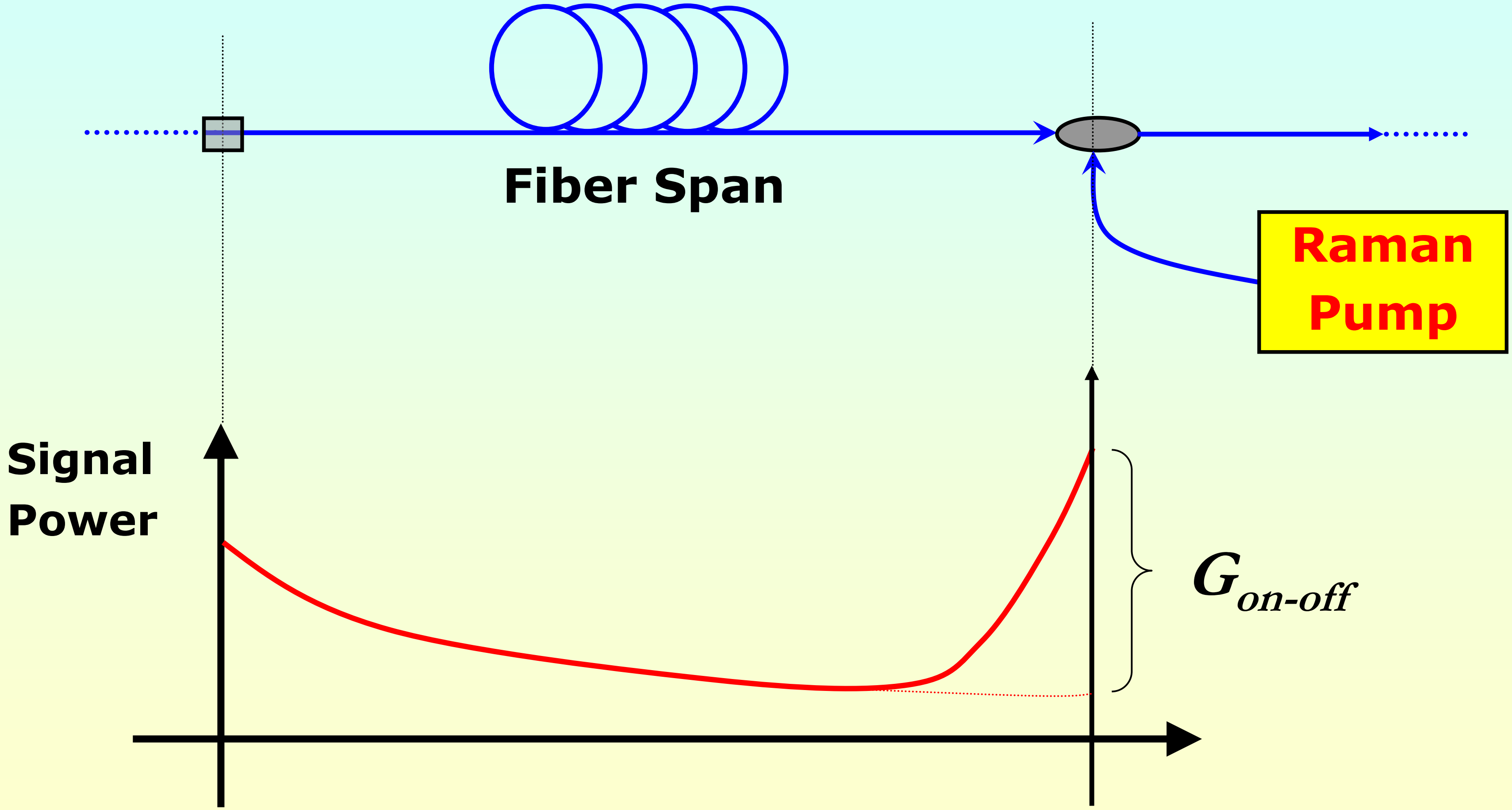
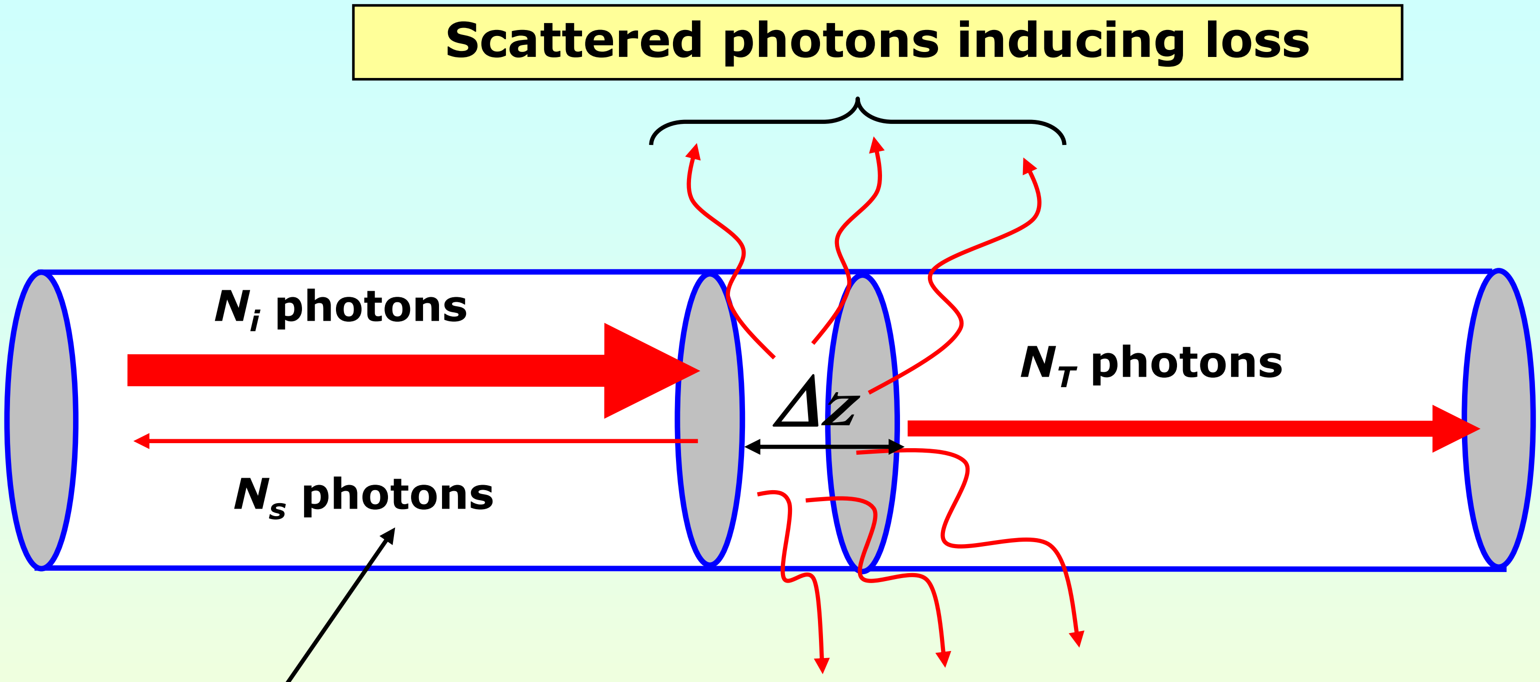
OUTLINE

- Introduction to the Raman Amplification
- Rayleigh Back-Scattering
- Model of Raman Amplifier
- Noise-Figure Definition
- Non-Linear Weight
- *RA* vs. *EDFA*
- Optimization Process for Hybrid Raman/Erbium-Doped Fiber Amplifiers (HFA)

What is a Raman Amplifier ?



Rayleigh Back-Scattering



Back-scattered photons are that part of scattered photons propagating in the opposite direction with respect to the signal

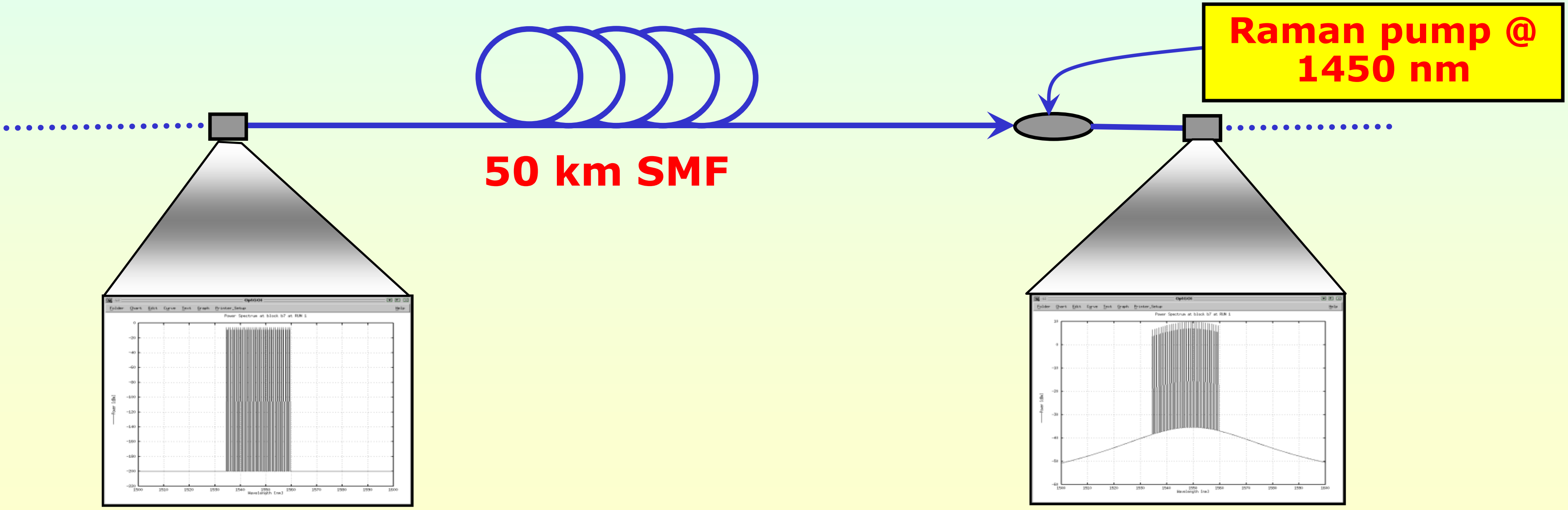
- ***R*** is the **capture factor**
- It is the ratio of back-scattered photons to all the scattered photons. $R \in [0;1]$
- It is specified in units of dB
- Typical value: -30 dB

Raman Amplification

Multiple scattered signal components

Multiple scattered noise components

$$P_{out}(f) = \exp\{-\alpha_S L\} G_{on-off}(f) \cdot P_{in}(f) + \sum_{i=1}^{+\infty} P_{out}^{(i)}(f) + S_{ASE}^{(0)}(f) + \sum_{i=1}^{+\infty} S_{ASE}^{(i)}(f)$$



Gain & Noise

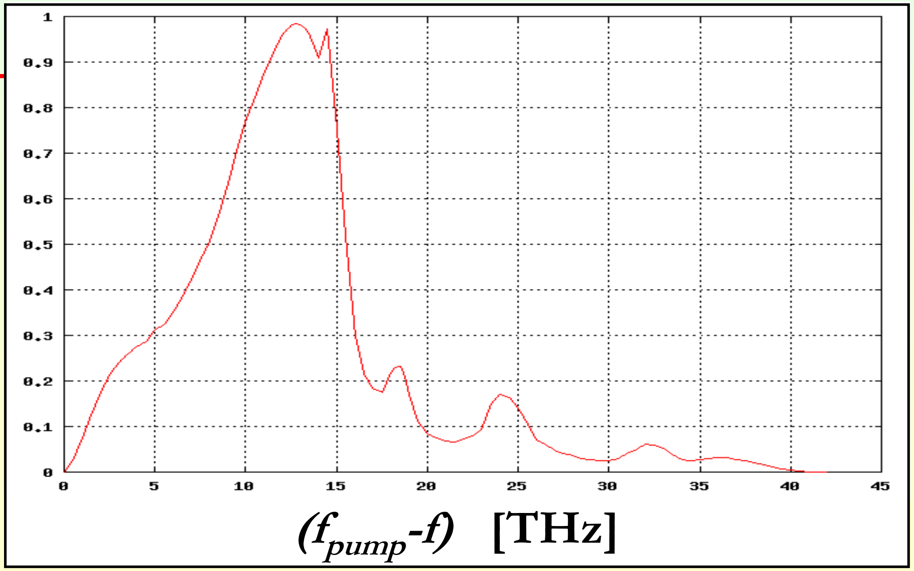
On-Off Gain

$$G_{on-off}(f) = \exp\left\{ C_R(f) P_{pump,0} \frac{1-\exp[-\alpha_p L_{span}]}{\alpha_p} \right\}$$

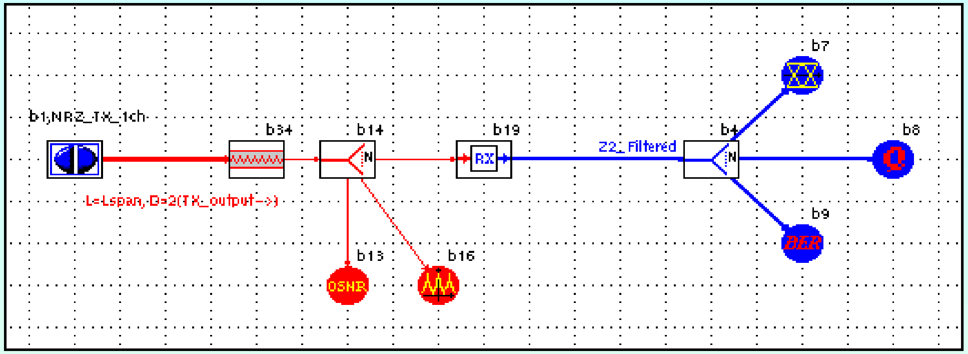
ASE Noise

$$S_{ASE}^{(0)}(f) = h f C_R(f) G_{on-off}(z, f) \exp\left\{-\alpha_S L_{span}\right\} \int_0^{L_{span}} P_{pump}(\zeta) G_{RA}^{-1}(\zeta, f)\, \mathrm{d}\zeta$$

$$C_R(f) = \frac{1}{k_{pol}} \frac{g_R(f_{pump} - f)}{A_{eff}} \cdot \frac{f_{pump}}{f_{ref}}$$

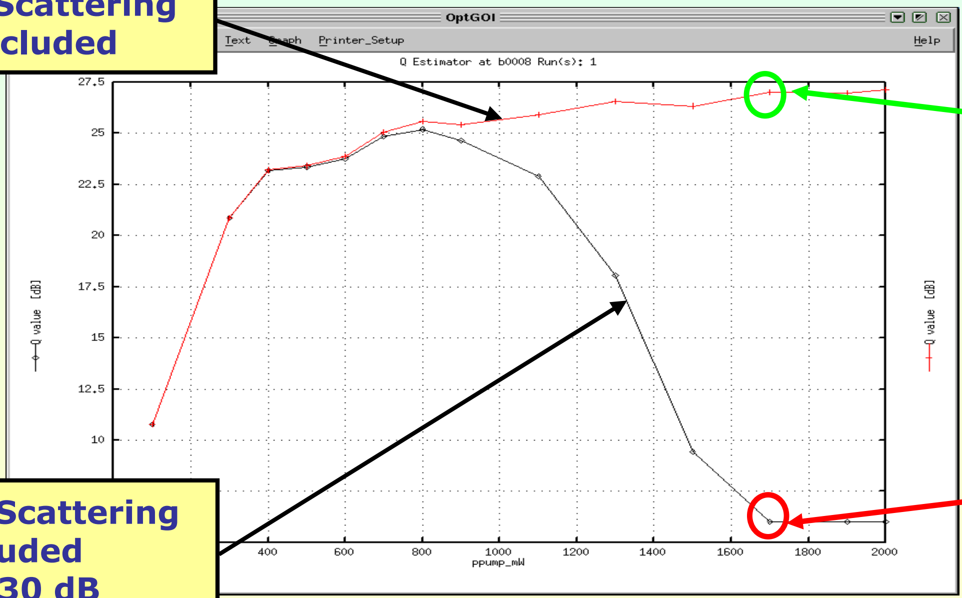


Q vs. Pump Power

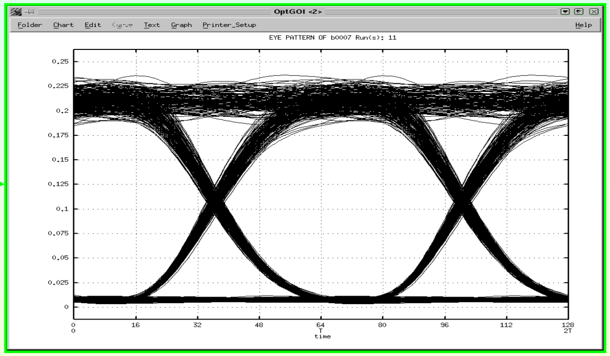


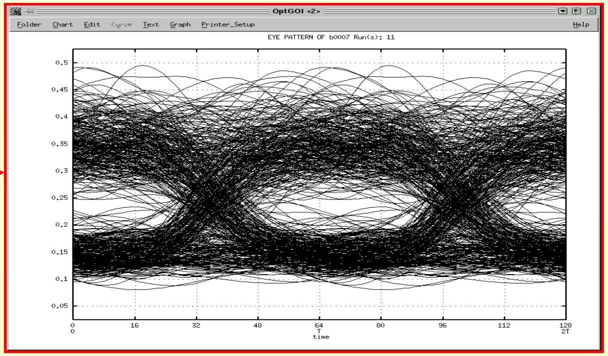
- Fiber: DS
- Distance: 50 km
- Receiver: sensitivity = -30 dBm
- Rayleigh Scattering: R = -30 dB
- Laser source power: -23 dBm
- Raman pump direction: counter-prop
- Raman pump power: 0.1 to 2 W

Rayleigh Scattering Not Included



Rayleigh Scattering Included R = -30 dB

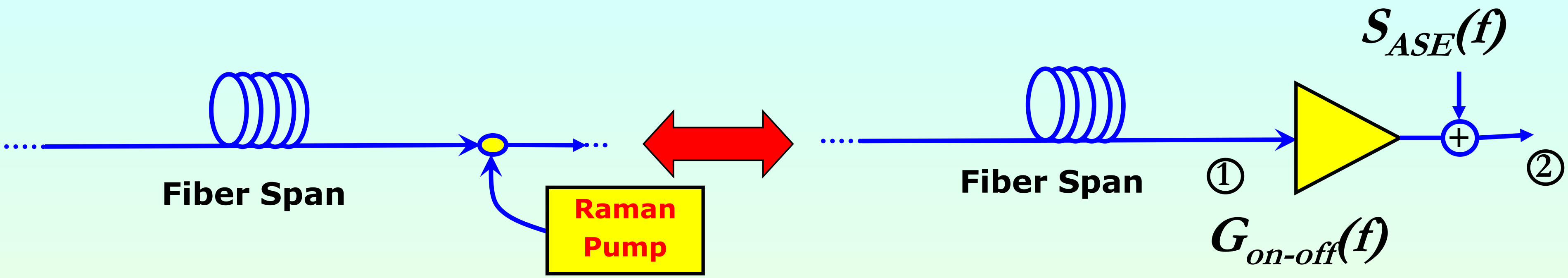




Noise-Figure: equivalent EDFA

"Classic"(℘) definition does not allow a direct comparison with EDFA

Equivalent lumped amplifier



Spontaneous Emission Factor

$$n_{sp,RA}(f) = \frac{S_{ASE}(f)}{hf\left[G_{on-off}(f) - 1\right]}$$

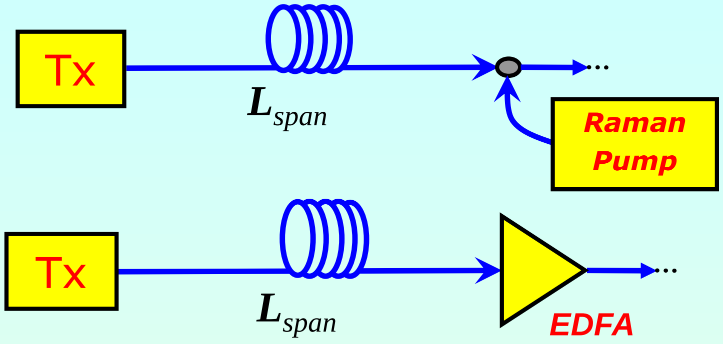
Noise-Figure

$$NF_{RA}(f) = \frac{1 + 2n_{sp,RA}(f)\left[G_{on-off}(f) - 1\right]}{G_{on-off}(f)} \approx$$

$$\approx 2n_{sp,RA}$$

(℘)*Emmanuel Desurvire, Erbium-Doped Fiber Amlifiers, Principles and applications, Wiley-Interscience, New York, 1994.*

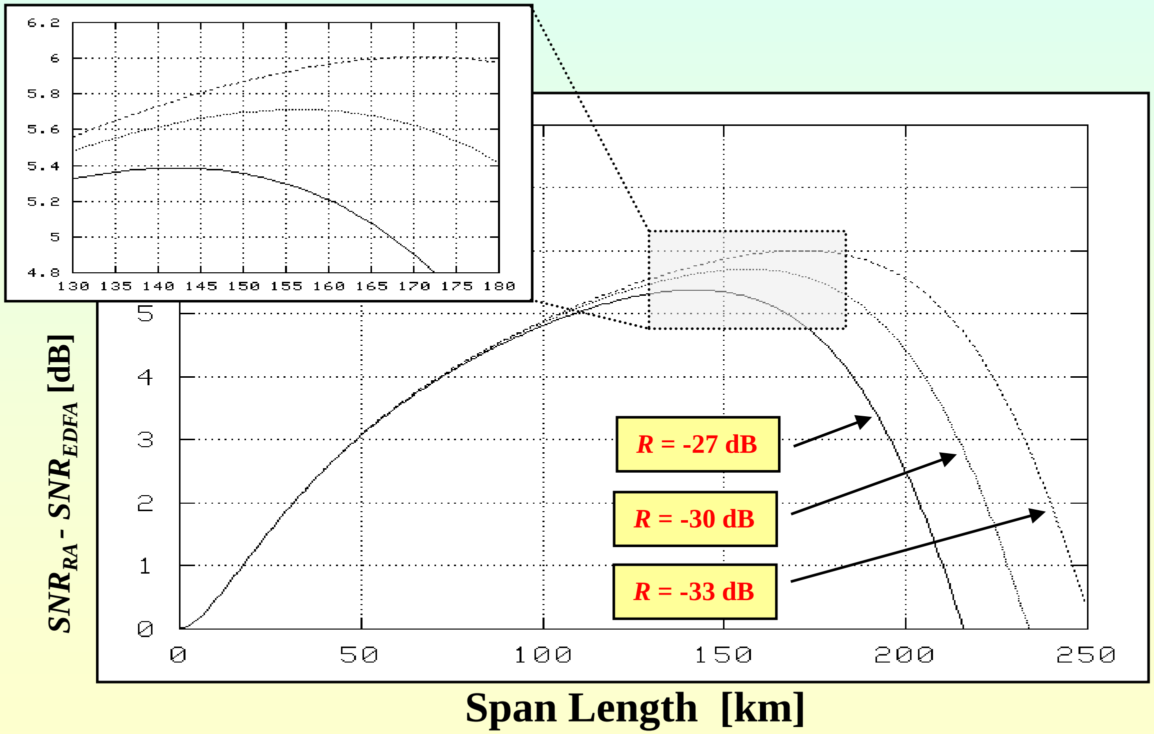
EDFA vs. RA



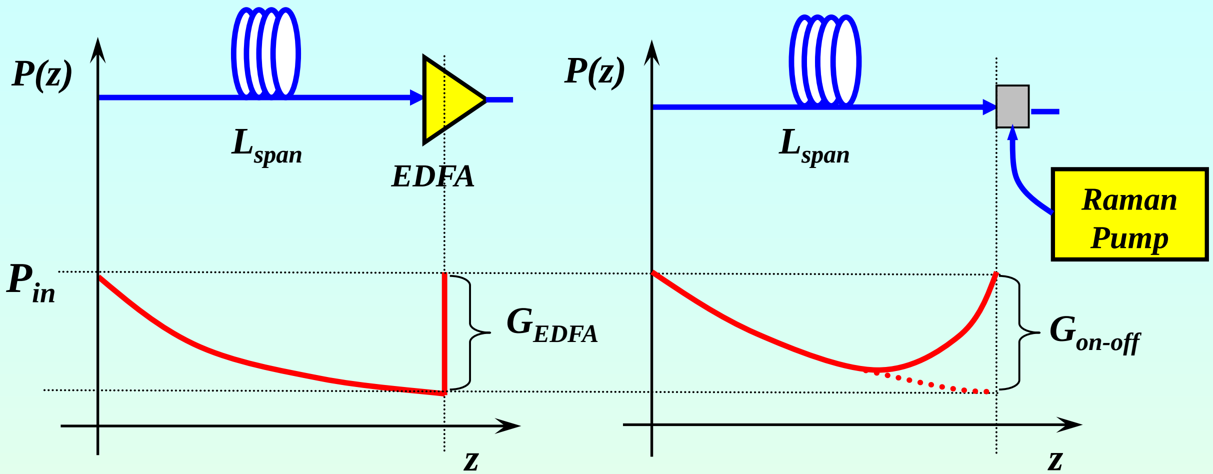
$$G_{on-off} = G_{EDFA} = \exp\{\alpha_S L_{span}\} \qquad P_{TX}^{EDFA} = P_{TX}^{RA}$$

$$0 < L_{span} < 250 \text{ km} \qquad NF_{EDFA} = 3 \quad \text{dB}$$

$$SNR_{RA} - SNR_{EDFA} = NF_{EDFA} - NF_{RA}$$

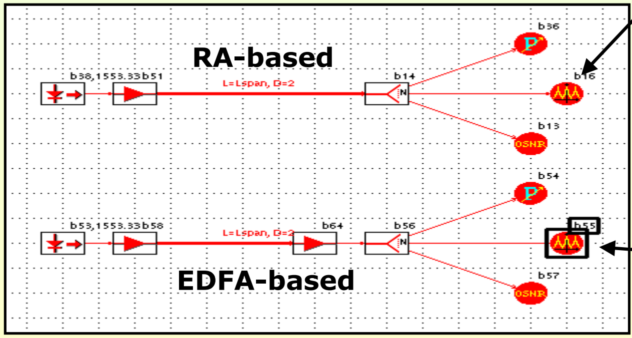


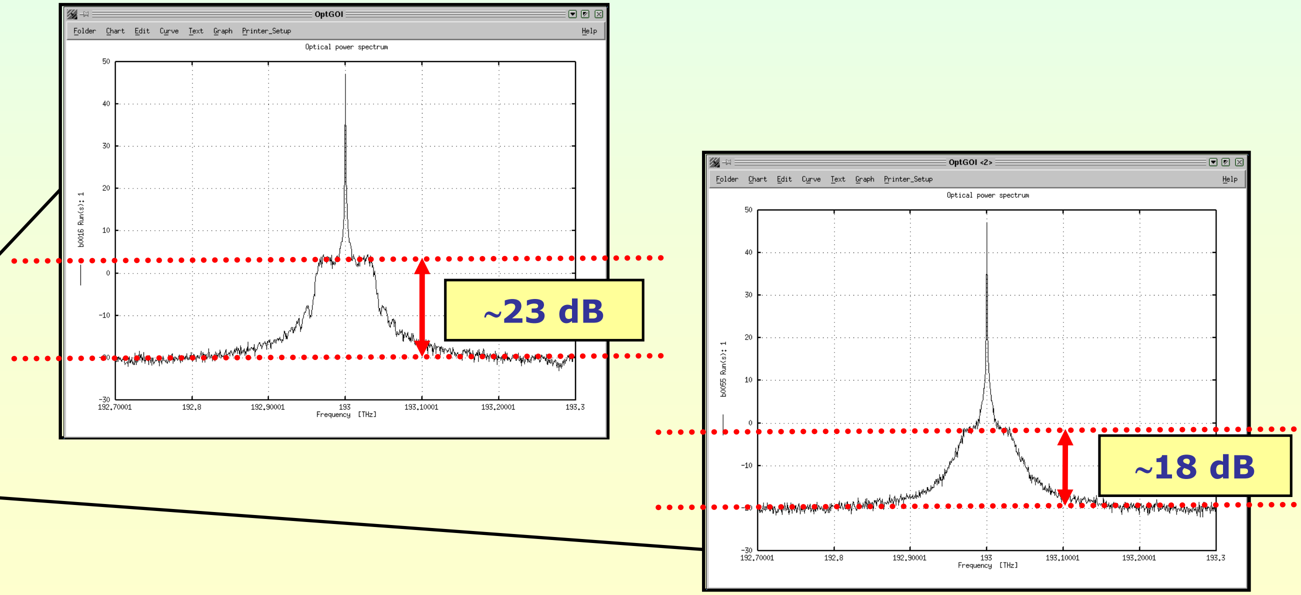
Non-Linear Impact: EDFA vs. RA



EDFA- and RA-based system have a different power distribution along the fiber-span. With the same P_{in}/P_{out} behavior RA-based systems have an higher *effective* power- level

- Fiber: DS
- Distance: 50 km
- P_{in} = 16 dBm
- $G_{on\text{-}off} = G_{EDFA} = 10$ dB





Non-Linear Weight

Non-linear weight definition

$$K_{NL} = \gamma \int_0^{L_{link}} P(z)\,\mathrm{dz} \quad [\mathrm{rad}]$$

It is the overall non-linear phase-shift the signal experiences along the system

$$K_{NL}^{EDFA} = \gamma\, L_{eff}^{EDFA}\, P_{in} = \gamma\, P_{in} \int_0^{L_{span}} \exp\{-\alpha_S z\}\,\mathrm{dz} \approx \frac{\gamma\, P_{in}}{\alpha_S}$$

$$K_{NL}^{RA} = \gamma\, P_{in} \int_0^{L_{span}} \exp\{-\alpha_S z\} G_{RA}(\mathrm{z})\,\mathrm{dz} = \gamma\, P_{in}\, L_{eff}^{RA} > K_{NL}^{EDFA}$$

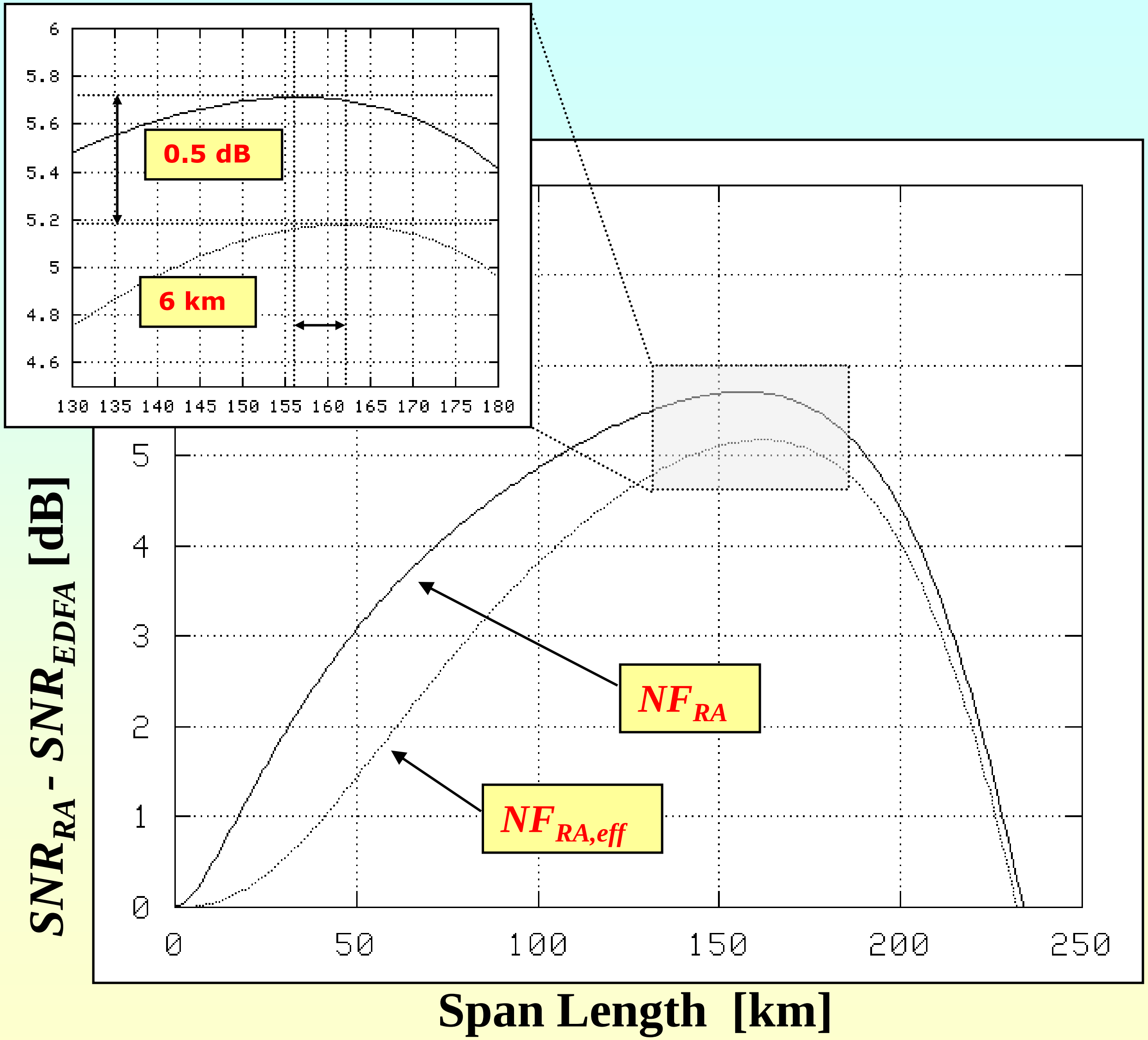
Power reduction for RA

$$k_{eff} = \frac{L_{eff}^{RA}}{L_{eff}^{EDFA}}$$

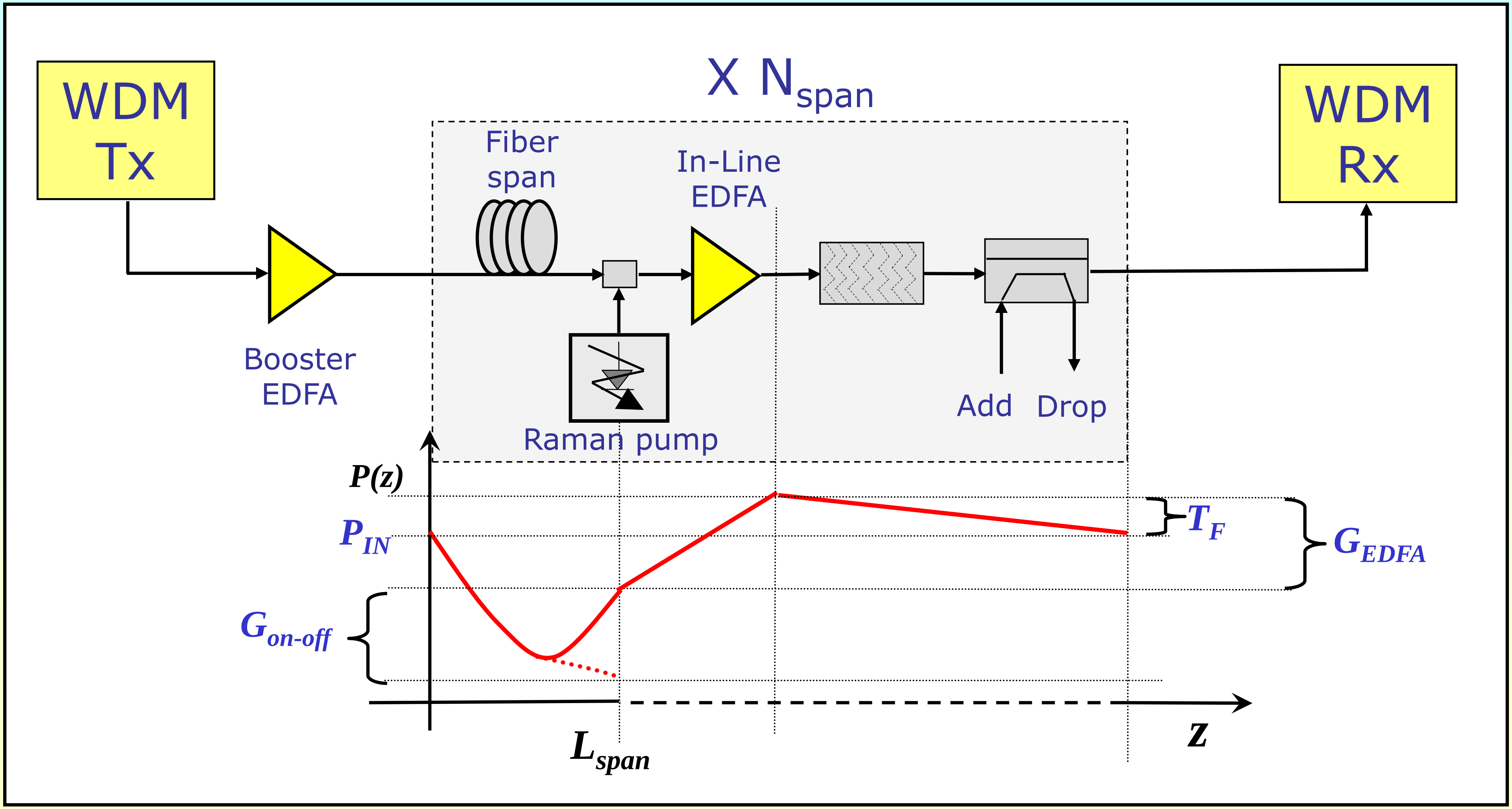
In RA-based systems transmitted power must be reduced of the factor k_{eff} to have the same non-linear impact, therefore, to allow a direct comparison with EDFA's an effective spontaneous emission factor can be defined

$$n_{sp,eff}^{RA} = n_{sp}^{RA} \frac{L_{eff}^{RA}}{L_{eff}^{EDFA}} > n_{sp}^{RA}$$

$$NF_{RA,eff}(f) \approx 2 \frac{L_{eff}^{RA}}{L_{eff}^{EDFA}} \frac{S_{ASE}(f)}{h f \left[G_{on-off}(f) - 1\right]}$$



The analyzed set-up



HFA: Hypotheses

Transparency condition ⟺ $\exp\left\{-\alpha_S L_{span}\right\} G_{on-off} T_F G_{EDFA} = 1$

$$G_{on-off}^{dB} = \frac{K_{gain}}{100} 10 \log_{10}\left\{\frac{1}{\exp\left\{-\alpha_S L_{span}\right\} T_F}\right\}$$

K_{gain}

0 % → *100 %*

EDFA HFA RA

HFA: Signal-to-Noise Ratio

The non-linear weight is set and the launched power is fixed

$$P_{IN} = \frac{K_{NL}}{\gamma \, L_{eff} \, N_{span}}$$

$$SNR = \frac{K_{NL}}{\gamma h f B_n} \cdot \frac{\exp\left\{-\alpha_S \frac{L_{TOT}}{N_{span}}\right\}}{N_{span}^2 L_{eff} \left(n_{eq}^{RA} + \frac{n_{eq}^{EDFA}}{G_{on-off}} \right)}$$

$$n_{eq} = \frac{n_{sp}(G-1)}{G}$$

Equivalent Spontaneous Emission Factor

1 -> *SNR* fixed

Given a required *SNR* value, the system is optimized in order to minimized the *non-linear weight* K_{NL} versus the number of spans N_{span}

2 -> K_{NL} fixed

Given a non-linear weight K_{NL} the *SNR* is maximized versus the number of spans N_{span}

3 -> N_{span} fixed

Given the distance between the stations ($L_{span} = L_{TOT}/N_{span}$), the system is optimized in order to maximize the *SNR* for each K_{NL}

Optimization process with a given K_{NL}

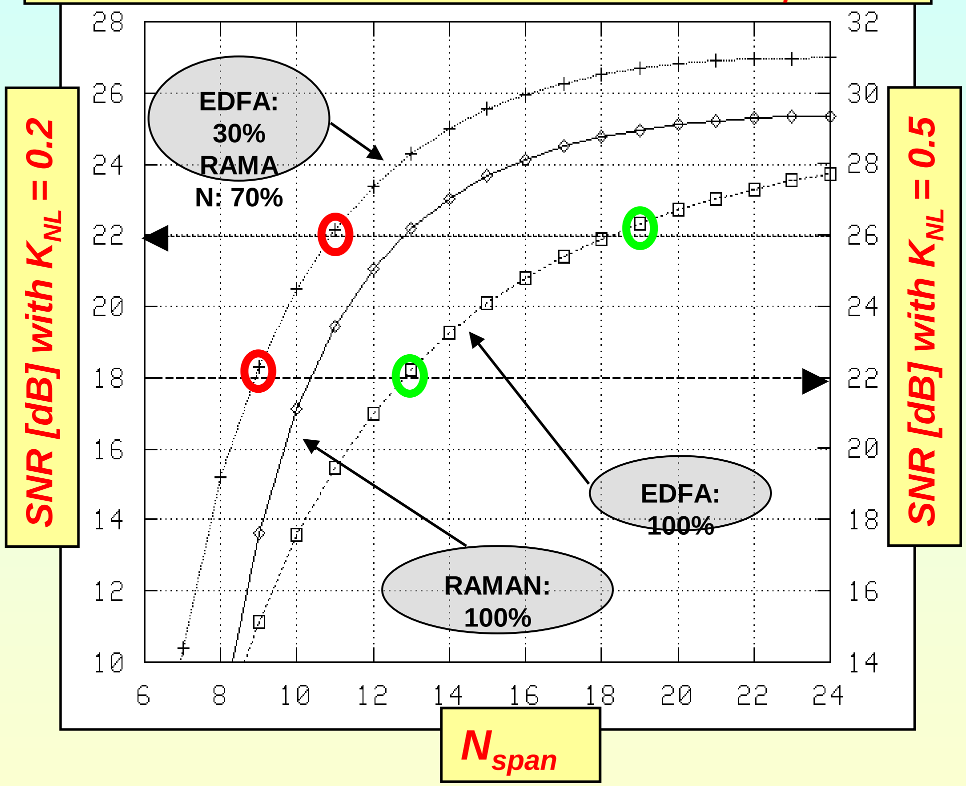
- Required $BER = BER_{max}$ ➡ Minimum $SNR = SNR_{min}$
- Fix Margin ➡ $SNR = SNR_{min} + Margin$
- Evaluate the optimal configuration with a given K_{NL}
- Simulate the configuration
- $BER > BER_{max}$ ➡ Non-Linear impact is too strong, start again the procedure with a smaller K_{NL} or with a modulation format less sensitive to the non-linearities
- $BER < BER_{max}$ ➡ **OK!**

HFA: Use Case

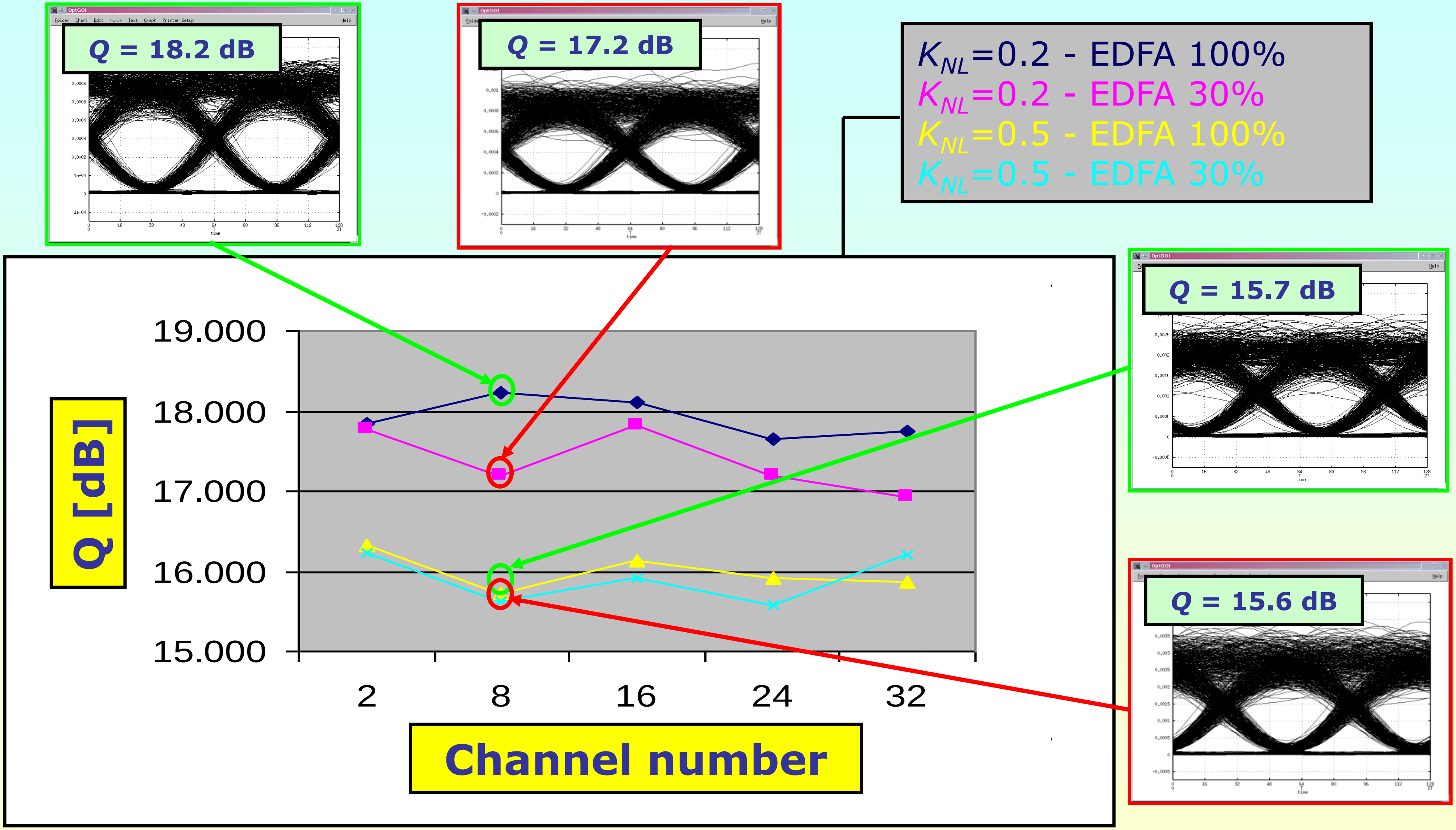
- Total length: L_{TOT} =1500 km
- Number of channels: 32
- Channel spacing: 50 GHz
- Signal loss: α_S = 0.2 dB/km @ 1550 nm
- Pump loss: α_P = 0.3 dB/km @ 1450 nm
- D =5.7 ps/nm/km
- D' = 0.037 ps/nm²/km
- 100% dispersion compensation
- Ideal Gain Flattening Filter
- Passive components loss: T_F = 10 dB

	Unit	Knl = 0.2	Knl = 0.2	Knl = 0.5	Knl = 0.5
		EDFA 30%	EDFA 100%	EDFA 30%	EDFA 100%
N_{span}		11	19	9	13
L_{span}	[km]	136.364	78.947	166.667	115.385
P_{ch}	[dBm]	-3.606	-5.308	1.503	0.224
P_{pump}	[dBm]	28.274	-	28.928	-
G_{EDFA}	[dB]	11.2	25.8	13	33.1
G_{RAMAN}	[dB]	26.1	-	30.3	-

K_{NL} Fixed: *SNR* vs. N_{span}



Simulation: *Q* values and Eye-Diagram



Conclusions

- **Raman amplification** has been briefly described
- **Noise-Figure** for Raman Amplifiers has been reviewed in order to show the advantages introduced by the use of RA
- Non-linear impact has been analyzed both for RA and EDFA and the **non-linear weight** has been introduced
- An algorithm to **optimize HFA-based systems** has been proposed