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OptSim 3.0

Hybrid Raman/Erbium-Doped Fiber Amplifiers: a Promising Technology for Multi-Terabit Systems

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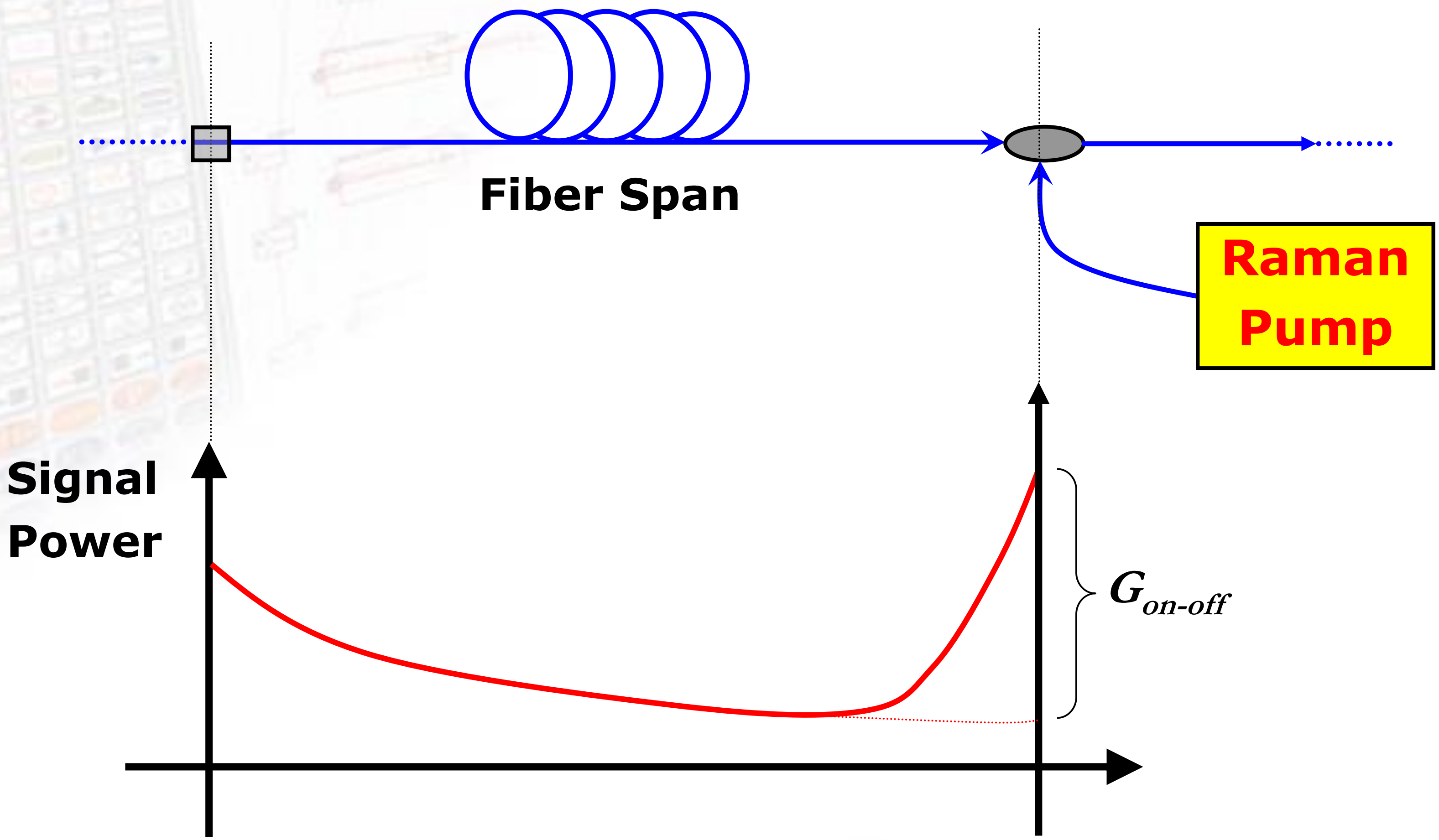
- Introduction to the Raman Amplification
- Simple Model
- Rayleigh back-scattering
- Noise-Figure Definition
- Non-linear weight
- *RA* vs. *EDFA*
- Hybrid Raman/Erbium-Doped Fiber Amplifiers

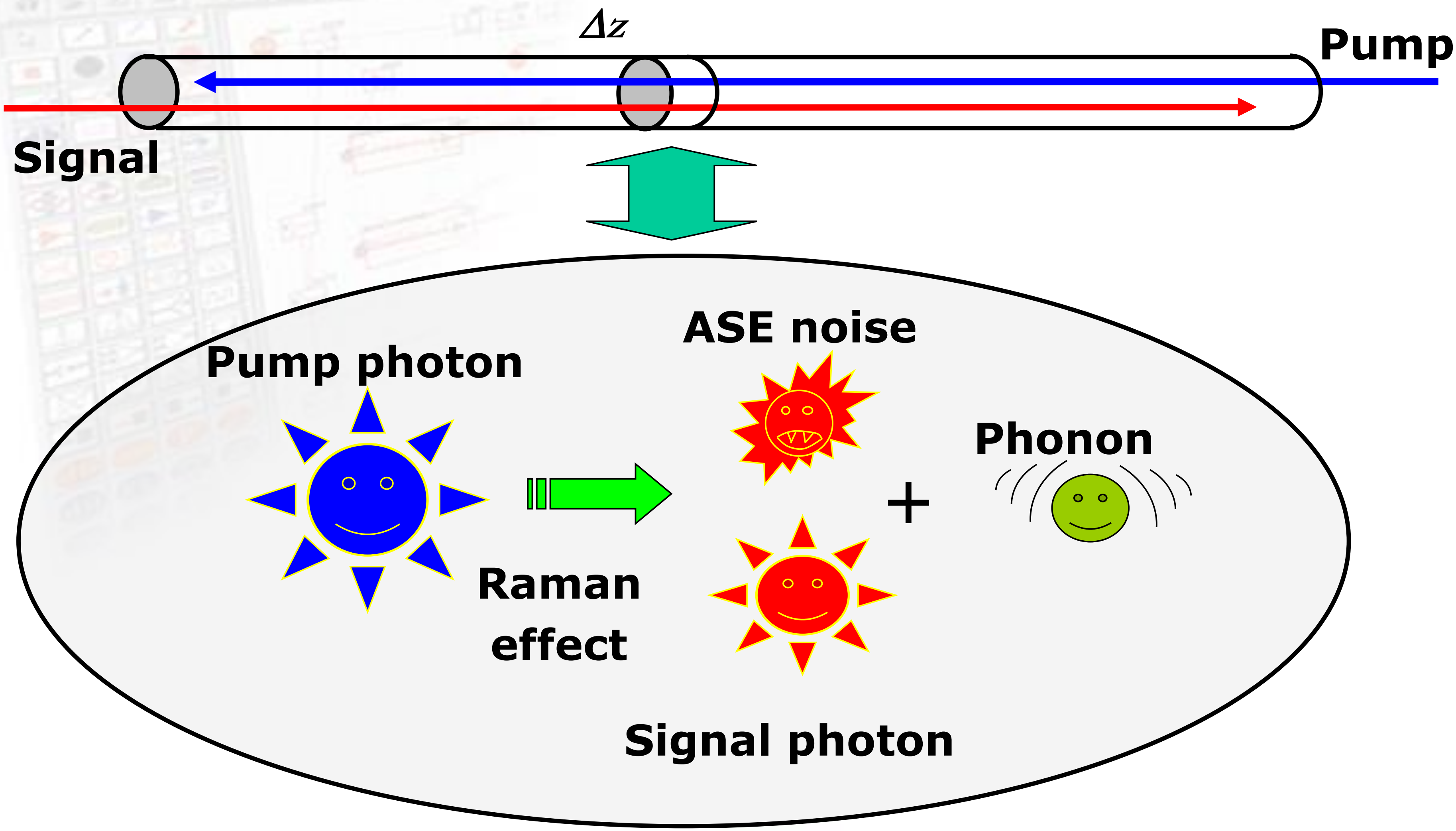
What is a Raman Amplifier ?



Hypotheses

- Single-pump
- Co-propagating, Counter-propagating and bi-directional pump
- Full spectral analysis
- Undepleted pump assumption
- Rayleigh back-scattering is not considered
  - No back-scattered components of the signal
  - No back-scattered components of the ASE noise

How does it work?



The Equation

Loss term

Noise term

Raman gain term

$$\boxed{\frac{dP(f)}{dz}} = -\boxed{\alpha_S(f)\,P(f)} + \boxed{C_R(f)\,P_{pump}(z)\,P(f)} + \boxed{h\,f\,C_R(f)\,P_{pump}(z)}$$

Pump

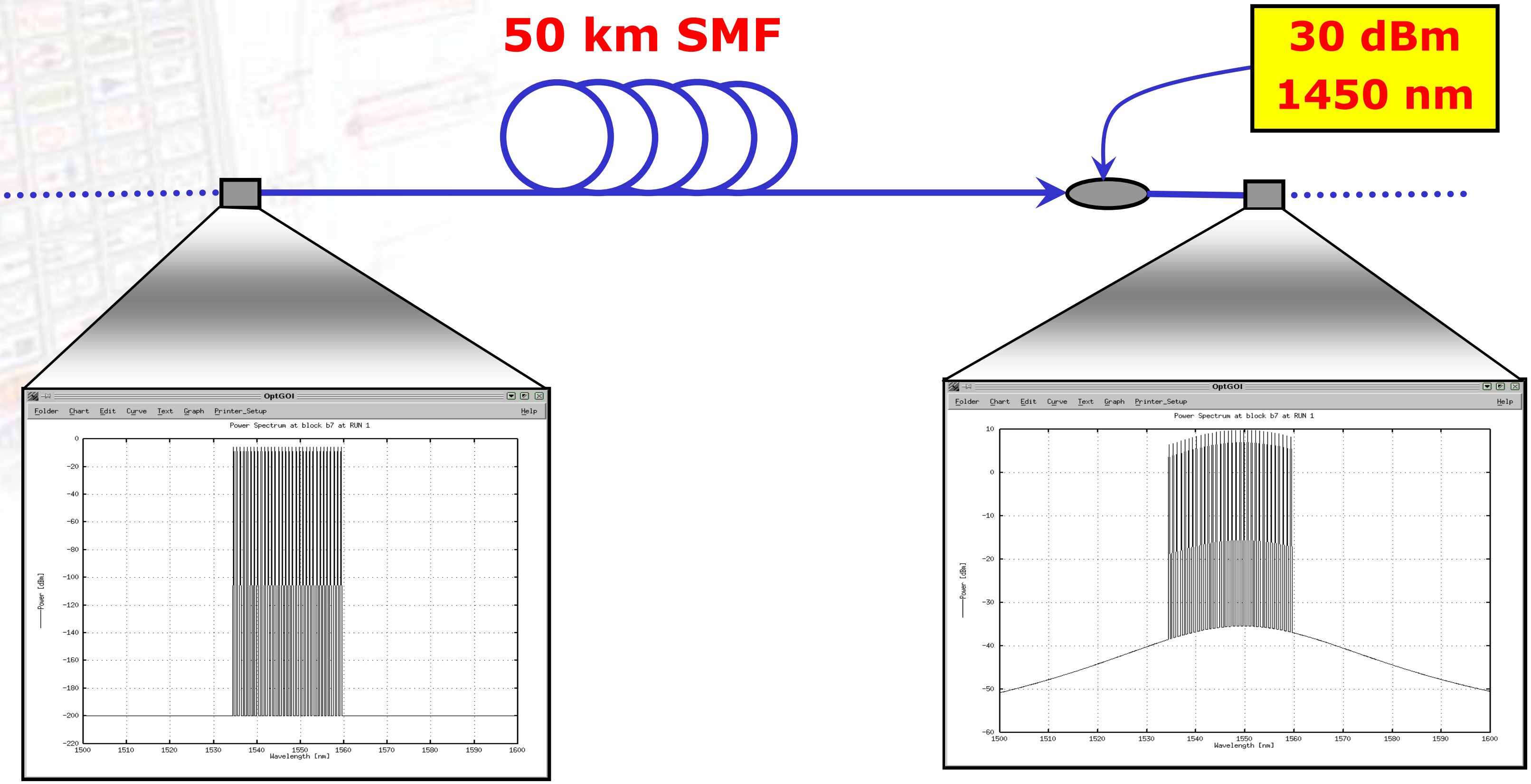
Propagating power derivative

Co-prop: $P_{pump}(z) = P_{pump,0}\exp\left\{-\alpha_P\left(L_{span} - z\right)\right\}$

Counter-prop: $P_{pump}(z) = P_{pump,0}\exp\left\{-\alpha_P z\right\}$

Raman Amplifier: simple model

$$P_{out}(f) = \exp\left\{-\alpha_S L_{span}\right\} G_{on-off}(f) \cdot P_{in}(f) + S_{ASE}(f)$$



Power evolution along the fiber-span

$$G_{RA}(z, f) = \frac{P(z, f)}{P(0, f)} = \exp\left\{ \int_0^z \left[C_R(f) P_{pump}(\zeta) - \alpha_S(f) \right] \mathrm{d}\zeta \right\}$$

The On-off Gain

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

The ASE spectral density

Along the fiber-span ....

$$S_{ASE}(f,z) = h\,f\,C_R(f)\,G_{RA}(z,f)\int_0^z P_{pump}(\zeta)\,G_{RA}^{-1}(\zeta,f)\,\mathrm{d}\zeta$$

... at the output of the fiber-span

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

Raman Amplifier: the gain profile

Signal frequency

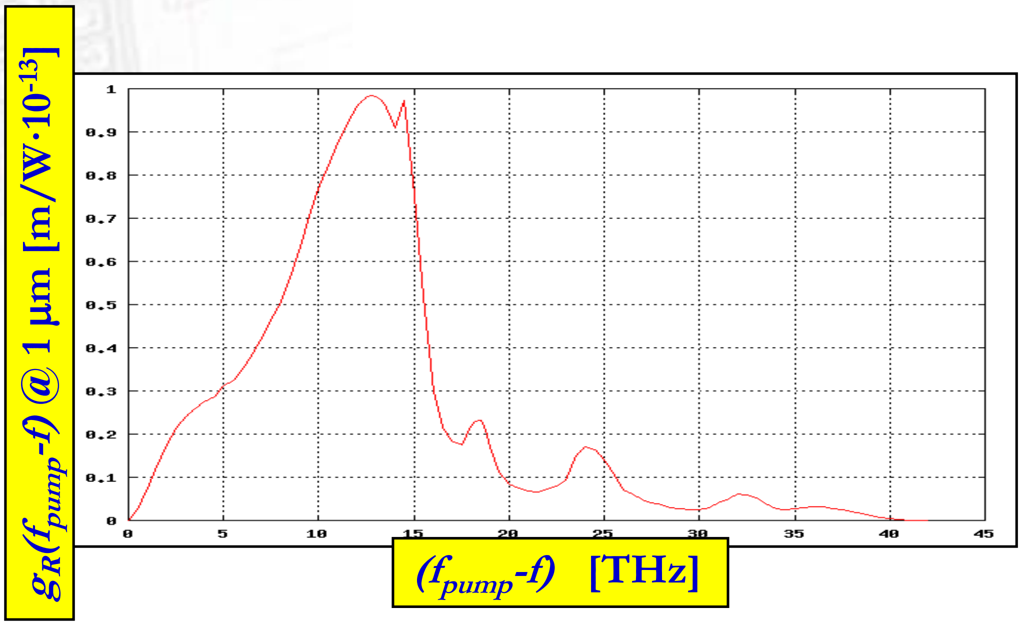
Raman profile

Pump frequency

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

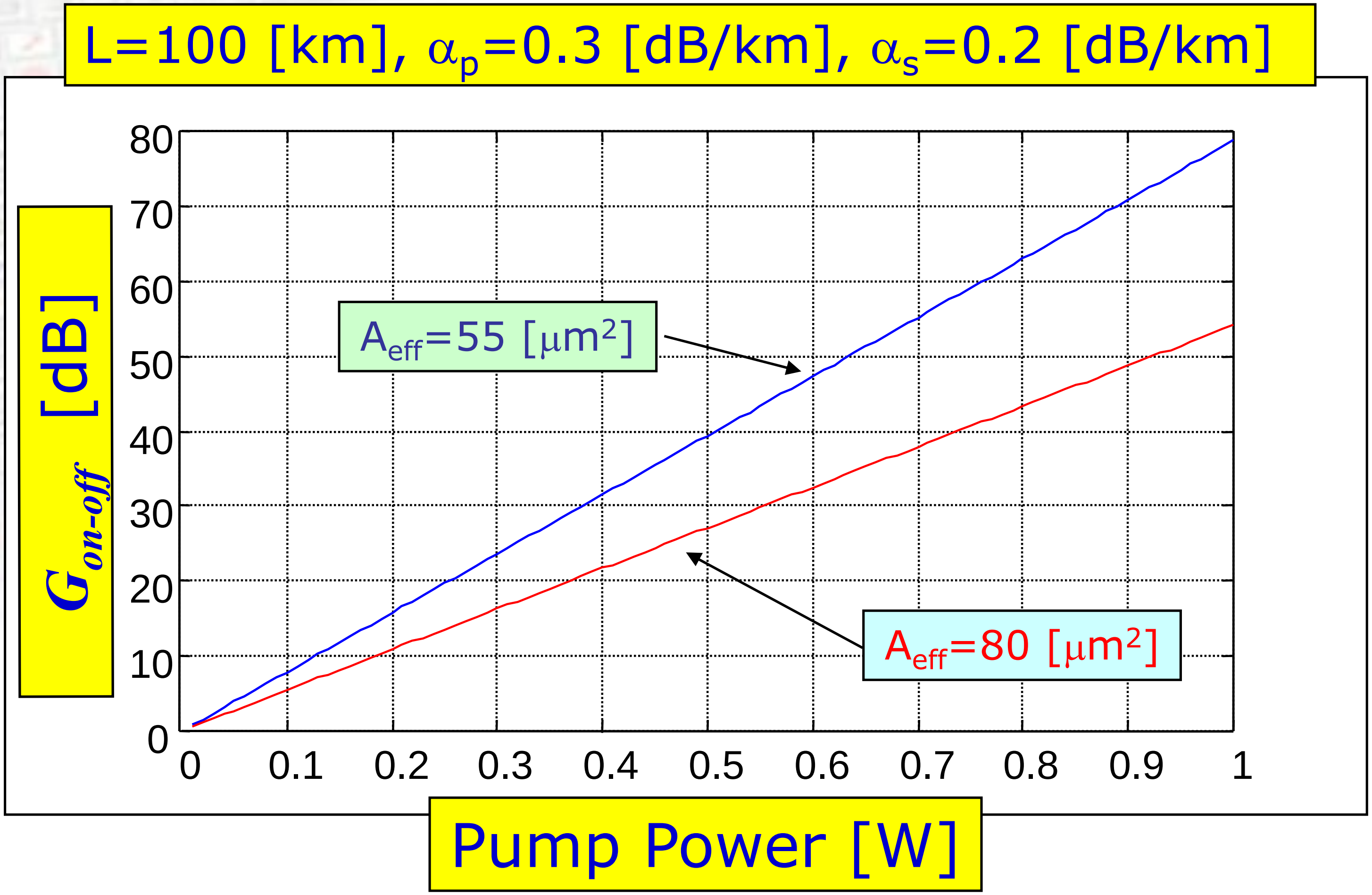
Effective Area

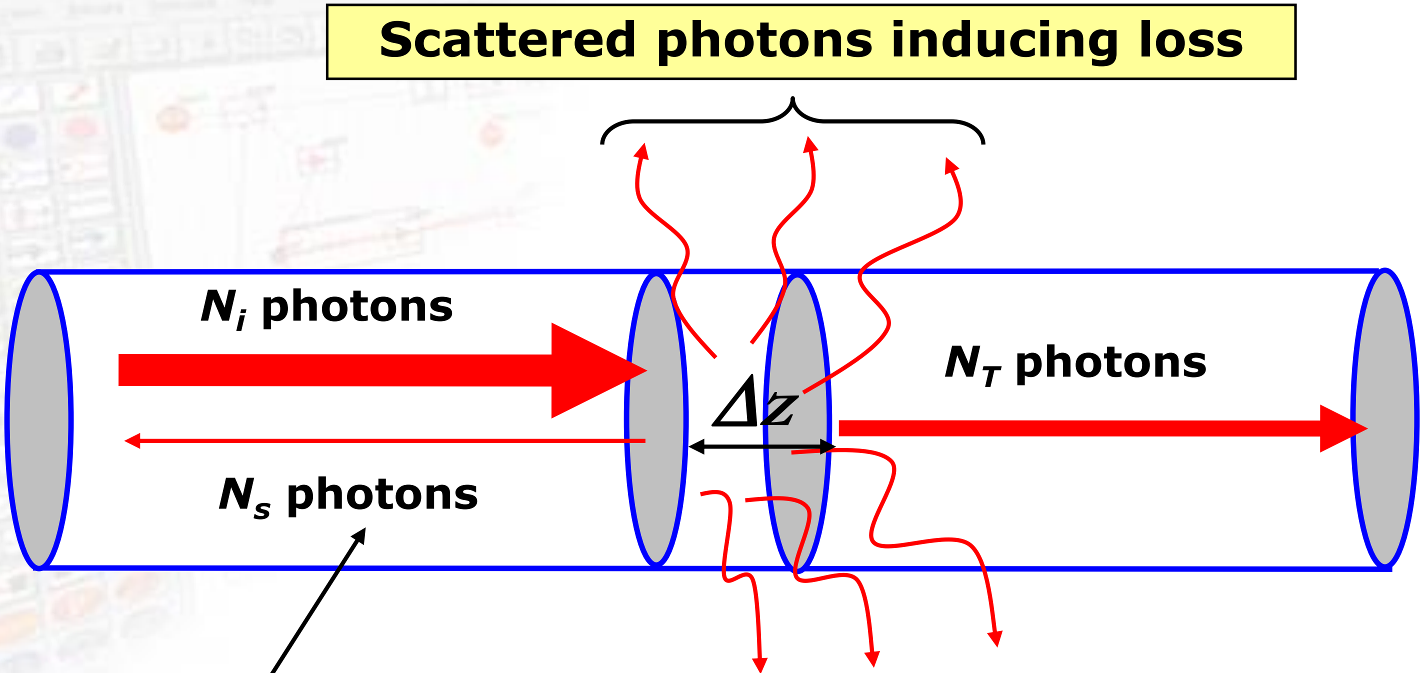
Reference frequency



Silica fibers

Raman Amplifier: Gain vs. Pump Power

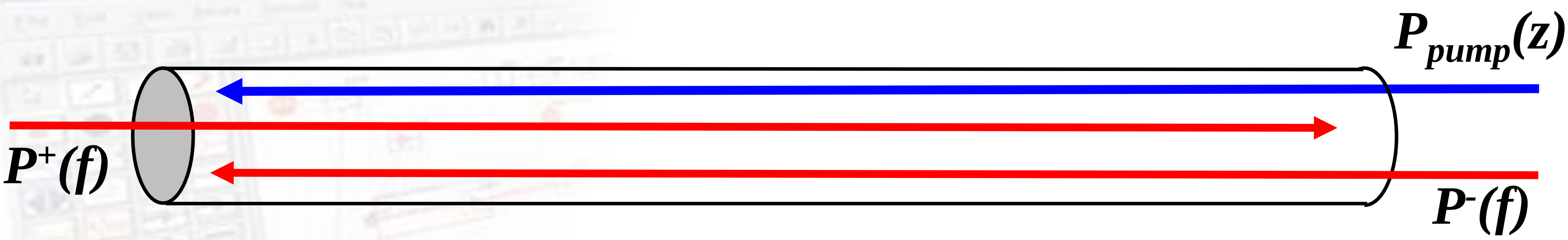




Back-scattered photons are that part of scattered photons propagating in the opposite direction with respect to the signal

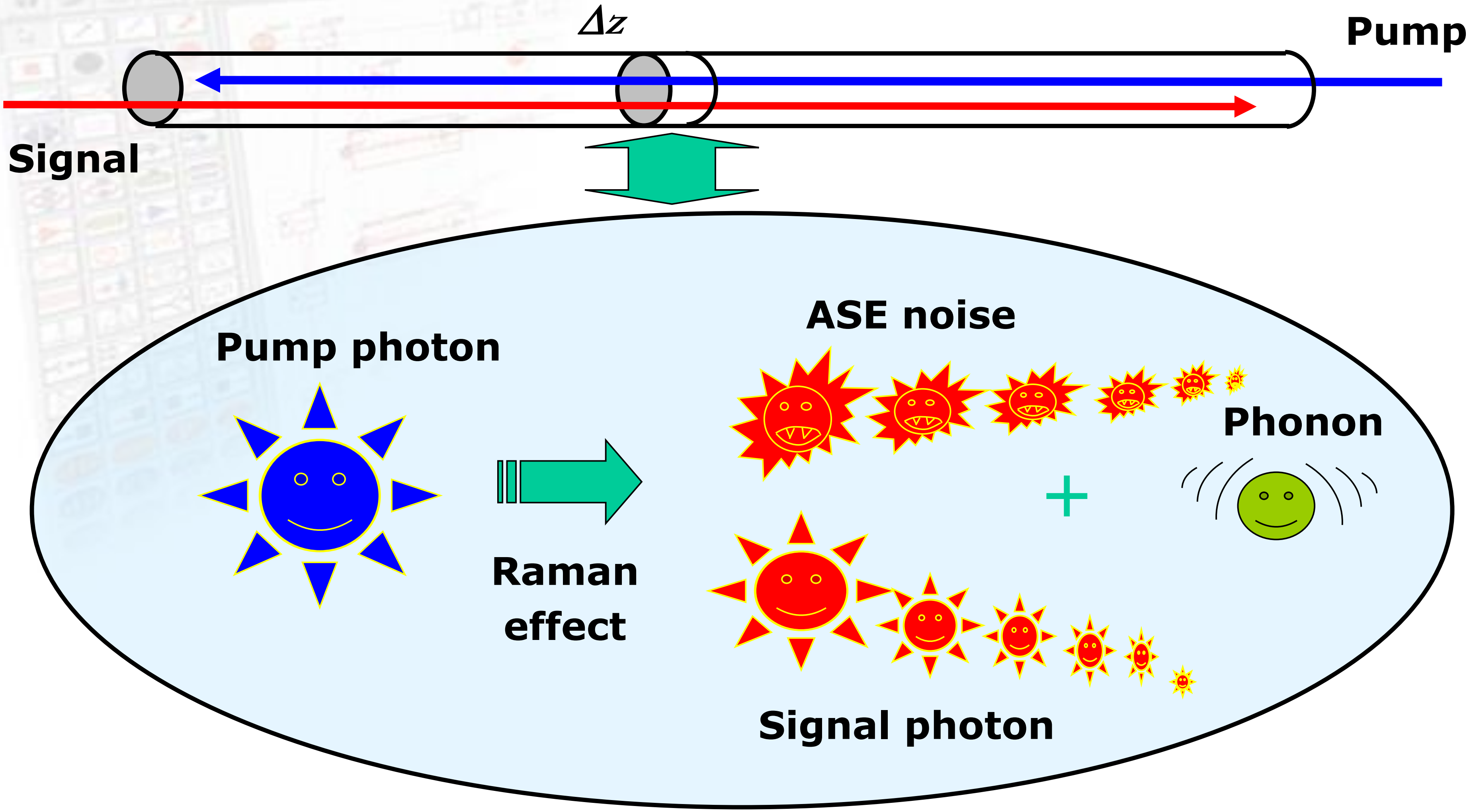
- ***R*** is the **capture factor**
- It is the ratio of back-scattered photons to all the scattered photons. ***R*** $\in$ [0;1]
- It is specified in units of dB
- Typical value: -30 dB

Raman Amplifier: Rayleigh Scattering

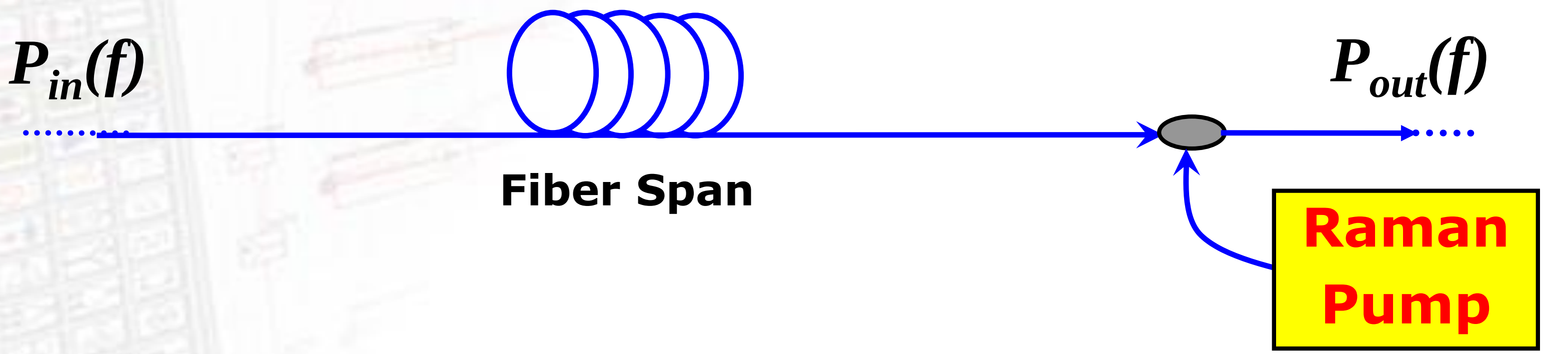


$$\begin{cases} \dfrac{dP^+(f)}{dz} = -\alpha_S(f)P^+(f) + C_R(f)P_{pump}(z)P^+(f) + \boxed{R\alpha_S(f)P^-(f)} + \\ \qquad + hfC_R(f)P_{pump}(z) \\ \dfrac{dP^-(f)}{dz} = +\alpha_S(f)P^-(f) - C_R(f)P_{pump}(z)P^-(f) - \boxed{R\alpha_S(f)P^+(f)} - \\ \qquad - hfC_R(f)P_{pump}(z) \end{cases}$$

Rayleigh Back-Scattering:



Raman Amplifier & Rayleigh Scattering System Behavior:



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

Multiple scattered signal components

Multiple scattered noise components

Importance of considering Rayleigh Scattering

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Rayleigh Scattering Limitations in Distributed Raman Pre-Amplifiers

P. B. Hansen, L. Eskildsen, A. J. Stentz, T. A. Strasser, J. Judkins, J. J. DeMarco, R. Pedrazzani, and D. J. DiGiovanni

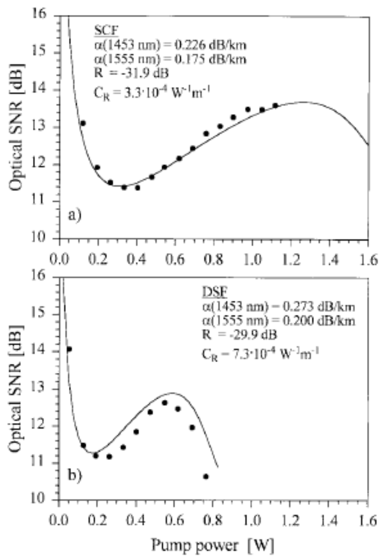


Fig. 2. Measured (solid circles) and calculated (solid lines) optical SNR in a 0.2-nm bandwidth against pump power at a wavelength of 1453 nm for (a) SCF and (b) DSF. Fiber parameters for the numerical simulation are shown as inserts.

A high-power 1453-nm pump source is capable of launching up to 1.1 W backward in the transmission fiber via a wavelength selective coupler. The optical SNR including Rayleigh scattering of ASE and signal, was measured in a bandwidth of 0.2 nm at the output of the Raman pre-amplifier. The SNR is shown as a function of the launched pump power for SCF and DSF in Fig. 2(a) and (b), respectively. Notice that an optical spectrum analyzer, which is used for this measurement, does not distinguish between signal and its double reflected component. Local maximums of the optical SNR are measured to be $\geq$13.6 dB (13.6 dB measured at the maximum pump power of 1100 mW) for the SCF and 12.6 dB at 550 mW for the DSF.

Raman Amplifier: the advanced model

Hansen *et al.* showed that only 2 components derived from Rayleigh scattering have a strong impact on the system performance.

$$P_{out}(f) = \boxed{\exp\{-\alpha_S L\} G_{on-off}(f) \cdot P_{in}(f)} + \boxed{S_{ASE}^{(0)}(f)} + \boxed{S_{ASE}^{(1)}(f) + S_{ASE}^{(2)}(f)}$$

Amplified Signal

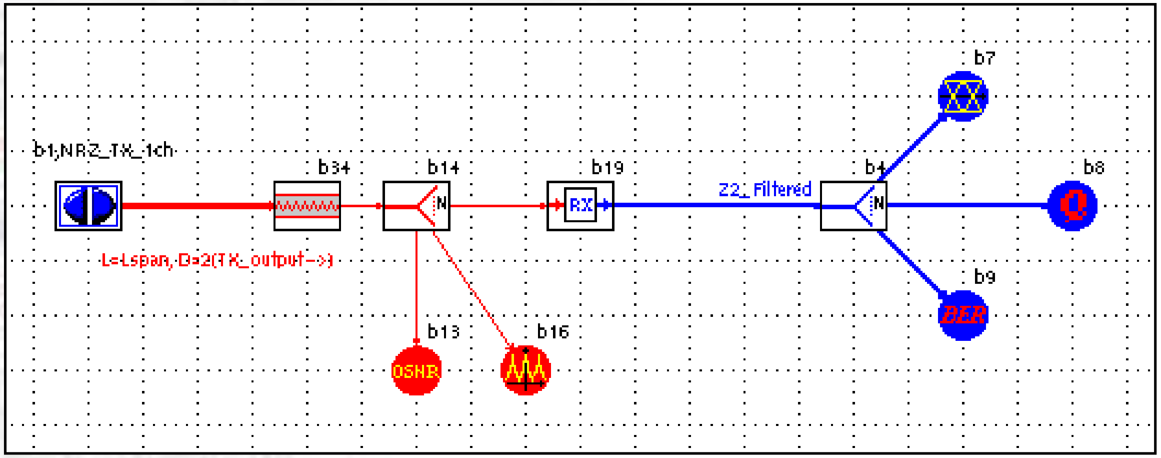
Forward Noise

Single- and Double-Scattered noise components

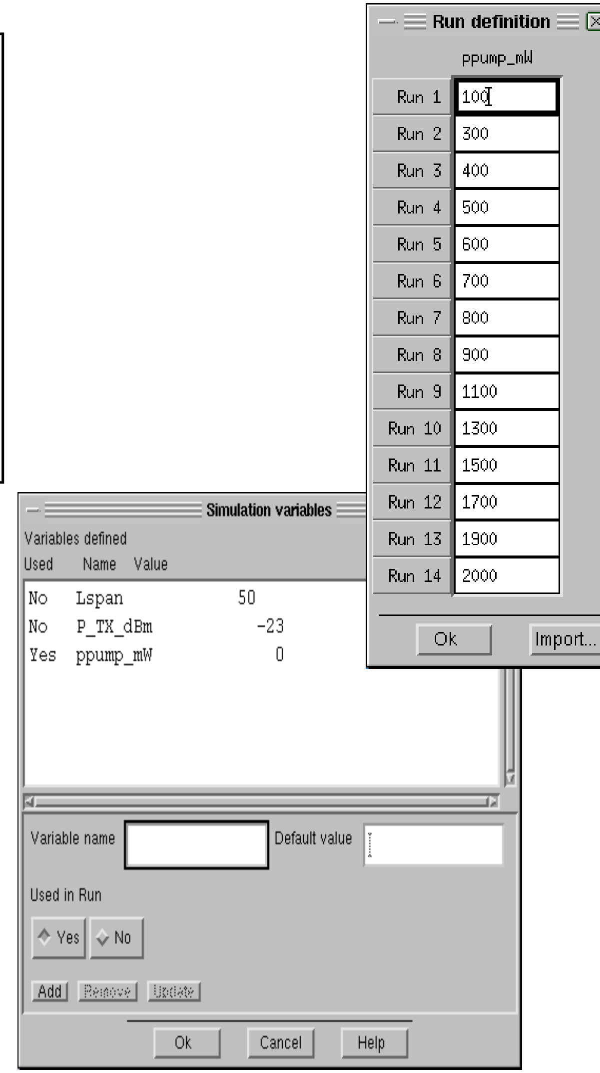
Raman Amplifier: implemented features

- Single co- and counter-propagating pump
- Realistic shape (e.g. user-defined) for the Raman profile: no Lorentzian fitting
- ASE noise with frequency dependent shape
- Rayleigh back-scattering of noise: single- and double-scattered noise components are fully considered
- Inclusion of Raman amplification during SPT simulation for fast system optimization
- Raman amplification is simulated step-by-step to fully take into account the effect of distributed signal growth

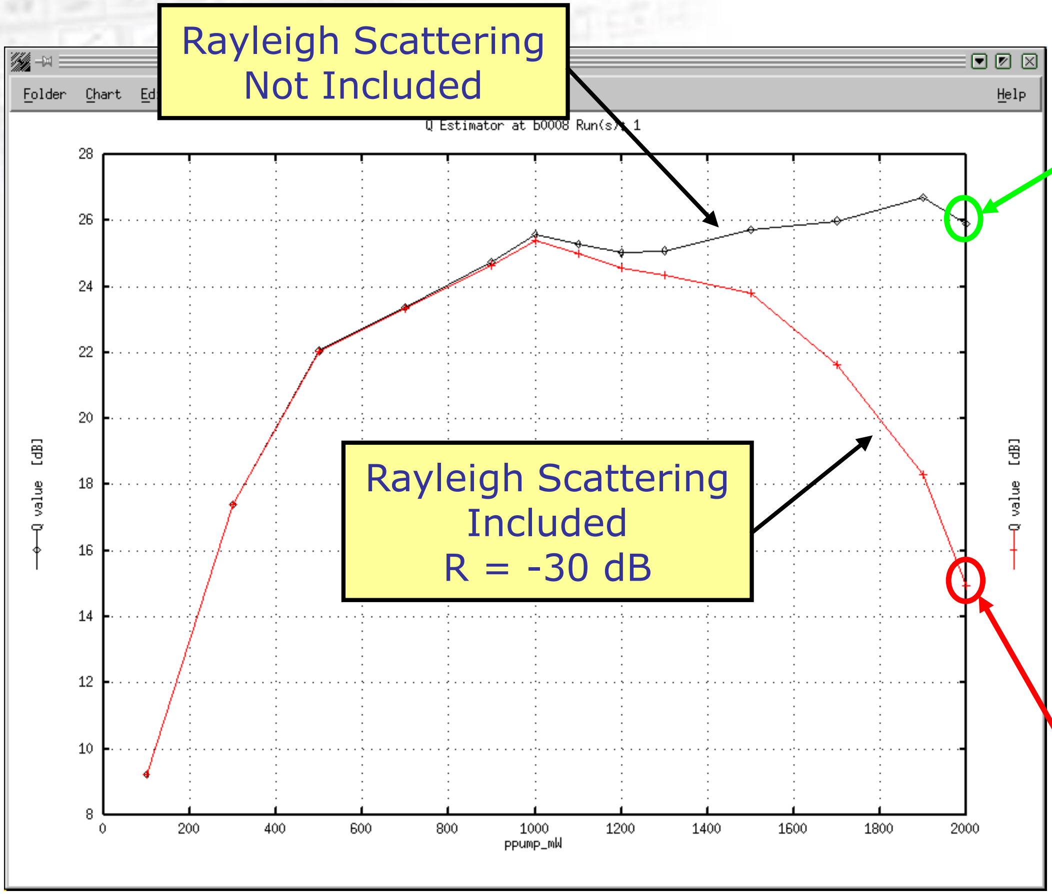
Importance of back-scattering: example

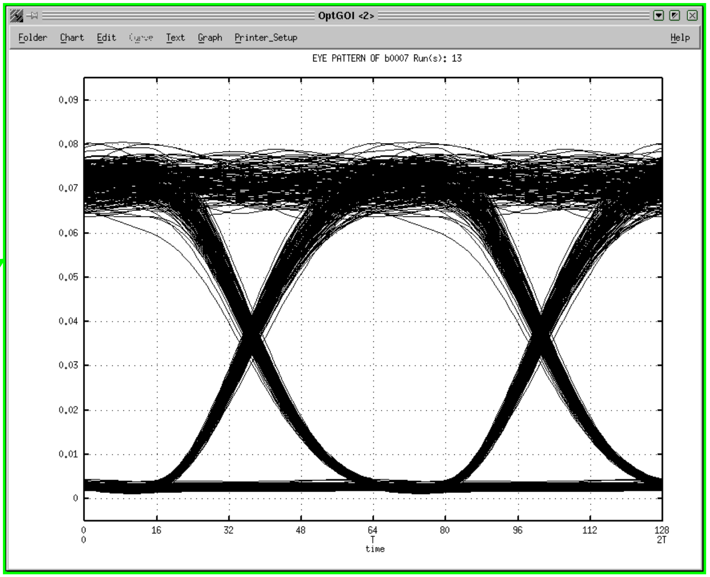


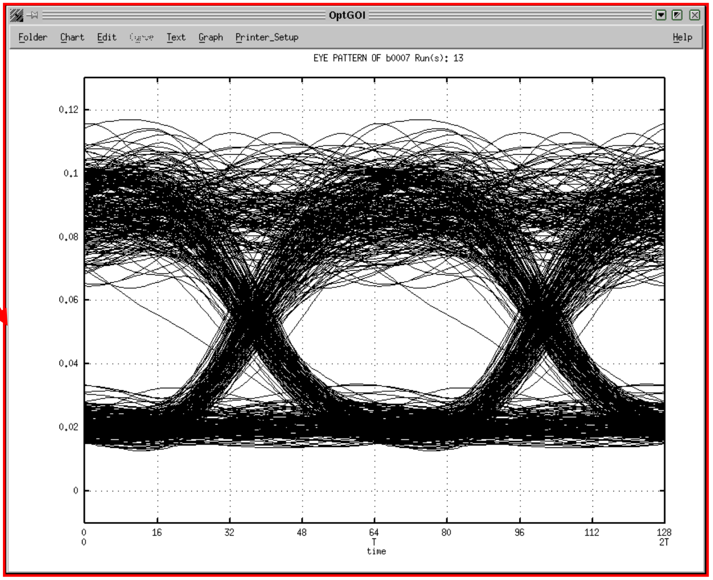
- Fiber: SMF or DS
- Distance: 50 km
- Receiver: sensitivity = -30 dBm
- Rayleigh Scattering: R = -30 dB
- Laser source power: -23 dBm
- Raman pump direction: counter-prop
- Raman pump power: 0.1 to 2 W



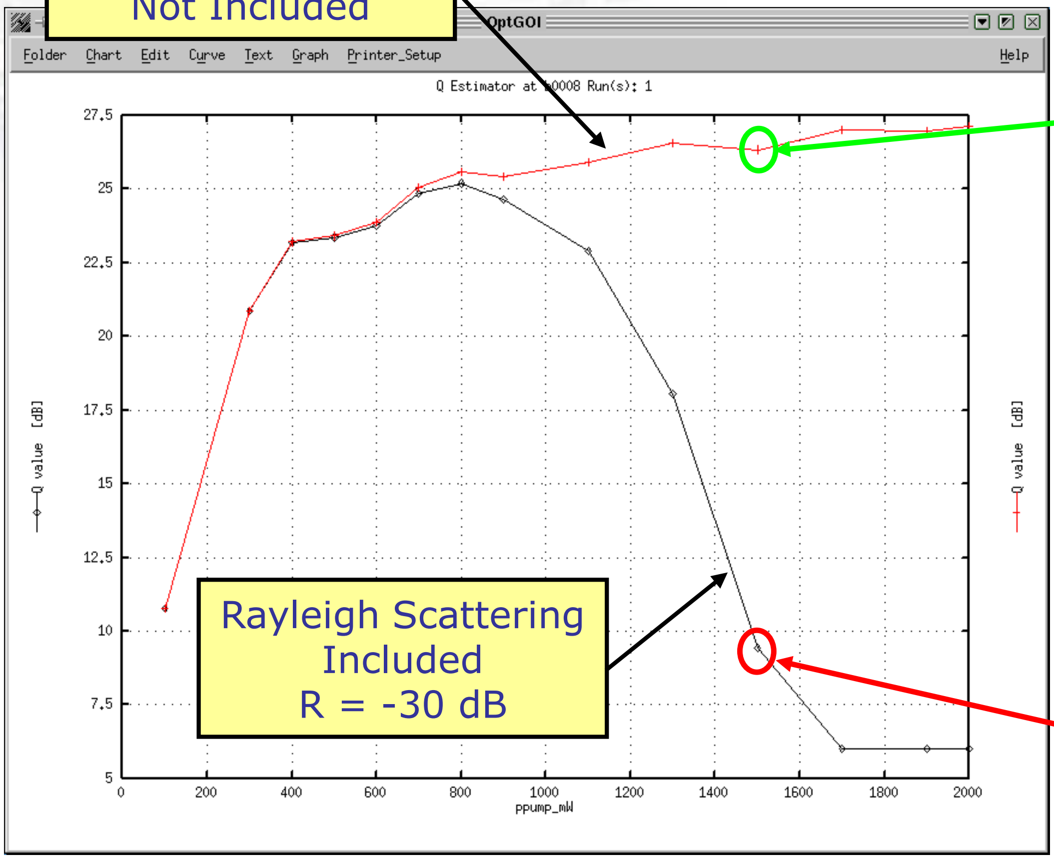
SMF: Q vs. pump power

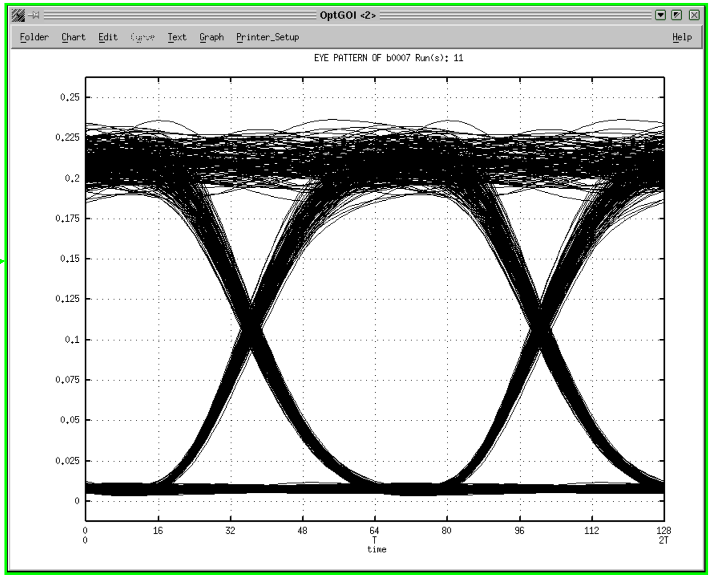


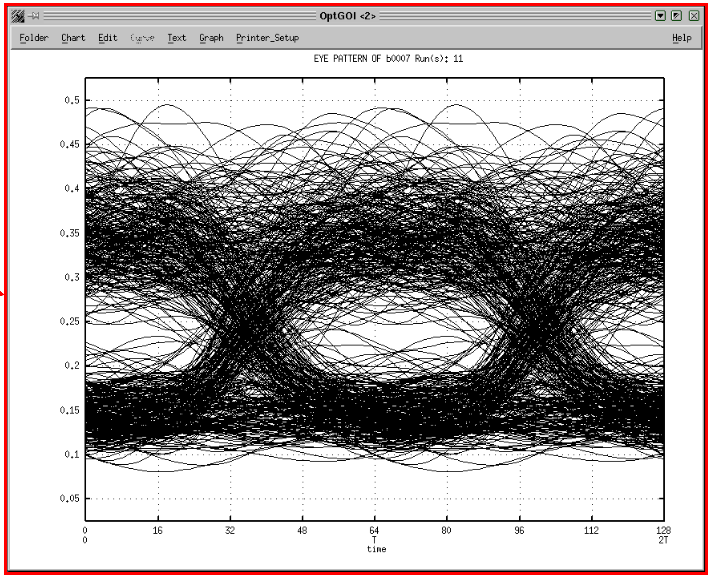




DS: Q vs. pump power

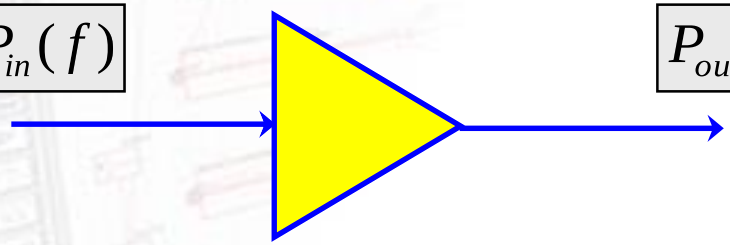






Desurvire's[☞] definition

$P_{in}(f)$



$P_{out}(f) = G(f)P_{in}(f) + S_{noise}(f)$

$$NF(f) = \frac{1 + 2S_{noise}(f)}{G(f)} = \frac{1 + 2n_{sp}(f)\left[G(f) - 1\right]}{G(f)}$$

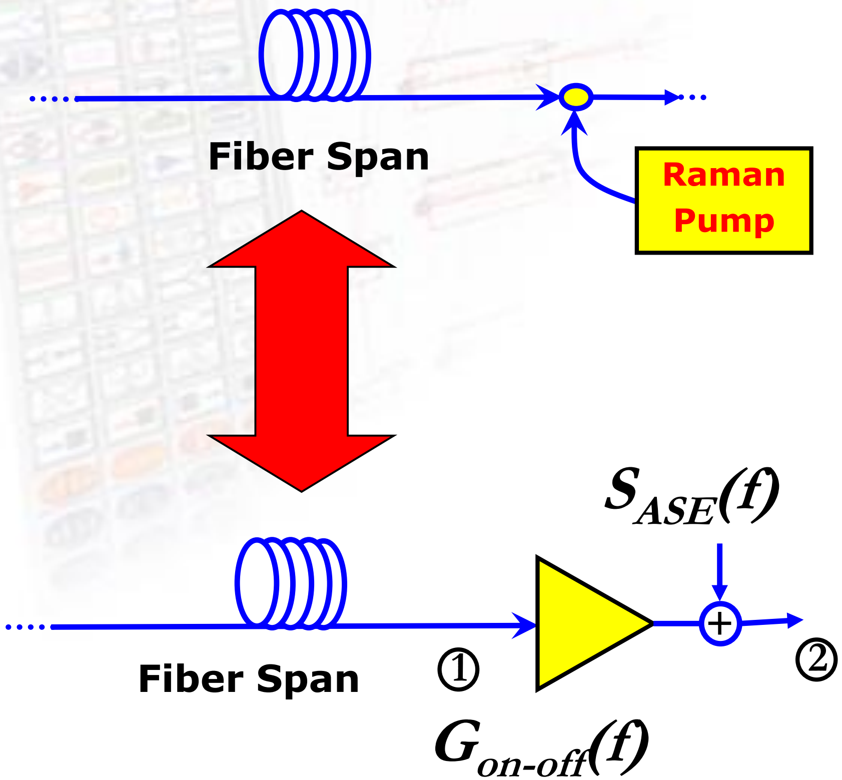
(☞)*Emmanuel Desurvire, Erbium-Doped Fiber Amlifiers, Principles and applications, Wiley-Interscience, New York, 1994.*

Following the Desurvire's definition for RA

$$NF(f) = \frac{1}{\exp\{-\alpha_S L\} G_{on-off}(f)} \left(1 + 2 \frac{S_{ASE}(f)}{h f} \right)$$

It is a rigorous definition, but it does not allow a direct comparison with EDFA's, because it also includes the fiber loss

Equivalent-EDFA definition



Spontaneous Emission Factor

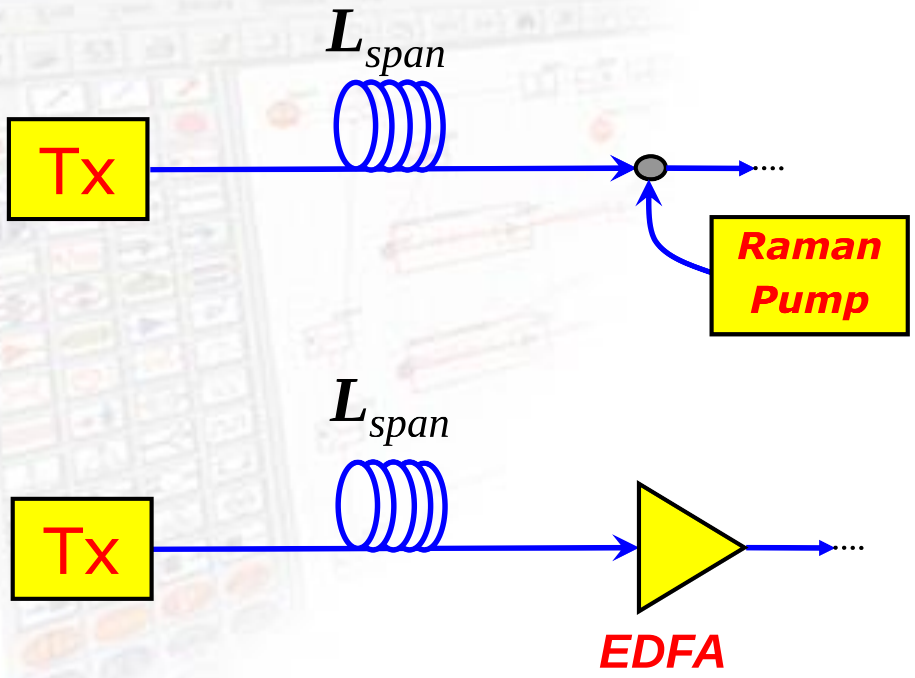
$$n_{sp,RA}(f) = \frac{S_{ASE}(f)}{hf\left[G_{on-off}(f) - 1\right]}$$

Noise-Figure

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

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

EDFA vs. RA



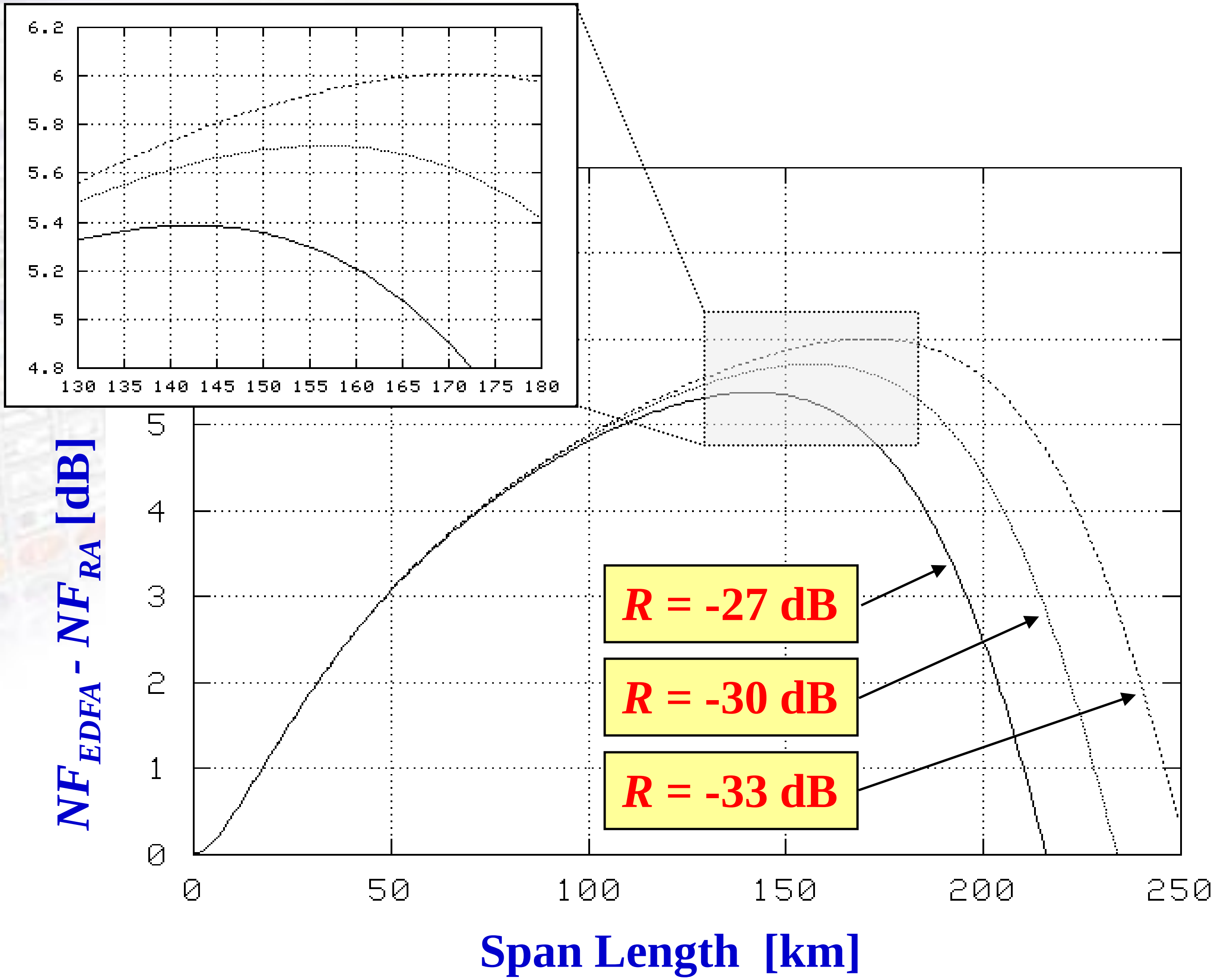
$$G_{on-off} = G_{EDFA} = \exp\{+\alpha_S L_{span}\}$$

$$0 < L_{span} < 250 \ \text{km}$$

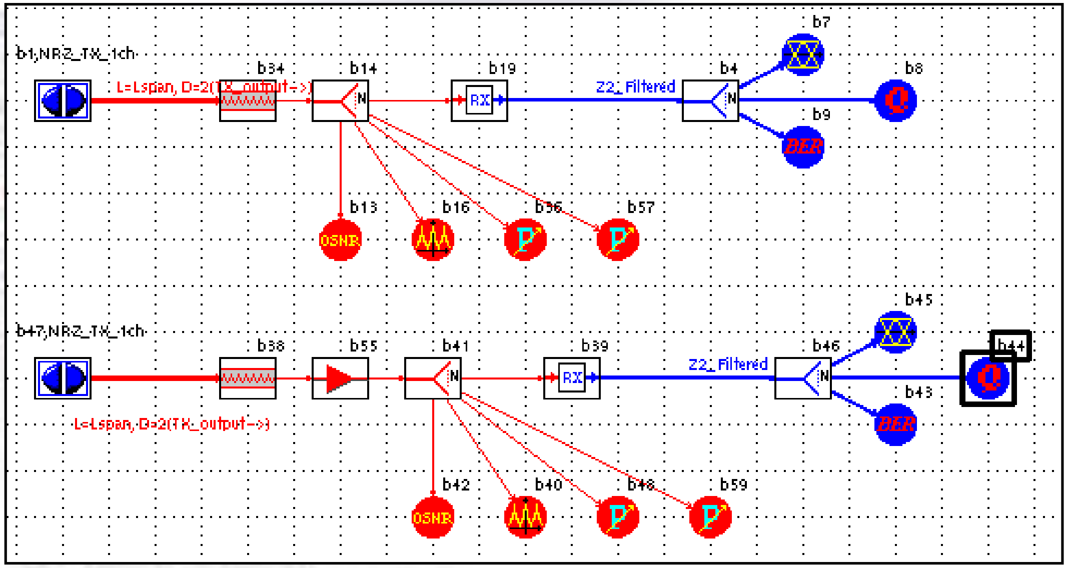
$$P_{TX}^{EDFA} = P_{TX}^{RA}$$

$$NF_{EDFA} = 3 \quad \text{dB}$$

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

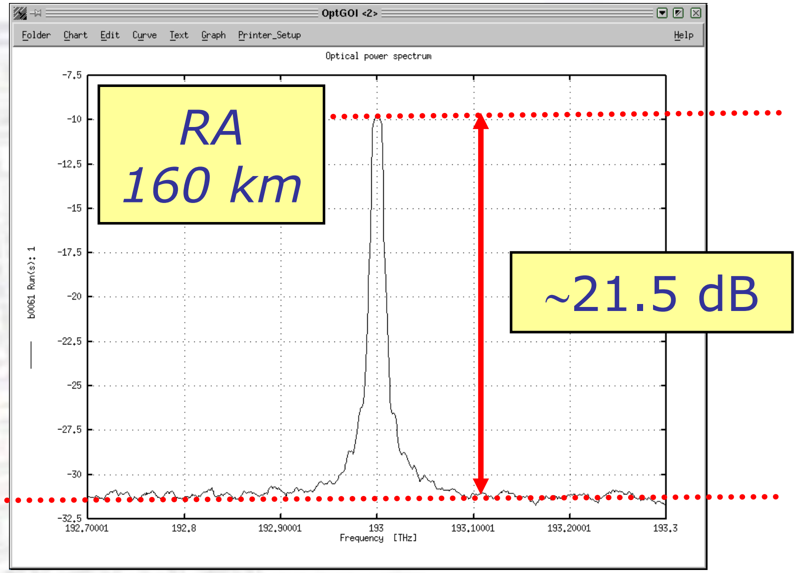

6.2
6
5.8
5.6
5.4
5.2
5
4.8
130 135 140 145 150 155 160 165 170 175 180
NF_{EDFA} - NF_{RA} [dB]
0
1
2
3
4
5
0 50 100 150 200 250
R = -27 dB
R = -30 dB
R = -33 dB
Span Length [km]

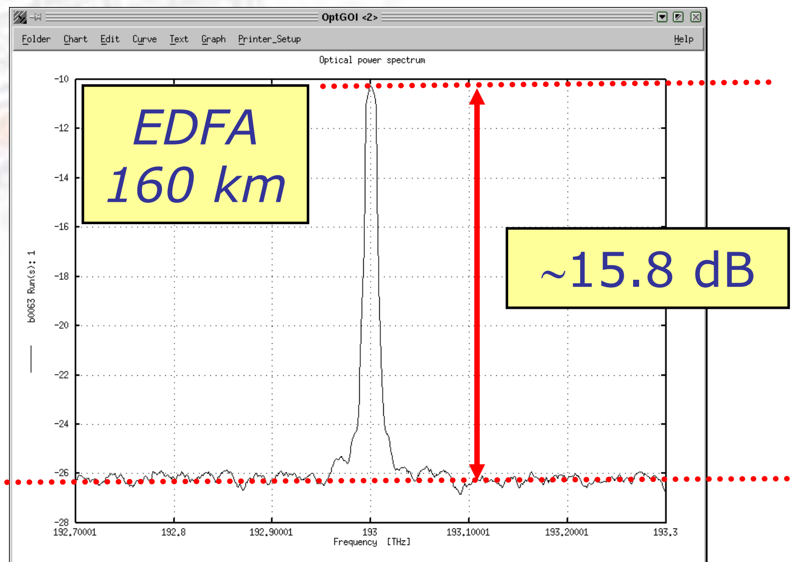
EDFA vs. RA: an example

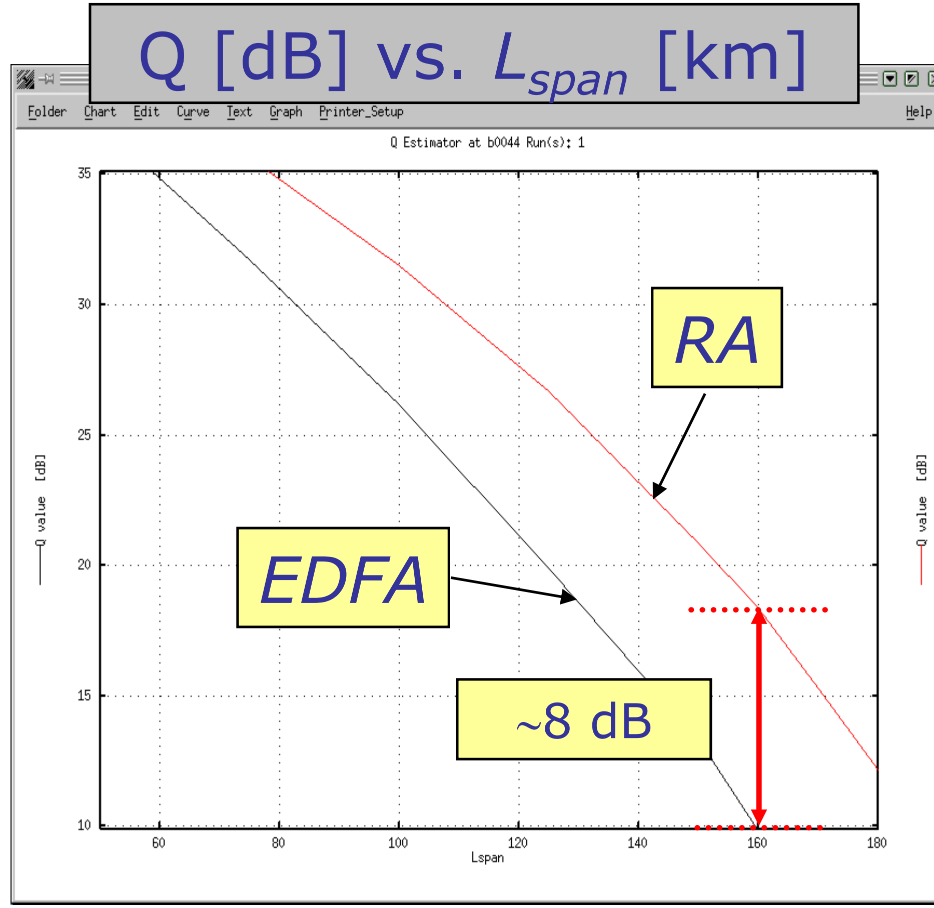


- Fiber: DS
- Distance: 50 to 180 km
- Receiver: sensitivity = -30 dBm
- Rayleigh Scattering: R = -30 dB
- Laser-source power: -7 dBm
- Pump direction: counter-prop.
- $G_{on\text{-}off} = G_{EDFA}$ = fiber loss

EDFA vs. RA: an example

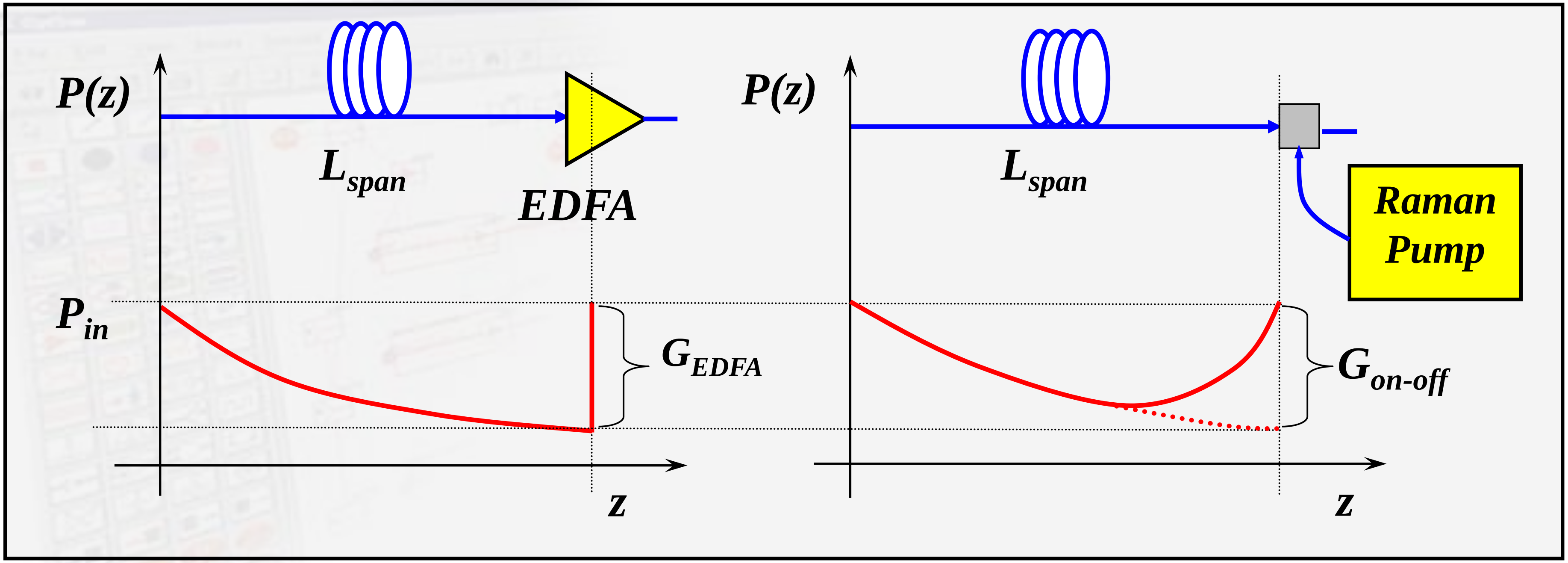






21.5 - 15.8 = 5.7 dB
as predicted

Non-Linear Impact

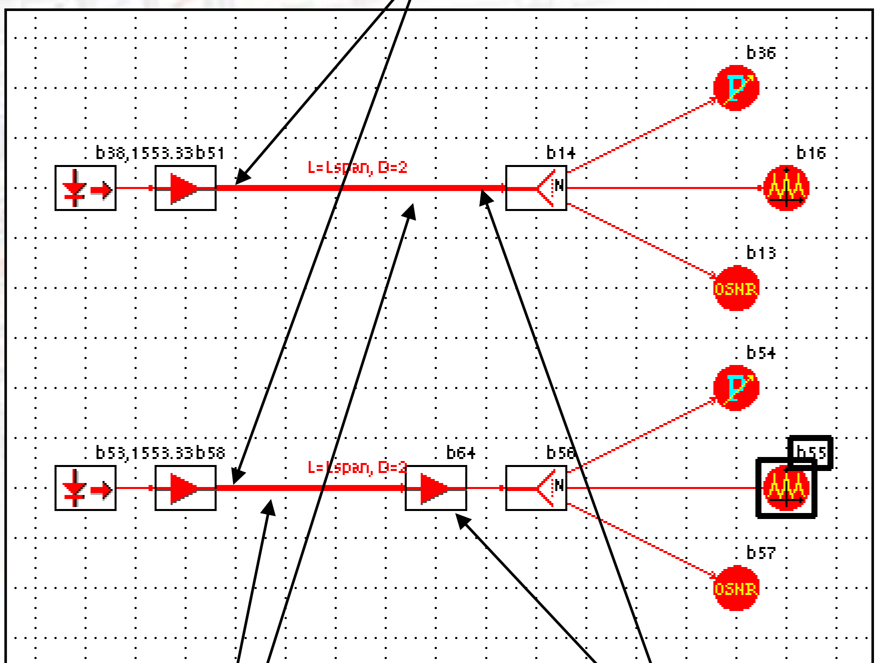


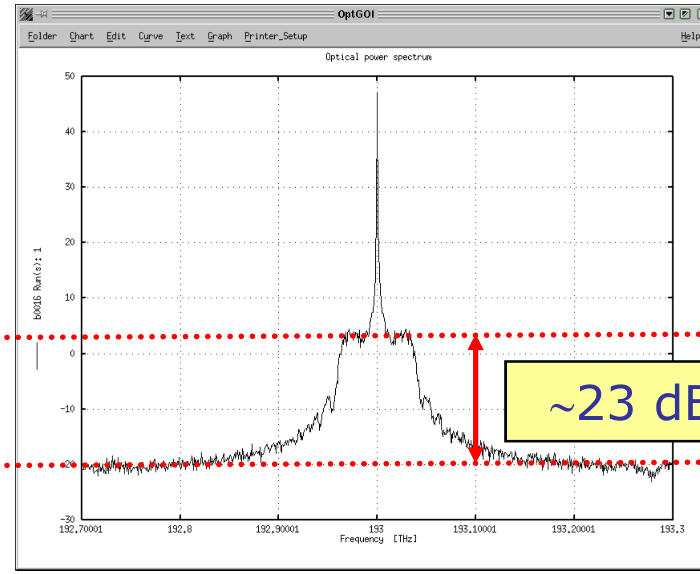
EDFA- and RA-based system have a different power distribution along the fiber-span. With the same P_{in}/P_{out} behavior RA-based systems have an higher *effective* power-level

In RA-based systems a lower power-level must be used to have a comparable effect of non-linearities

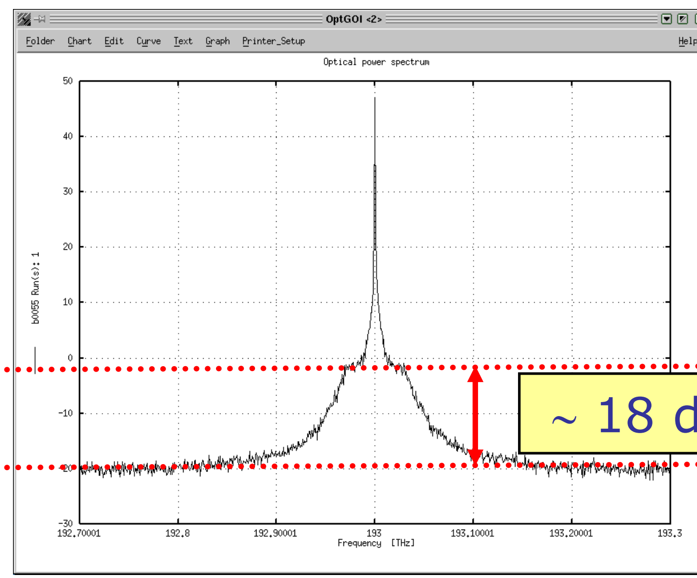
Non-Linear Impact: an example

P_{in} = 16 dBm





~23 dB



~ 18 dB

$G_{on\text{-}off}$ = G_{EDFA} = 10 dB

50 km DS fiber

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Non-linear weight definition

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

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

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

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

Non-Linear Weight

$$K_{NL}^{RA} = K_{NL}^{EDFA} = K_{NL}$$

$$\gamma P_{in}^{EDFA} L_{eff}^{EDFA} = \gamma P_{in}^{RA} L_{eff}^{RA}$$

$$P_{in}^{RA} = P_{in}^{EDFA} \frac{L_{eff}^{EDFA}}{L_{eff}^{RA}}$$

$$SNR_{EDFA} = \frac{P_{in}^{EDFA}}{n_{sp}^{EDFA}(G-1)hfB_n}$$

$$SNR_{RA} = \frac{P_{in}^{RA}}{n_{sp}^{RA}(G-1)hfB_n} = \frac{P_{in}^{EDFA}}{n_{sp}^{RA}(G-1)hfB_n} \frac{L_{eff}^{EDFA}}{L_{eff}^{RA}} = SNR_{EDFA} \frac{n_{sp}^{EDFA}}{n_{sp}^{RA}} \frac{L_{eff}^{EDFA}}{L_{eff}^{RA}}$$

Effective noise-figure for RA

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

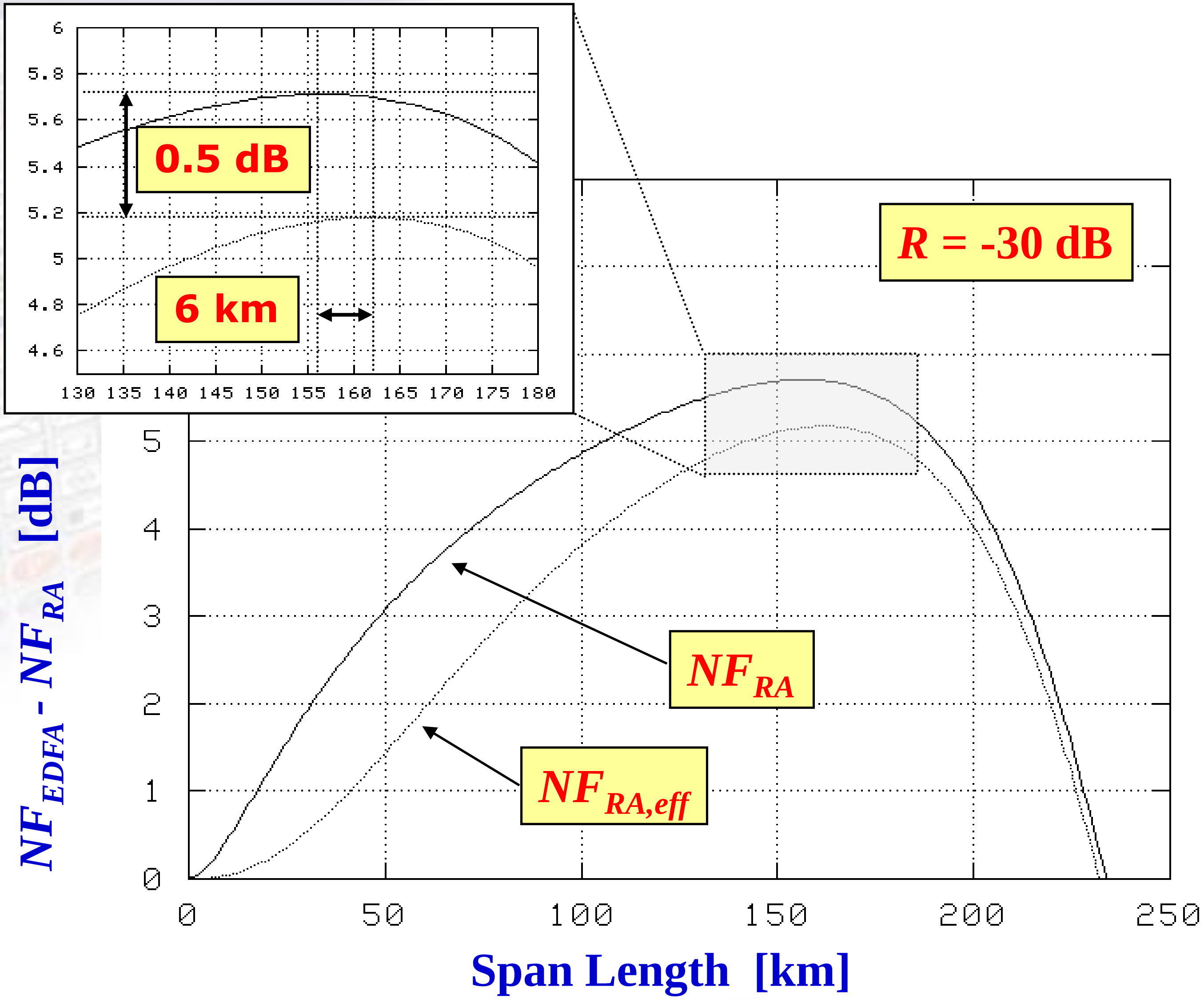
$$n_{sp,eff}^{RA} = n_{sp}^{RA} \frac{L_{eff}^{RA}}{L_{eff}^{EDFA}} > n_{sp}^{RA}$$

Effective spontaneous emission factor

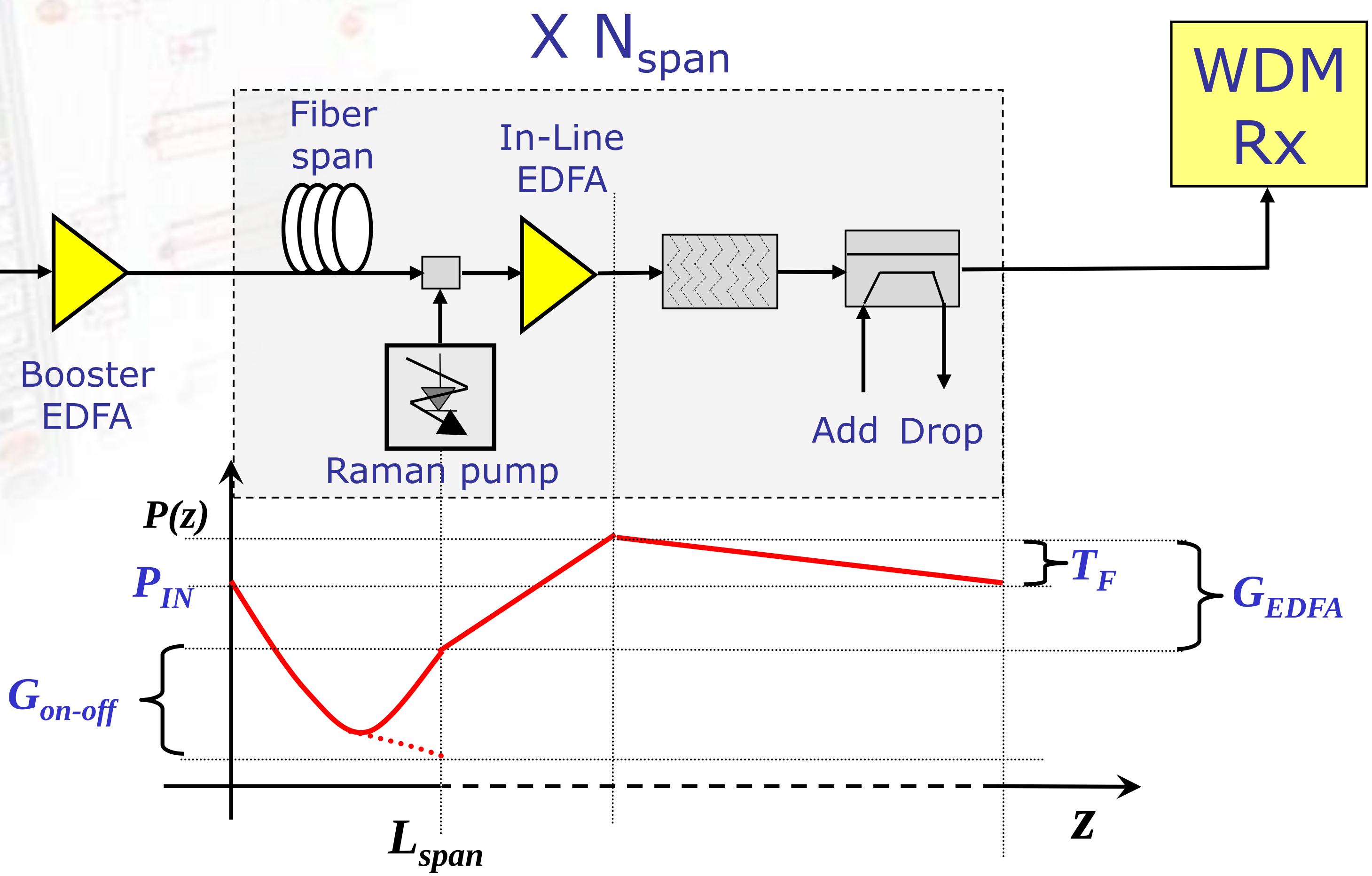
Effective Noise-Figure

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

Effective noise-figure for RA



The analyzed set-up



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

Signal-To-Noise Ratio at the output of the system

$$SNR = \frac{P_{IN}}{hfB_n} \cdot \frac{\exp\left\{-\alpha_S \dfrac{L_{TOT}}{N_{span}}\right\}}{N_{span}\left(n_{eq}^{RA} + \dfrac{n_{eq}^{EDFA}}{G_{on-off}}\right)}$$

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

Equivalent Spontaneous Emission Factor

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

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

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

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 to maximize the *SNR* for each K_{NL}

Optimization process

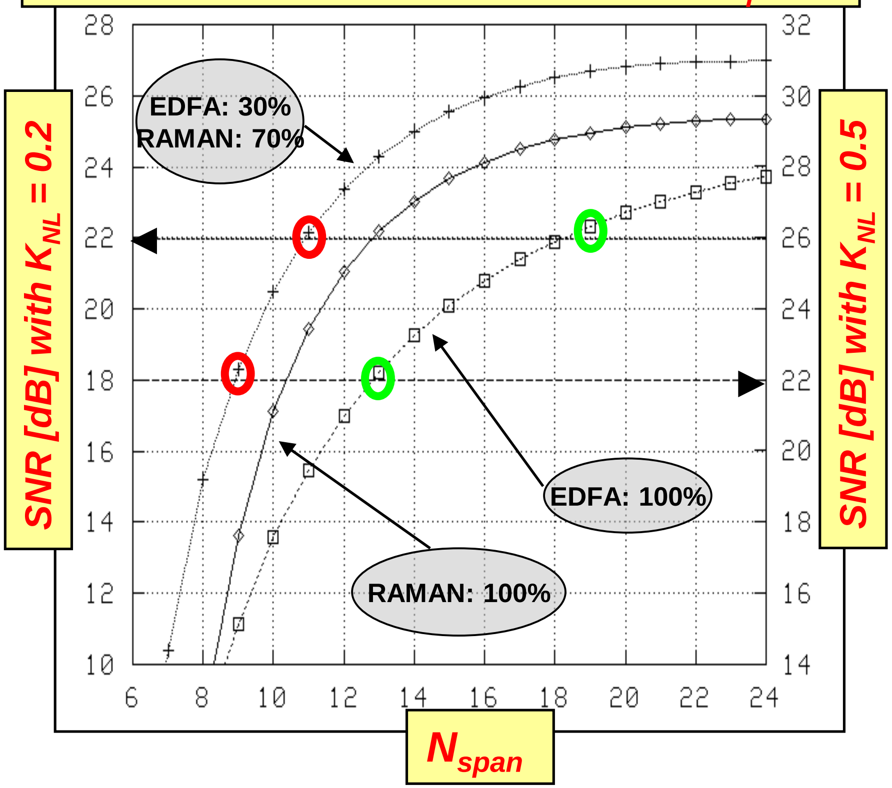
- Required $BER = BER_{max}$ ➡ Minimum $SNR = SNR_{min}$
- Fix Margin ➡ $SNR = SNR_{min} + Margin$
- Evaluate the optimal configuration with a given K_{NL}
- Simulate the configuration
- $BER > BER_{max}$ ➡ Non-Linear impact is too strong, start again the procedure with a smaller K_{NL} or with a modulation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

Medium-Haul DWDM System

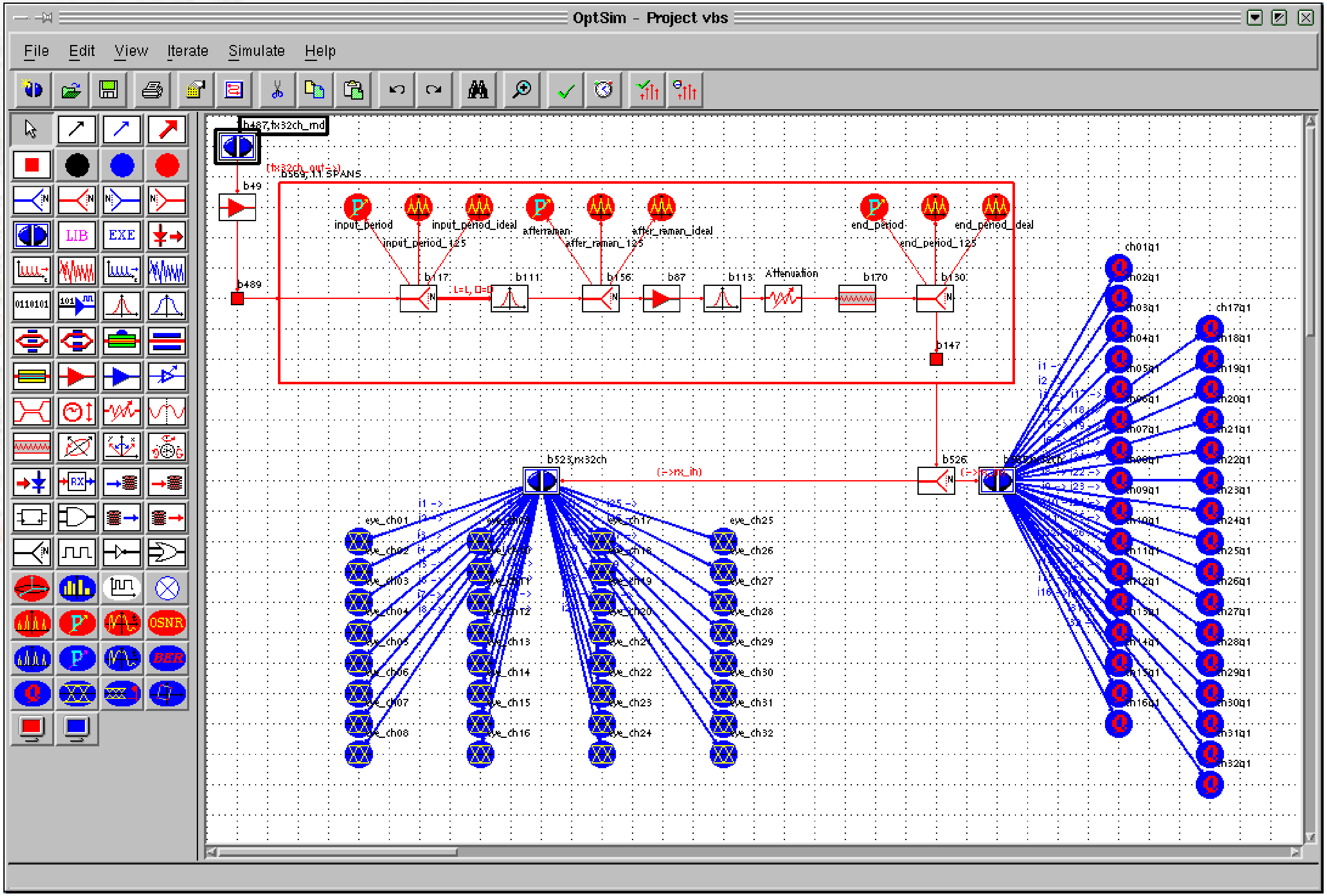
- Total length: L_{TOT} =1500 km
- Number of channels: 32
- Channel spacing: 50 GHz
- Signal loss: α_S = 0.2 dB/km @ 1550 nm
- Pump loss: α_P = 0.3 dB/km @ 1450 nm
- D =5.7 ps/nm/km
- D' = 0.037 ps/nm²/km
- 100% dispersion compensation
- Ideal Gain Flattening Filter
- Passive components loss: T_F = 10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

	Unit	Knl = 0.2 EDFA 30%	Knl = 0.2 EDFA 100%	Knl = 0.5 EDFA 30%	Knl = 0.5 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	-

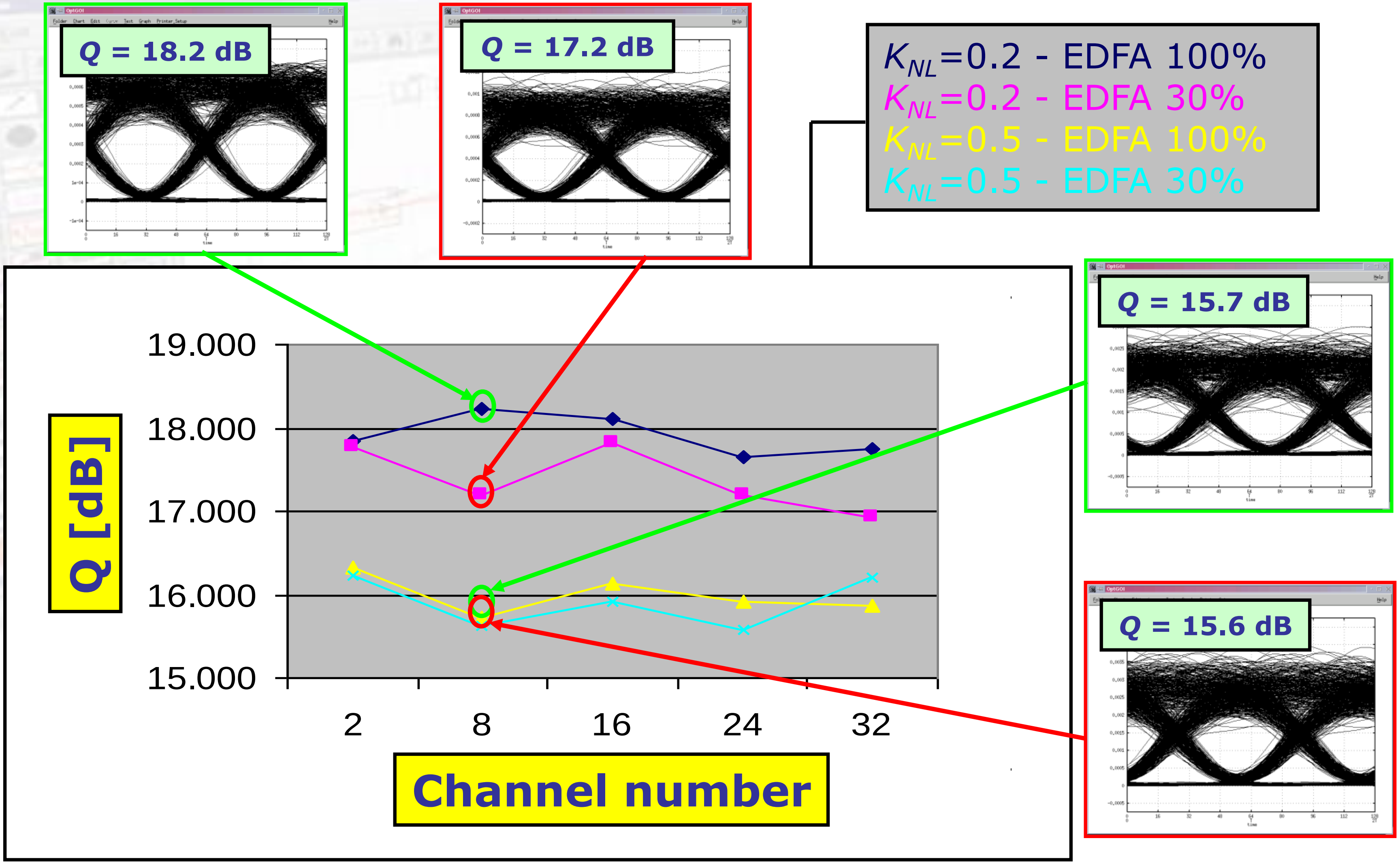
K_{NL} Fixed: SNR vs. N_{span}



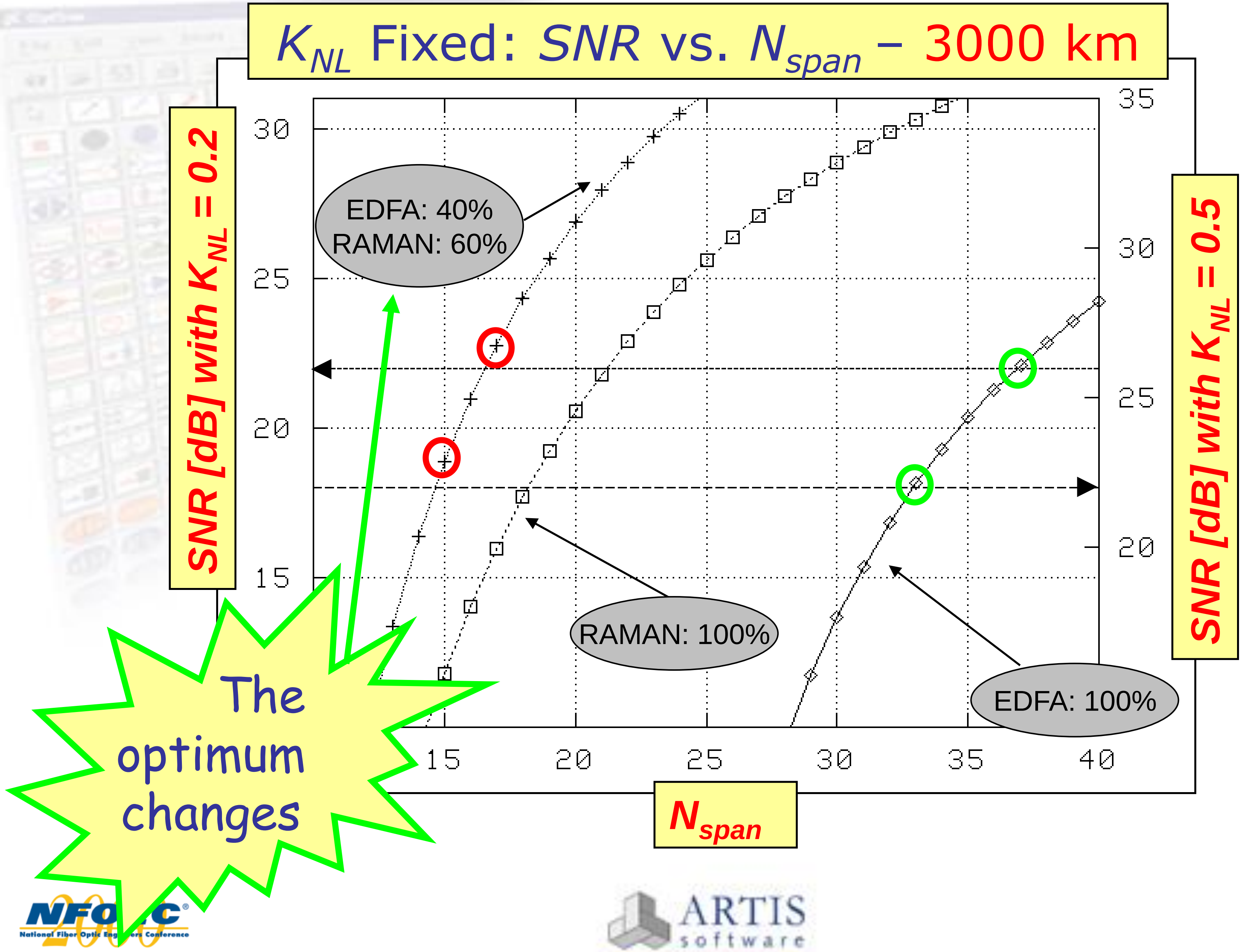
Simulation: *OptSim* layout



Simulation: *Q* values



HFA: Use Case (NO lumped loss)



- **Saturation**
  - It occurs when the transfer of pump-power is so strong to deplete the pump-power itself. This phenomenon is more important in forward-pumped RA
- **Multi-pump Raman Amplifier**
  - If the RA bandwidth wants to be enlarged a multi-pump configuration must be used.

- **Multi-pump Raman amplifier**
- **Pump definition:**
  - Frequency and power for each pump
  - ASCII file containing the measured power spectrum of the pumps
- **Saturation characteristics and interactions between pumps**
- **Interference caused by the single- and double-scattered signal components**