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STATISTICAL PROPERTIES AND SYSTEM IMPACT OF MULTI-PATH INTERFERENCE IN RAMAN AMPLIFIERS

V. Curri[1,2], G. Rizzo[1]

[1]*Optical Communications Group*
Politecnico di Torino
Torino - ITALY
OptCom@polito.it
www.OptCom.polito.it

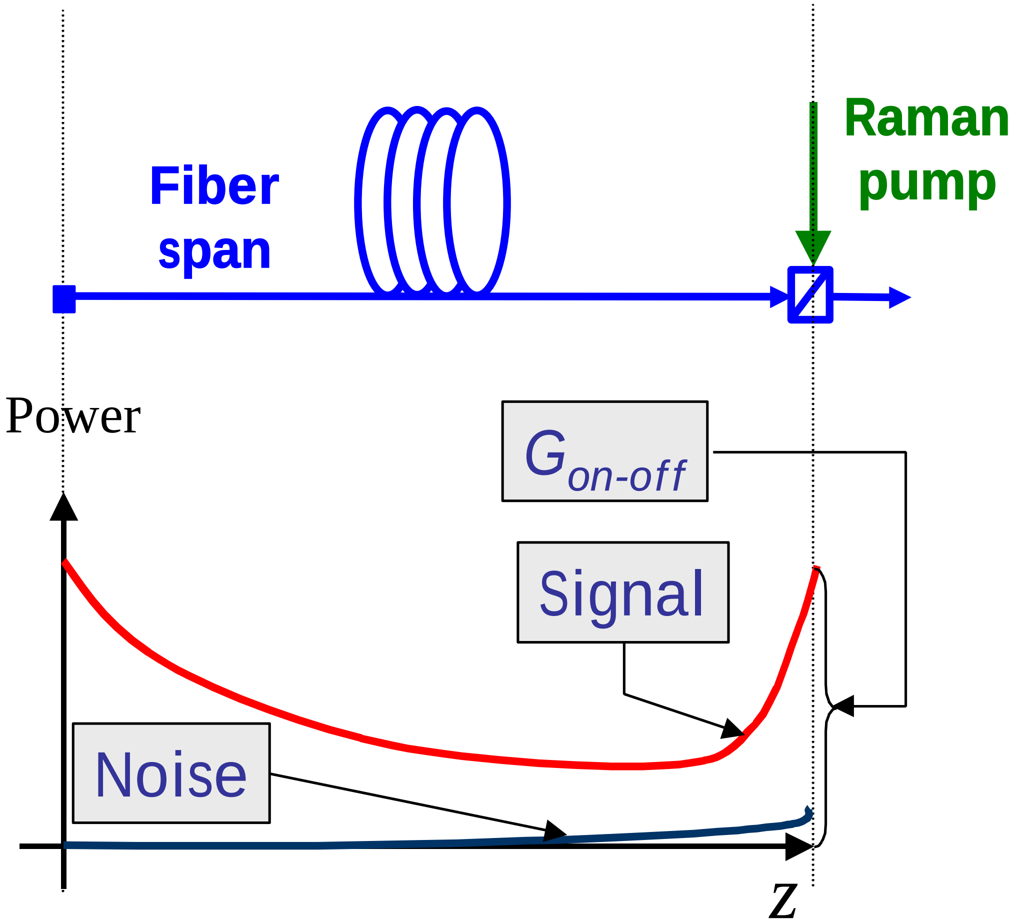
[2]*ARTIS Software Corporation*
San José
California
RnD@Artis-Software.com
www.Artis-Software.com

This work…

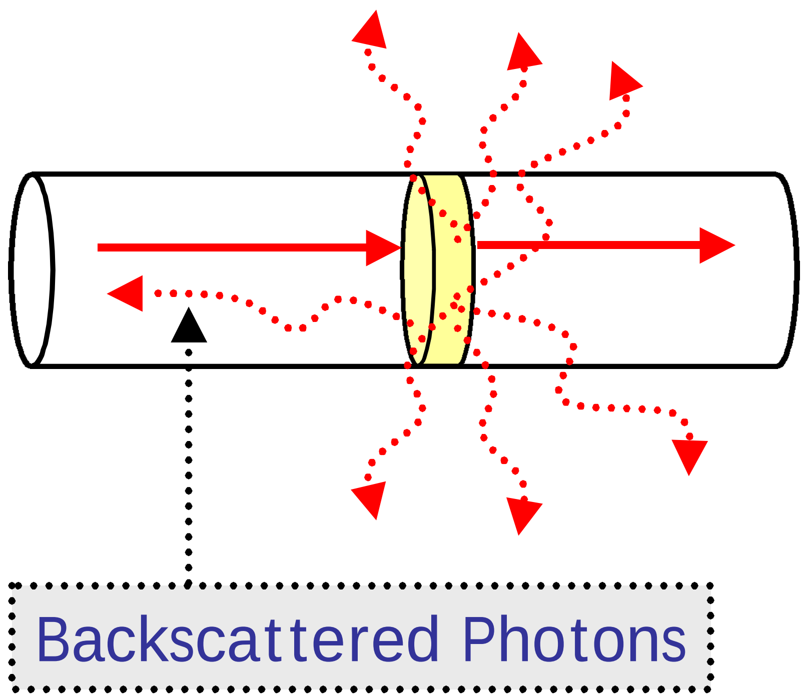
- Raman amplification interacts with Rayleigh Scattering.
  - ASE noise ⟹ additive noise components.
  - Signal ⟹ Multi-Path Interference (MPI).
- ASE reflections have been analyzed and characterized.
- MPI has been observe but not studied in detail.
- Purpose of this work is to statistical characterize MPI.
- Noise figure definition is extended in order to include MPI impairments as well as the Q evaluation.
- The proposed analysis is applied to a single-span scenario.

Raman Amplification and Rayleigh Scattering

Raman Amplification

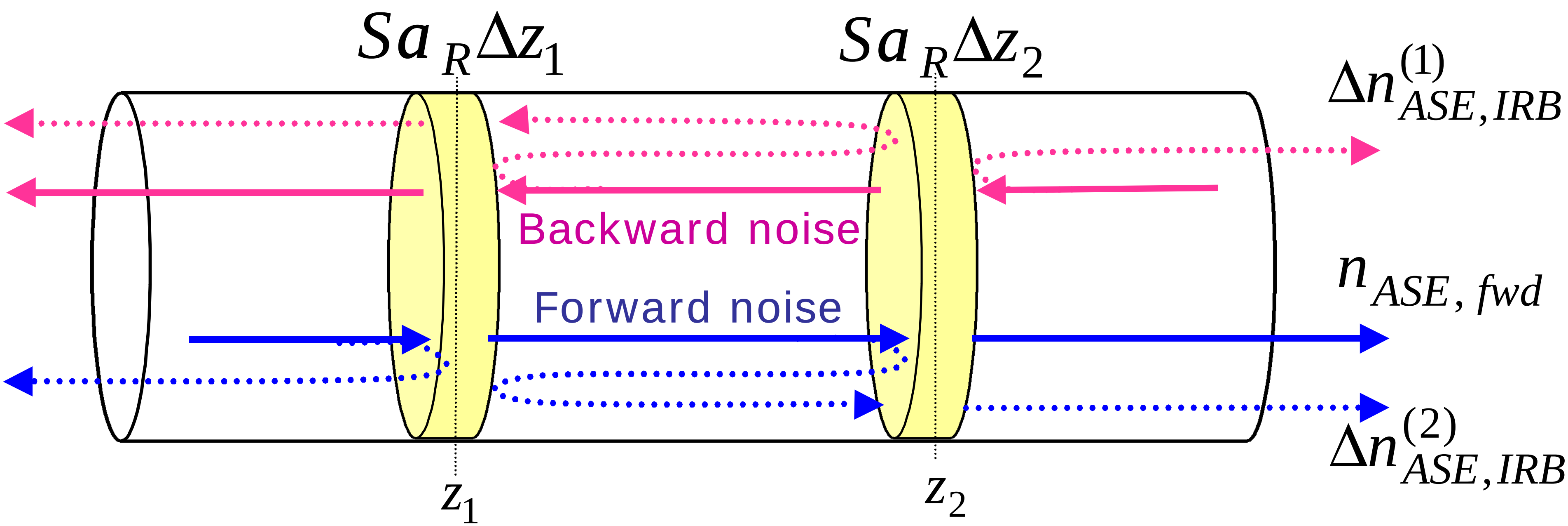


Rayleigh Scattering



$$\mathrm{d}P_{BS} = S\alpha_R\,\mathrm{d}z$$

Multiple Reflections of ASE noise



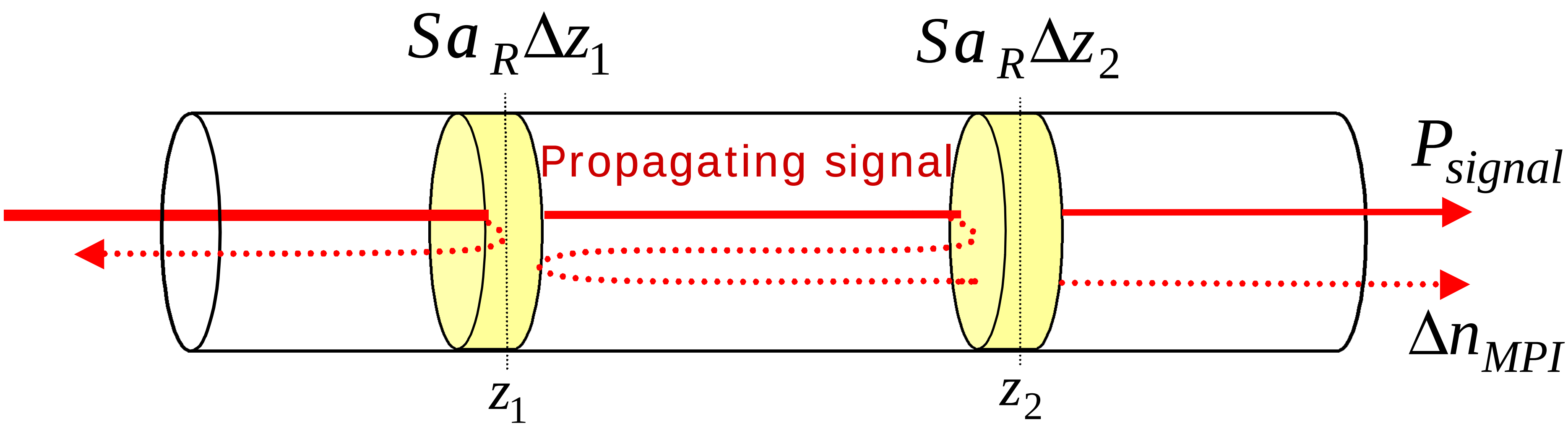
Infinite Rayleigh Backscattered (IRB)

$$\Delta n_{ASE,IRB} = \Delta n^{(1)}_{ASE,IRB} + \Delta n^{(2)}_{ASE,IRB} + \ldots = \sum_{i=1}^{+\infty} \Delta n^{(i)}_{ASE,IRB}$$

Integrating along z

$$n_{ASE,IRB}$$

Multiple Reflections of Signal

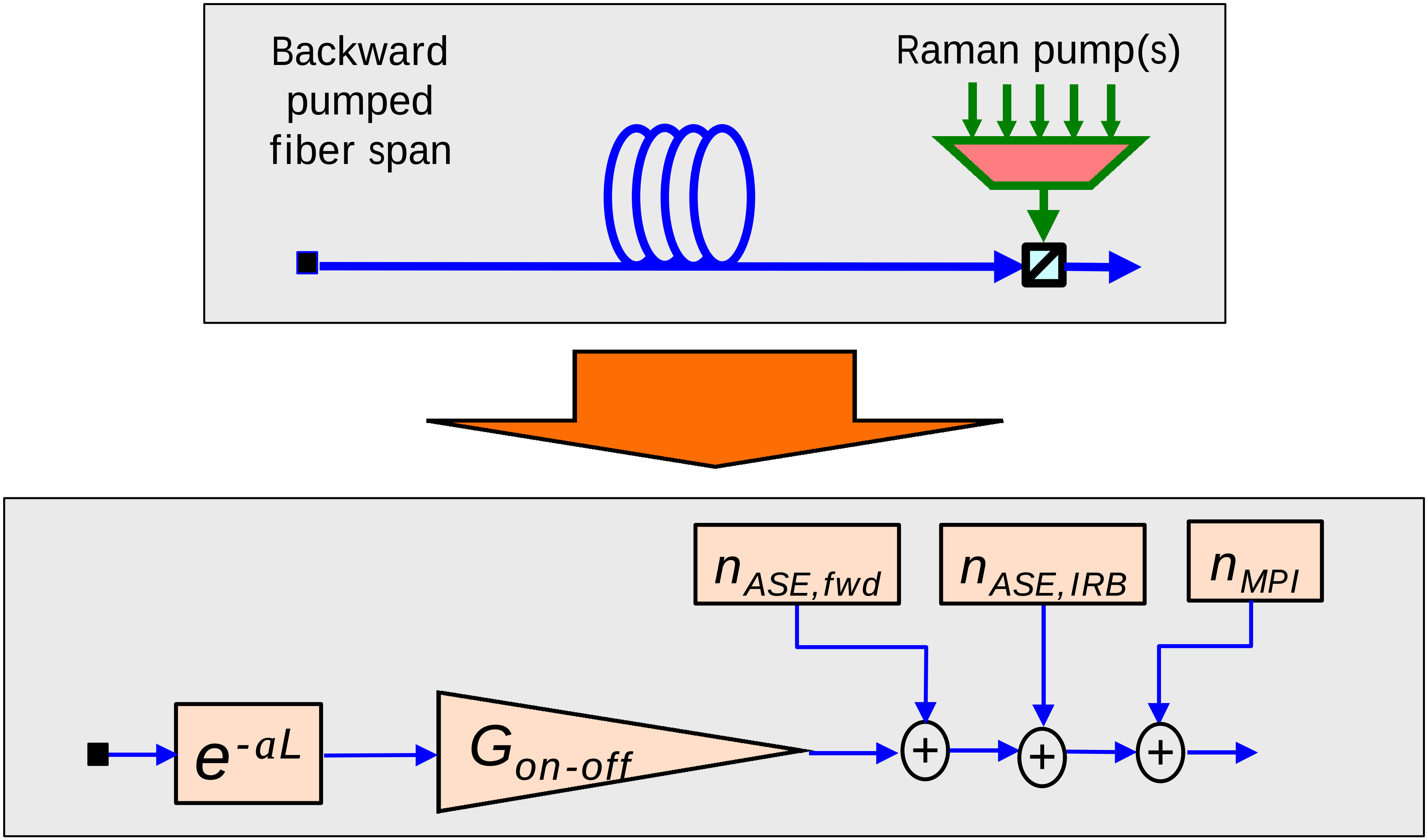


For signal, we consider double reflections only → $\Delta n_{MPI}(z_1, z_2)$

Integrating... →

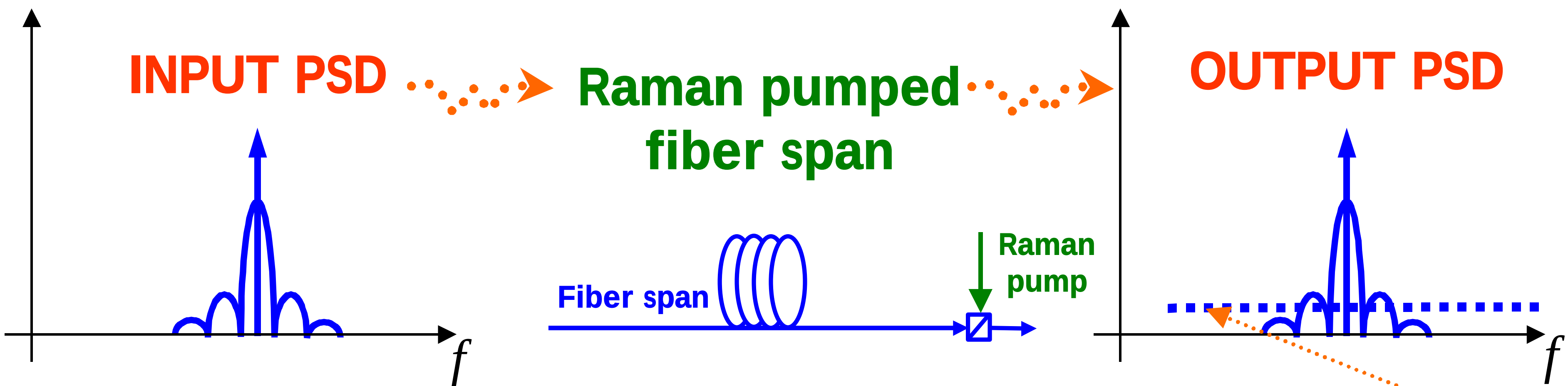
$$n_{MPI}(L) = \int_0^L \int_0^{z_2} \Delta n_{MPI}(z_1, z_2)\, \mathrm{d} z_1\, \mathrm{d} z_2$$

Raman Amplifier: the Equivalent Scheme



Power Spectral Density of ASE noise

- Random process $n_{ASE,fwd}(t)$ is a Gaussian random process that can be approximated as white over a single channel bandwidth.
- The same approximation is valid for the random process $n_{ASE,IRB}(t)$.

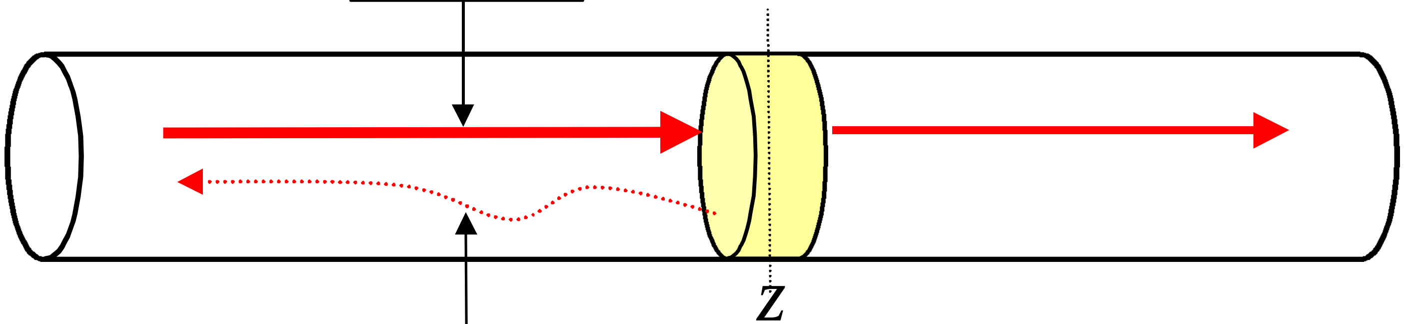


System impact of ASE noise can be analyzed using tools developed for EDFAs, i.e., D. Marcuse, *Derivation of analytical expressions for the Bit-Error Probability in lightwave systems with amplifiers*, JLT, Dec. 90.

$$S_{ASE,fwd}(f) + S_{ASE,IRB}(f)$$

Rayleigh Scattering: a Random Process

$E_{dir}(t,z)$ — **Amplitude of optical field**



$E_b(t,z)$ — **Amplitude of backscattered optical field**

$$r(z) = \frac{E_b(t,z)}{E_{dir}(t,z)} = r_P(z) + j r_Q(z)$$

$r_P(z),\ r_Q(z)$ — **Gaussian random processes**

$$R = S\alpha_R$$

$$\langle r_P(z_1)\ r_P(z_2)\rangle = \langle r_Q(z_1)\ r_Q(z_2)\rangle = \frac{R}{2}\delta(z_1 - z_2)$$

$$\sigma_P^2 = \sigma_Q^2 = \frac{R}{2}$$

Power Spectral Density of MPI

Considering propagating signal is a PRBS NRZ coded and Rayleigh Scattering is a random process, the resulting output random process can be statistically characterized

Gaussian Random Processes

$$n_{MPI}(t) = n_{MPI}^{P}(t) + j\, n_{MPI}^{Q}(t)$$

PSD of MPI

$$S_{MPI}(f) = \frac{R^2}{2} G_{on-off} \exp(-aL)\{S_S(f)K_r + P_{ave} d(f)\}$$

Power of MPI

$$s^{2}_{MPI} \cong \frac{R^2}{2} G_{on-off} \exp(-aL)(K_r + 1)P_{ave}$$

$$K_r = \int_0^L \int_0^{z_2} \exp[-2a(z_2 - z_1)]\, G_{RA}^2(z_1; z_2)\, dz_1\, dz_2$$

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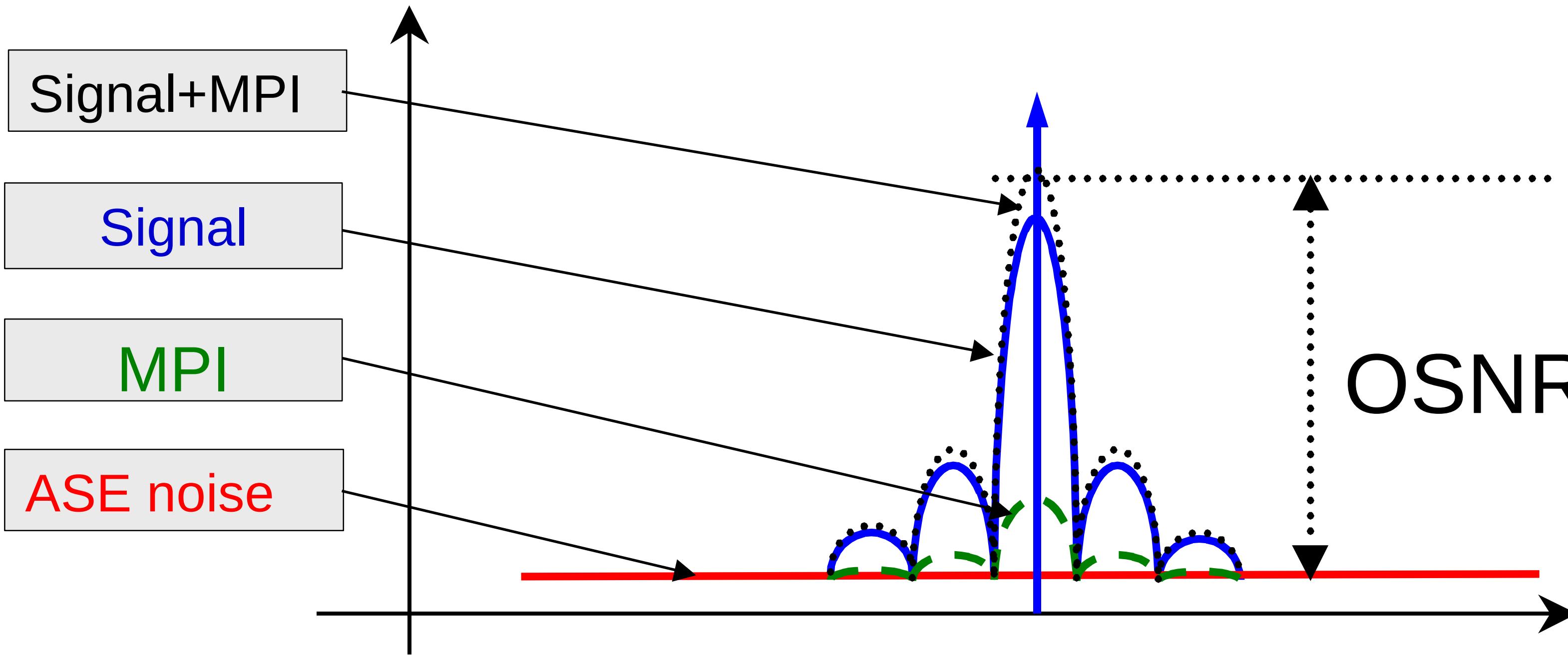
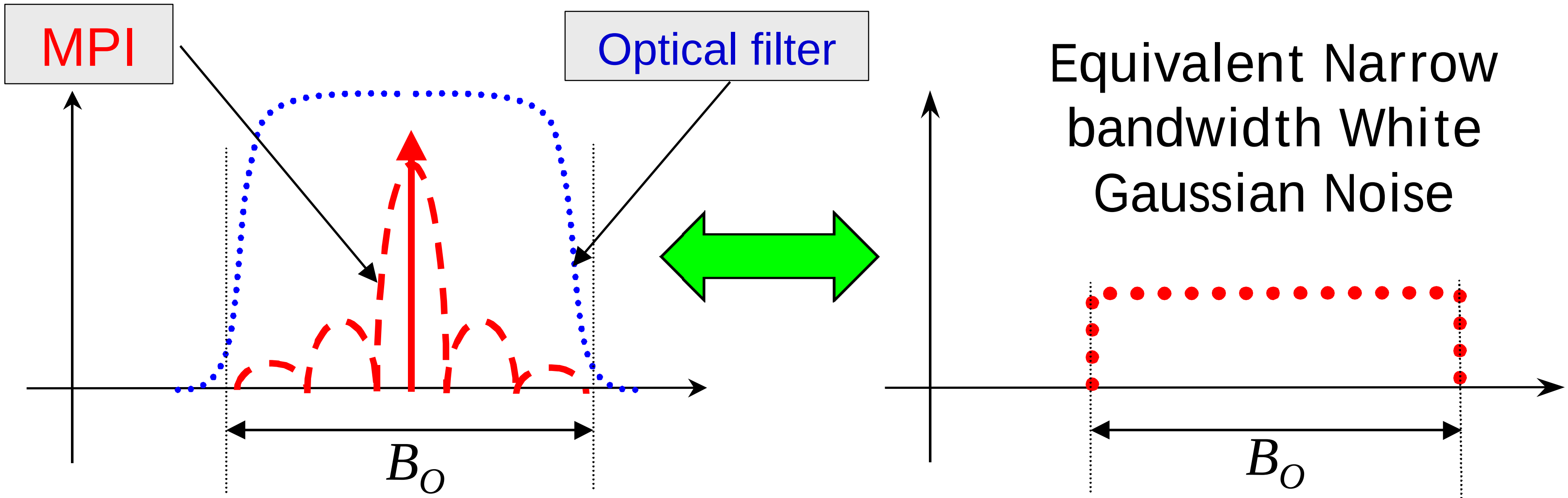
System Impact of MPI



If performance estimation is done through OSNR measurements, results can be inaccurate. Cause of inaccuracy is that as signal power, signal+MPI power is considered, while as noise power ASE noise only is measured.

Noise Figure Definition

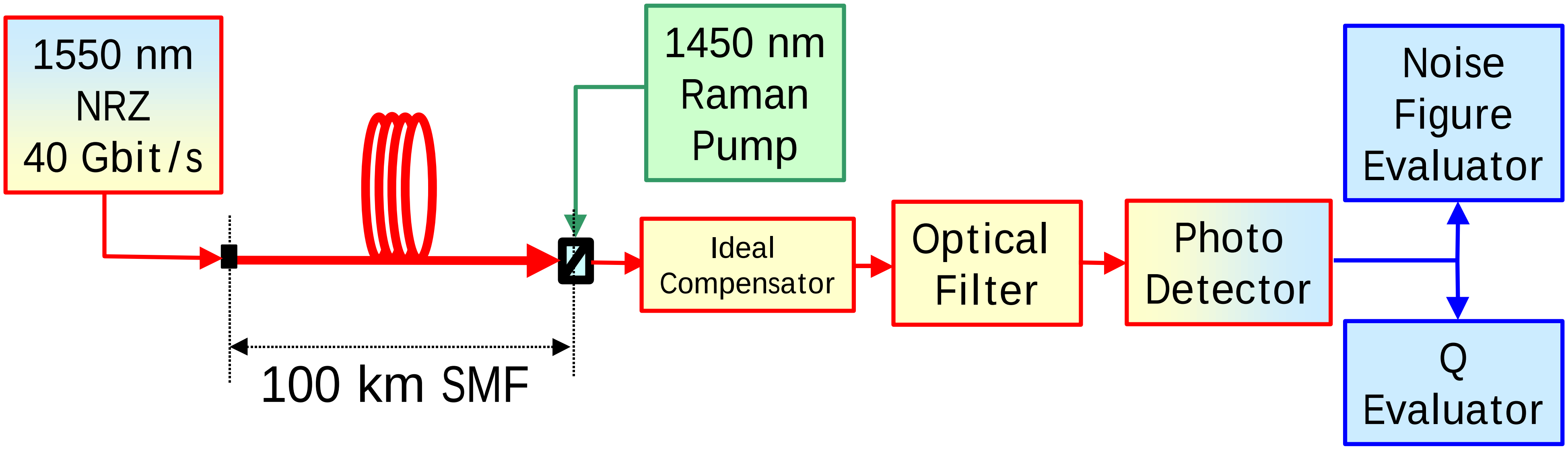


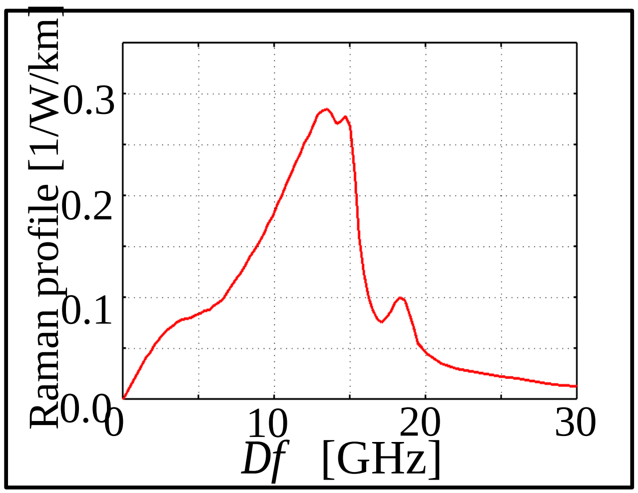
It can be included in the

Noise Figure and **Q estimation**

$$F_{eq}(f) = \frac{1}{G_{on-off}(f)}\left[1 + 2\frac{S_{ASE}(f)}{hf} + 2\frac{s^{2}_{MPI}}{hfB_o}\right] = F_{eq,ASE} + F_{eq,MPI}$$

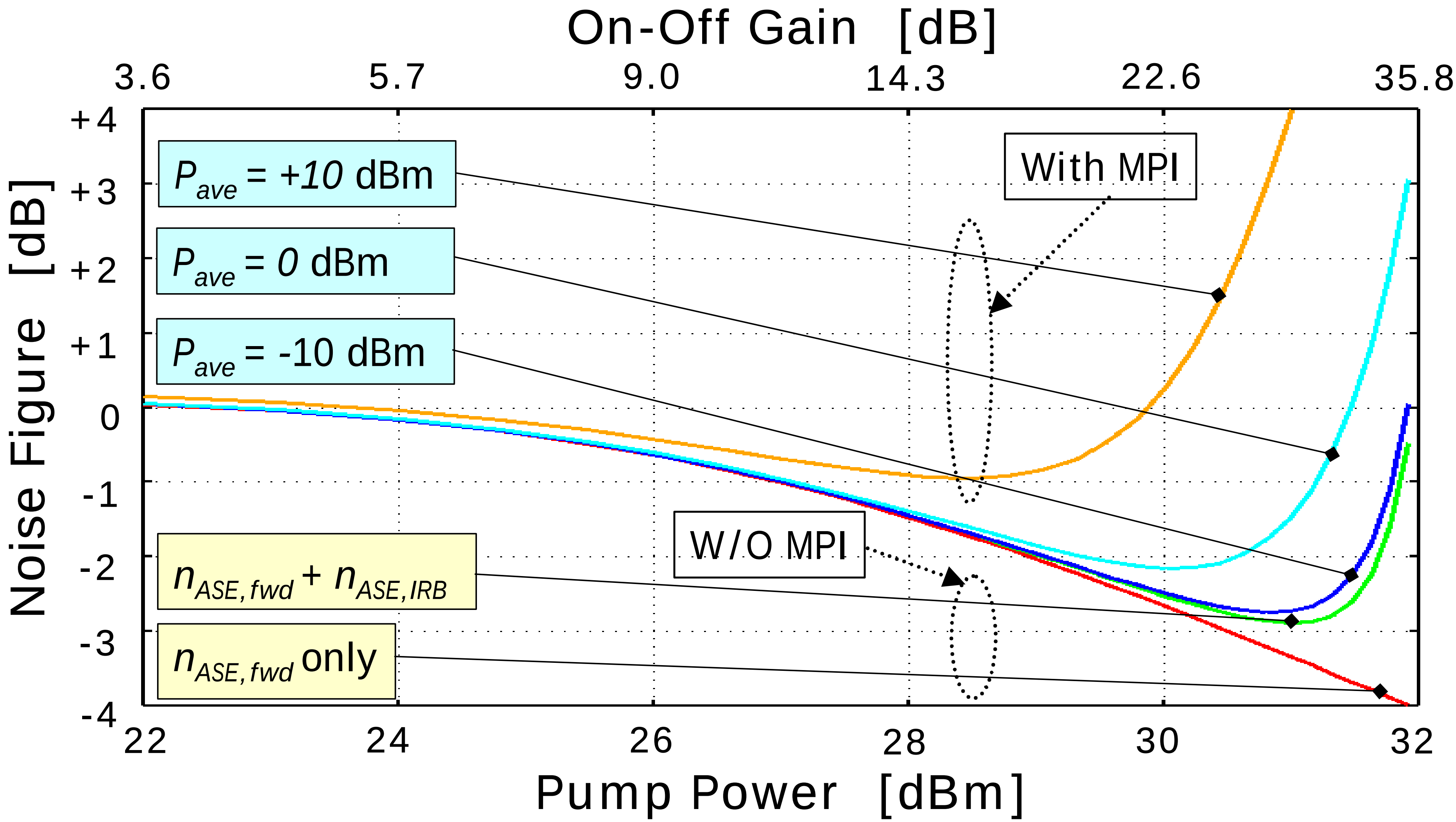
A Simple Example



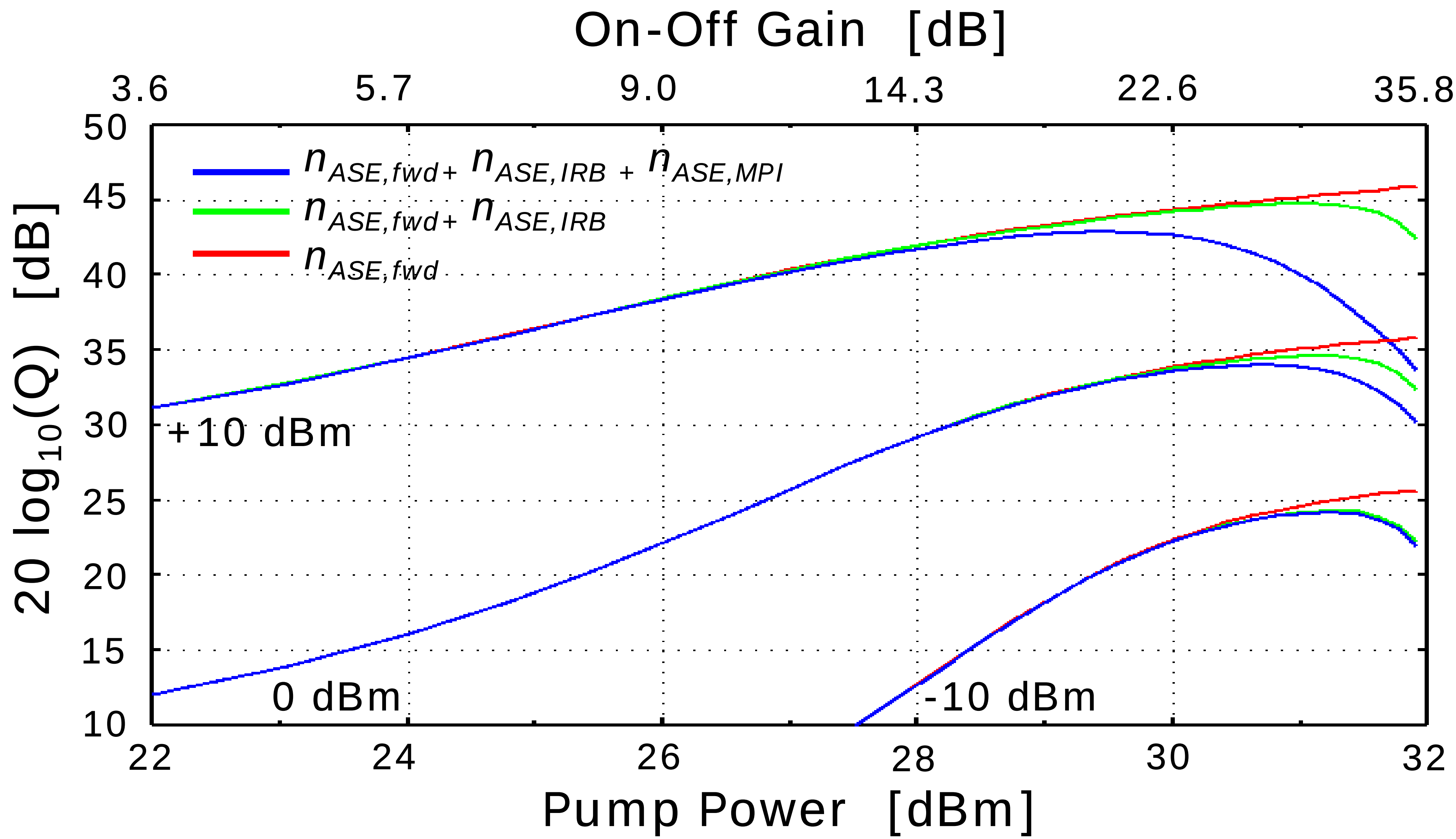


- Tx power: -10 → +10 dBm.
- Pump Power: +22 → +32 dBm.
- Raman gain with no pump depletion.
- Influence **ASE noise** and **MPI**.
- OSNR analysis, no propagation effects

Noise Figure plot

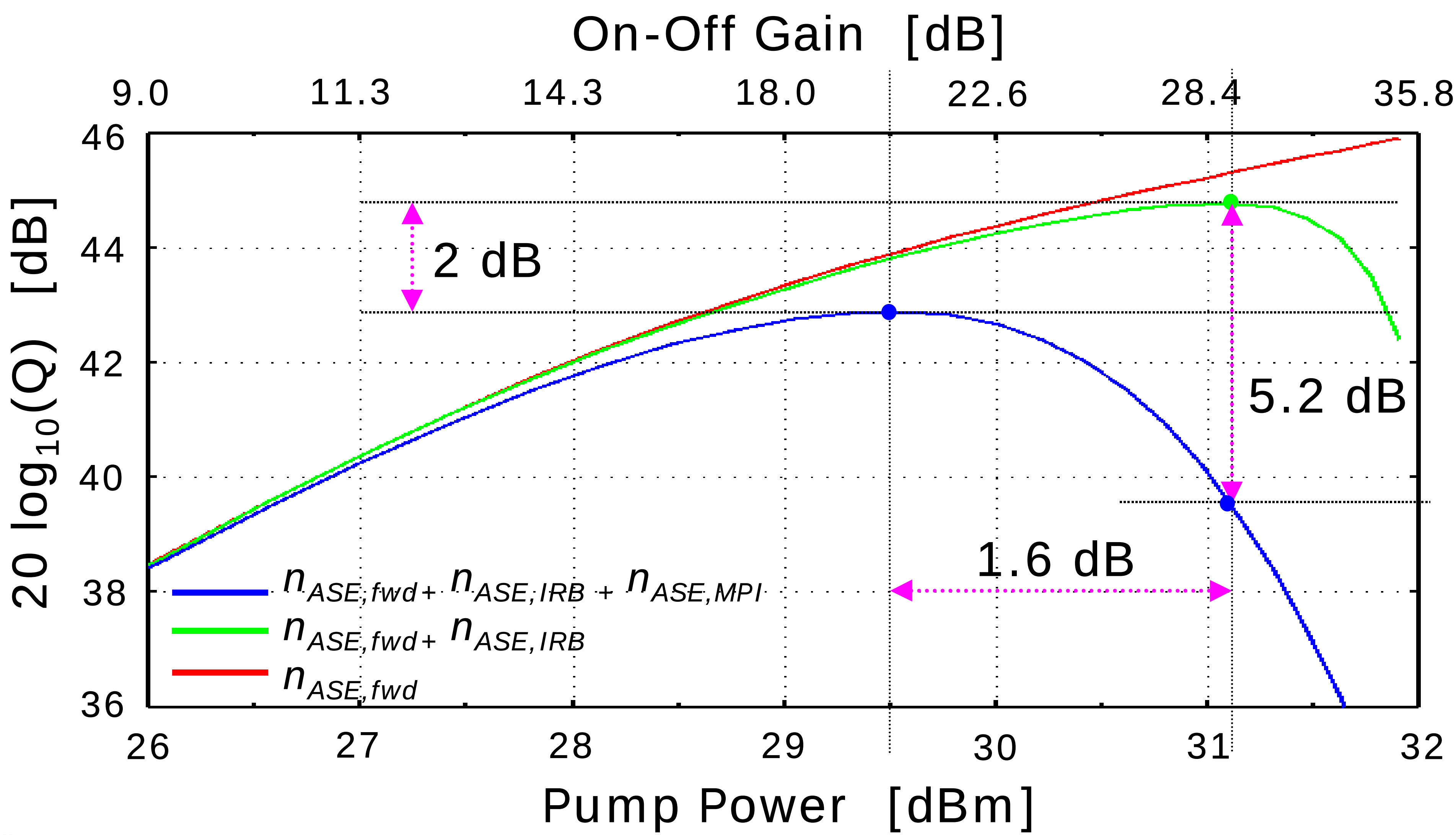


Q plot



On-Off Gain [dB]
3.6
5.7
9.0
14.3
22.6
35.8
$n_{ASE,fwd} + n_{ASE,IRB} + n_{ASE,MPI}$
$n_{ASE,fwd} + n_{ASE,IRB}$
$n_{ASE,fwd}$
20 log$_{10}$(Q) [dB]
50
45
40
35
30
25
20
15
10
+10 dBm
0 dBm
-10 dBm
22
24
26
28
30
32
Pump Power [dBm]

Zoom of Q plot at +10 dBm



Conclusions

- Interaction of Raman amplification with Rayleigh Backscattering has been fully described.
  - Multiple reflections of ASE noise generate additive noise component.
  - Double reflections of signal generate a narrow bandwidth interference: Multi-Path Interference (MPI).
- We demonstrate MPI is a Gaussian random process whose PSD presents the same shape of the signal PSD.
- In order to analyze the system impact of the MPI, the equivalent narrow bandwidth WGN is considered.
- MPI is included in the evaluation of Noise Figure and Q.
- MPI must be taken into account in RA design only in case of high-gain Raman amplifiers ($G_{on\text{-}off} > 15$ dB)

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