Raman Amplification for Telecom Optical Networks

Dominique Bayart
Alcatel-Lucent Bell Labs France, Research Center of Villarceaux

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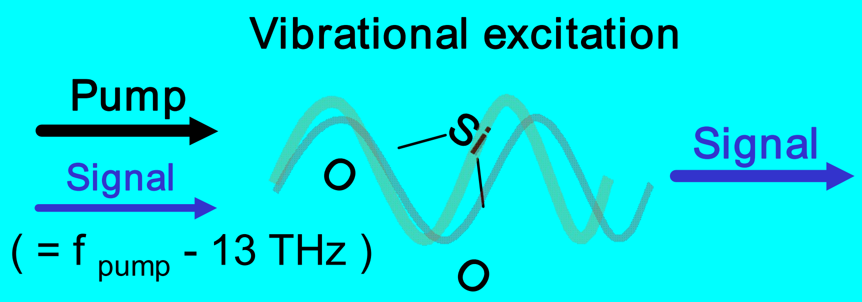
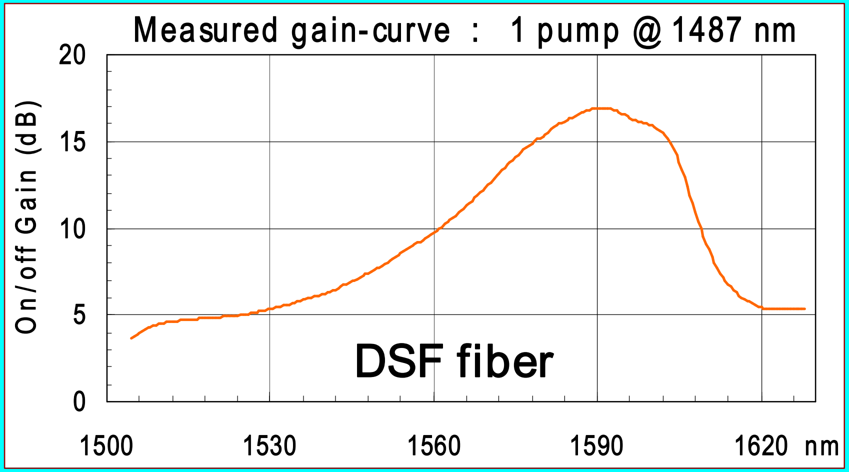
Outline of the talk

- Raman interaction of Light with the glass
- Spectral and power characteristics
- Noise performance and limitations (Rayleigh, noise transfer)
- System implementation
- Lumped Raman amplifiers

Raman amplification : Principle





$$G_{ON/OFF}^{dB} = \frac{10}{\ln 10} \cdot \frac{g_r}{A_{eff}} \cdot \frac{1 - e^{-\alpha_p \cdot L}}{\alpha_p} \cdot P_p$$

A_{eff} is the Raman effective area of the fiber

L_{eff} : Effective length of the fiber expressed as : $L_{eff} = \frac{1}{\alpha_\rho}$

Effect happens for any pump frequency, polarization dependent

Instantaneous effect (not the travel time of the pump along the fiber !)

Peak Raman shift = - 13 THz (glass phonon energy)

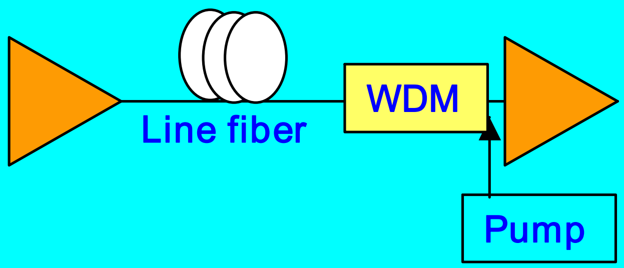
Top width = 2.5 THz, can be broadened with multi-λ pumping

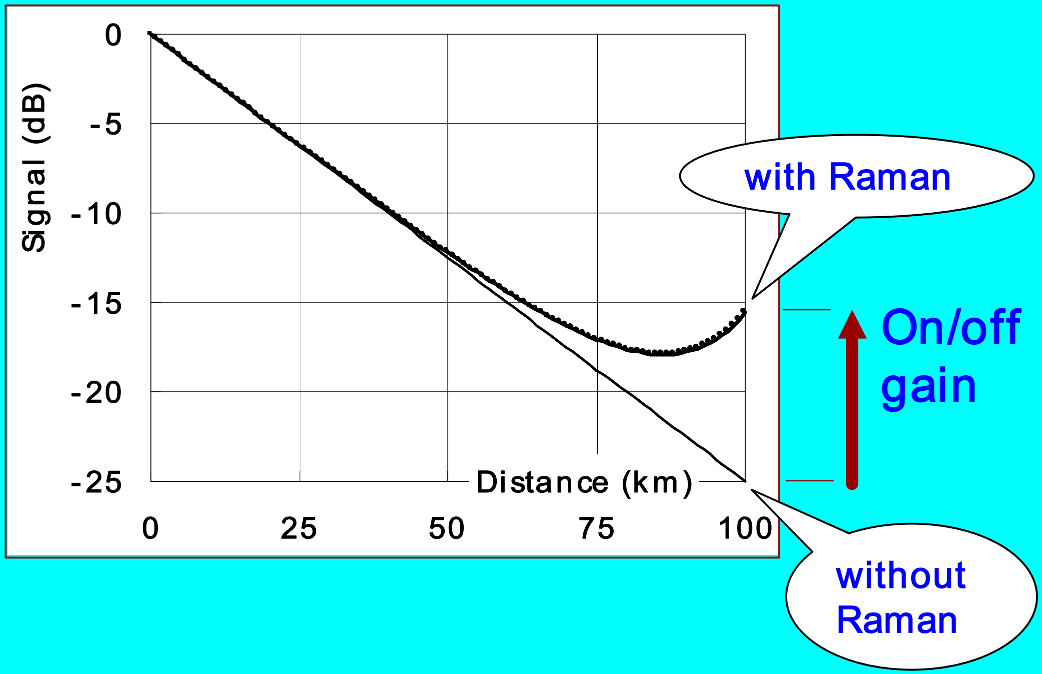
⇨ Long interaction fibers

⇨ Confinement

⇨ Attenuation at the pump wavelength is paramount

Distributed Raman Preamplification



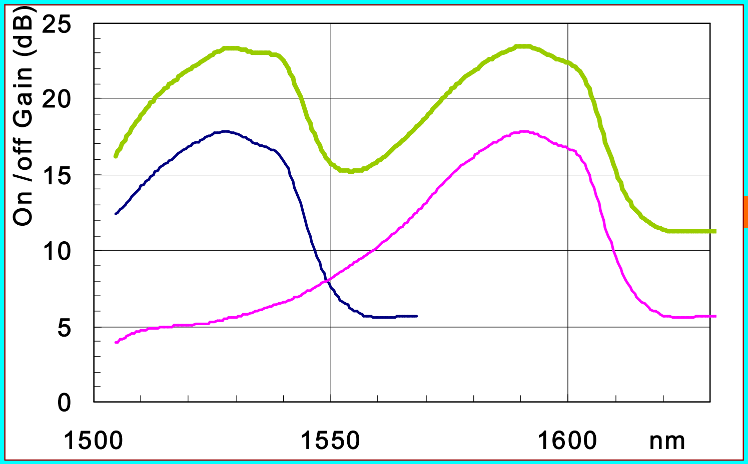


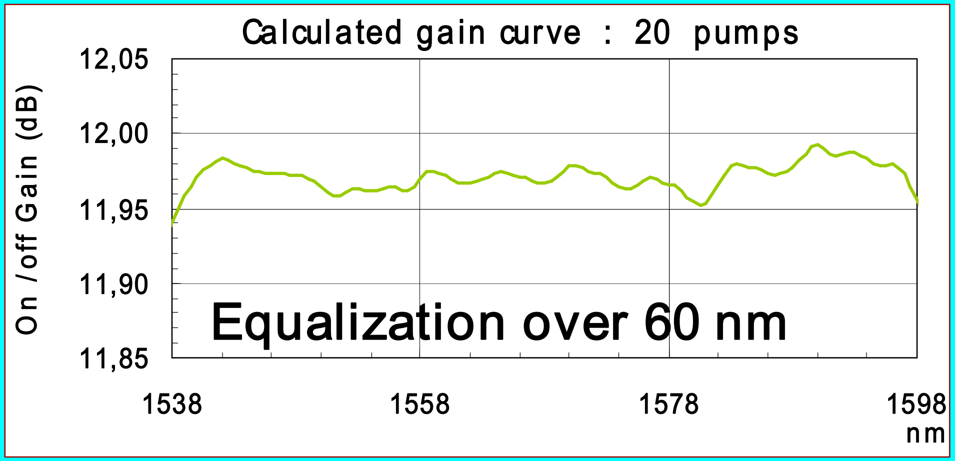
Preamplification (backward pumping : weak gain saturation)

Increase of the signal powers at the EDFA input

(improved signal to noise ratio)

Pump wavelength combination





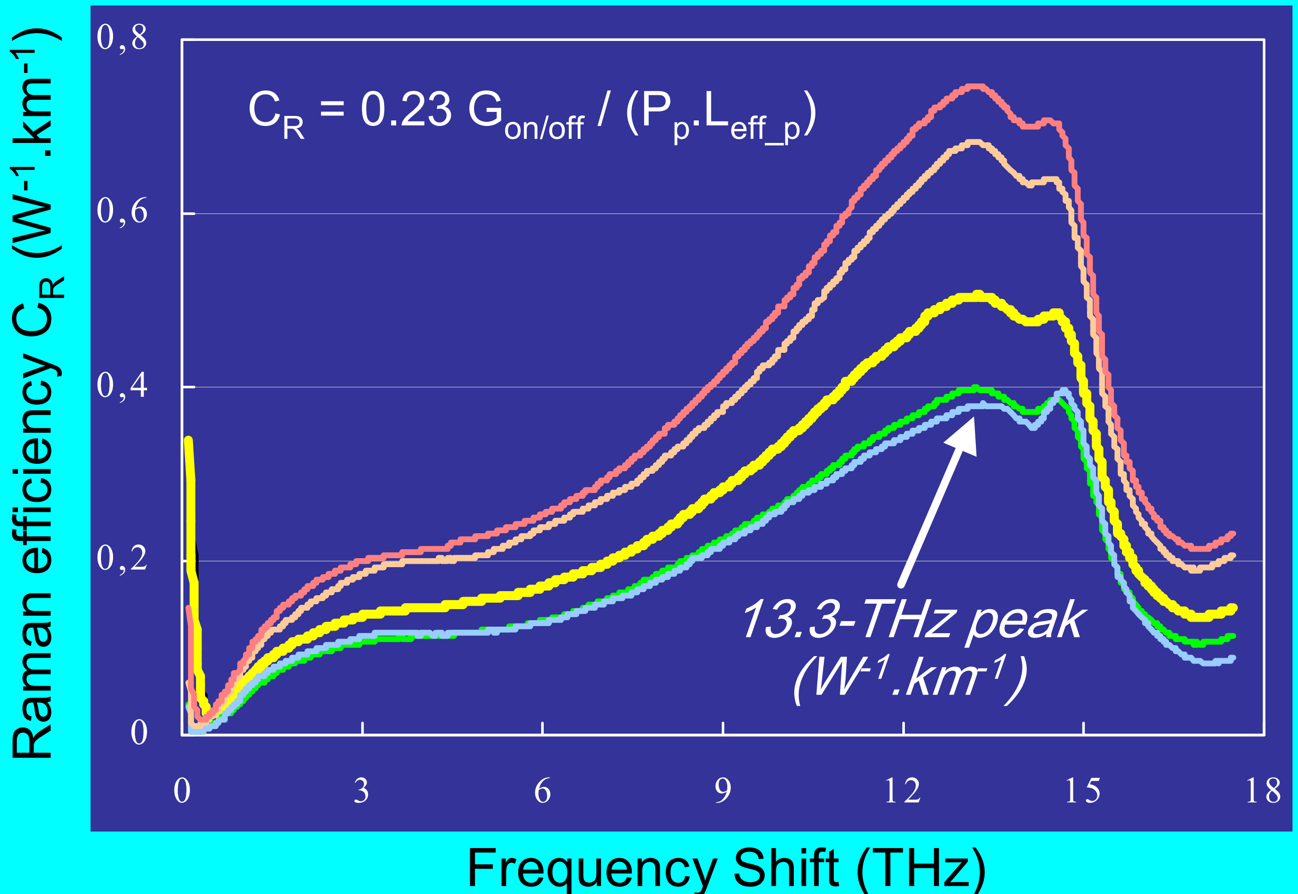
- ✓ 2 or 3 wavelengths enough for a 1-dB equalization over the C-band

  3 to 4 over the C+L band

- ➢ Semiconductor pumps need polarization multiplexing or depolarization using PANDA fiber at 45 deg.

Fiber efficiency per unit length and per W of pump

1486-nm pumping

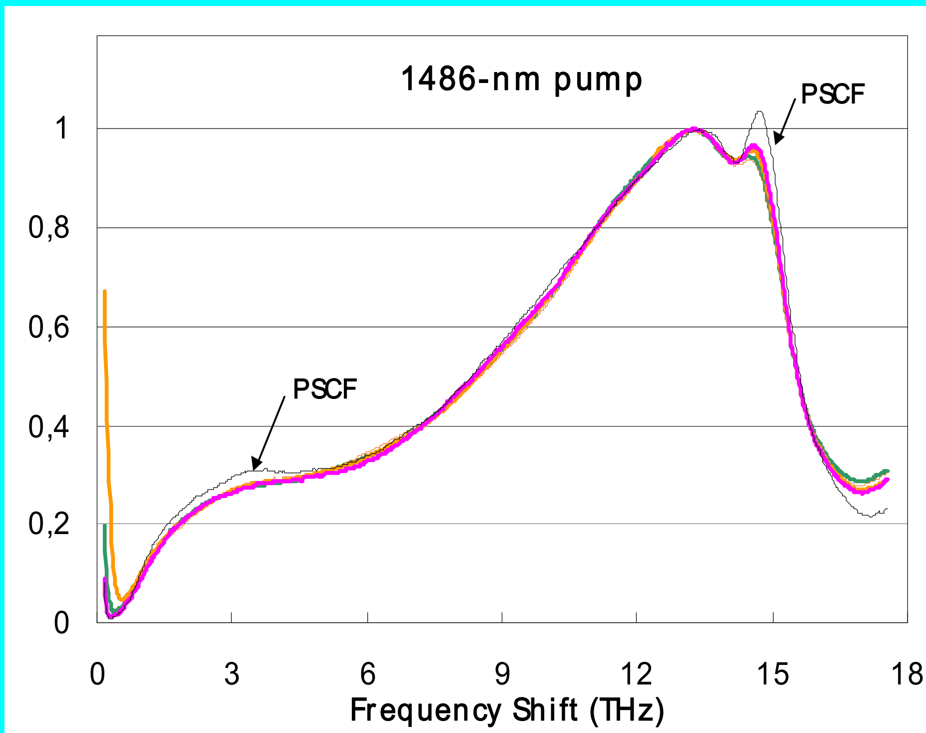


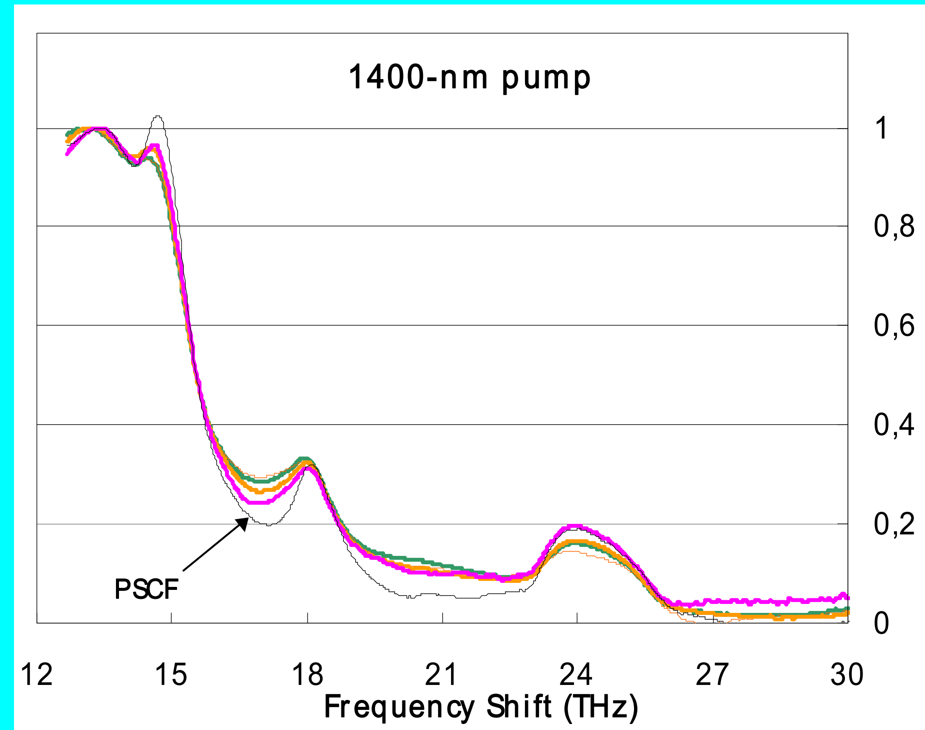
	C_R Max
NZDSF+	*0.75*
NZDSF-	*0.68*
TeraLight	*0.51*
SMF	*0.40*
PSCF	*0.38*

PSCF : Pure Silica Core Fiber

Normalized Gain Spectra

CURVES NORMALISED RELATIVE TO 13.3-THz PEAK



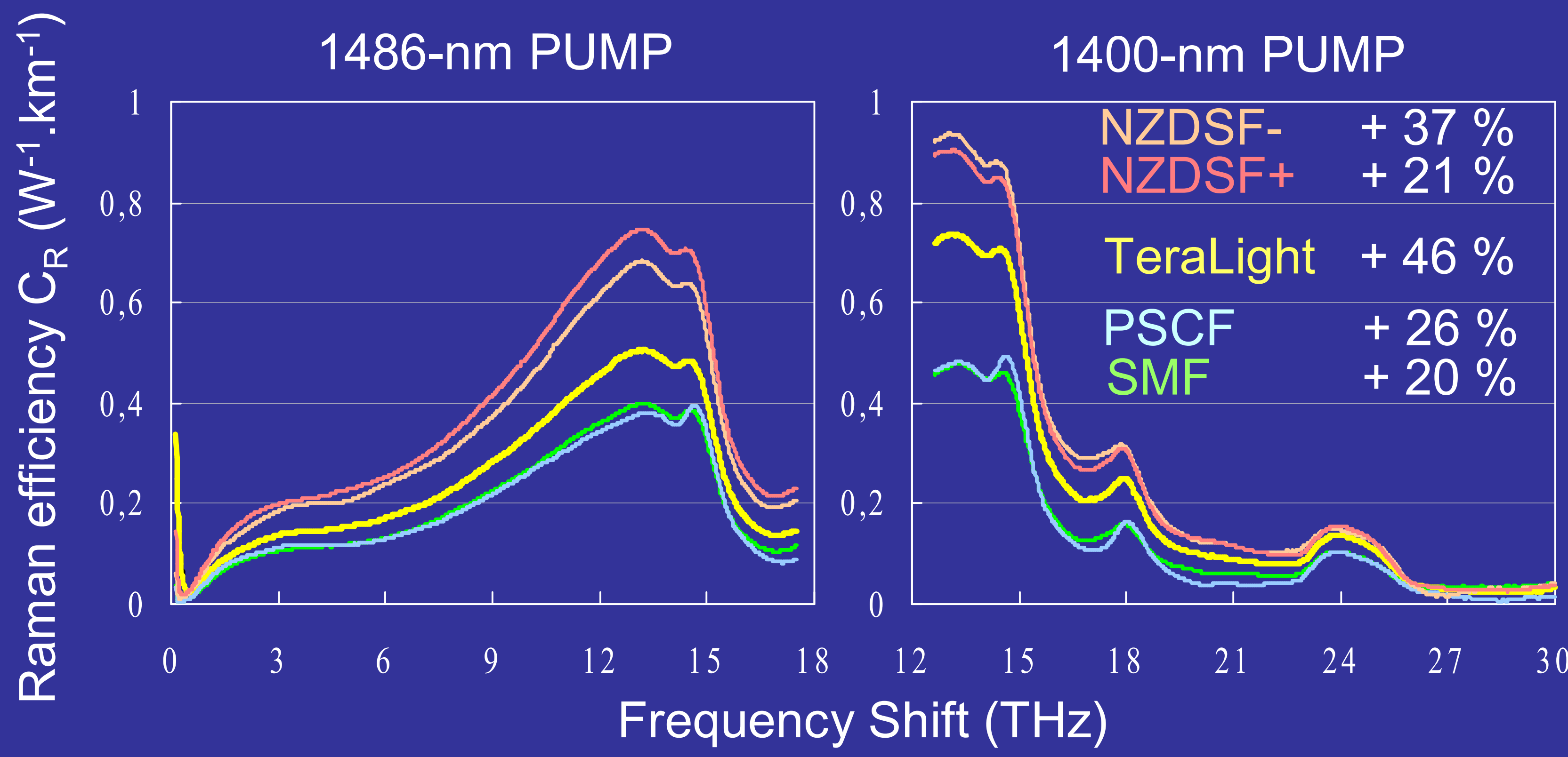


Boson-peak relative-intensity higher with SiO_2 than with GeO_2

13.3-THz peak : Ge-dependent, extends up to > 20 THz

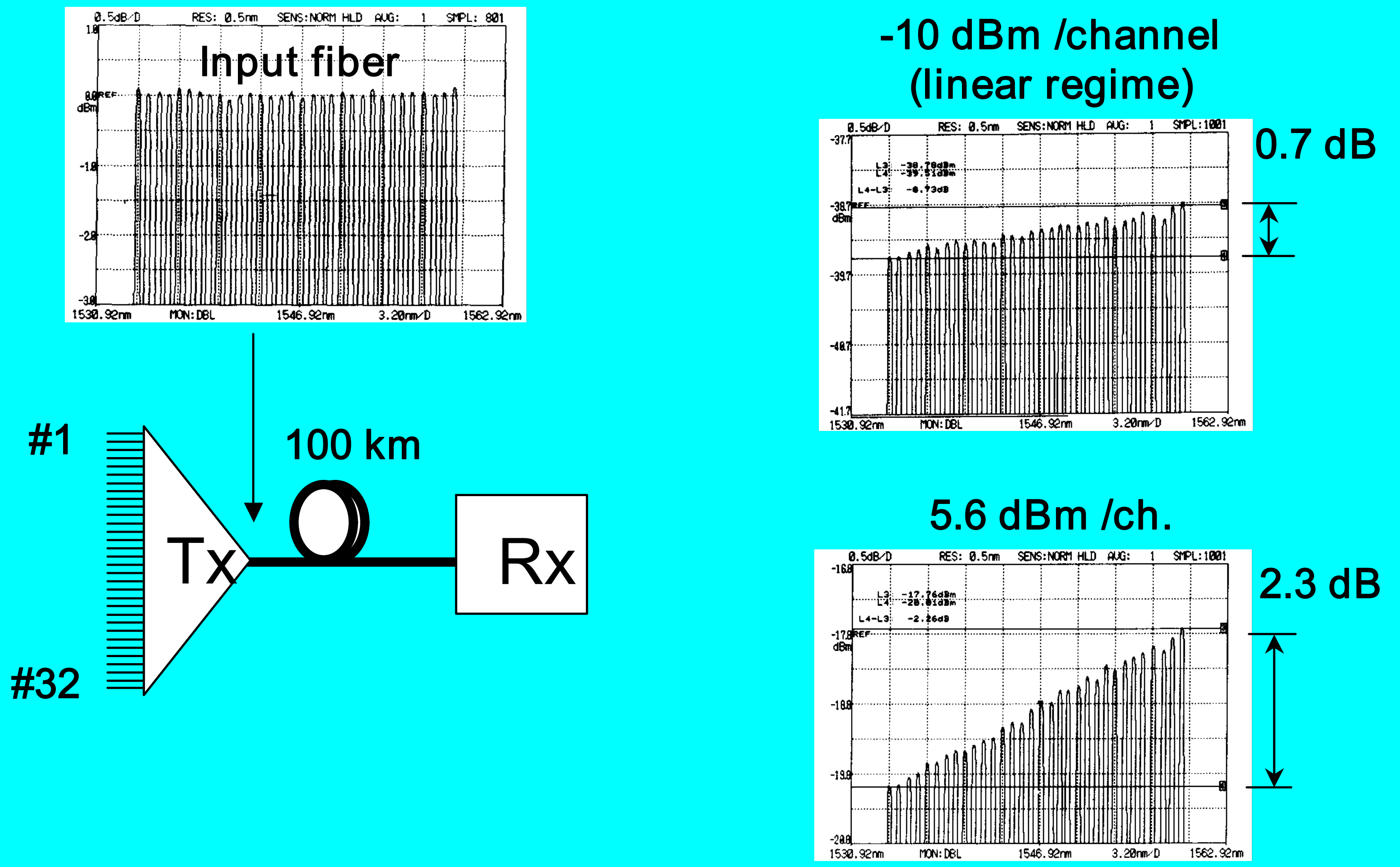
Sharp 14.5-THz and 18-THz peaks specific to SiO_2

Fiber efficiency is pump wavelength dependent

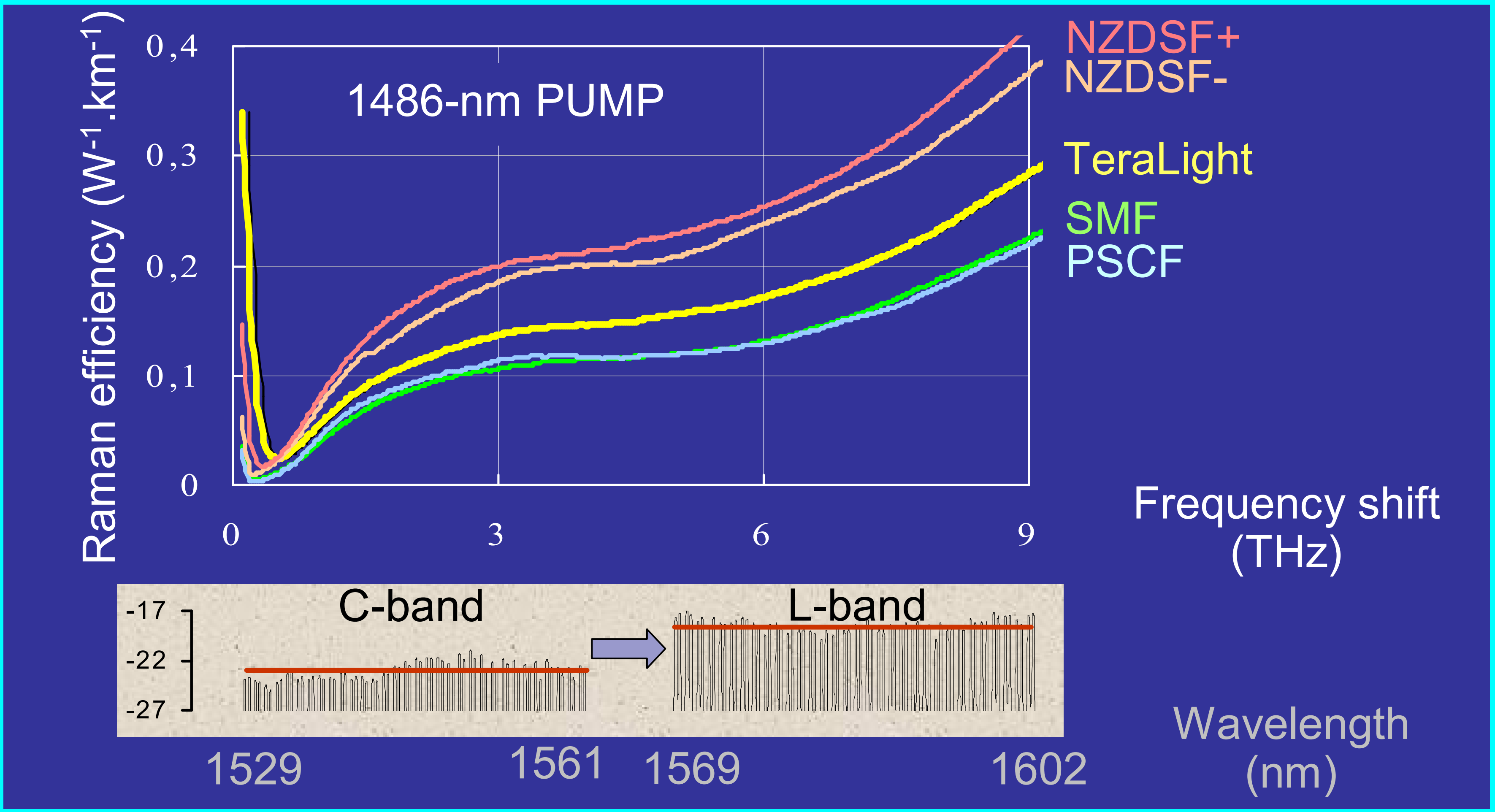


☞ Pump/signal/core overlap

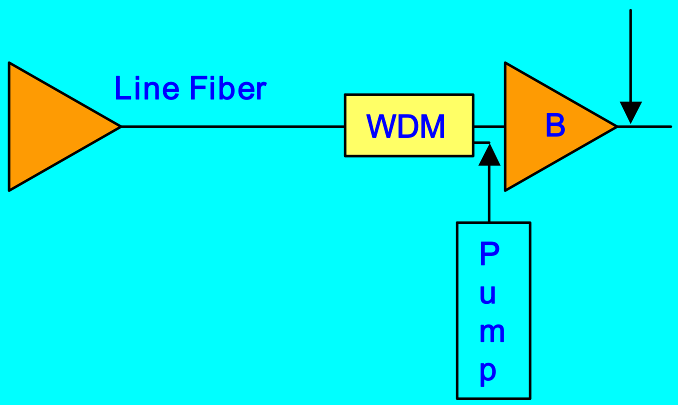
Effect of interchannel Raman depletion



Small-frequency-shift energy transfers



Noise figure for Distributed Raman Preamplification

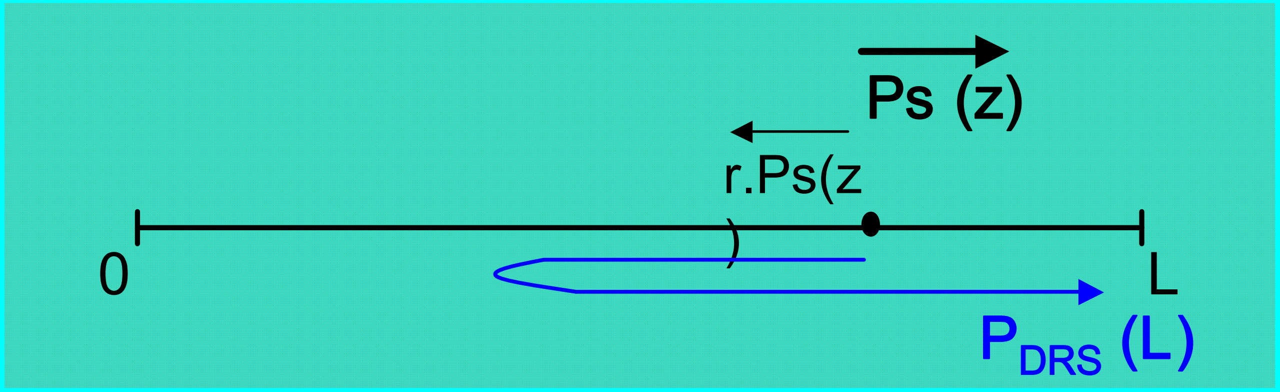


Intrinsic noise parameter = 3dB (quantum limit)

Equivalent noise figure = *the noise figure of an EDFA located in B point and providing with the Raman ON/OFF gain*

Equivalent noise figures can be equal or lower than 0 dB

Double-Rayleigh Scattering



- Signal (neglecting the DRS term): $P_S(z) = P_S(0).G_{net}(0 \to z)$
- Simple Rayleigh-scattered signal: $P_{RS}(y) = \int_y^L r.P_S(z).G_{net}(y \to z).dz$
- Double Rayleigh-scattered signal: $P_{DRS}(L) = \int_0^L r.P_{RS}(y).G_{net}(y \to L).dy$

$\Rightarrow$ DRS noise-to-signal ratio at the end of the fibre: $R_{DRS} = P_{DRS}(L)/P_S(L)$

Double-Rayleigh Scattering (DRS)

- DRS is a delayed copy of the signal => beating noise at detection with the signal by quadratic detection:

$$RIN(f) \approx R_{DRS} \frac{2}{\pi} \frac{\Delta\nu}{(f^2 + (\Delta\nu)^2)}$$

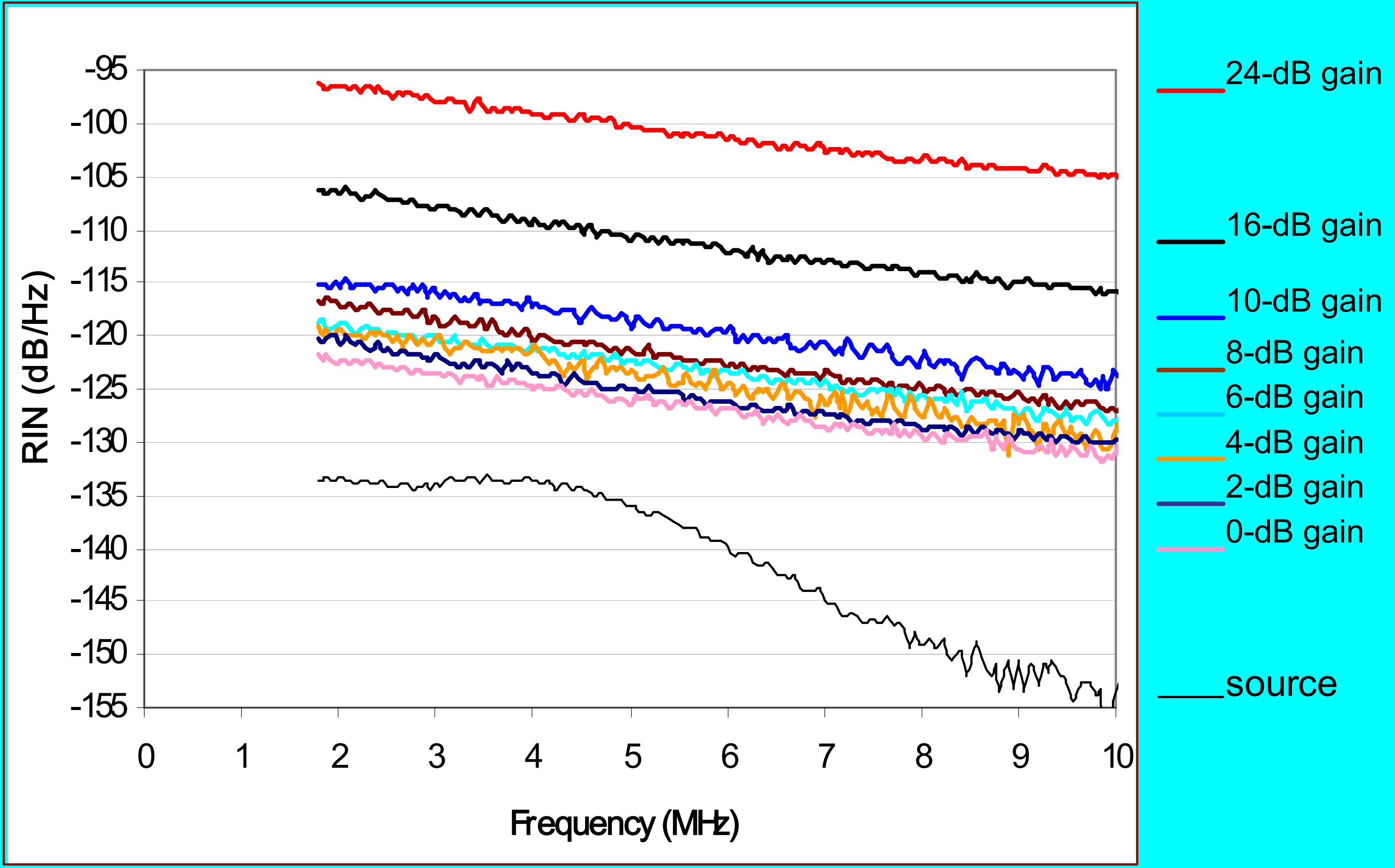
- Exists in all transmissions but is more penalizing with distributed Raman amplification: DRS is amplified during its double-path

- Crucial issue: DRS impairment is a limit to high amounts of Raman gain

- ASE and DRS essentially differ by their spectral distribution:

  - ASE is constant with wavelength in the range of the signal bandwidth
  - DRS is a replica of the signal optical spectrum

Electrical measurement of DRS



Signal-ASE and signal-DRS beat noises

- Reference case:
  NRZ, broad optical filtering

$$\sigma^2_{sg\text{-}ASE} = 4\eta^2 N^{sg\,polar}_{ASE} P_S B_{elec}$$

$$\sigma^2_{sg\text{-}DRS} = 2\eta^2 P^{sg\,polar}_{DRS} P_S$$

- General case:
  any format

$$\sigma^2_{sg\text{-}ASE} = k_{ASE} . P_{ASE} P_S$$

$$\sigma^2_{sg\text{-}DRS} = k_{DRS} . P_{DRS} P_S$$

depend on:

- modulation format (signal pattern)

- optical and electrical filters at reception

Conclusion on Double-Raleigh Scattering

DRS is a major limitation of the maximum Raman gain that can be obtained in the line fiber

- Limits Raman advantage in backward pumping
- Max gain closed to 23 dB

For all Raman pumping of the line fiber

- Need for forward pumping
  - ✓ See related issues (RIN, …)
- Or use of Raman pumping into the DCF
  - ✓ Increases non-linear effects in the DCF

Pump-to-signal RIN transfer

Raman effect is very fast (femtosecond)

Locally, the intensity fluctuations of the pump are totally transferred to the signal by gain (dB)

Effect averaged

- by counter propagation (backward pumping)
- only by chromatic dispersion for forward pumping

Transfer functions

Assumptions:

Distributed Raman amplification: long fiber (50 -100km)

Moderate Raman gain, moderate pump RIN

No pump depletion

$$RIN_S(f) = RIN_P + 20\log\left[\frac{\langle G_{ON/OFF}\rangle}{10/\ln(10)}\right] - 10\log\left[1+\left(\frac{f}{f_c}\right)^2\right]$$

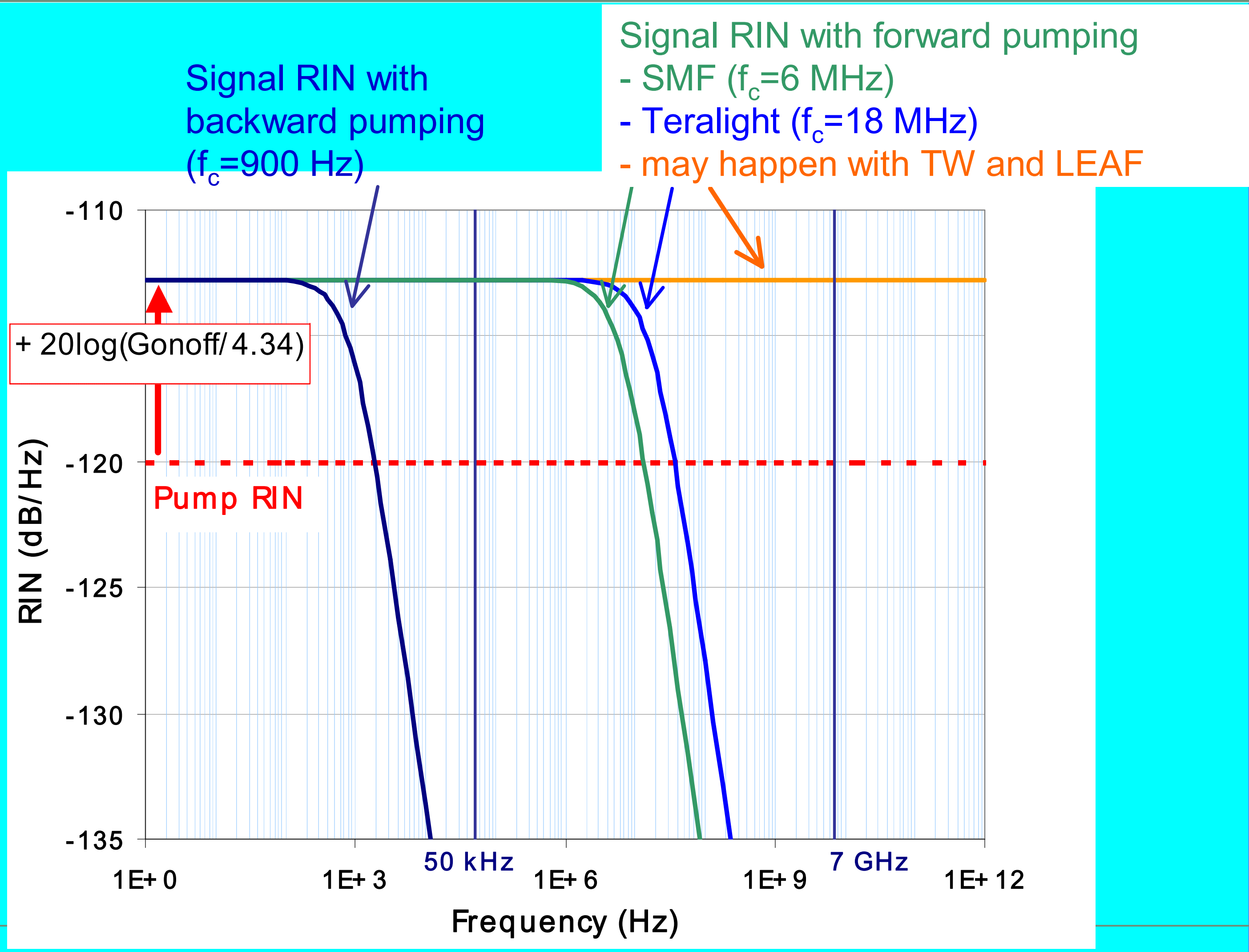
with $f_c = \dfrac{\alpha_P V_S}{4\pi}$ for backward pumping

and $f_c = \dfrac{\alpha_P}{2\pi\left(\dfrac{1}{V_S} - \dfrac{1}{V_P}\right)}$ for forward pumping

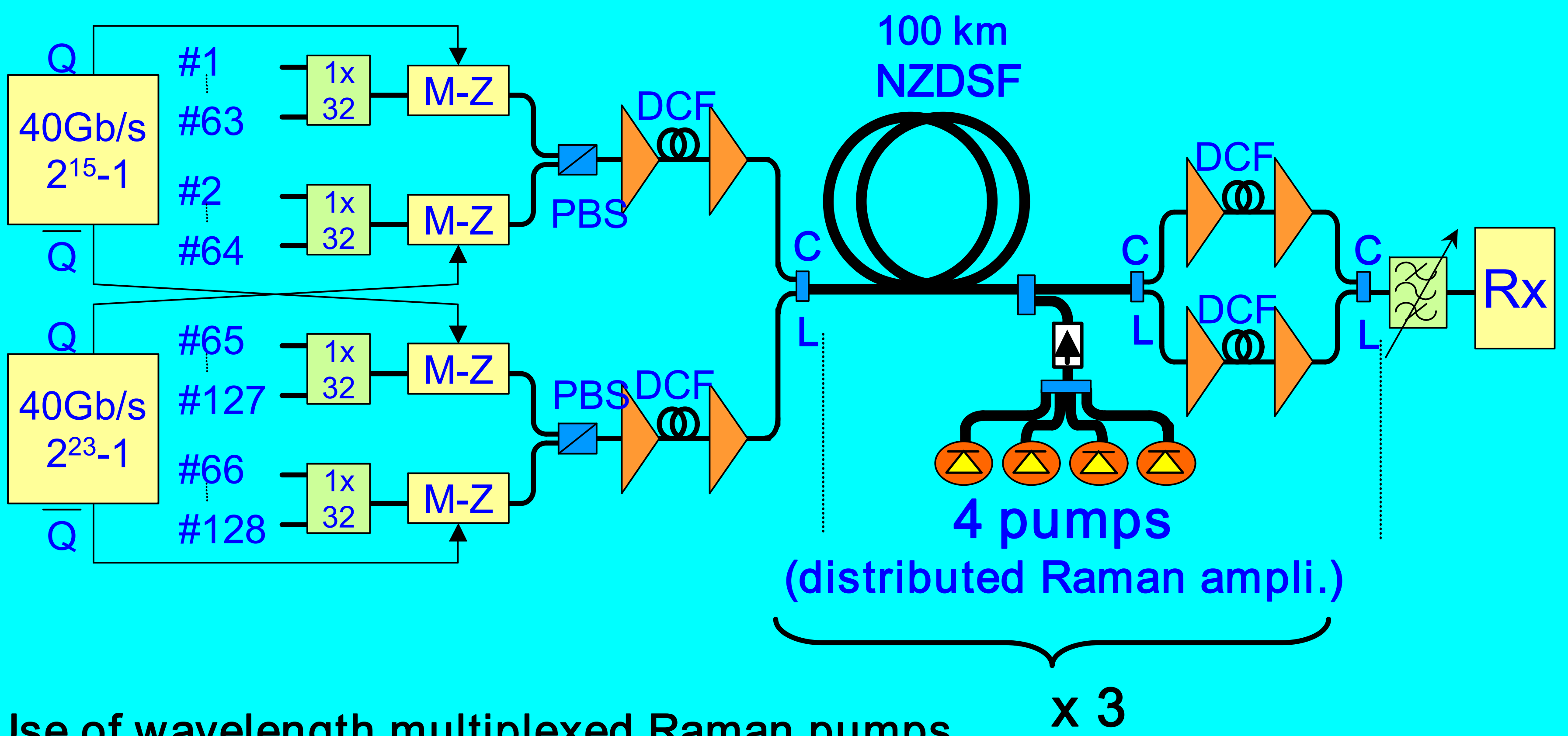
Reference: C. R. S. Fludger and al., Electron. Lett., 2001, **37**, (1), pp. 15-17

Transfer functions

With:
RIN$_P$=-120dB/Hz
Gonoff =10dB
α_P=0.25 dB
λ_P=1450nm
λ_S=1550nm



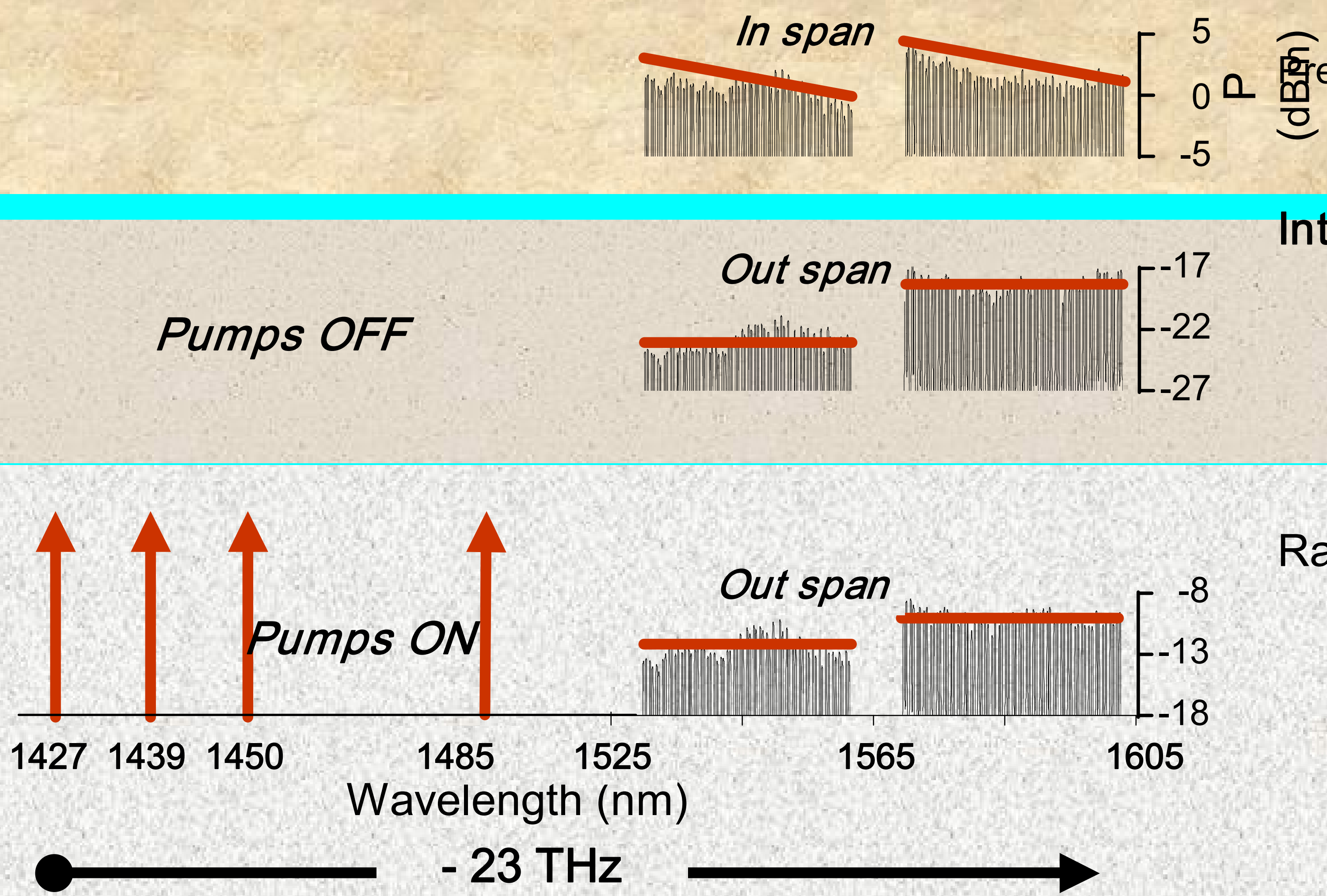
Raman amplification : Implementation



Use of wavelength multiplexed Raman pumps

Efficiency depends on fiber type and characteristics

Stimulated Raman Scattering



Pre-tilt ≈3dB

Intraband-tilt compensated but C-to-L energy-transfer

Raman gain

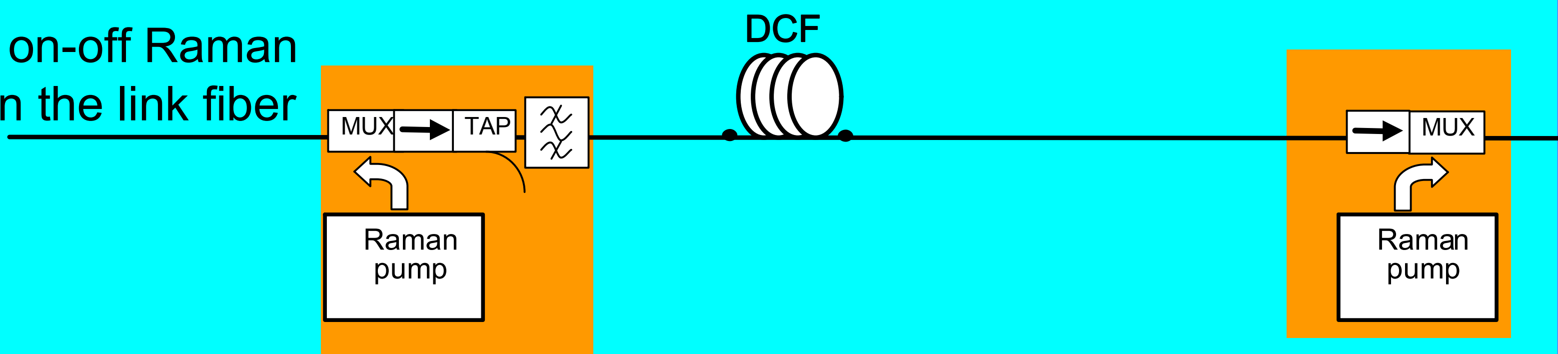
12dB C-band

10dB L-band

All Raman pumping schemes

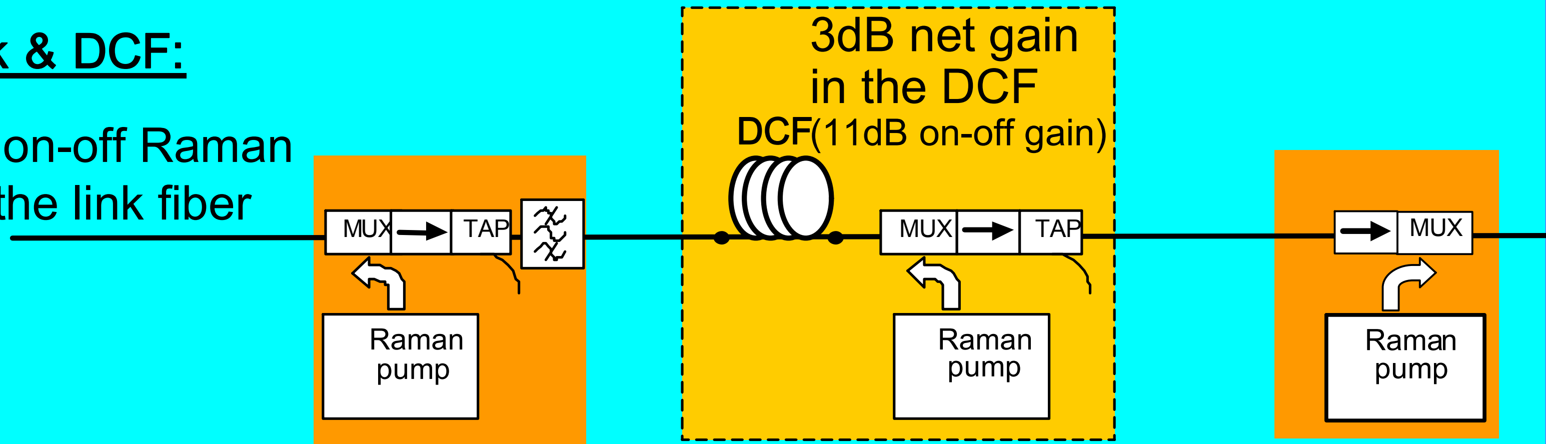
DRA in the link:

31dB on-off Raman gain in the link fiber



DRA in the link & DCF:

21.5dB on-off Raman gain in the link fiber



Criteria for performance assessment (ULH)

Final impairment of the amplifier on the system:

Generation of noise $$C_{noise} = N_{ASE}B_{elec} + \frac{1}{2} * \frac{5}{9} . R_{DRS}P_{in}$$

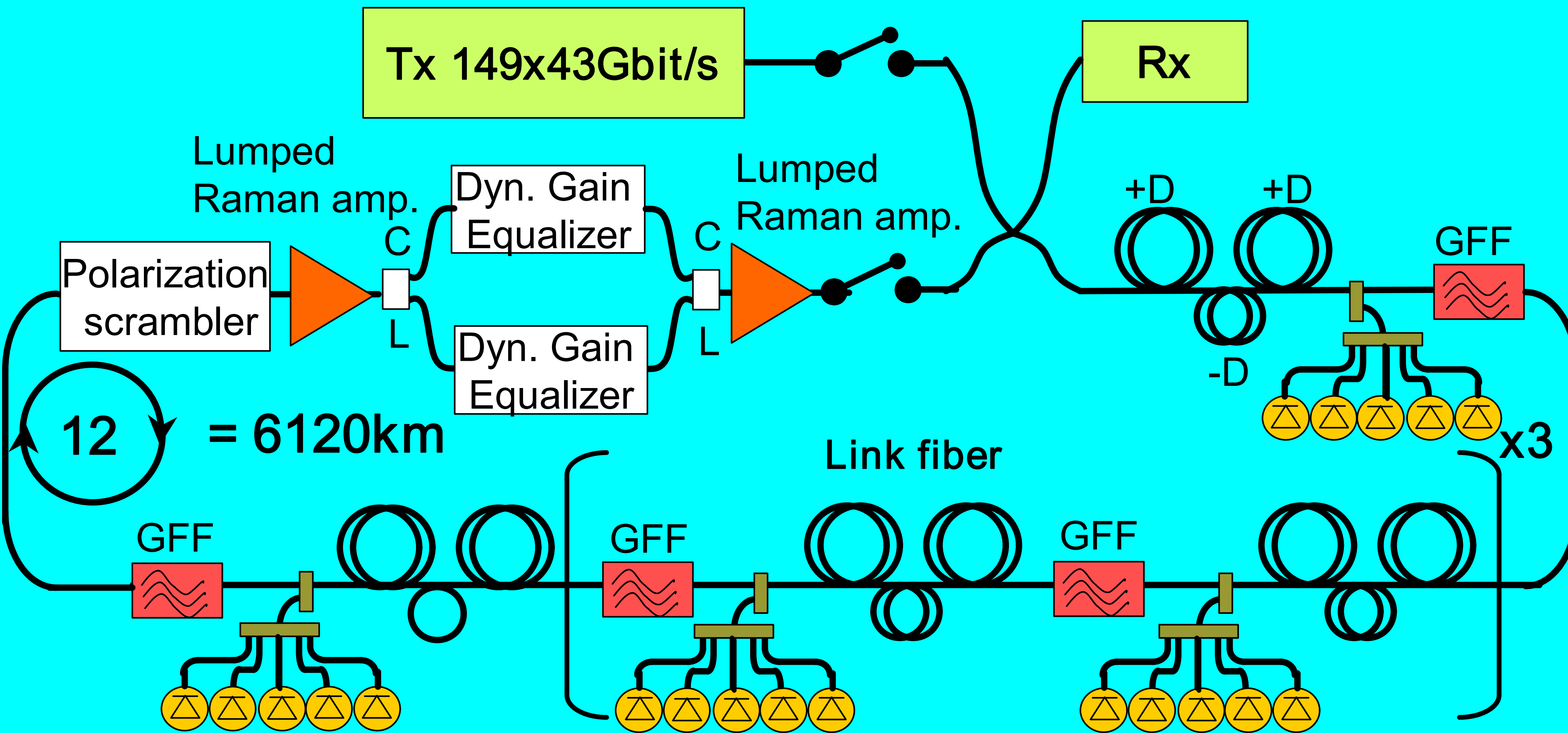
Non-linear phase $$C_{phase} = \gamma \int_0^L G_{Net}(z)\,dz$$

Achievable distance is proportional to $\left(C_{noise}C_{phase}\right)^{-1/2}$

$\rightarrow$ Parameter C = $C_{noise}.C_{phase}$ (the smaller the better)

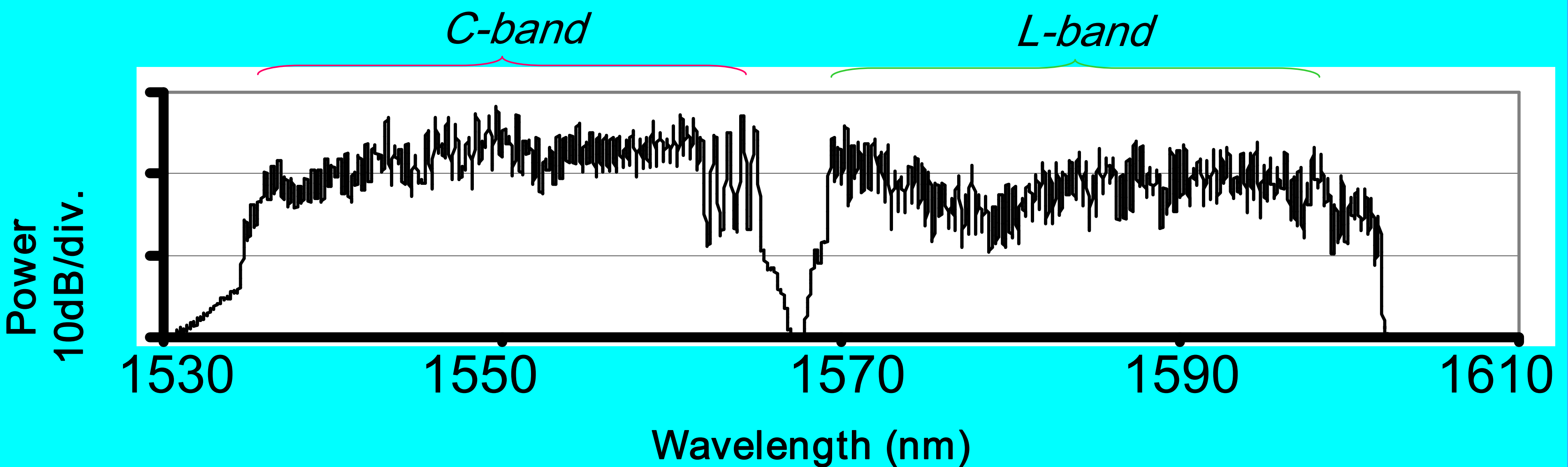
Co-pumping issues to be accounted aside

All-Raman transmission of 6 Tbit/s over 6120 km



All Raman amplification (First+Second order)

Experimental results with all-Raman amplification Spectrum after 6,120km with 149 DPSK channels



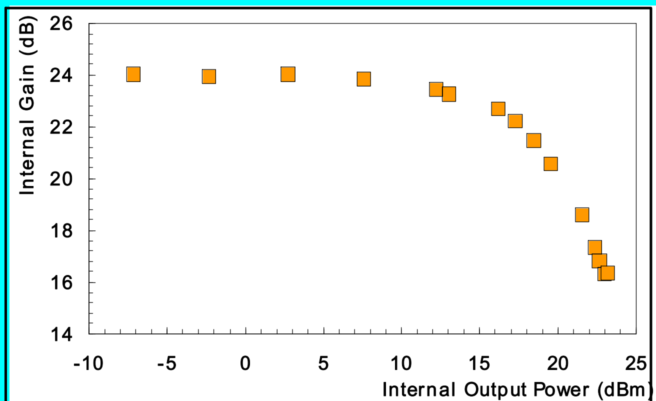
In C-band: more odd than even channels

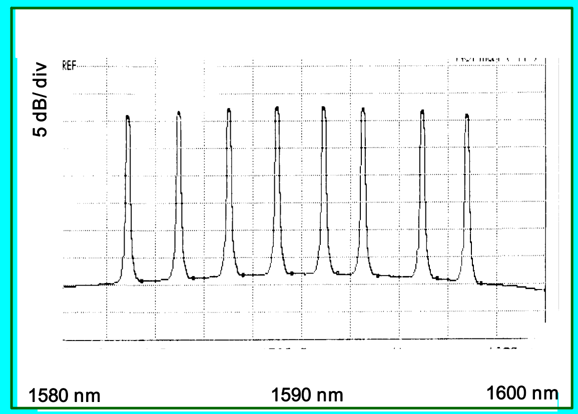
Gain excursion close to 10 dB after 6120km

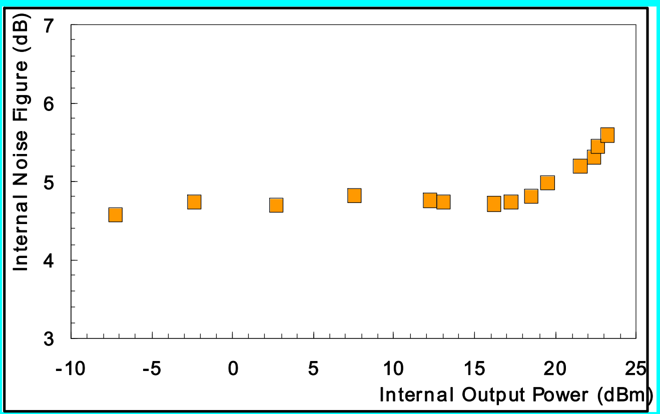
OSNR_0.1nm > 16.9dB in L band

OSNR_0.1nm > 14.6 dB in C band

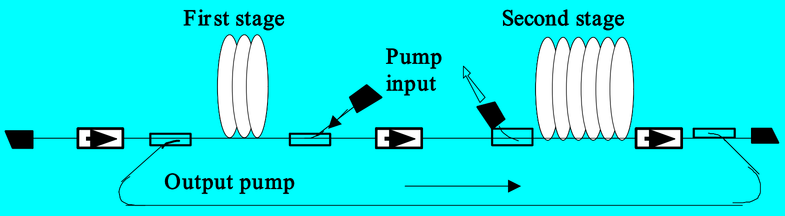
Lumped Raman Amplifier







- Use of a specific Raman fiber
    - e.g. Photonic Crystal Fiber
- <u>On-demand gain bandwidth and location</u>
- Weaker sensitivity to signal gain saturation compared to EDFAs
- Robust noise figure in high power input signal regime



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