Raman Amplification
for Telecom Optical Networks

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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
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-\( \lambda \) 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)
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

\[ C_R = 0.23 \frac{G_{\text{on/off}}}{(P_p \cdot L_{\text{eff,p}})} \]

- NZDSF+: 0.75
- NZDSF-: 0.68
- TeraLight: 0.51
- SMF: 0.40
- PSCF: 0.38

1486-nm pumping

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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

- 1486-nm PUMP
  - NZDSF- + 37%
  - NZDSF+ + 21%
  - TeraLight + 46%
  - PSCF + 26%
  - SMF + 20%

- 1400-nm PUMP

Pump/signal/core overlap
Effect of interchannel Raman depletion

Input fiber

-10 dBm /channel (linear regime)

100 km

5.6 dBm /ch.

#1

#32

0.7 dB

2.3 dB
Small-frequency-shift energy transfers

![Graph showing Raman efficiency versus frequency shift (THz) and wavelength (nm).](image)

- **Raman efficiency ($W^{-1} \cdot km^{-1}$)**
  - NZDSF+
  - NZDSF-
  - TeraLight
  - SMF
  - PSCF

- **Frequency shift (THz)**
- **Wavelength (nm)**
  - C-band: 1529, 1561, 1569, 1602
  - L-band: 1486 nm PUMP
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

1. Signal (neglecting the DRS term): 
   \[ P_S(z) = P_S(0) \cdot G_{net}(0 \rightarrow z) \]

2. Simple Rayleigh-scattered signal: 
   \[ P_{RS}(y) = \int_y^L r \cdot P_S(z) \cdot G_{net}(y \rightarrow z) \cdot dz \]

3. Double Rayleigh-scattered signal: 
   \[ P_{DRS}(L) = \int_0^L r \cdot P_{RS}(y) \cdot G_{net}(y \rightarrow L) \cdot dy \]

⇒ DRS noise-to-signal ratio at the end of the fibre:

\[ \frac{P_{DRS}(L)}{P_S(L)} \]

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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

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Signal-ASE and signal-DRS beat noises

- **Reference case:**
  - NRZ, broad optical filtering

  \[
  \sigma^2_{\text{sg-ASE}} = 4\eta^2 N_{\text{ASE}} \text{polar} P_S B_{\text{elec}}
  \]

  \[
  \sigma^2_{\text{sg-DRS}} = 2\eta^2 P_{\text{DRS}} \text{polar} P_S
  \]

- **General case:**
  - any format

  \[
  \sigma^2_{\text{sg-ASE}} = k_{\text{ASE}} P_{\text{ASE}} P_S
  \]

  \[
  \sigma^2_{\text{sg-DRS}} = k_{\text{DRS}} P_{\text{DRS}} P_S
  \]

  depend on:
  - modulation format (signal pattern)
  - optical and electrical filters at reception

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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

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

with \( f_c = \frac{\alpha_P V_S}{4\pi} \) for backward pumping

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

Transfer functions

With:
\[ \text{RIN}_\text{P} = -120 \text{dB/Hz} \]
\[ \text{Gonoff} = 10 \text{dB} \]
\[ \alpha \text{P} = 0.25 \text{ dB} \]
\[ \lambda \text{P} = 1450 \text{nm} \]
\[ \lambda \text{S} = 1550 \text{nm} \]

Signal RIN with backward pumping (\(f_c = 900 \text{ Hz}\))

Signal RIN with forward pumping
- SMF (\(f_c = 6 \text{ MHz}\))
- Teralight (\(f_c = 18 \text{ MHz}\))
- may happen with TW and LEAF

\[ + 20 \log(\text{Gonoff}/4.34) \]

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Raman amplification : Implementation

Use of wavelength multiplexed Raman pumps

Efficiency depends on fiber type and characteristics
Stimulated Raman Scattering

In span

Out span

Pumps OFF

Pumps ON

Wavelength (nm)

- 23 THz

Raman gain
12dB C-band
10dB L-band

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

Pre-tilt ≈ 3dB

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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
- 3dB net gain in the DCF (11dB on-off gain)
Final impairment of the amplifier on the system:

\[ C_{\text{noise}} = N_{\text{ASE}} B_{\text{elec}} + \frac{1}{2} \frac{5}{9} \cdot R_{\text{DRS}} P_{\text{in}} \]

\[ C_{\text{phase}} = \gamma \int_0^L G_{\text{Net}}(z) \, dz \]

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

\( \rightarrow \) Parameter \( C = C_{\text{noise}} \cdot C_{\text{phase}} \) (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
- On-demand gain bandwidth and location
- Weaker sensitivity to signal gain saturation compared to EDFAs
- Robust noise figure in high power input signal regime

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« Erbium-doped fiber amplifier, Principles and Applications »

« Erbium-doped fiber amplifier, Device and System Developments »,
Emmanuel Desurvire, Dominique Bayart, Bertrand Desthieux, Sébastien Bigo,
Wiley (2002), New-York

« Undersea Fiber Communications Systems »
Chap. 4, Optical Amplification, Dominique Bayart