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Optical Amplification Tutorial

8 April 2015

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Benefits from Optical Amplification

Benefits from Optical Amplification

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- Bit rate and protocol agnostic:
  - Can amplify direct or coherent detection signals
  - Can amplify amplitude and/or phase modulated signals
  - Can amplify any bit rate
- Reliable:
  - No high-speed electronics
  - Initially used in high-capacity submarine applications
- Single- and multi-channel operation
- High service velocity when new channels are added
- Cost effective:
  - A single amplifier can amplify virtually any channel count (the cost does not scale up linearly with the number of optical wavelengths transported in the fiber)
  - Low capital and operational expenditures

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Erbium-Doped Fiber Amplification (EDFA) Basics

EDFA Synoptic

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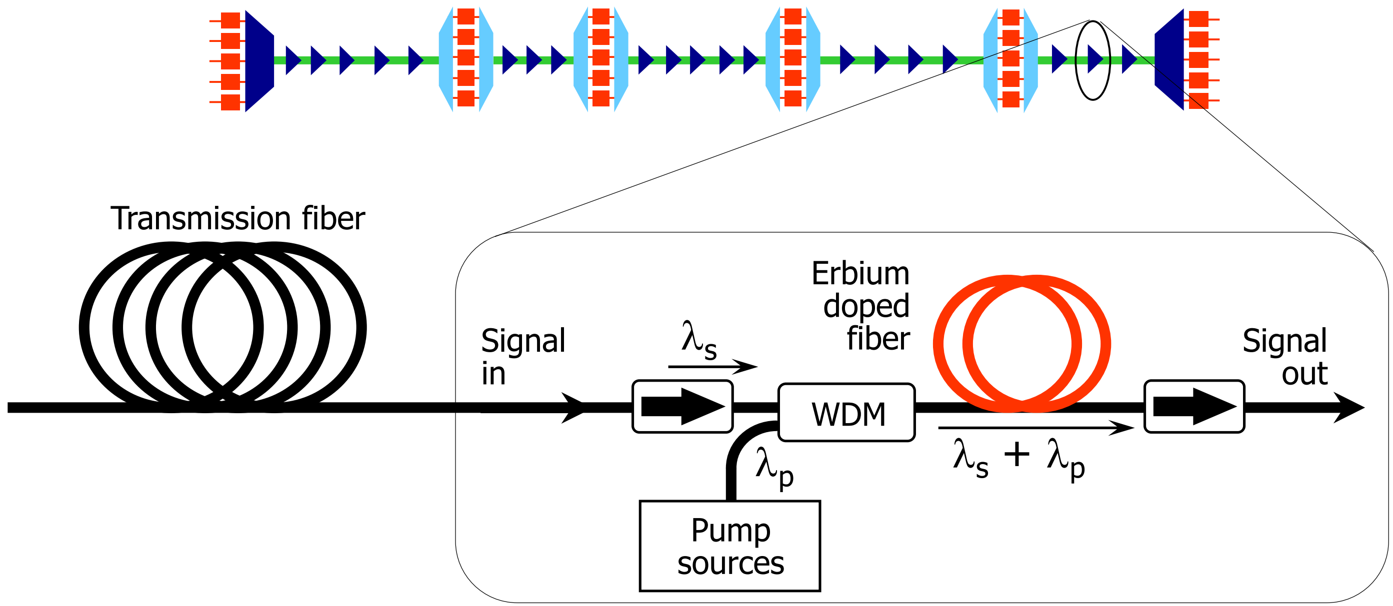

- Semiconductor pump sources @ 980 and/or 1480 nm
  - Typically 3 pumps are used in high-performance EDFAs
- Optical isolators: protection against external reflections
- WDM: multiplexing into the doped fiber the signal and pump waves

➔ Optical amplification is confined to the erbium doped fiber coil (a few tens of meters).

Brief EDFA History

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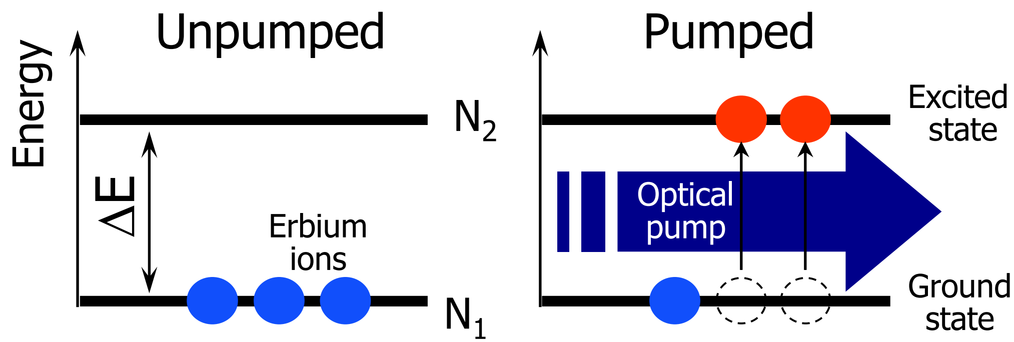
- 1964: C. Koester and E. Snitzer
  - 1 meter long neodymium-doped fibre
  - 10 µm core, 1 mm cladding
  - Pulsed signal at 1.06 µm
  - Optical pumping via flash tube
- 1986: New research work with fiber amplifier at 1.55 µm
- 1989: First transmission system experiments with erbium-doped fiber amplifiers
- 1993: EDFA deployment in the field in submarine and terrestrial systems
- 1996:
  - 5 Gbit/s fiber cable over 9,000 km (Japan-USA cable)
  - Amplification of multiple wavelengths simultaneously

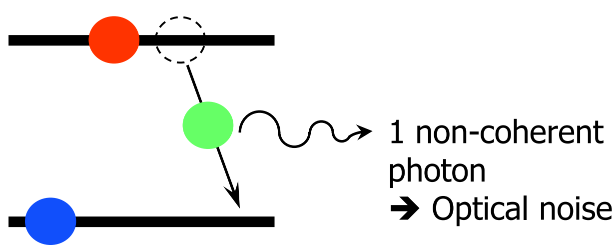
EDFA Principle



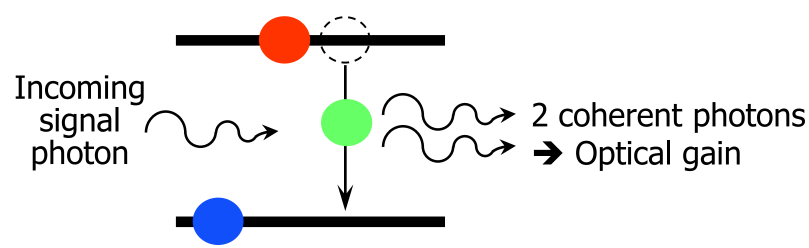
➔Potential laser transition at λ:

$$\Delta E = h \times \nu = h \times \frac{c}{\lambda}$$

- What happens to excited erbium ions ?
  - Non-radiative de-excitation: no "optical" impact
  - Radiative de-excitation:
    - Spontaneous emission

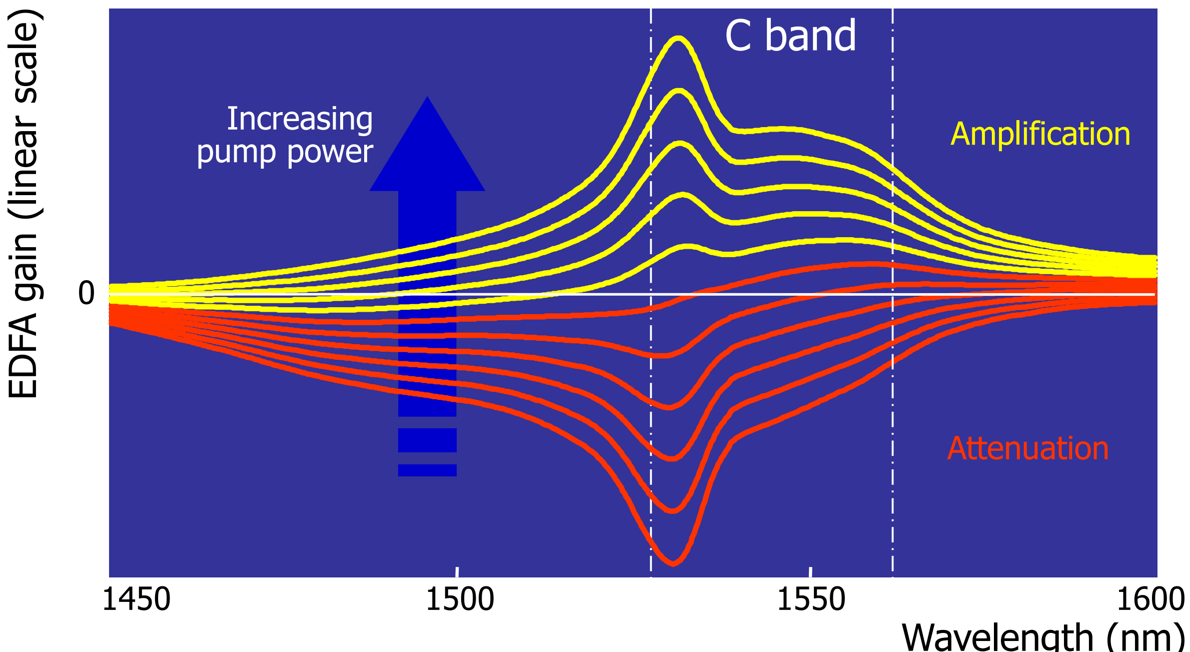


Stimulated emission



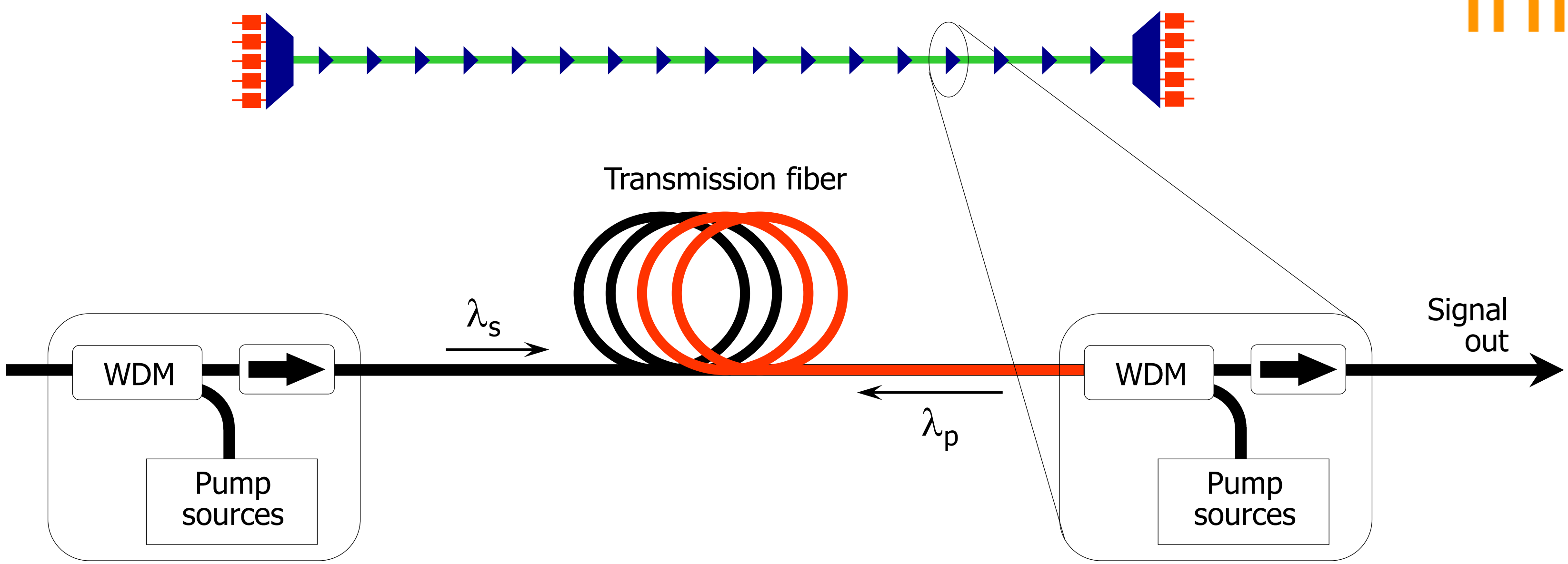
EDFA Gain Characteristics

- EDFA gain level and profile governed by the pump power:
  ➔ Below a given pumping threshold, the EDFA is opaque.
- The intrinsic EDFA gain profile is not uniform across conventional band (C band: 1530-1560 nm):
  ➔ Additional gain flattening filters are mandatory (not power efficient as the extra optical gain is shaved off, not redistributed in other spectral regions).



Raman Amplification Basics

Raman Amplifier Synoptic



- Semiconductor pump sources around 1450 nm for optical gain around 1550 nm
- Optical isolators: protection against external reflections
- WDM: launching into the transmission fiber the pump wave (Backward mode in the example above)

➔ Raman amplification occurs inside the transmission fiber along the several tens of kilometers' preceding the Raman amplifier.

Brief Raman Amplifier History

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- 1928: Basic scattering effect discovered by Chandrasekhar Venkata Raman (First Asian Scientist to be awarded the Nobel Prize in 1930)
- 1972: R.H. Stolen and E.P. Ippen
  - Raman gain measured in optical fiber
- 1985: Optical transmission (with Soliton propagation) demonstrated by Linn Mollenauer using Raman amplifiers
- Beginning of 90's: In competition with EDFA for first practical applications (EDFA won)
- End of 90's: The return of Raman amplification driven by:
  - Higher [Capacity x Distance] metric required
  - Availability of reliable high-power pump sources
  - Opening of new optical bandwidth

Raman Effect Principle

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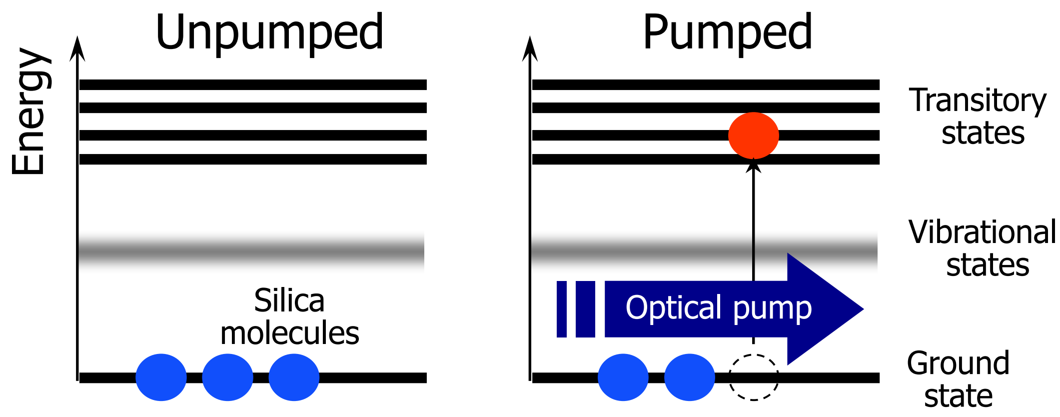
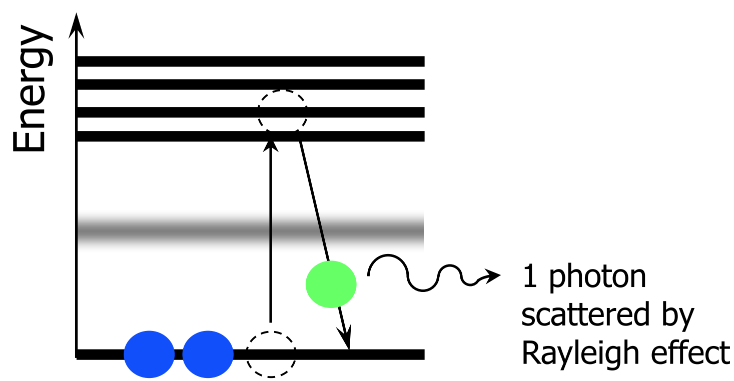


- The excited molecule will immediately relax its energy state emitting a photon:
  - The most probable outcome is that the state to which the molecule returns is the same as that from which it started, in which case the emitted photon is Rayleigh scattering.



Raman Effect Principle

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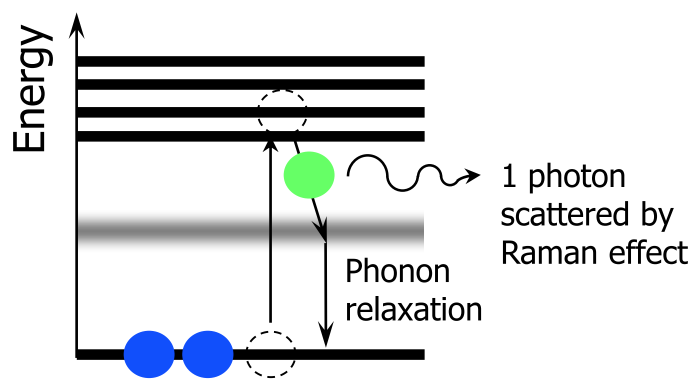
- The excited molecule will immediately relax its energy state emitting a photon:
  - The next most probable outcome is that the molecule returns to a higher vibrational energy state.
    - The resulting scattered light must, by conservation of energy, be of a lower energy (i.e. lower frequency or longer wavelength) than the incident light ($h\nu_s < h\nu_i$).
    - This is Stokes scattering resulting in **Raman effect**.
    - Raman scattering is an inelastic process in which part of the power is lost from an optical pump wave and absorbed by the transmission medium as phonons (vibrational energy). The remaining energy is then re-emitted as a wave of lower frequency.



Raman Amplifier Principle

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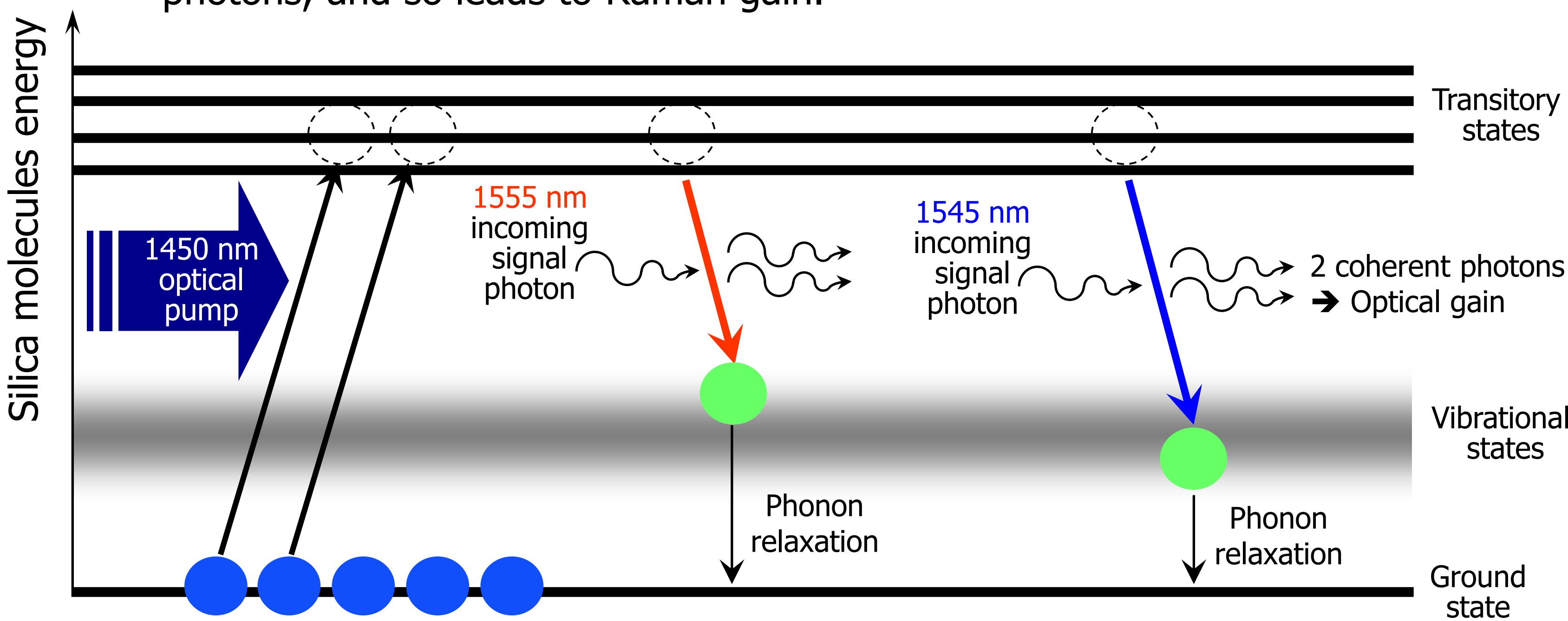
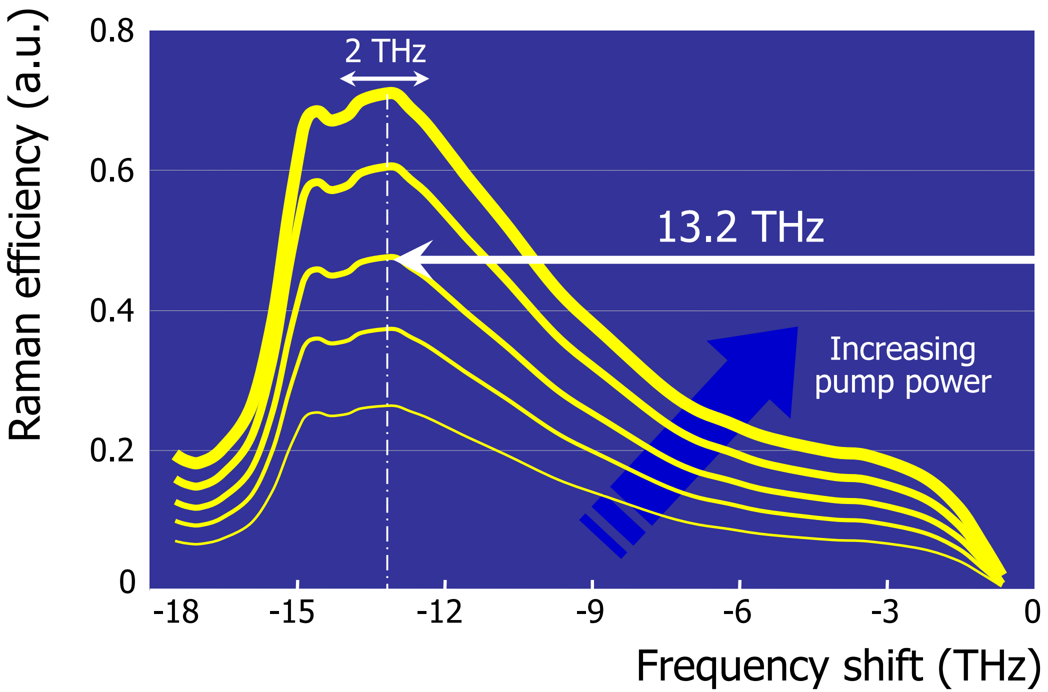
- Signal amplification occurs when an optical signal is transmitted with a frequency which falls within the Raman scattering spectrum of the pump source:
  - The signal triggers stimulated emission at the signal wavelength, which is in phase with, and propagates in the same direction as, the original signal photons, and so leads to Raman gain.



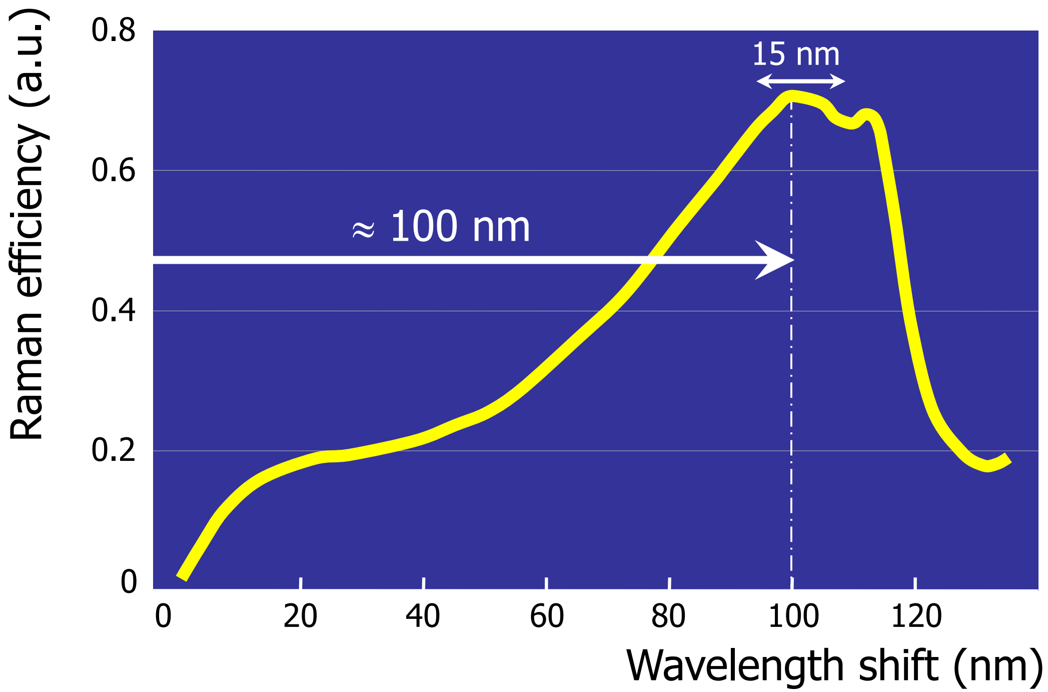
Raman Gain Characteristics

- Amplification of any optical signal by pumping at an optical frequency 13.2 THz (: silica phonon energy) higher than the frequency of the desired signal:
  - If unpumped, Raman amplifier does not go opaque.
  - Raman gain bandwidth of about 2 THz

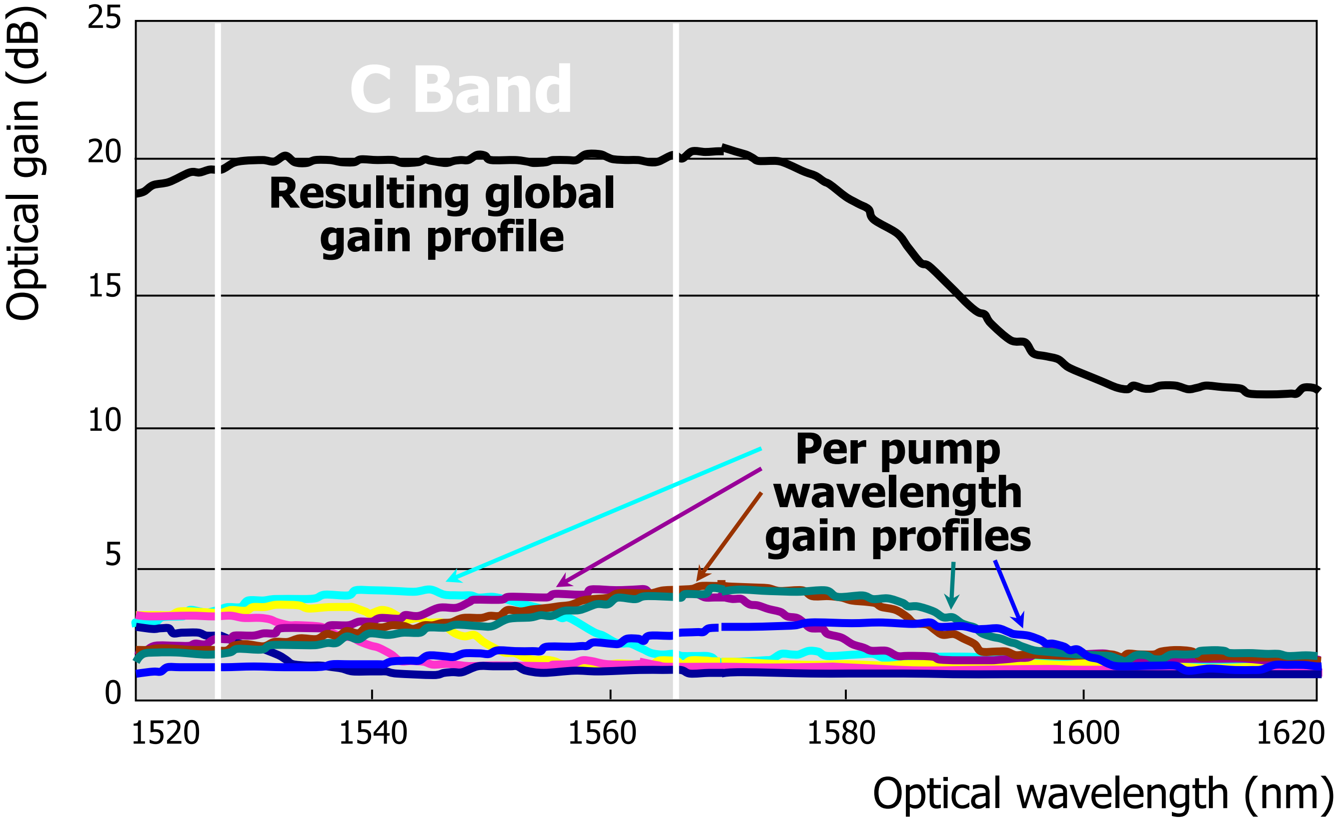


Raman Gain Characteristics

- Amplification of any optical signal by pumping at an optical wavelength 100 nm less than the wavelength of the desired signal in the 1550 nm area:
  - Raman gain bandwidth of about 15 nm
  - Can be broadened and flattened by multi-wavelength pumping



Raman Amplifier Gain Spectrum



Raman amplifier: optical bandwidth synthesizer

Raman Amplifier Gain Spectrum

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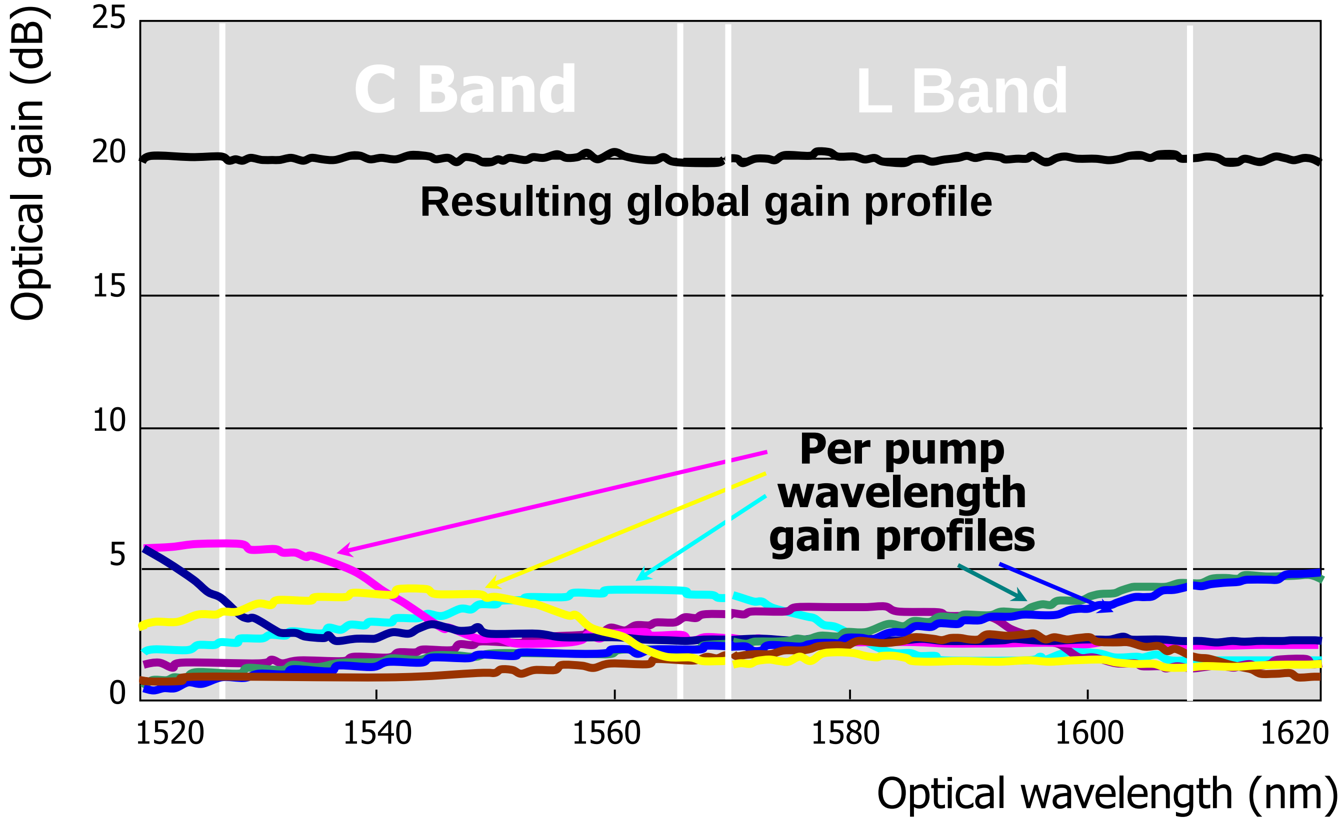

Raman amplifier: optical bandwidth synthesizer

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Optical Amplification, Optical Noise and Fiber Nonlinearities

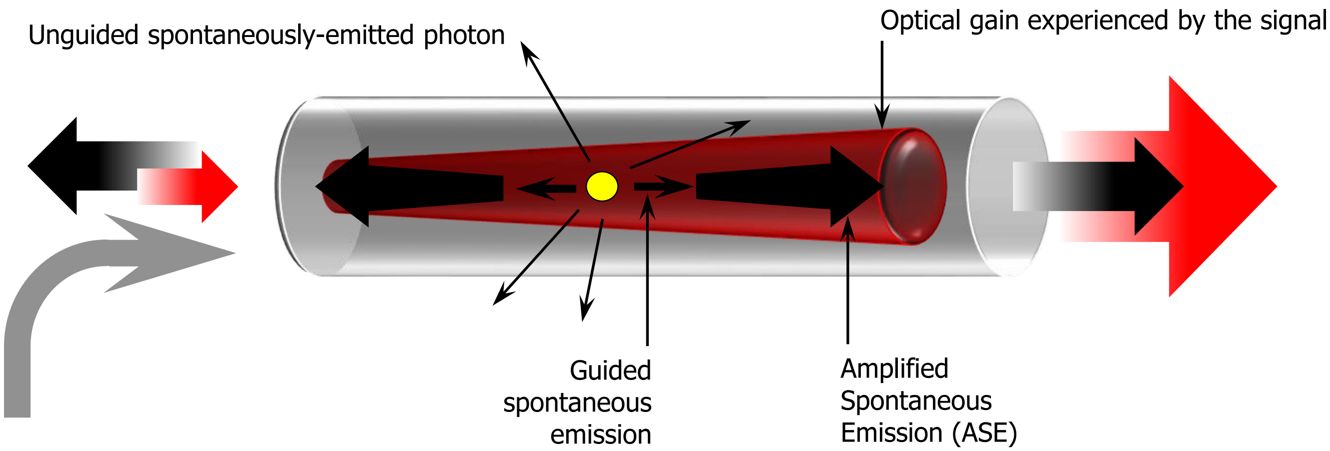
Generation of Optical Noise Within An Erbium-Doped Fiber

Optical signal

Optical pump

Erbium ions

Amplified Spontaneous Emission (ASE)



- Optical amplification is achieved at the expense of optical noise generation.
- Raman amplifiers also generate optical noise but in a lower amount.

Generation of Optical Noise From An Erbium-Doped Fiber

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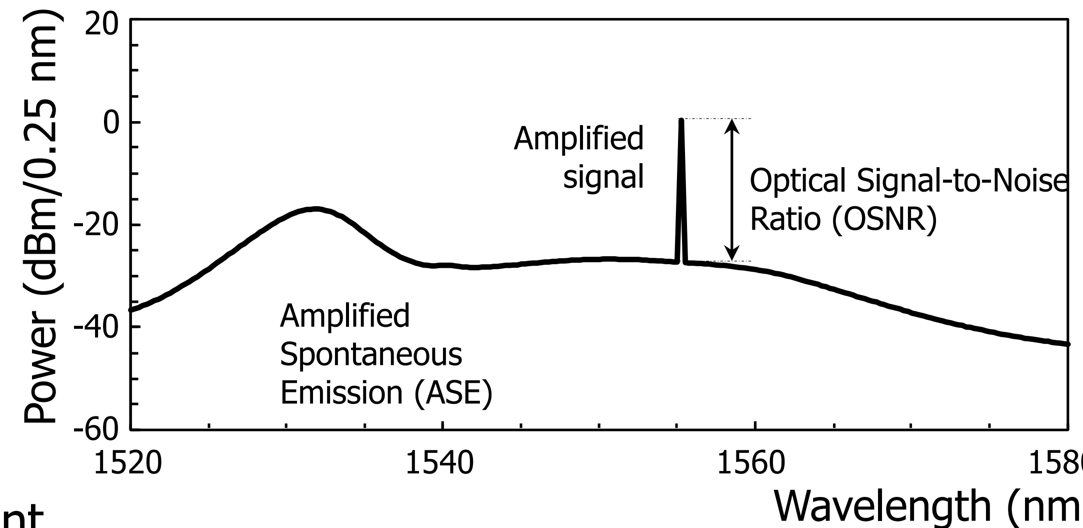
- Single wavelength amplified by an old-generation EDFA (unflatenned)



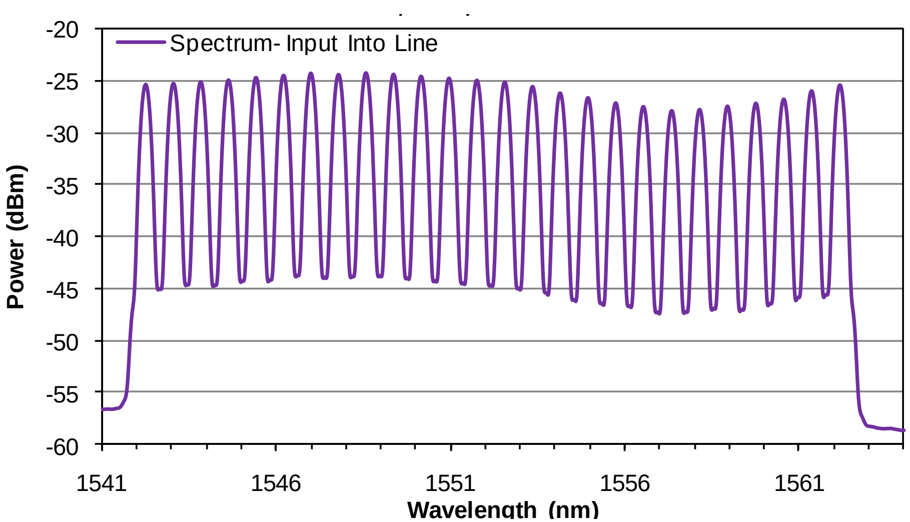
- The Amplified Spontaneous Emission (ASE) is a wideband, non-coherent, un-polarized light which will be detected as noise by the receive interface.

- Optical Signal-to-Noise Ratio (OSNR, in dB / 0.1 nm) – ratio between the signal power and the ASE noise power in a given optical bandwidth – is an important parameter for engineering optical links as any combination of modulation format and receiver technology imposes a minimal OSNR figure for properly detecting the data.

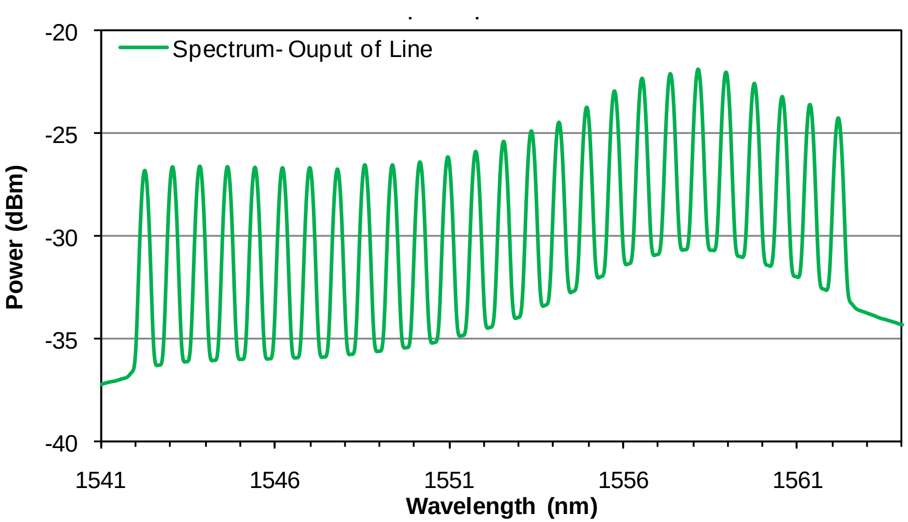
Generation of Optical Noise From A Raman Amplifiers String

- Multiple wavelengths at the input and output of a Raman amplifiers string

Input spectrum

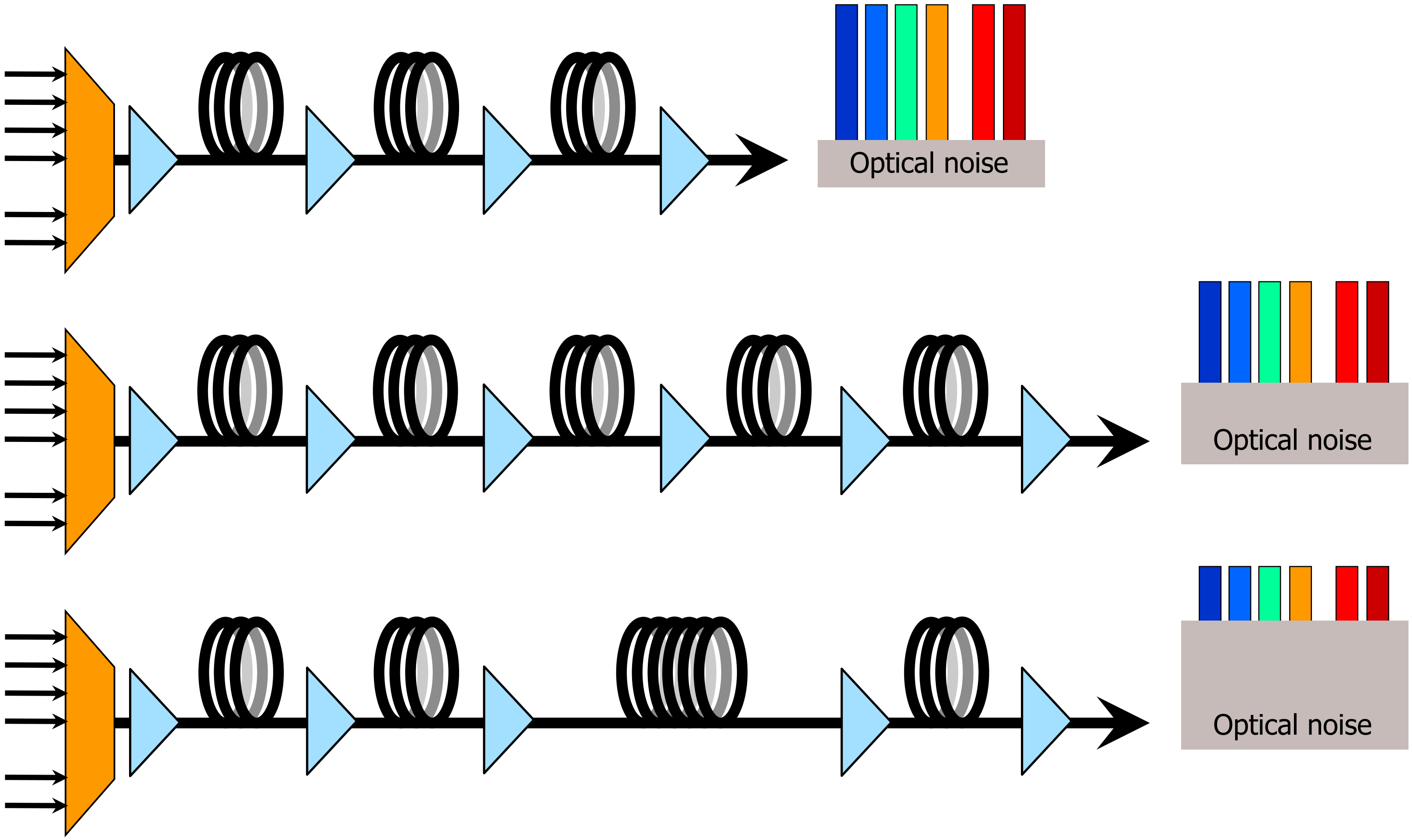


Output spectrum



- At the receive end the link, the system optimization parameter was the uniformization of the OSNR characteristic for all the wavelengths.

Optical Noise Accumulation



- Longer transmission distances and longer spans decrease the Optical Signal-to-Noise Ratio (OSNR) figure at the output end.

Optical Signal-to-Noise Ratio (OSNR) And Per Channel Power Management

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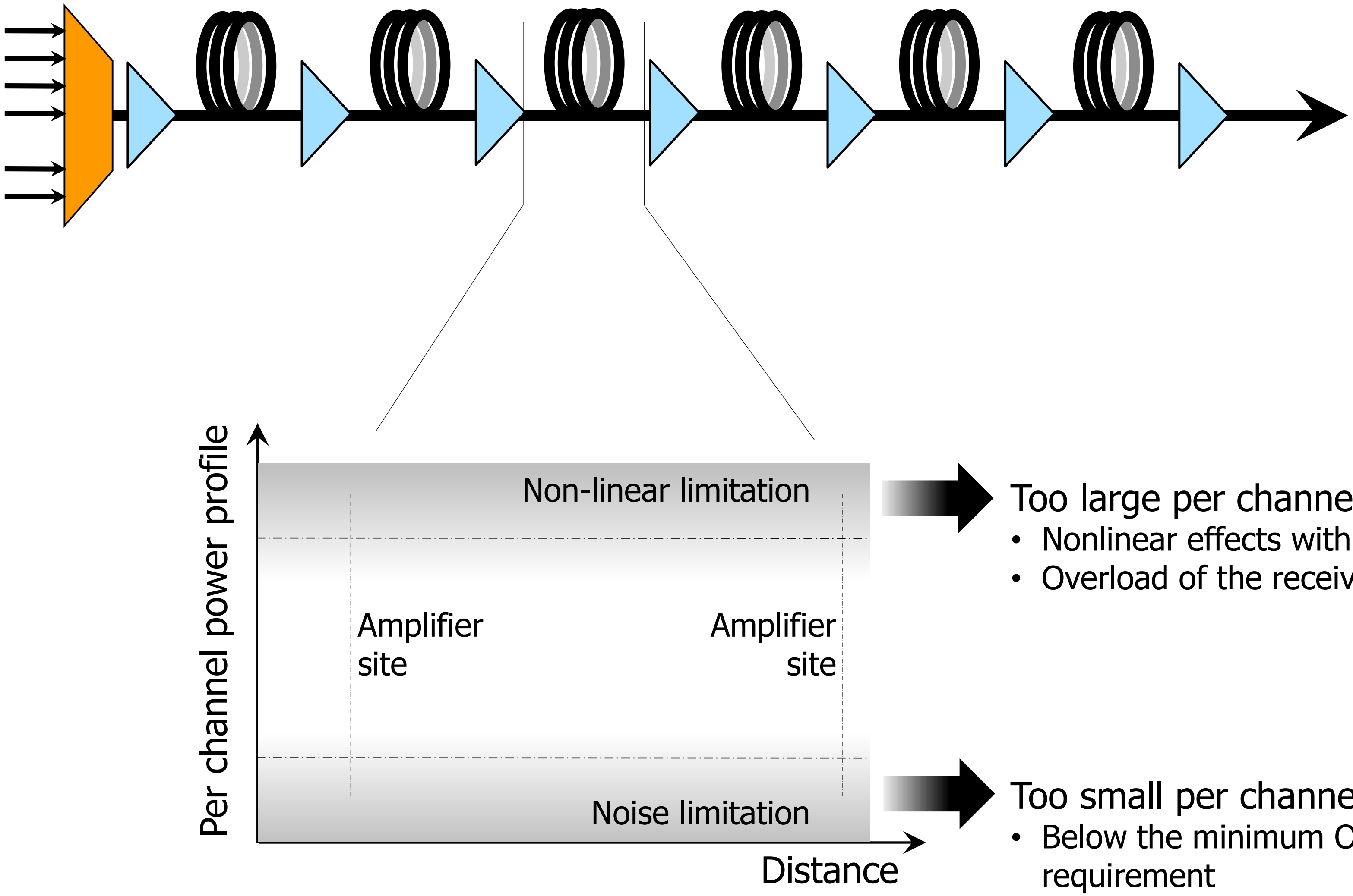


Too large per channel power:

- Nonlinear effects within the line fiber
- Overload of the receiver circuitry

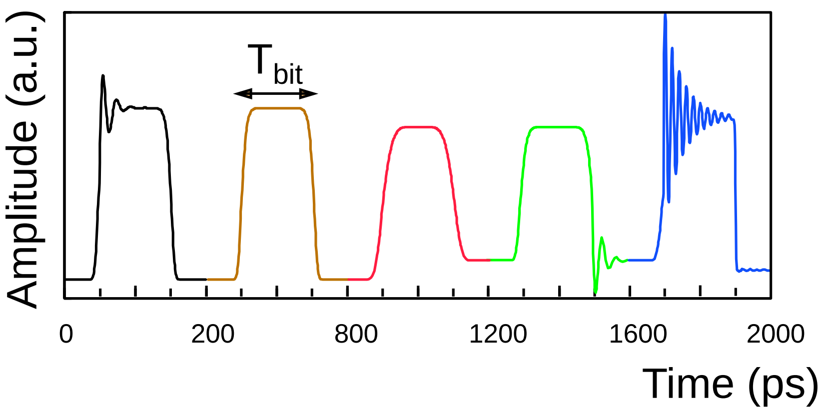
Too small per channel power:

- Below the minimum OSNR requirement
- Below the receiver sensitivity

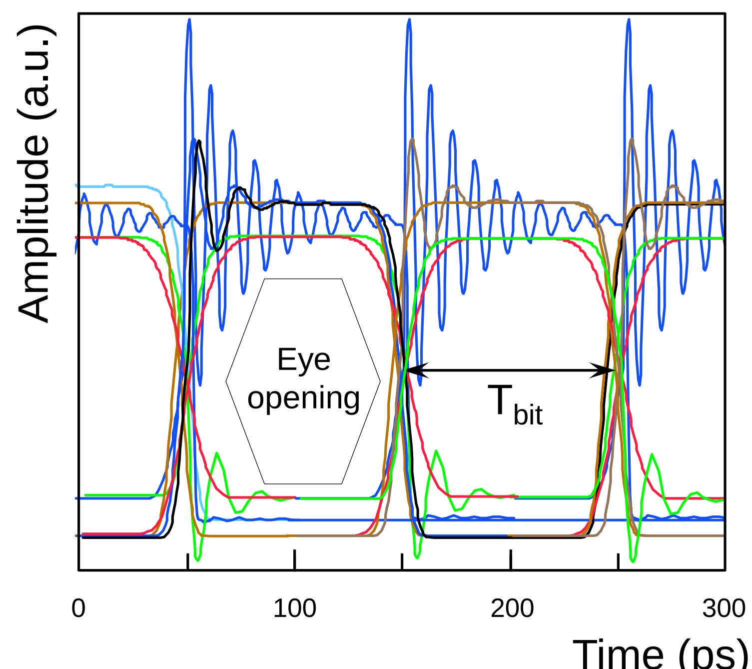
Digital Pulse Patterns And Eye Diagrams (For NRZ Signals)

- Eye diagram: oscilloscope display in which a digital data signal from a receiver is repetitively sampled and applied to the vertical input, while the data rate (clock signal) is used to trigger the horizontal sweep.

Synchronization by
the 10-Gbit/s data frame:
➔ Pulse pattern



Synchronization by
the 10-Gbit/s clock signal:
➔ Eye diagram



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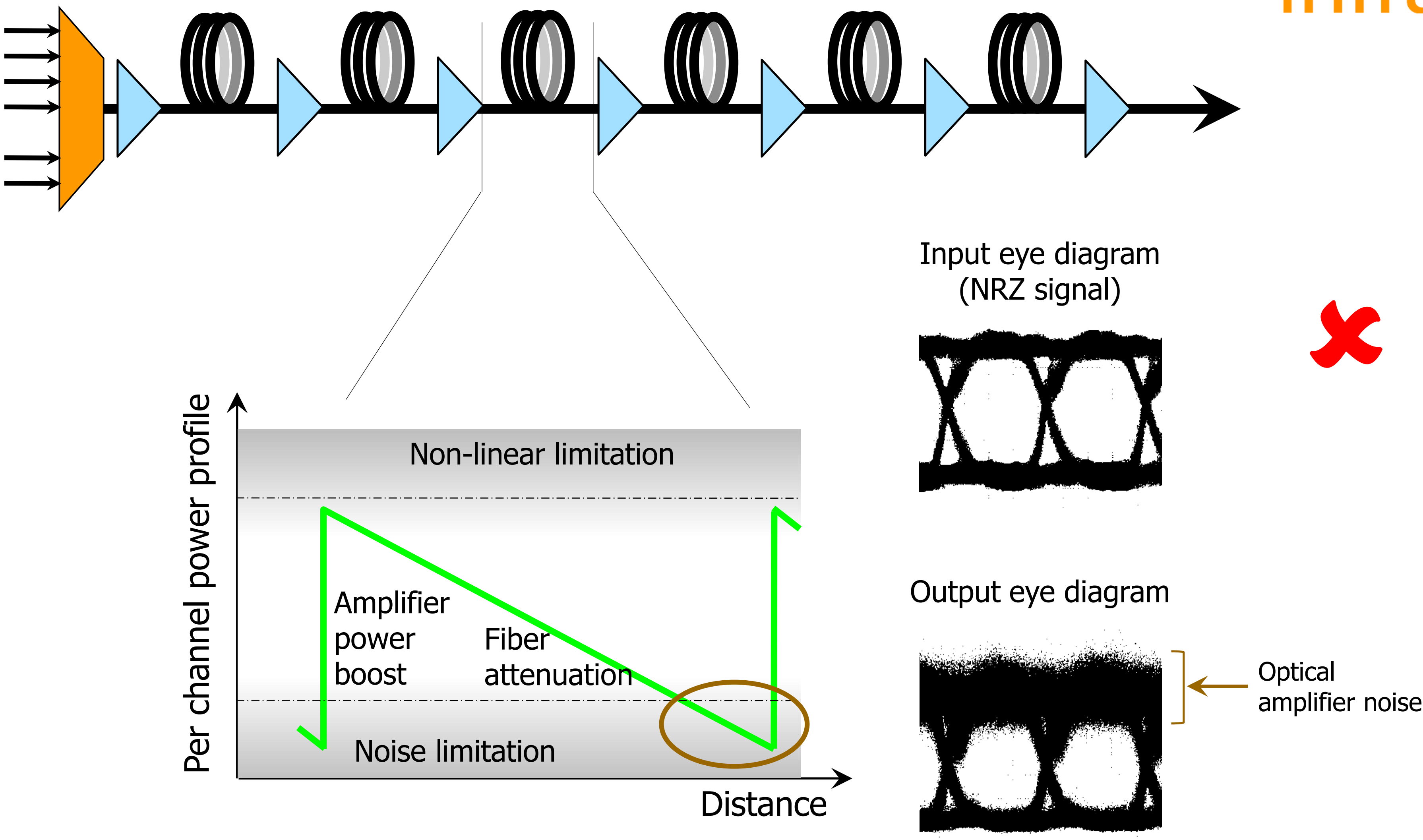

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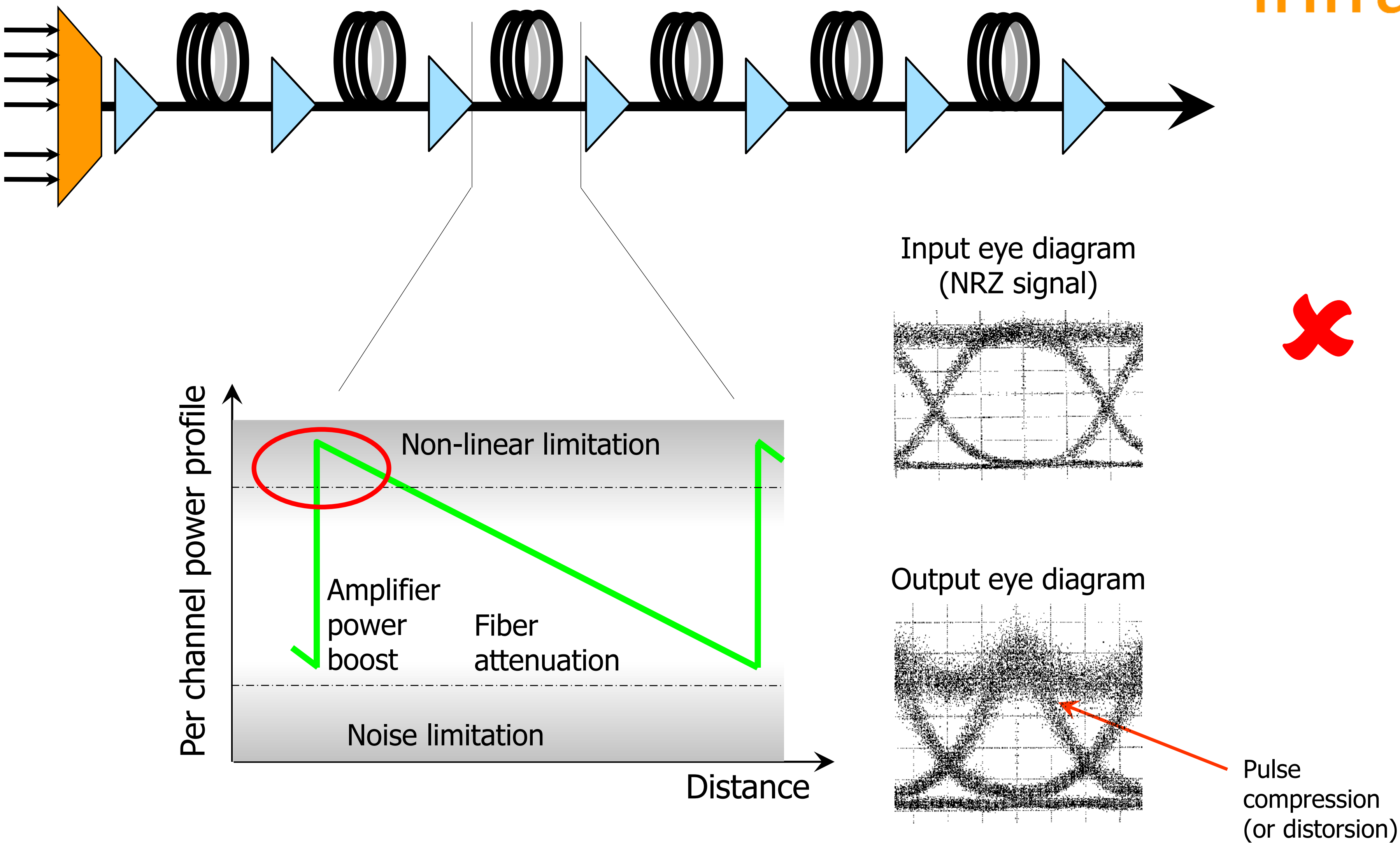

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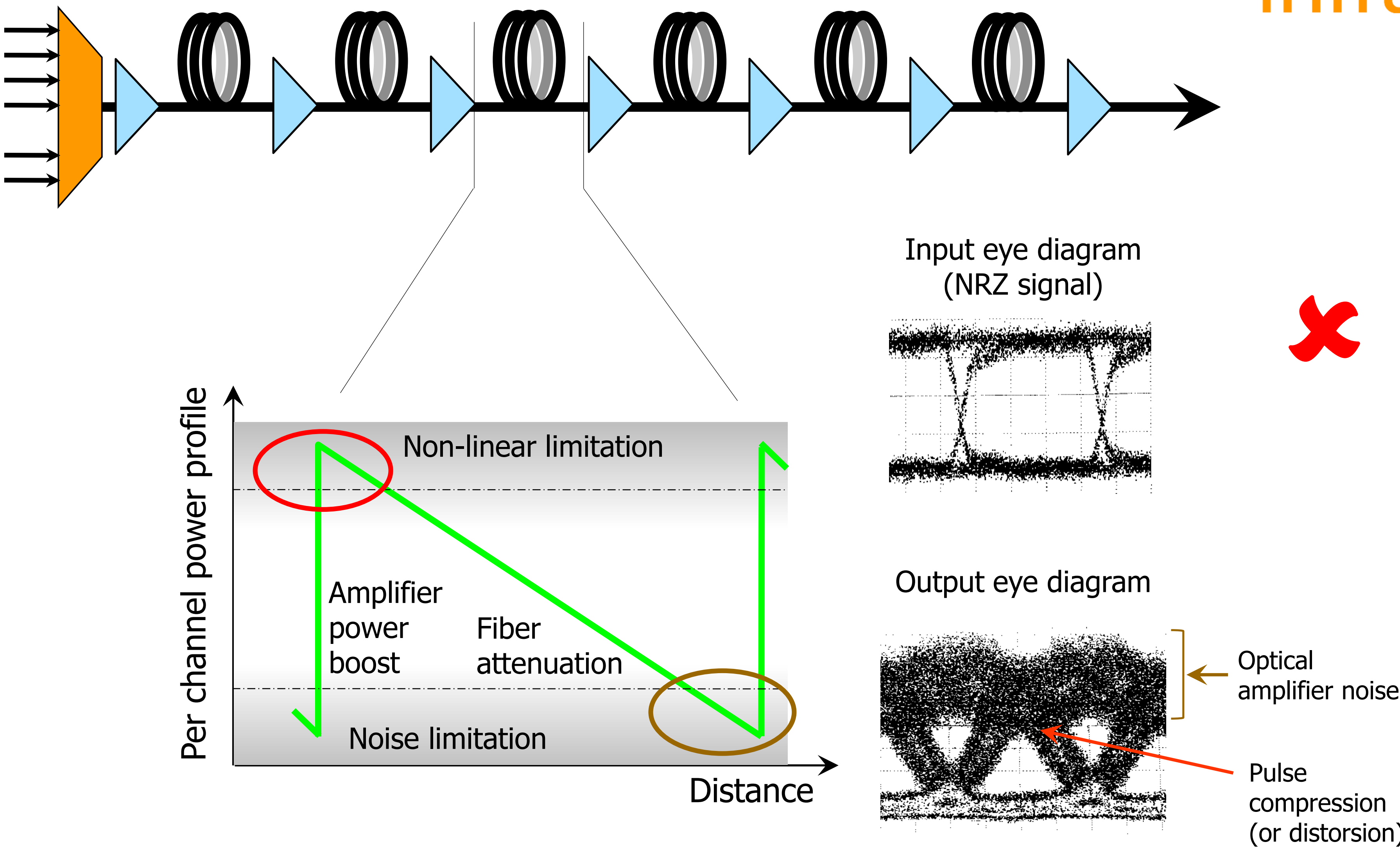

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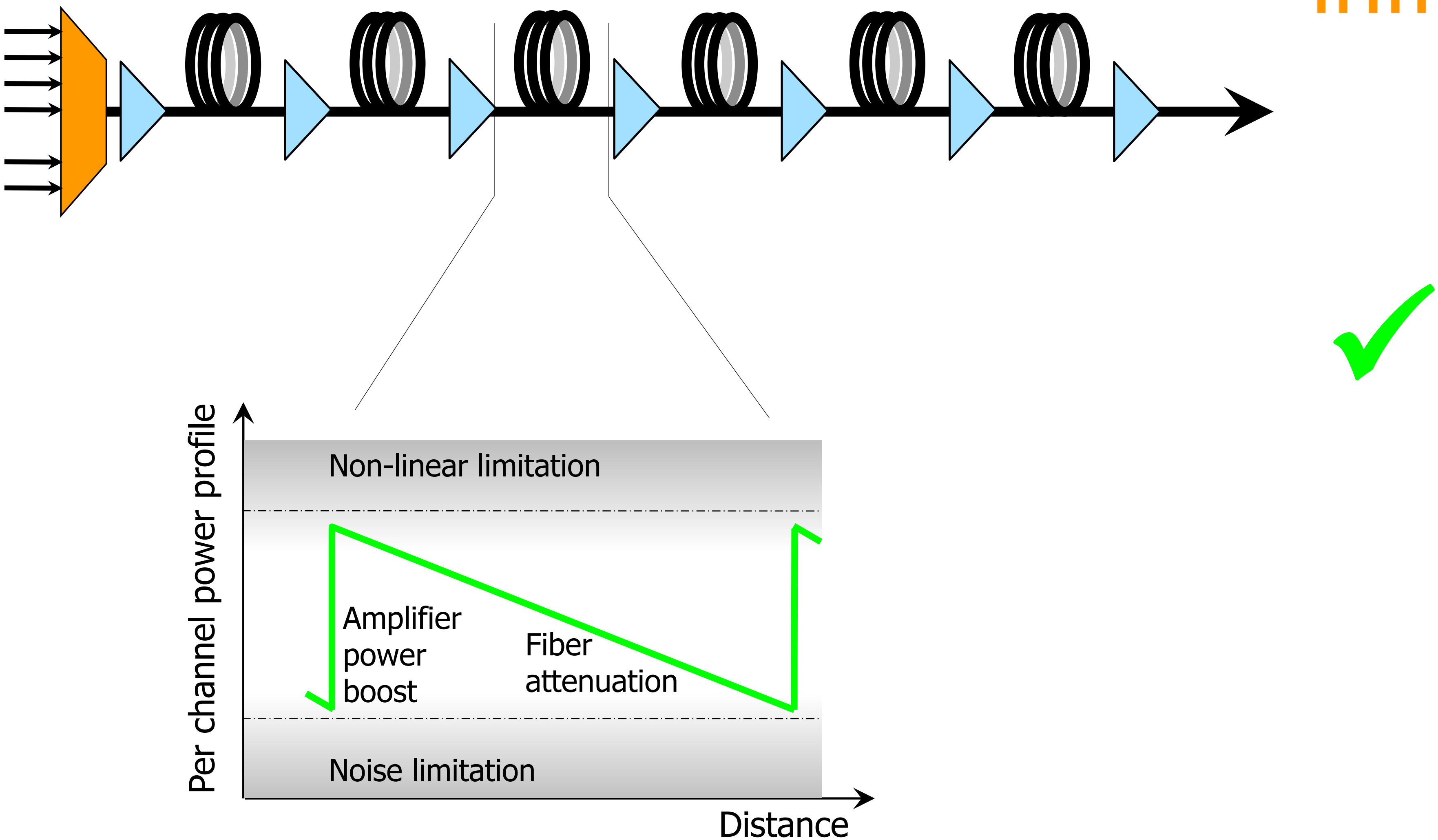

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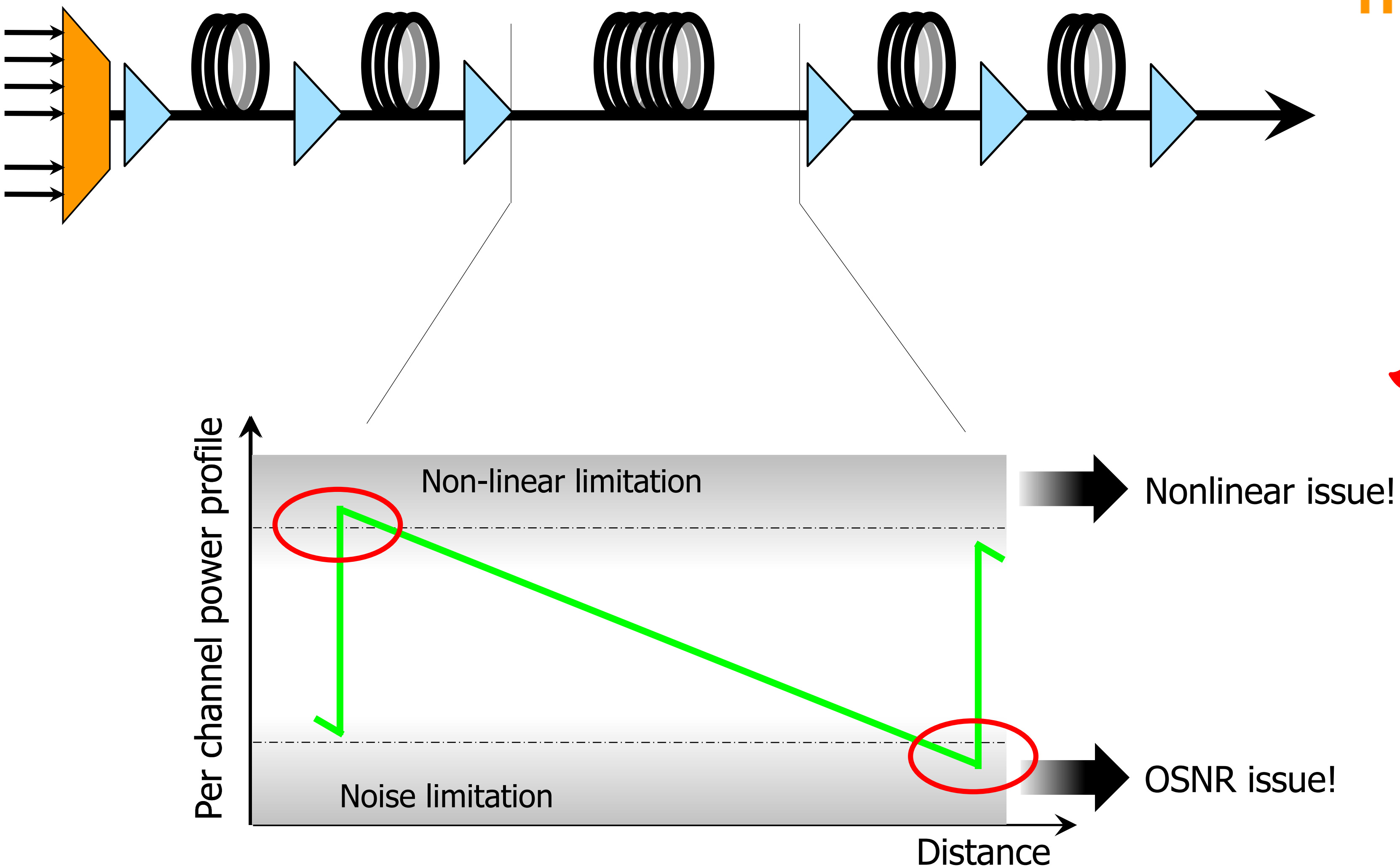

Optical Signal-to-Noise Ratio (OSNR) And Per Channel Power Management

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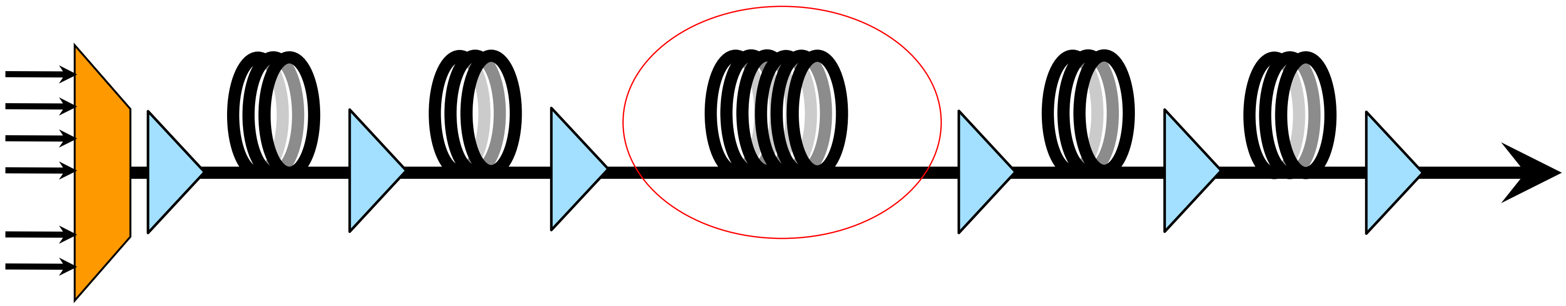

- Options to overcome the long span:
  - Build an intermediate site?
    Issues with
    1. CapEx
    2. OpEx
    3. Permitting
    4. Lead time
  - Terminate the long span at either end with back-to-back terminals?
    Issues with
    1. CapEx
    2. OpEx
    3. Incremental cost when new capacity is added
  - Create optical gain within the line fiber to avoid nonlinear/OSNR limitations and extend span performance

Optical Signal-to-Noise Ratio (OSNR) And Per Channel Power Management

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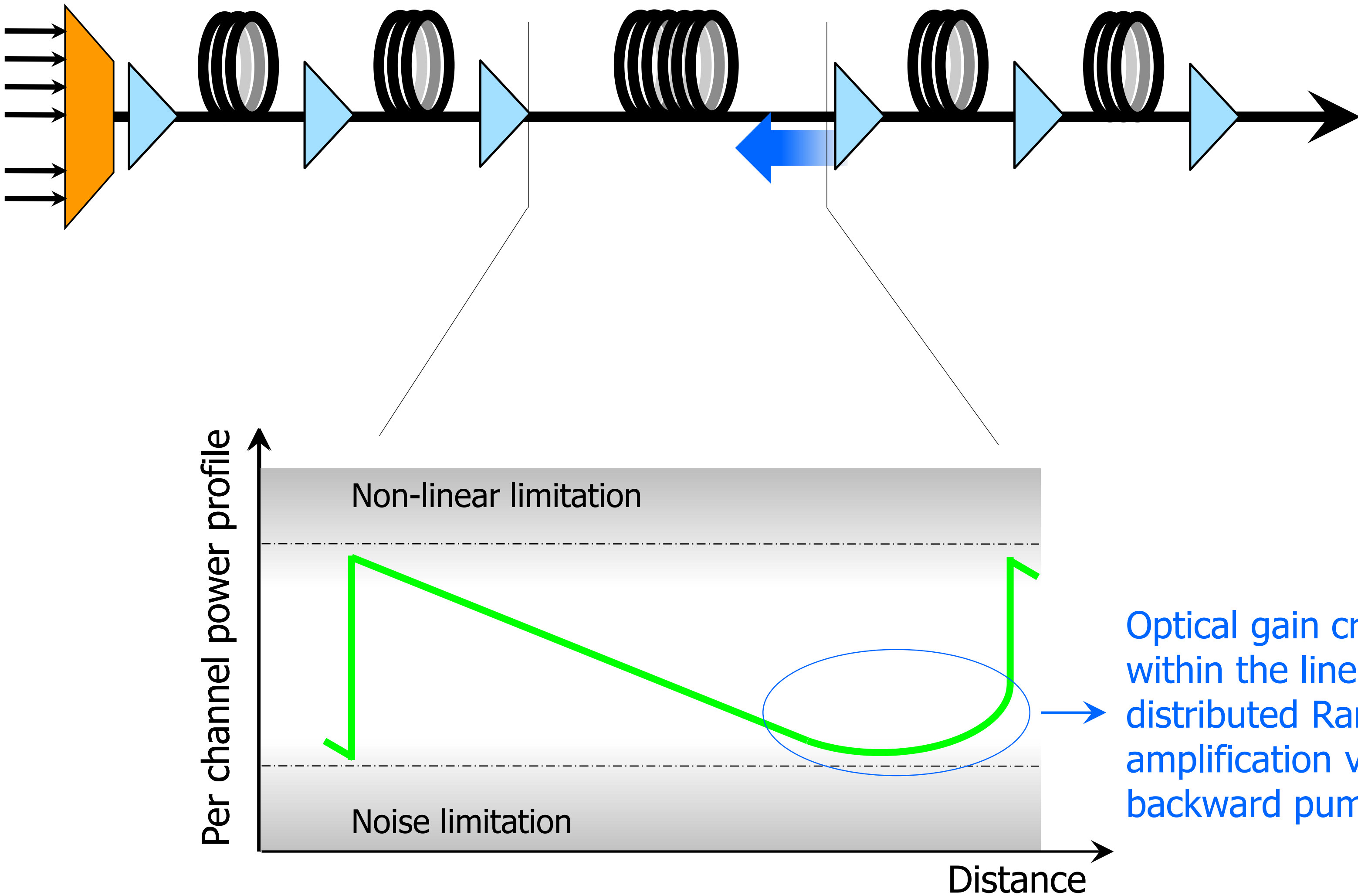
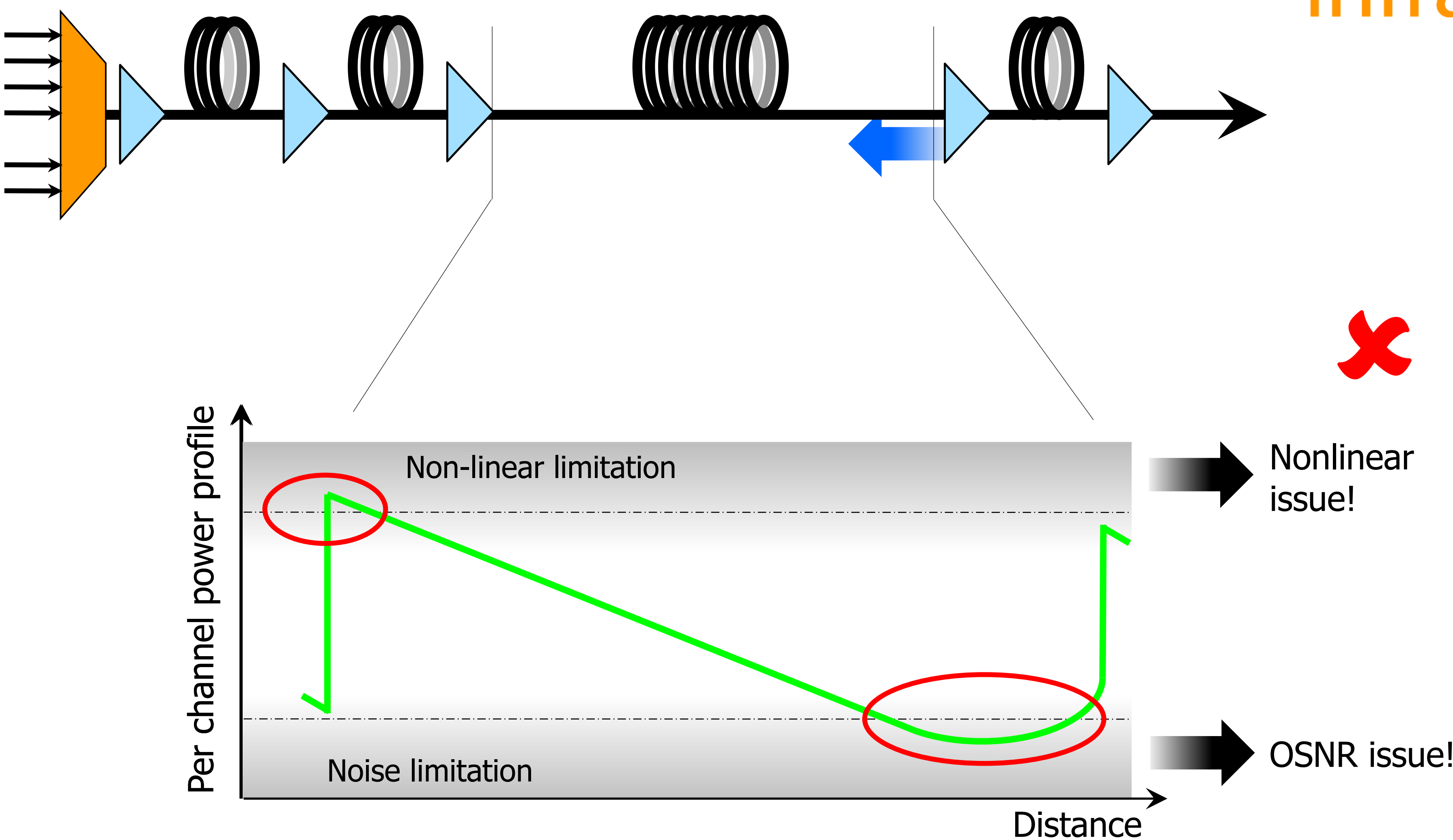


Optical gain created within the line fiber by distributed Raman amplification via backward pumping

Optical Signal-to-Noise Ratio (OSNR) And Per Channel Power Management



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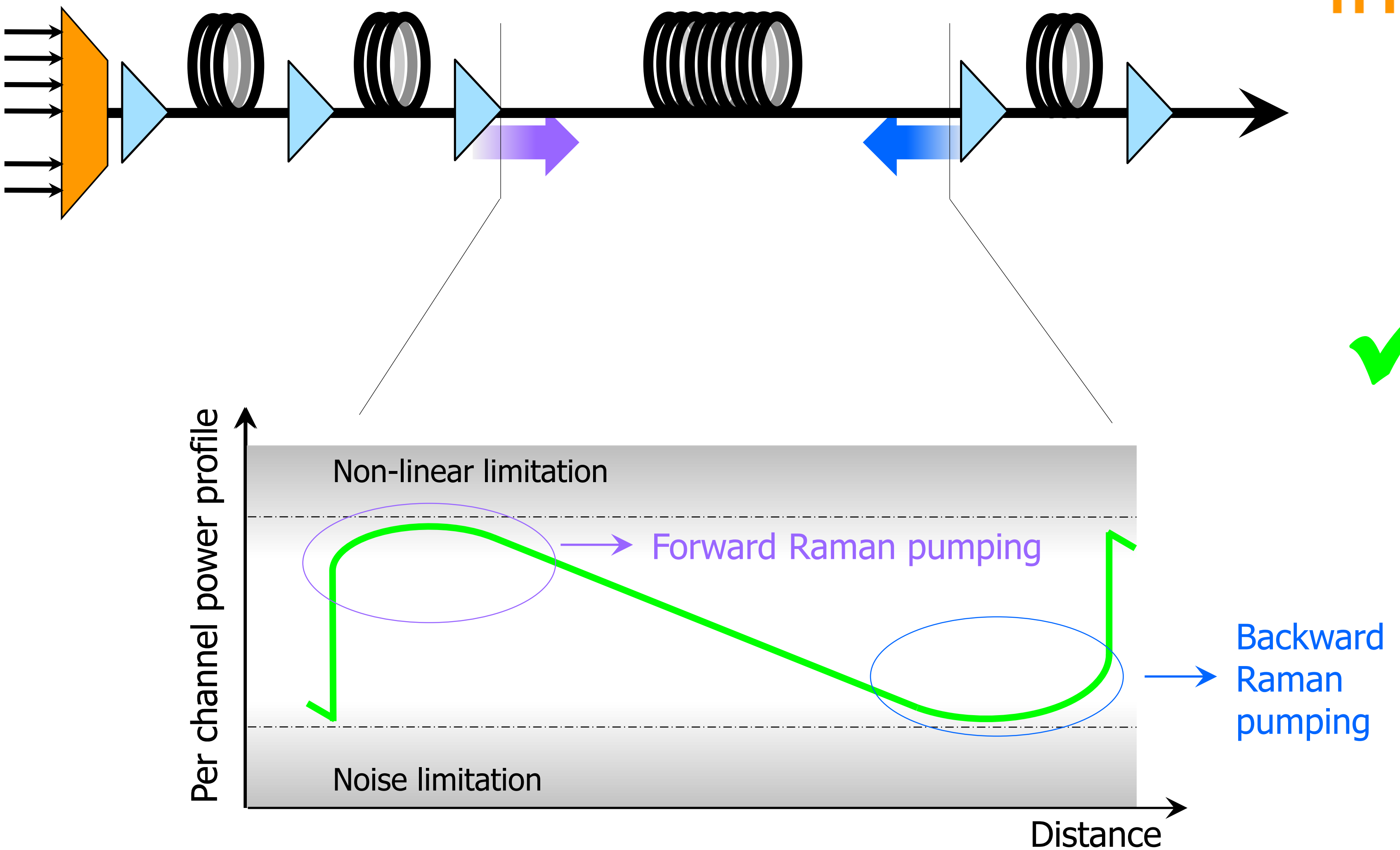

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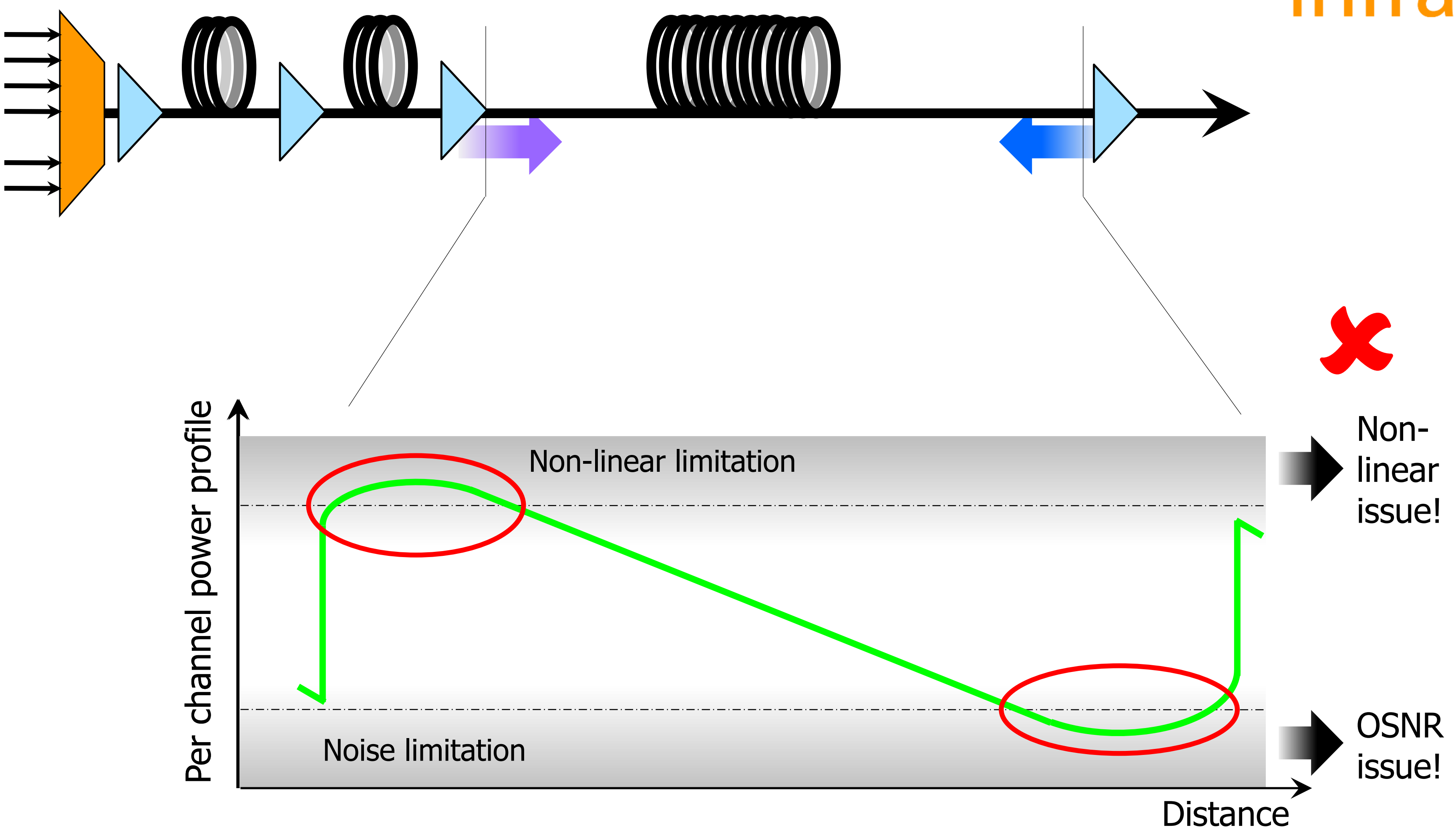

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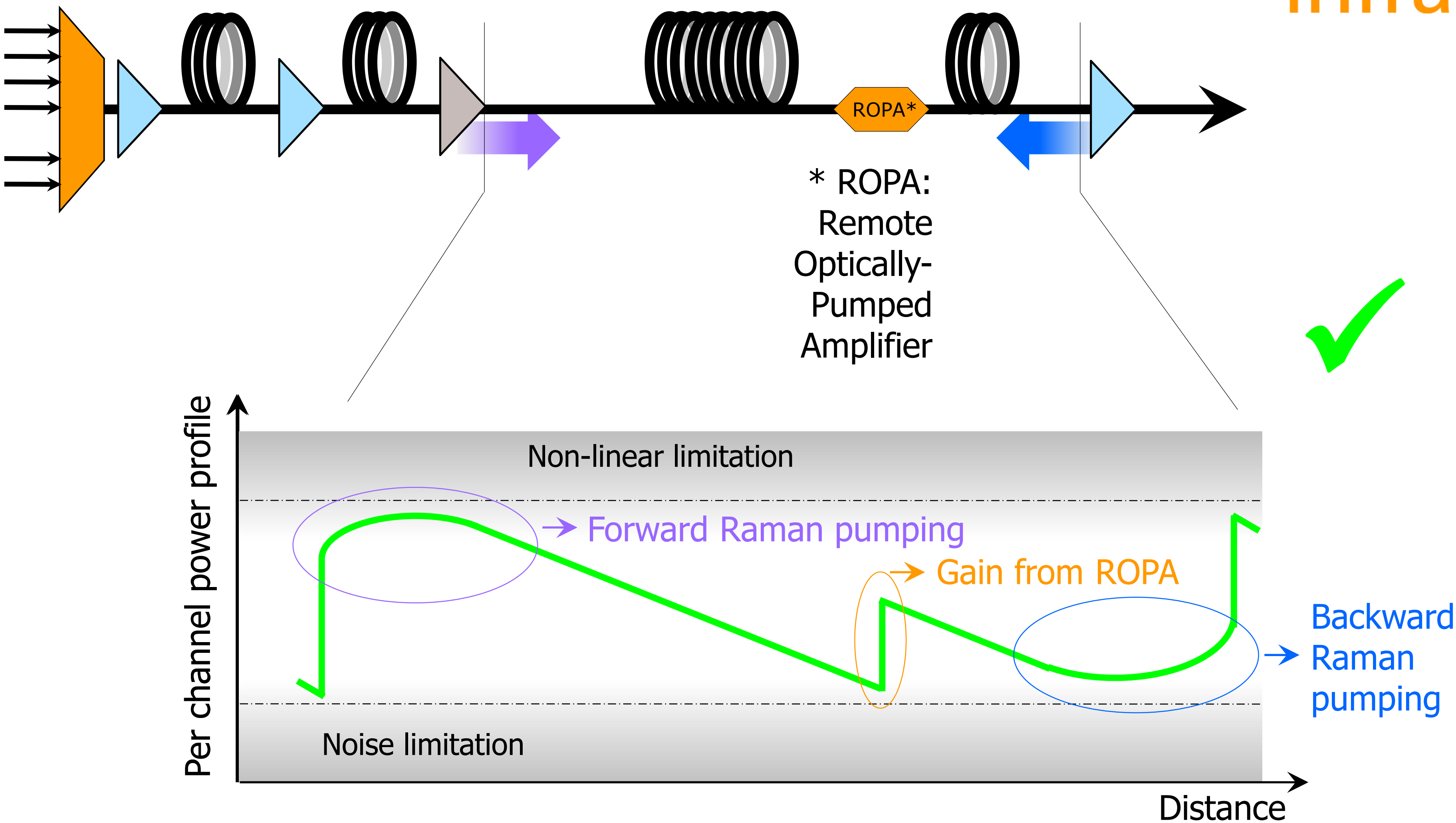

Combination of Raman Optical Amplification and Low-Loss Fiber

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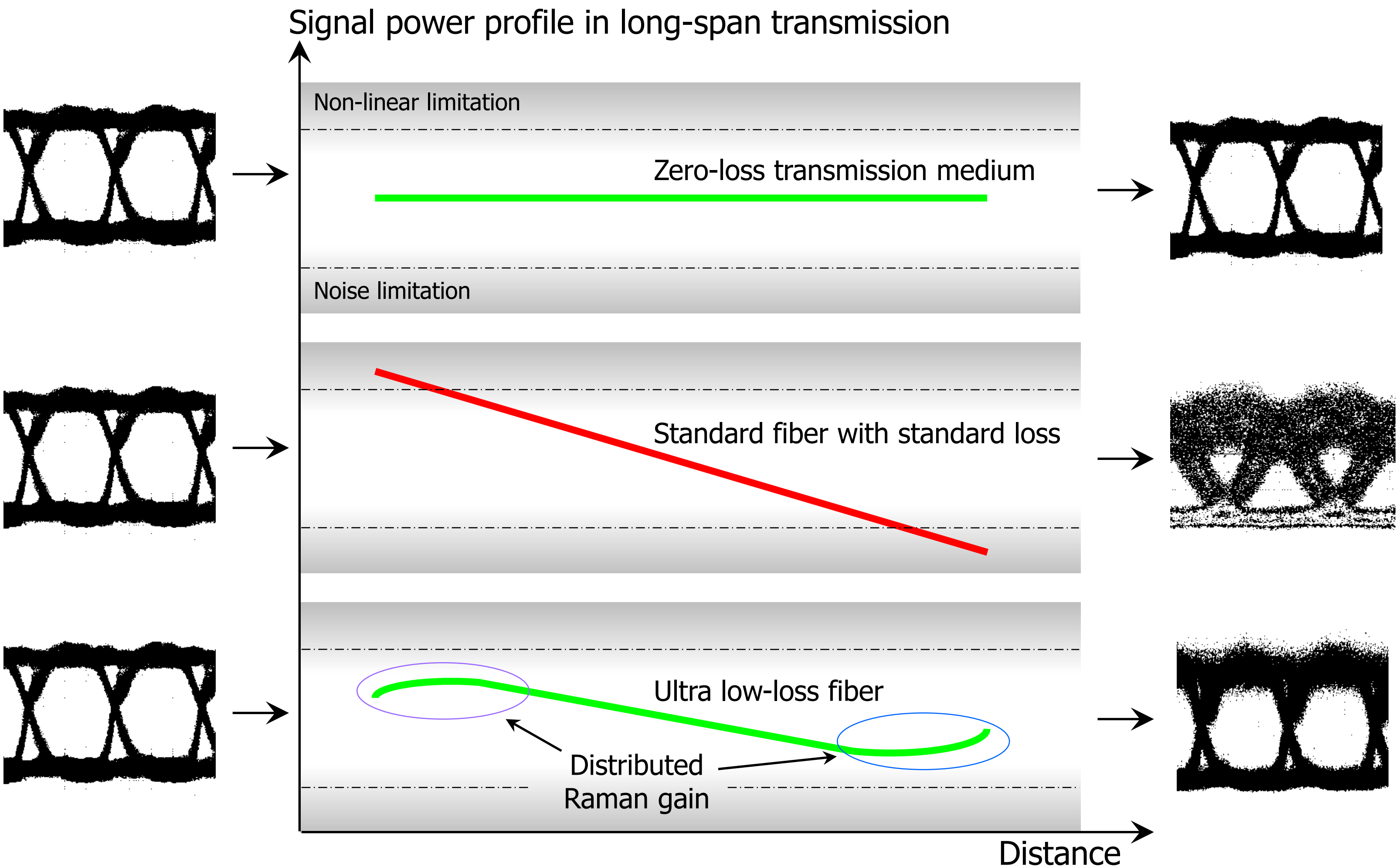

➔ Raman amplification helps to get closer to the ideal zero-loss case.

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The Optical Infrastructure Enabling Worldwide Web and Cloud