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Nonlinear Impairments in High Data Rate Transmission Systems

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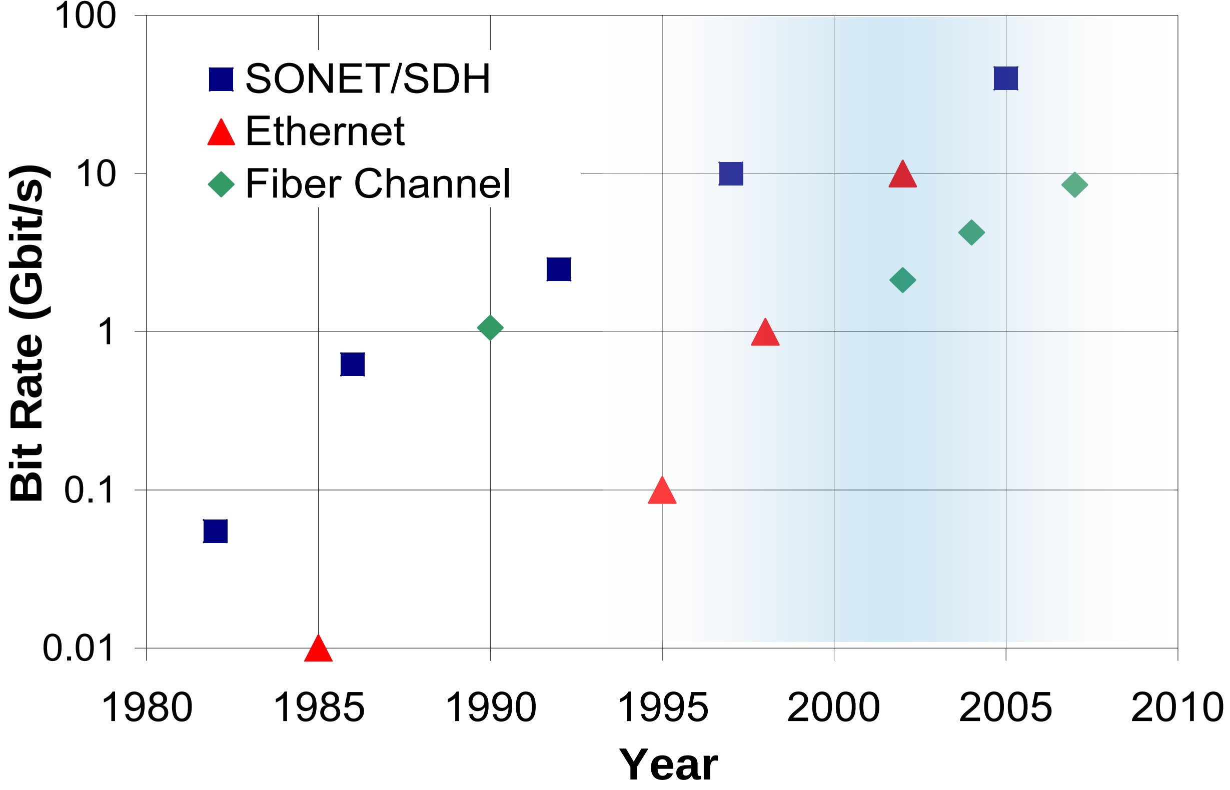
Outline

- Introduction:
  - Data rate evolution
  - Transmission systems

- Nonlinear fiber impairments
  - Stimulated Brillouin Scattering (SBS)
  - Stimulated Raman Scattering (SRS)
  - Self phase modulation (SPM)
  - Cross phase modulation (XPM)
  - Four Wave Mixing (FWM)

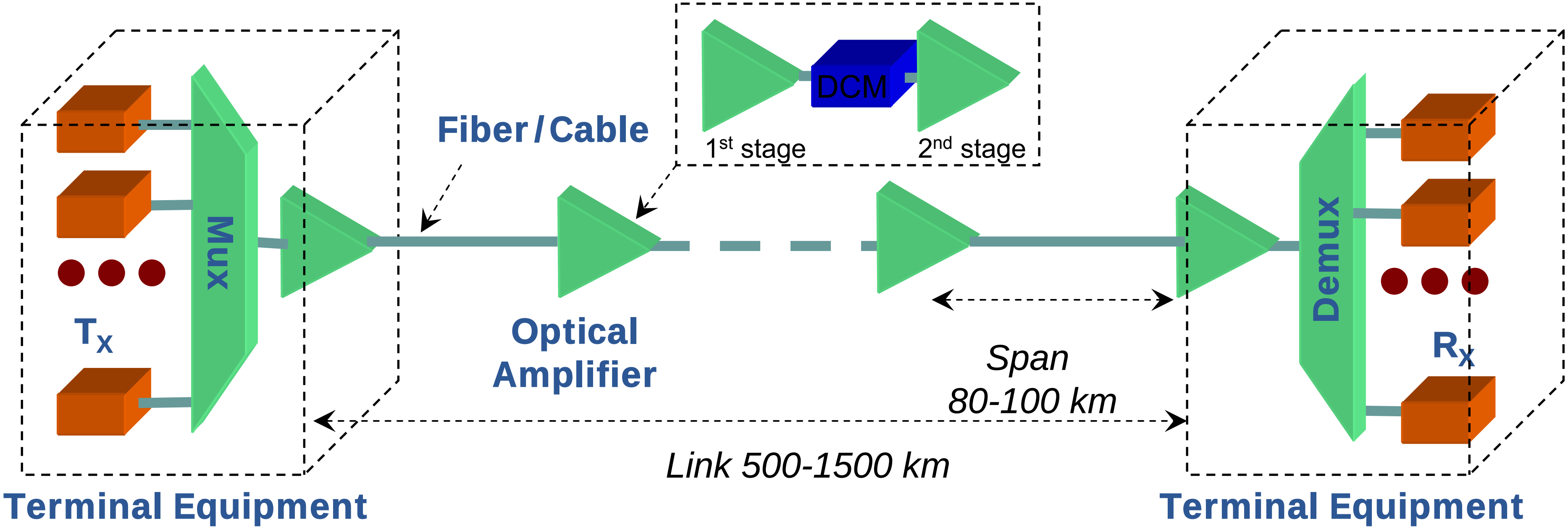
Line Rate Evolution



- Explosion of interest to fiber nonlinearities in the fiber optic system started with introduction of 10 Gb/s systems due to necessity to use *higher optical power for higher bit rates*

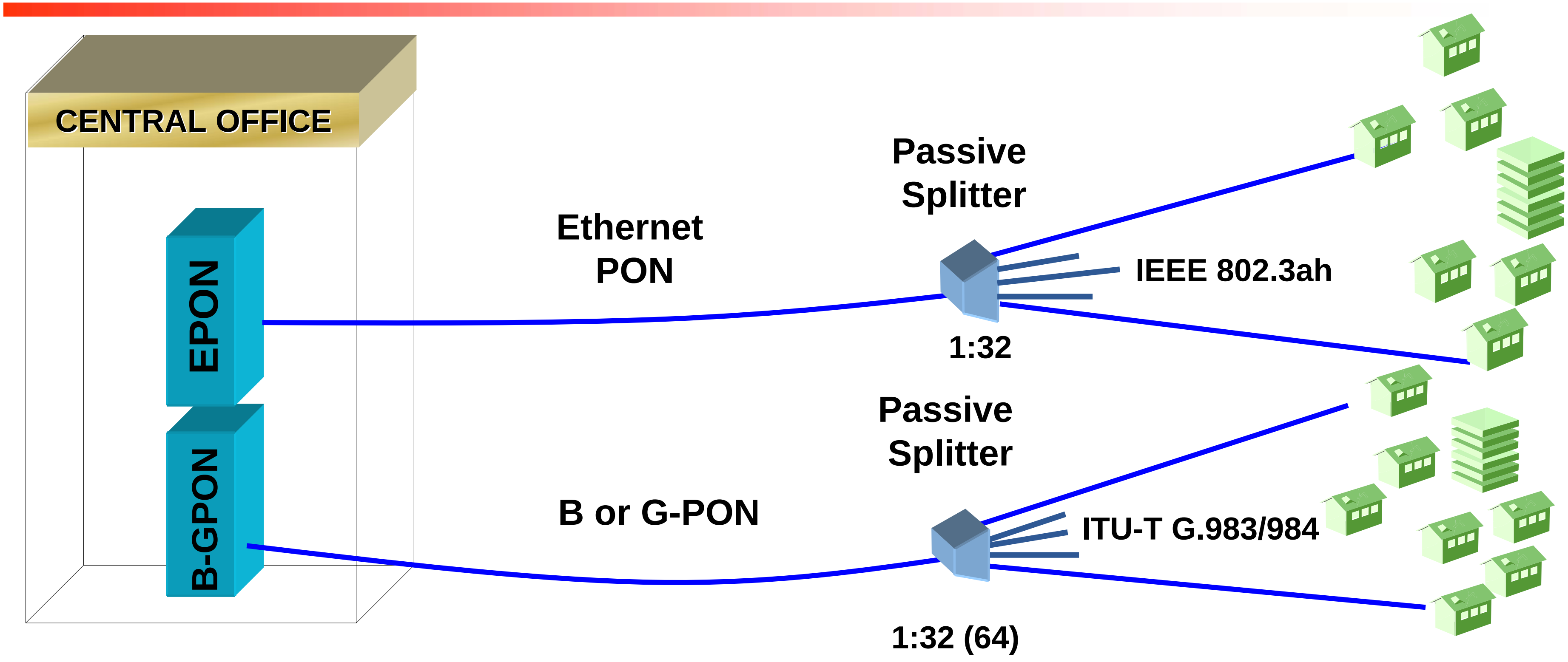
Where Fiber Nonlinearities Were Studied?

Long Haul WDM Transmission System



- Attributes of the long haul (LH) WDM transmission system
  - Link length 500-1500 km with span lengths of 80-100 km
  - Bit Rate 10 Gb/s, 100 or 50 GHz channel spacing on ITU grid
  - C band (1530 – 1565 nm) and L band (1570-1625 nm)
  - Erbium Doped Fiber Amplifier (EDFA) with 2 stages for DCM

Passive Optical Networks
Lower Nonlinearity due to Shorter Length



- Attributes of PONs
  - Link length up to 20 km, split ratio up to 64
  - Bit rates up to 2.5 Gb/s (10 Gb/s is considered)

Nonlinearities Fiber Impairments

Nonlinearity	*System impacted*	*How it impact the system*
Stimulated Brillouin Scattering	PON	Limits launched optical power, increases noise. Impairs video signal through CNR, CSO and CTB degradation
Stimulated Raman scattering	LH (WDM), PON	Transfers power from blue channel to red channels i.e. effectively increasing attenuation for blue channels. Raman Xtalk in PONs.
Self-phase modulation	LH	Distortion of the phase of transmitted optical pulse that is converted into amplitude distortion
Cross-phase modulation	LH (WDM)	Distortion of the phase of adjacent transmitted channel that is converted into amplitude distortion.
Four wave Mixing	LH (WDM)	Generation of the FWM tones that coincide with other channels. Appears like nonlinear noise

Stimulated Brillouin Scattering

(SBS)

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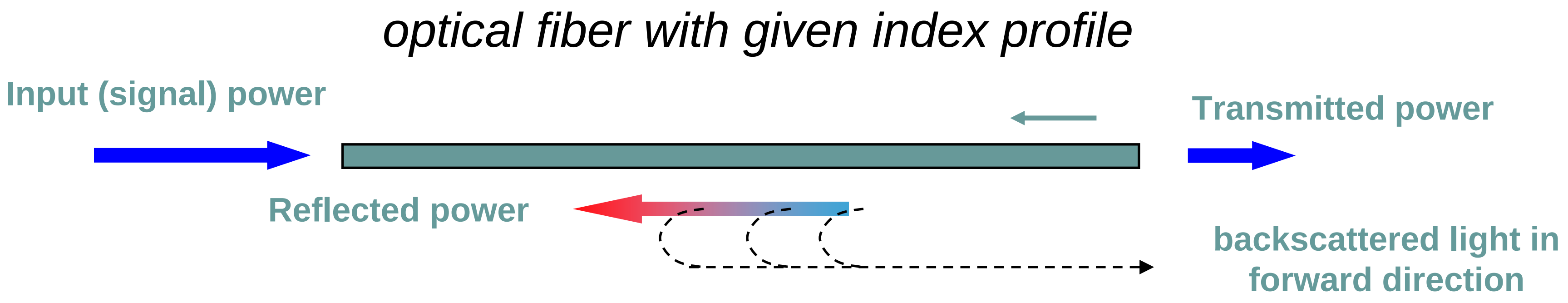
Experimental Observation of SBS



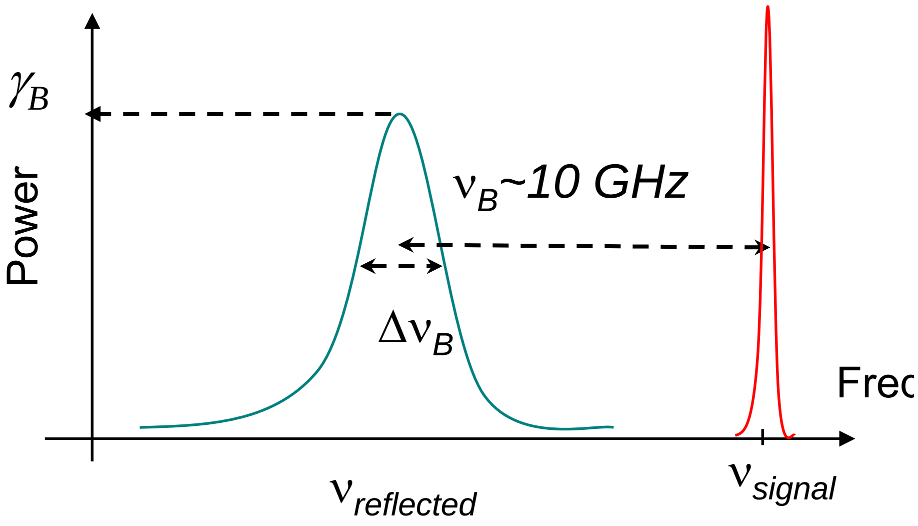
optical fiber with given index profile

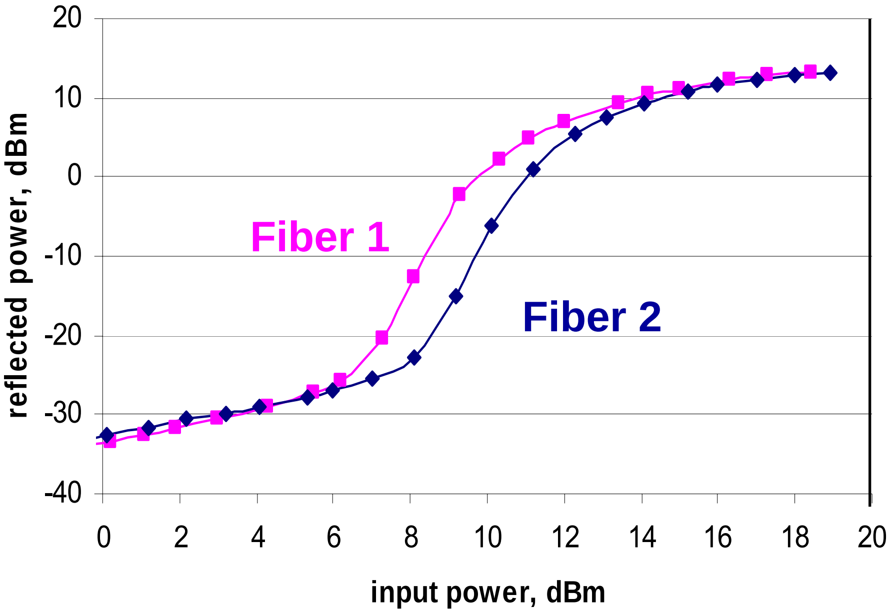
Input (signal) power

Transmitted power

Reflected power

backscattered light in forward direction





Spontaneous Brillouin Scattering

- Brillouin scattering occurs due to interaction of light with acoustic waves
- How it originates:

  thermal motion of molecules

  ↓

  pressure fluctuations (acoustic waves)

  ↓

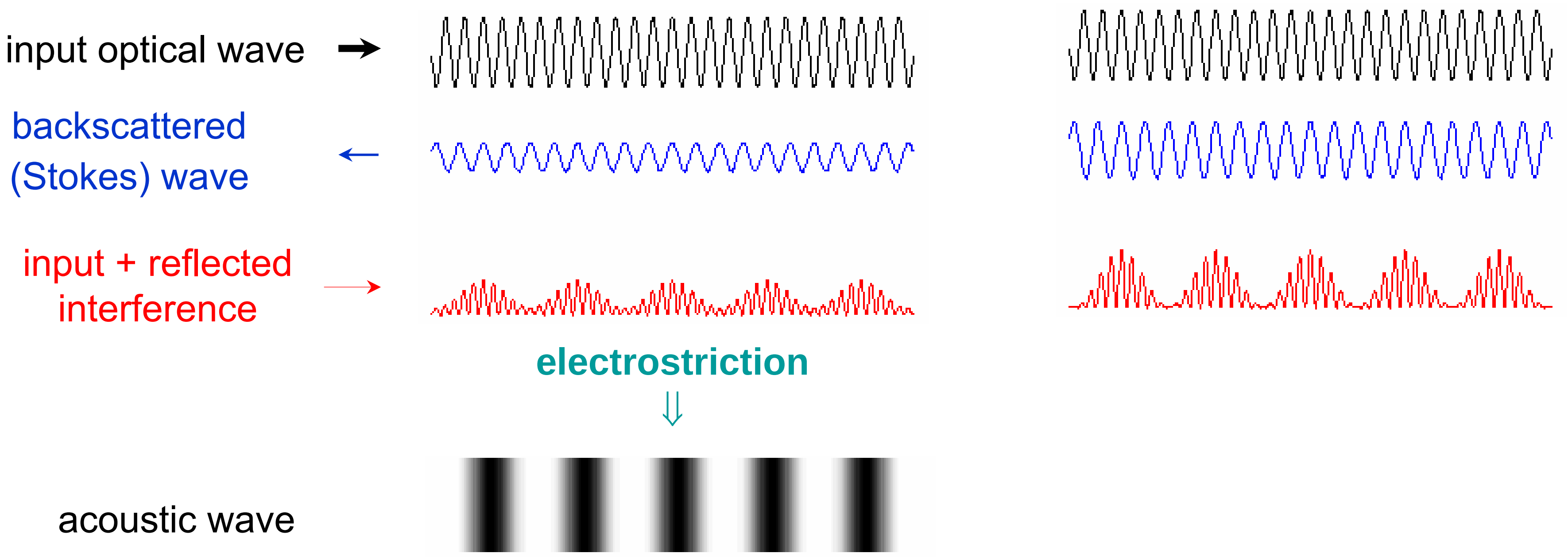
  refractive index variations

  ↓

  light scattering

- Most efficient scattering occurs in a backward direction and induces a Doppler frequency shift of the scattered light

Stimulated Brillouin Scattering



input optical wave →

backscattered (Stokes) wave ←

input + reflected interference →

electrostriction

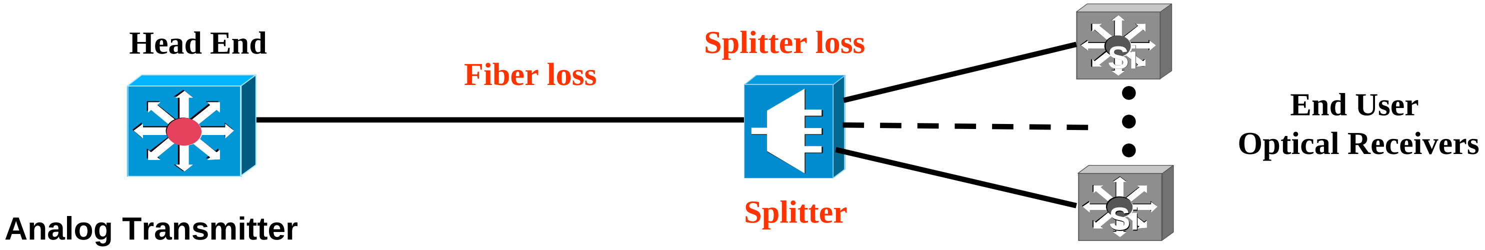
⇓

acoustic wave

- Backscattered light (Stokes wave) from acoustic noise interferes with the input optical wave
- An acoustic wave is generated due to electrostriction (increase in the material density in regions of high optical intensity)
- The acoustic wave further stimulates Brillouin scattering
- Brillouin scattering reinforces the acoustic wave and so on...

SBS limits maximum launch power to the fiber

- To maximize the number of network users or/and transmission distance or bit rate high input optical power is required



Head End

Fiber loss

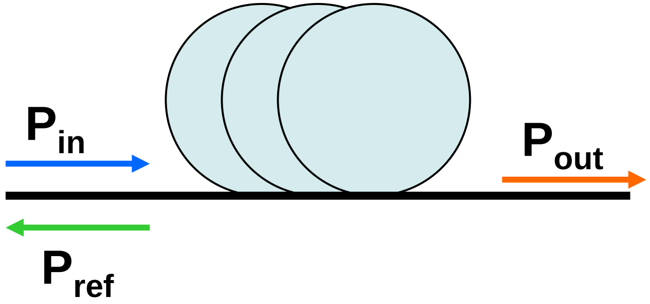
Splitter loss

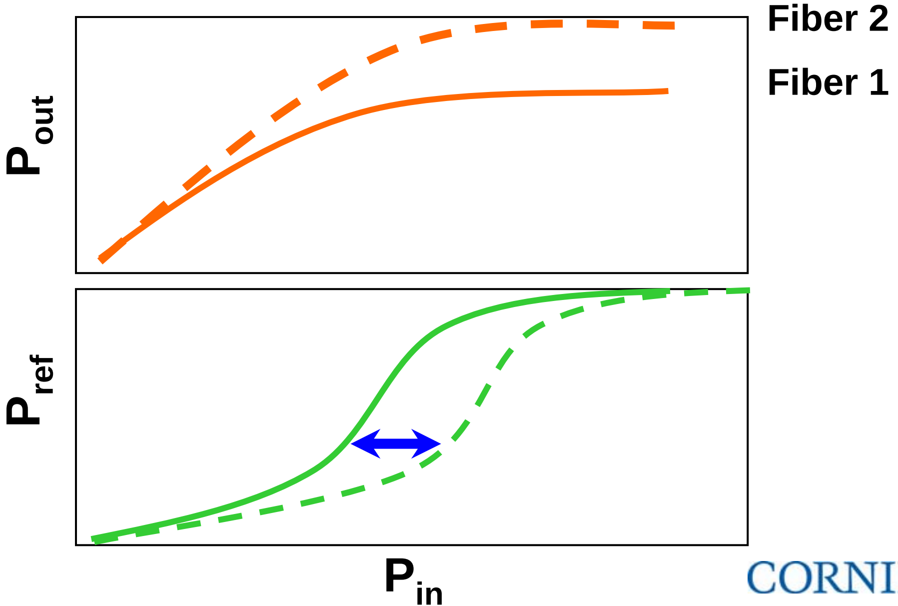
End User Optical Receivers

Analog Transmitter

Splitter

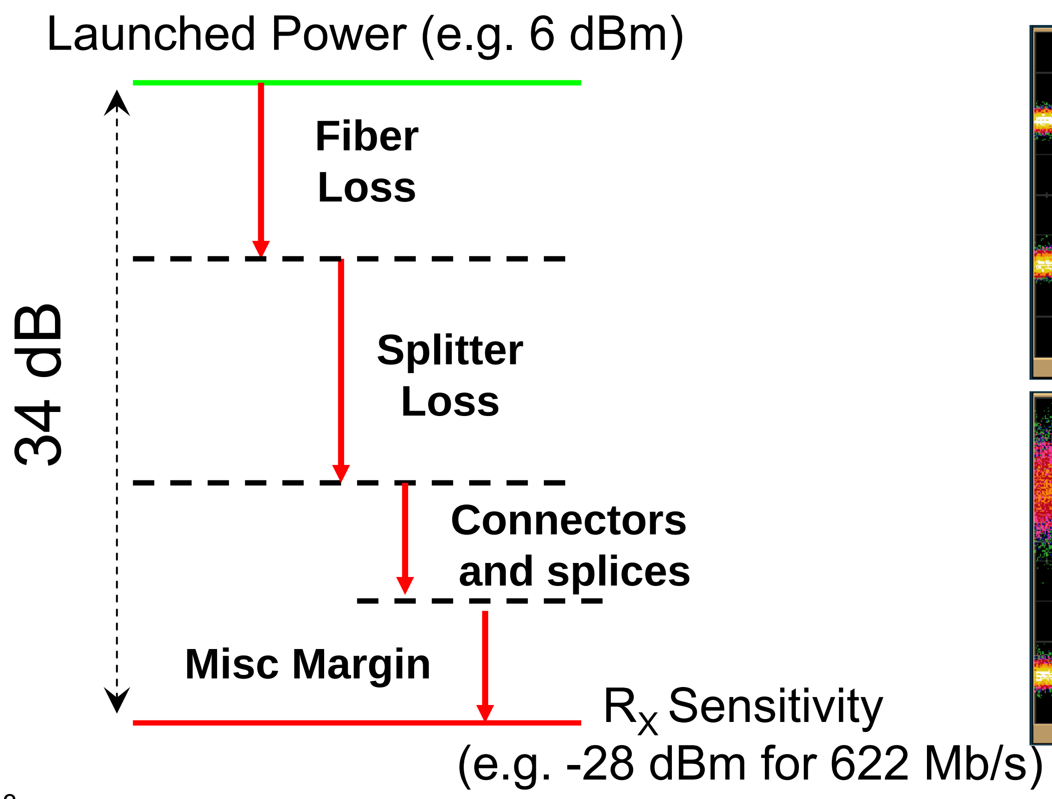
- Optical power launched in the fiber is limited by SBS





SBS Impact on Digital Transmission

- Limits power budget and reflects signal in Tx
- Creates additional noise from forward scattered Stocks component


Launched Power (e.g. 6 dBm)

34 dB

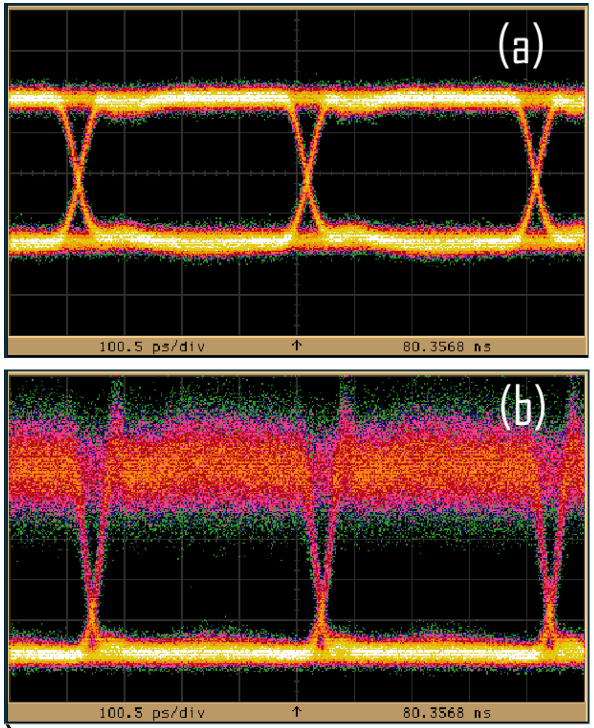
Fiber Loss

Splitter Loss

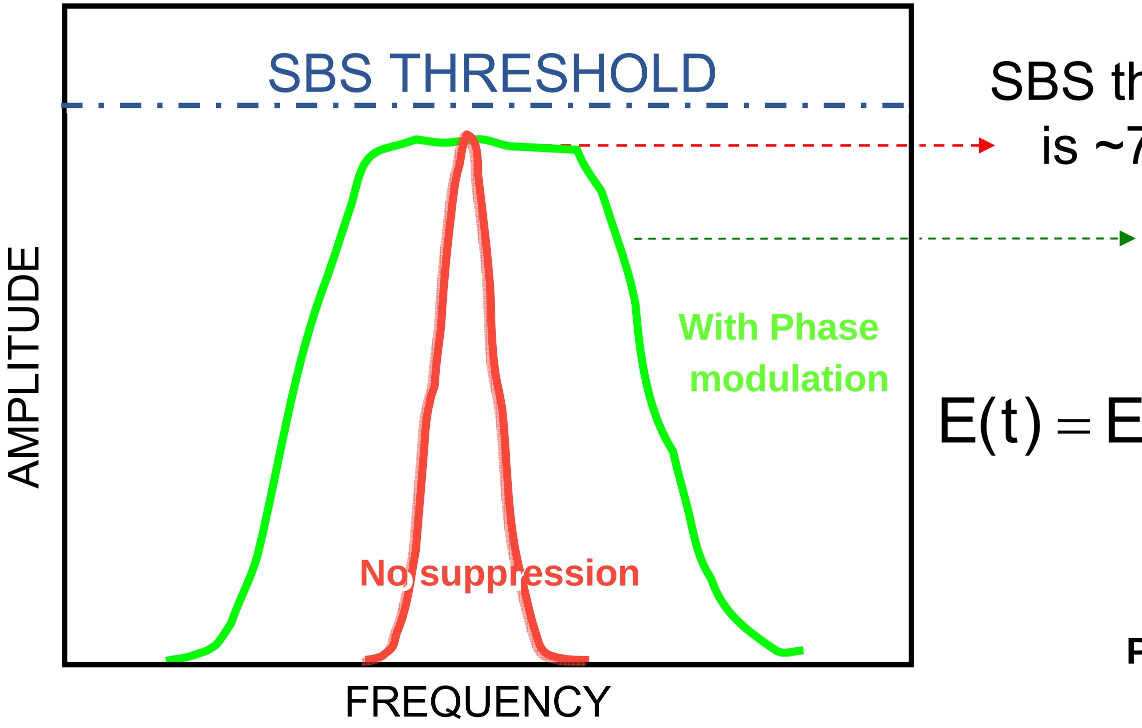
Connectors and splices

Misc Margin

R_X Sensitivity (e.g. -28 dBm for 622 Mb/s)



SBS Threshold Enhancement: Dithering



SBS threshold is ~7 dBm

Threshold is ~17dBm

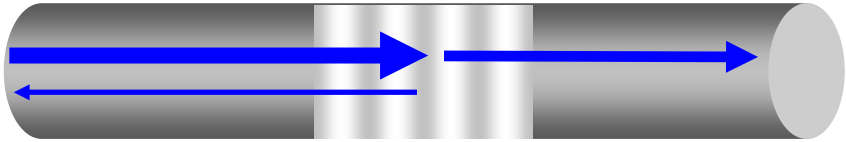
$$E(t) = E_0 \prod_{n=1}^{N} \exp(iA_n \cos(2\pi f_n t + \phi_n))$$

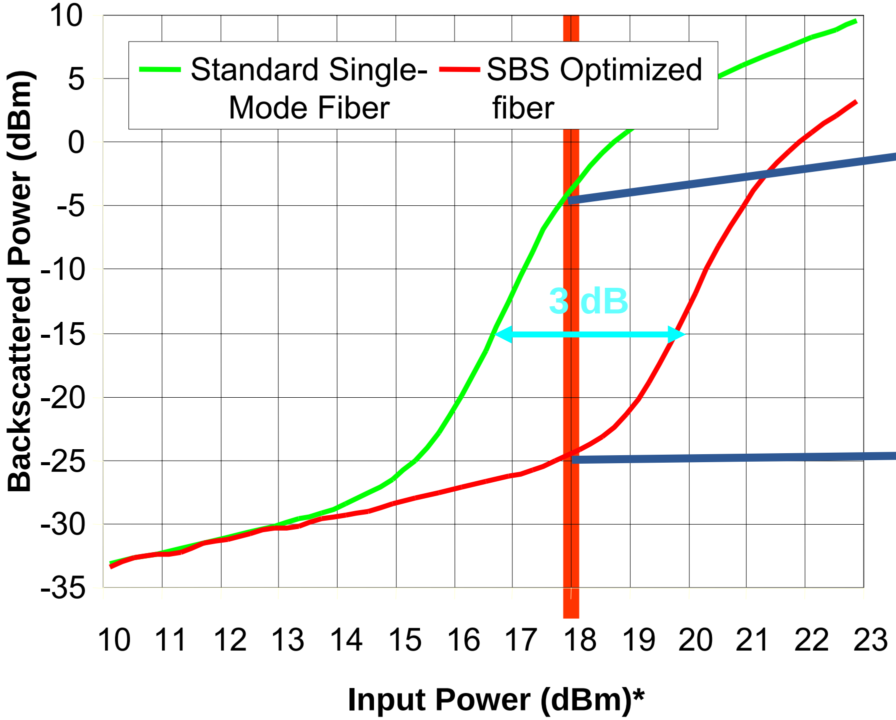
Phase Modulation Amplitude

Phase Modulation Frequency

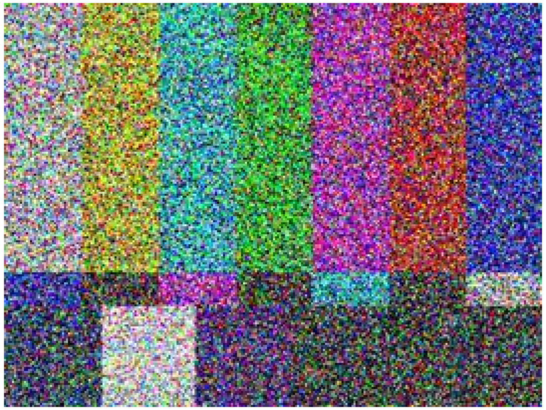
- Broadening linewidth spreads optical power across a wider spectrum, so peak power is below threshold but total power is increased
- "State of the art" externally-modulated transmitters typically have maximum SBS-limited output power of ~17 dBm.

SBS Threshold Enhancement: Fiber Design

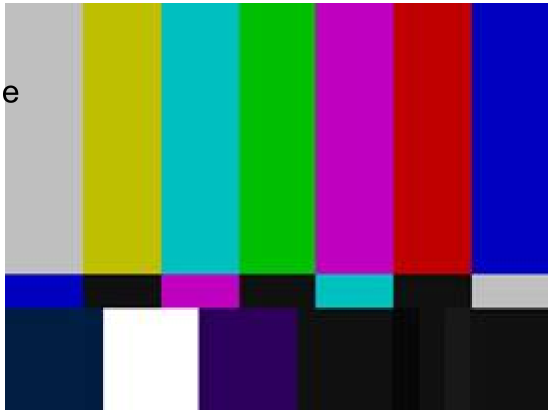




Picture quickly degrades above standard SBS threshold



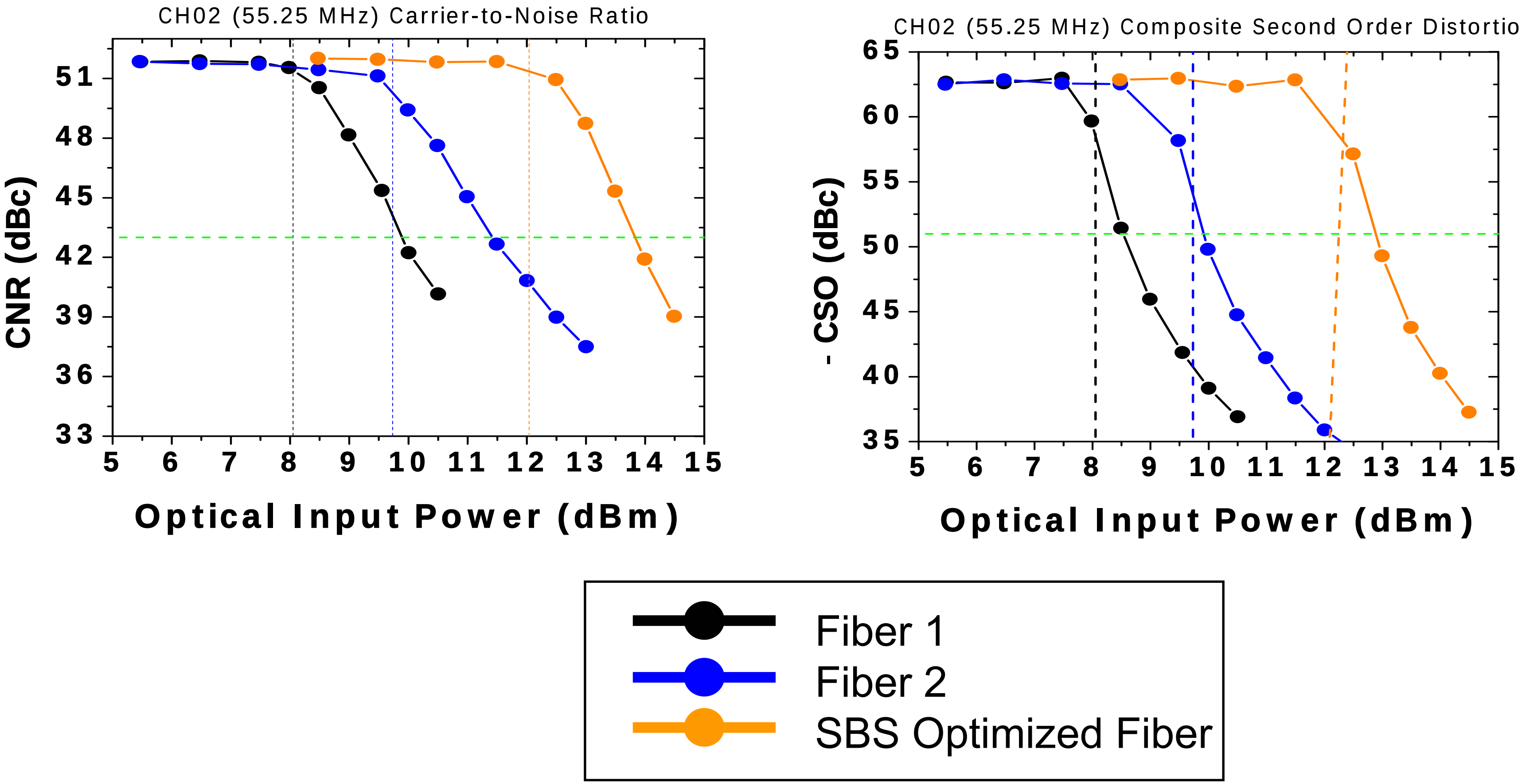
SBS optimization allows the same optical power with no degradation in picture quality



SBS optimized fibers allow double optical power with no degradation of video quality

*Impact of SBS will vary with distance, so higher powers may be supported at shorter distances. Values here are measured at 50 km.

Analog Distortion Measurements :
Fiber 1, Fiber 2 and SBS Optimized Fiber



**No Dithering is used in these measurements*

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Summary: Stimulated Brillouin Scattering

- SBS limits power of the digital signal launched in the fiber and thus limits max transmission distance or split ratio
  - Major degradation is due to increased insertion loss of fiber and lower optical power at the Rx

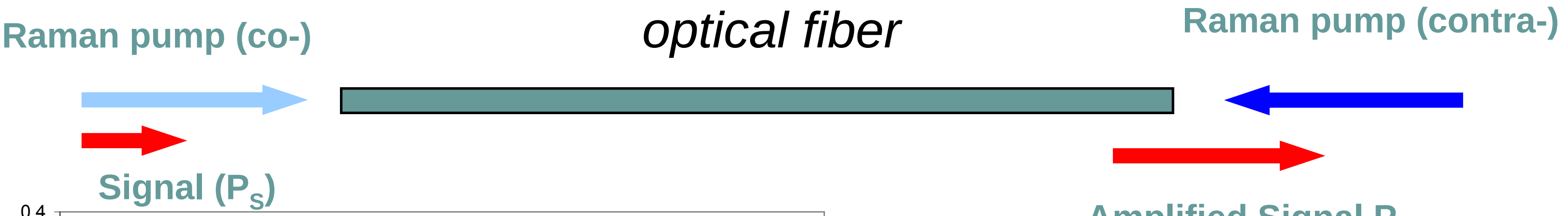
- SBS can be mitigated by
  - Dithering (spectral broadening of the launched signal)
  - Using fibers with increased SBS threshold

- Analog signal is much more sensitive to SBS because
  - Requires high power at the Rx and launched power
  - CNR and CSO degrade with the onset of SBS

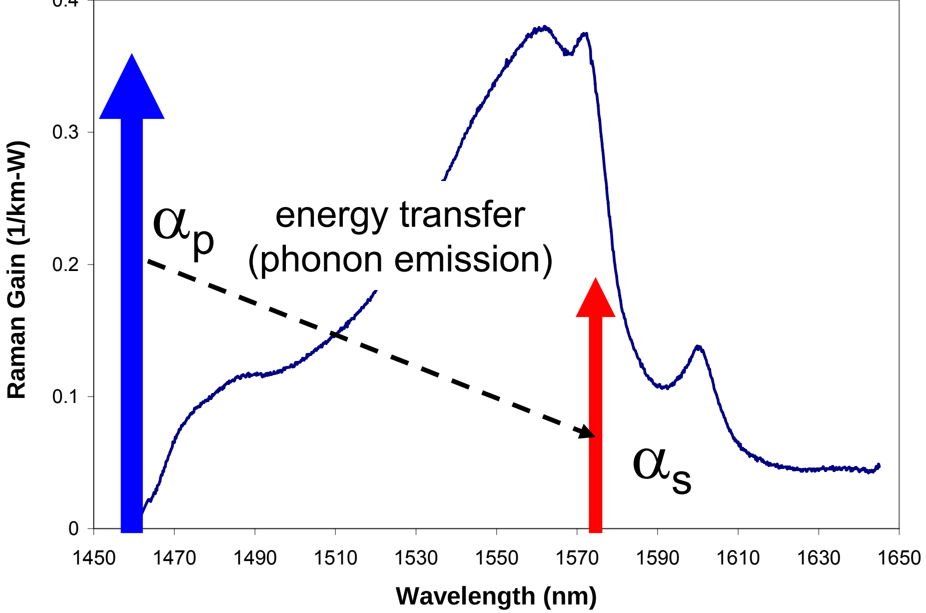
Stimulated Raman Scattering

(SRS)

Experimental Observation of SRS



Amplified Signal P_S

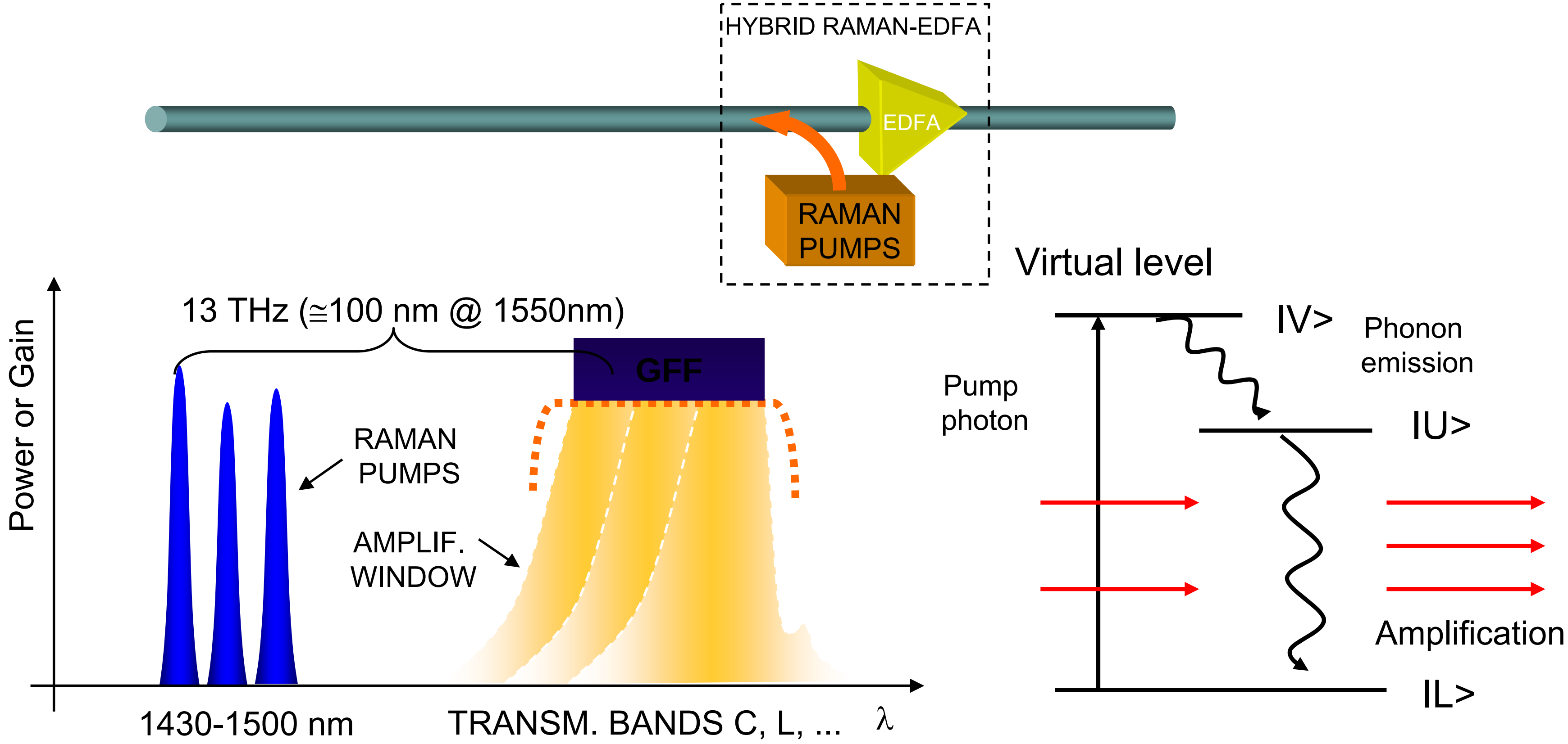


$$\frac{dP_s}{dz} = C_R P_s P_p - \alpha_s P_s$$

$$\frac{dP_p}{dz} = -\frac{\lambda_s}{\lambda_p} C_R P_s P_p - \alpha_p P_p$$

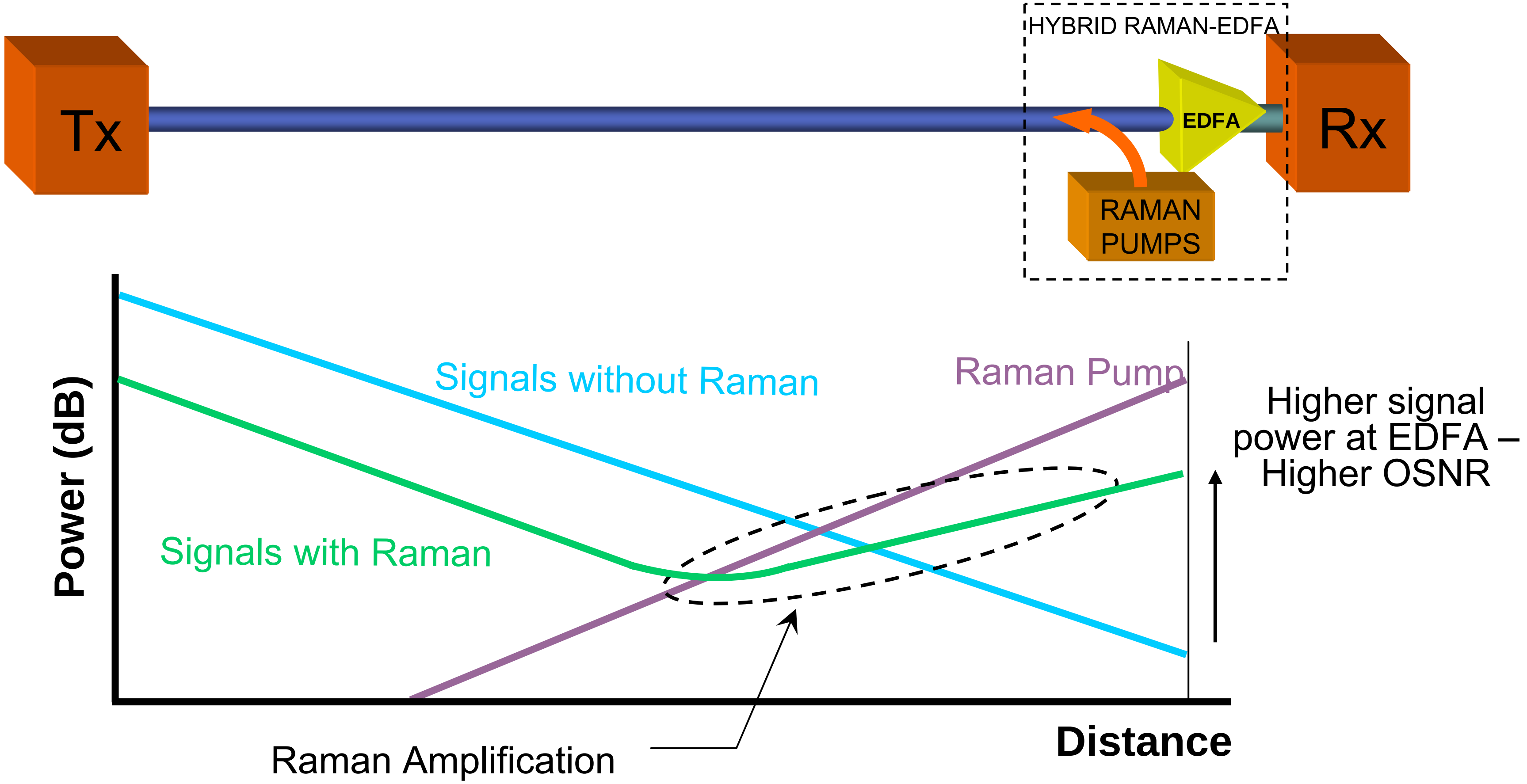
$$G_R = \exp\left[\frac{g_R}{A_{eff,Raman}} \frac{P_p(0)}{\alpha_p}\left(1 - e^{-\alpha_p z}\right)\right]$$

Raman Amplification



- Amplification by stimulated Raman scattering became feasible due to progress in semiconductor pumps

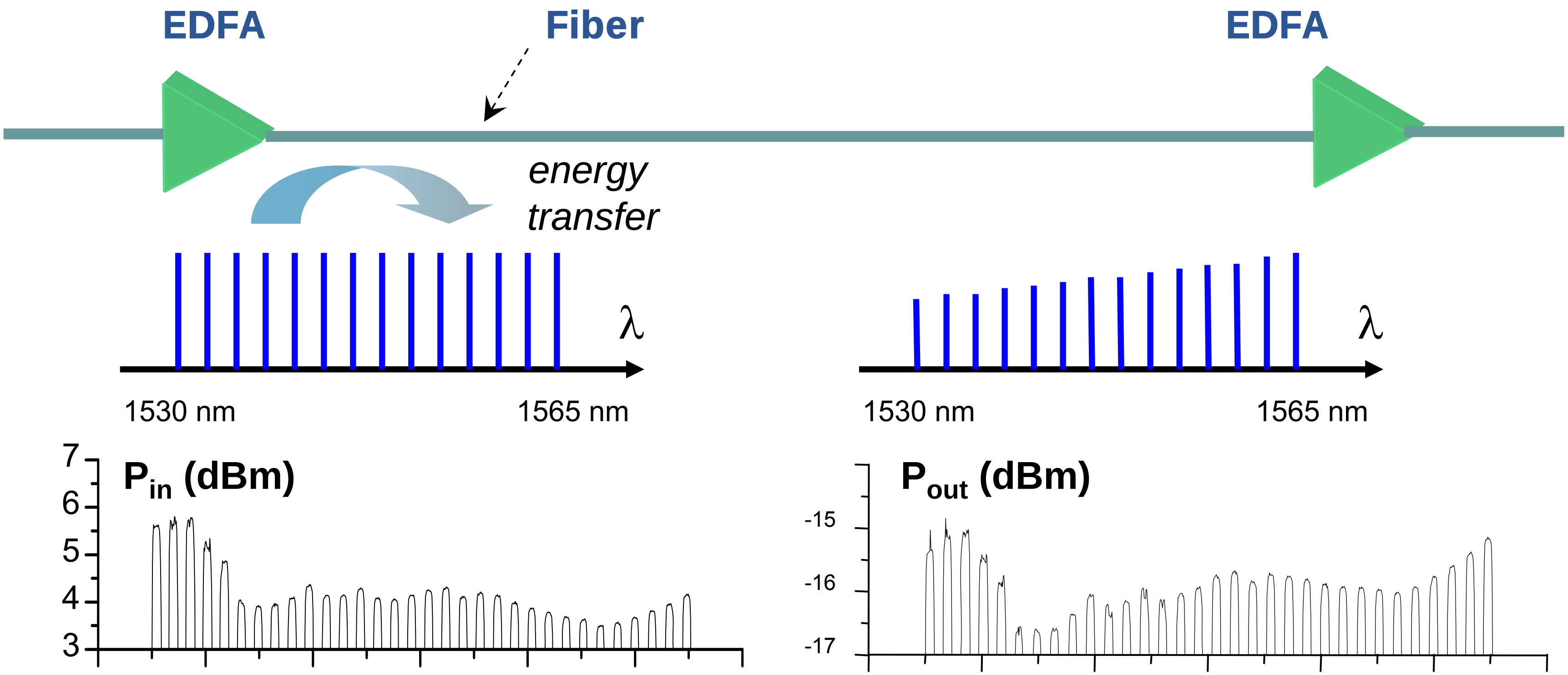
Raman Amplification OSNR Improvement



- Distributed Raman amplification improves OSNR by 3-5 dB

SRS Induced Impairments in WDM Systems

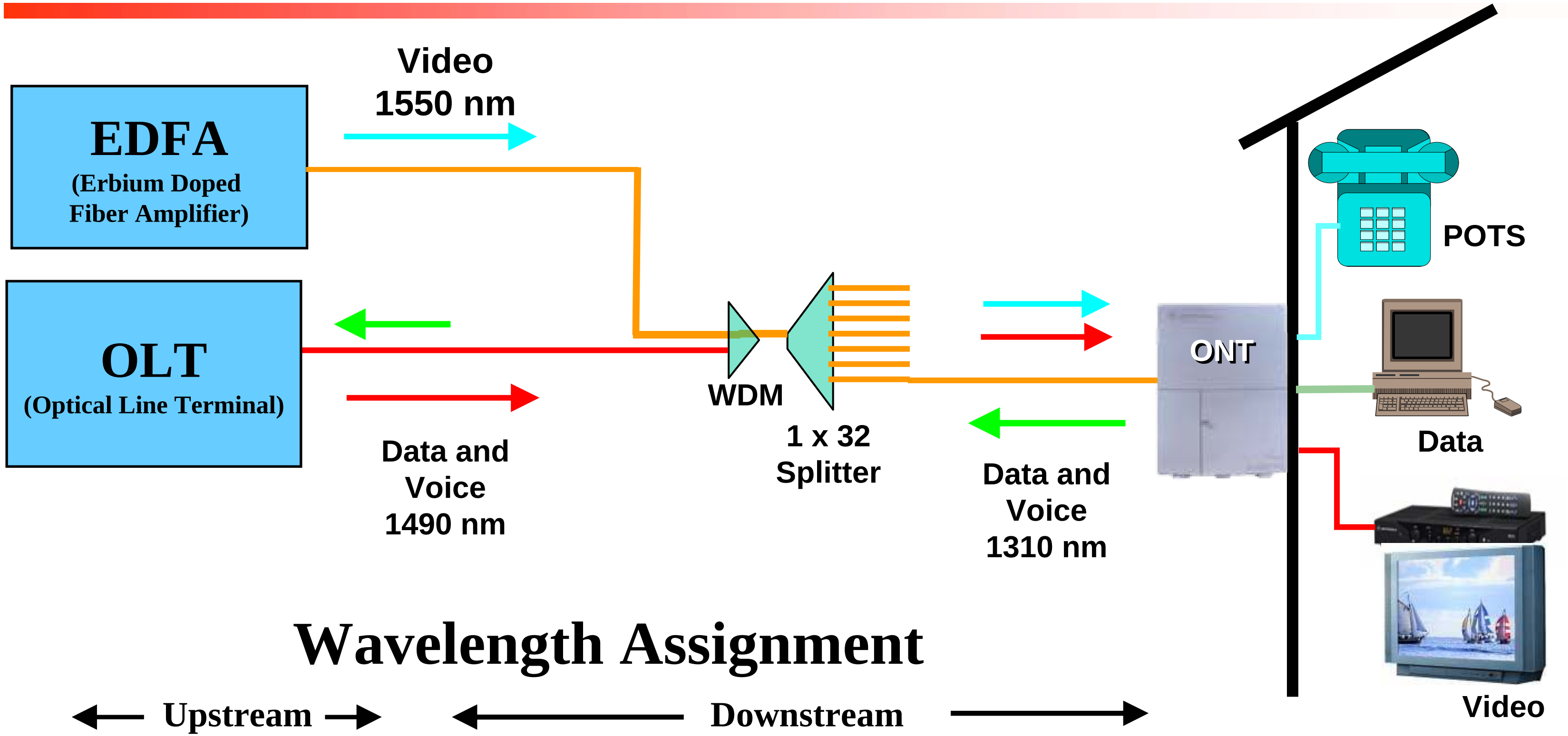
Signal to Signal Interaction (Raman Tilt)



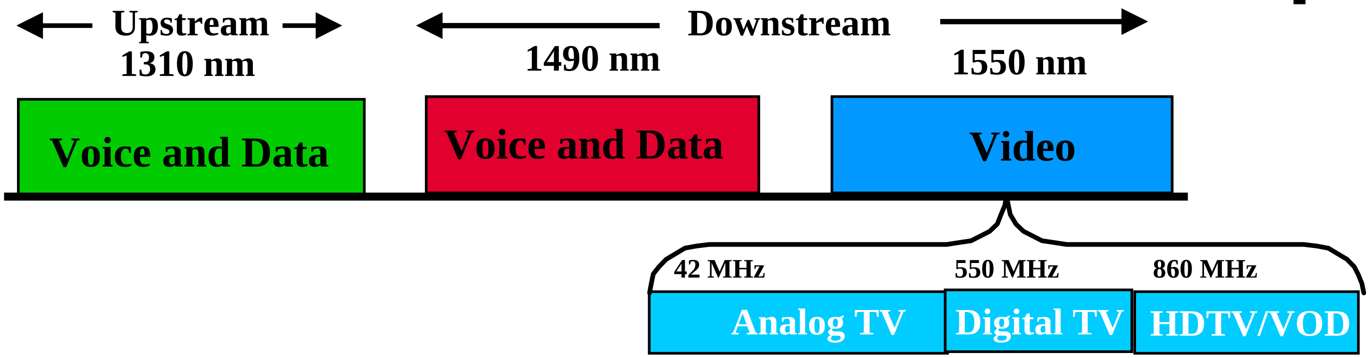
- SRS transfers energy from the signals in the blue part of the WDM spectrum to the signal in the red part as channel
- Appears as a increased “tilt” in fiber attenuation, blue channel experience excessive OSNR loss, can be mitigated by pre-emphasis

Raman Crosstalk in PONs (ITU-T G.983/984)

Wavelength Assignment



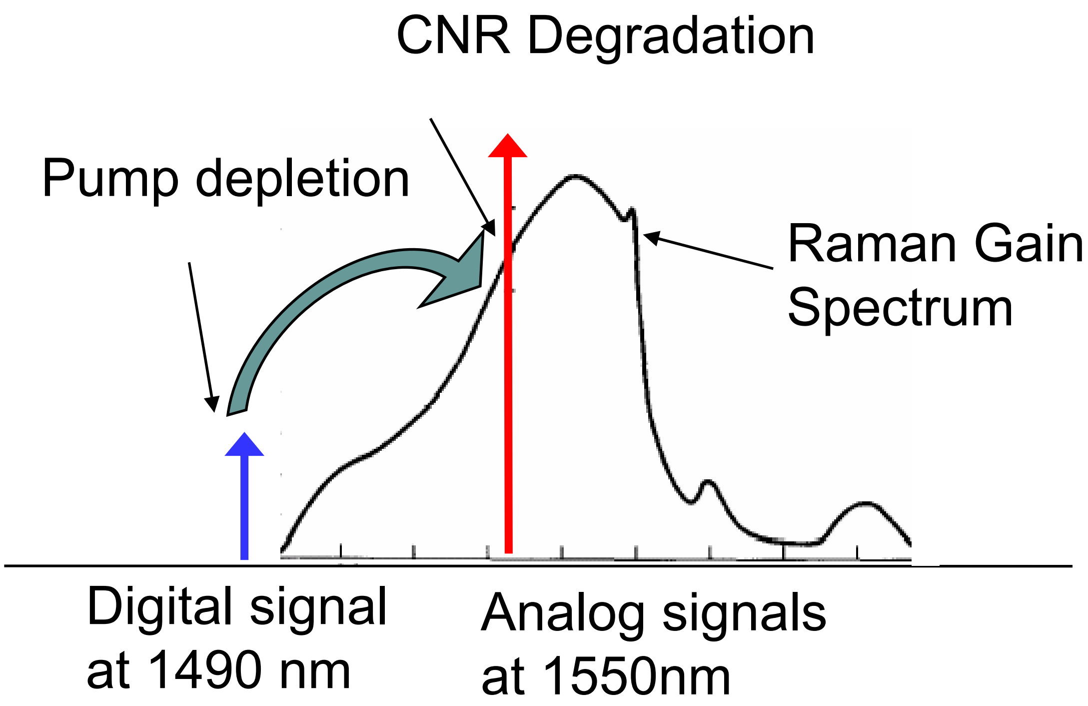
Wavelength Assignment



Raman Interaction

- Low power digital signal acts as Raman pump for high power analog signal

- Raman interaction causes two penalties
  - Power depletion of digital signal
  - CNR degradation of analog signal



Pump depletion: theoretical model

- Use undepleted signal approximation

$$\xcancel{\frac{dP_s}{dz} = C_R P_s P_p - \alpha_s P_s}$$

$$\frac{dP_p}{dz} = -\frac{\lambda_s}{\lambda_p} C_R P_s P_p - \alpha_p P_p$$

Extra loss due to Raman effect

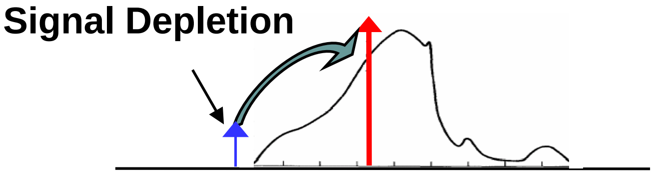
$$P_p(z) = P_{p0} \exp\left[-\frac{\lambda_s}{\lambda_p} C_R \frac{P_s(0)}{\alpha_s}\left(1 - e^{-\alpha_s z}\right) - \alpha_p z \right]$$

- Average power penalty

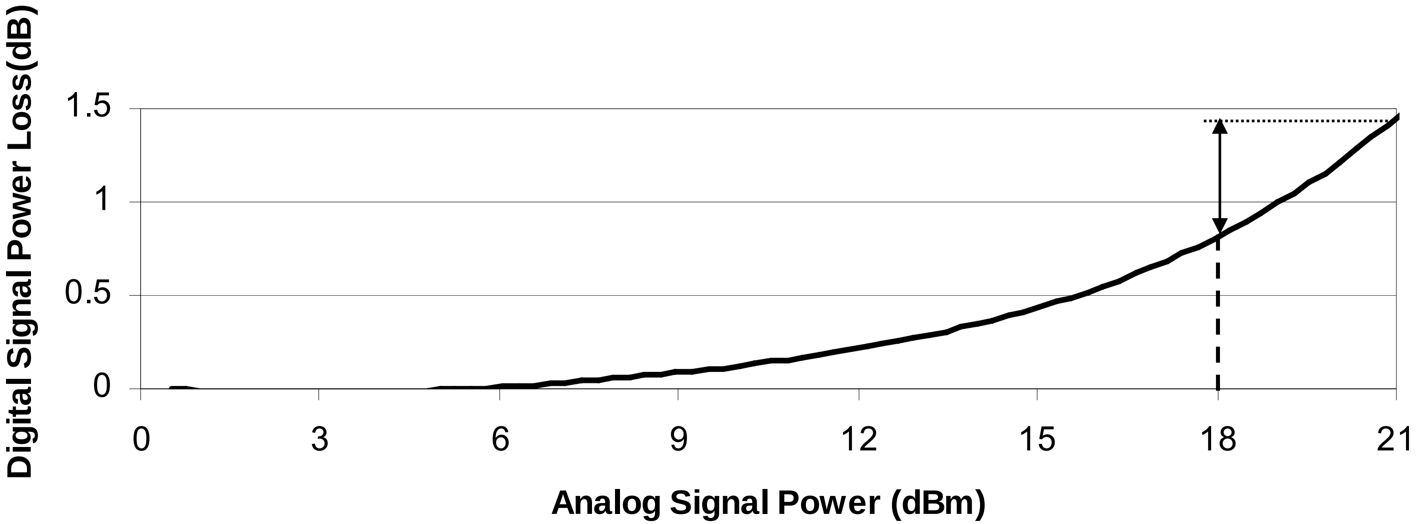
$$\kappa = (10 \log_{10} e) \lambda_s / \lambda_p$$

$$\Delta_{\mathrm{dB}} = \kappa C_R P_s L_{eff}$$

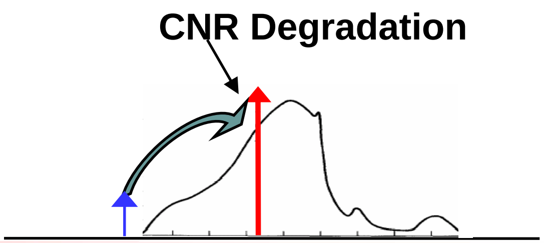
$$L_{eff} = (1 - e^{-\alpha_s L}) / \alpha_s$$



Digital Signal Depletion

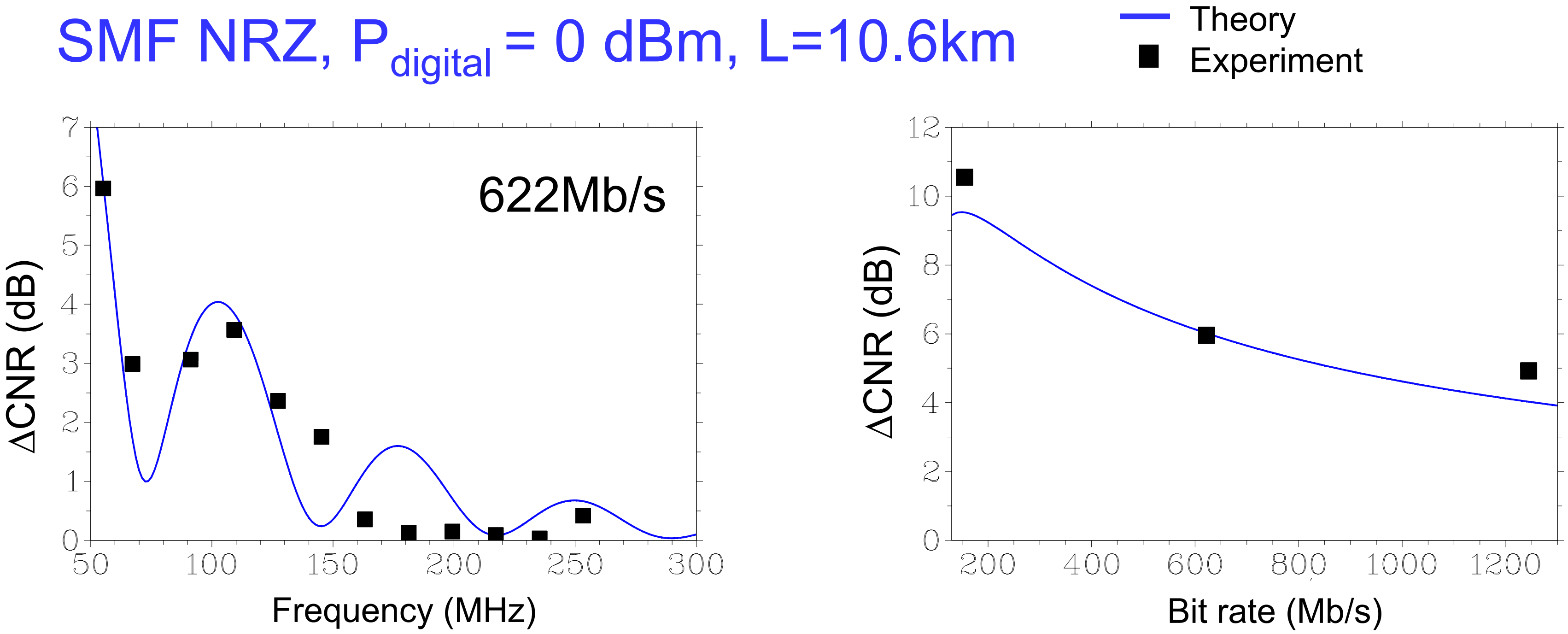


- Digital signal suffers from loss of power as the analog signal power is increased
- Effect occurs at current launched analog power levels (~18 dBm) and gets worse at stronger power levels
- Overcome by launching higher power digital signal



CNR degradation

SMF NRZ, $P_{digital}$ = 0 dBm, L=10.6km



- CNR penalty decreases with subcarrier frequency and bit rate
- Mitigated by pre-emphasis of subcarriers and higher bit rates

Summary: Raman Cross-Talk Penalties

- Raman amplifier based on SRS is employed in LH system to boost OSNR and extend the system reach

- SRS between individual channels in WDM systems results in "Raman tilt" that results in higher effective attenuation for short wavelength channel

- SRS can be impairment in PON systems
  - Depletion of 1490 nm digital signal in the presence of strong analog 1550 nm signal

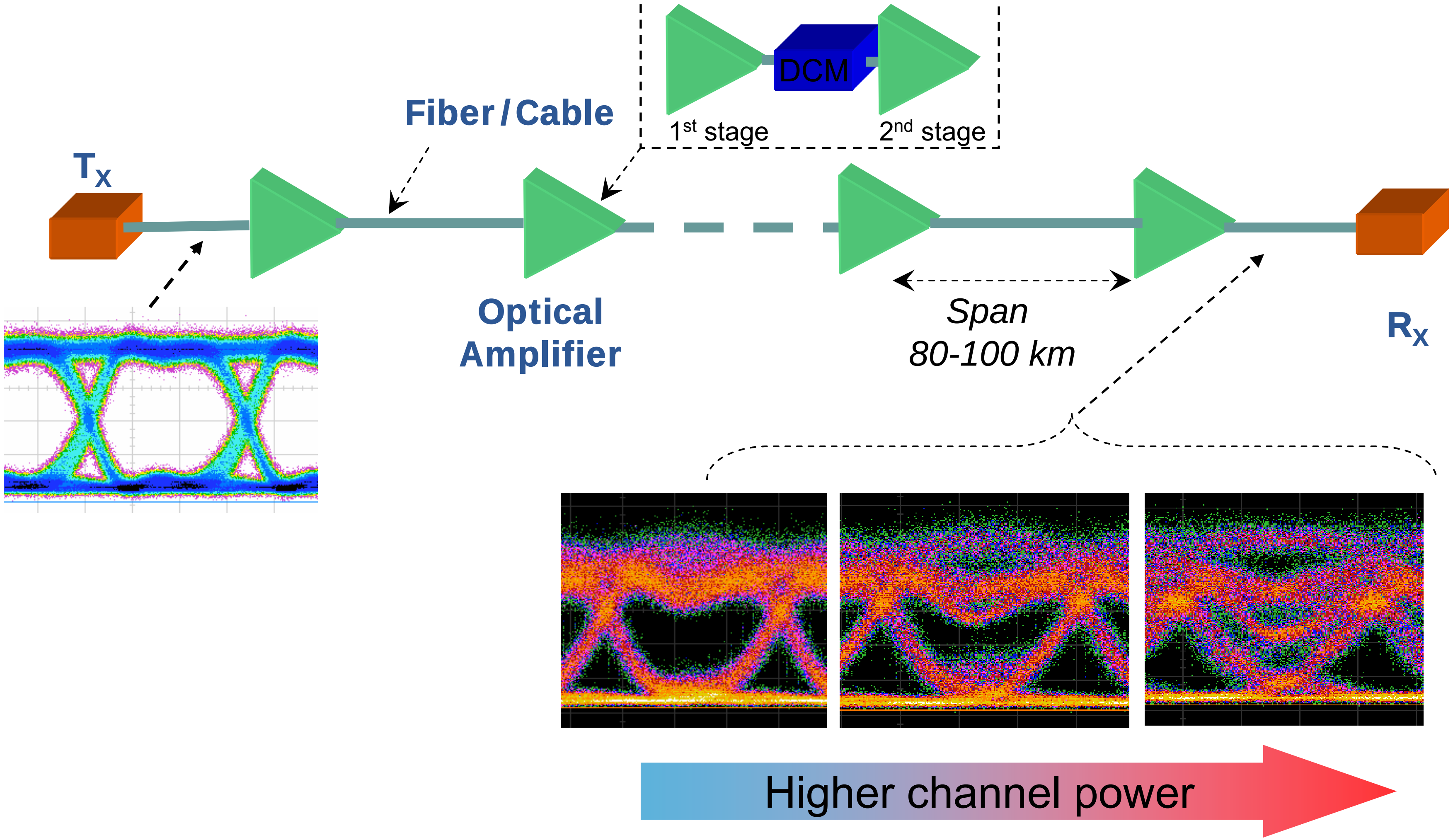
  - CNR degradation of analog signal due to transfer of power variations from digital signal

Self Phase Modulation (SPM)

Cross Phase Modulation (XPM)

Self-phase modulation (SPM)

Experimental observation



DCM

1st stage

2nd stage

Fiber / Cable

T_X

Optical Amplifier

Span 80-100 km

R_X

Higher channel power

Theoretical Description

Nonlinear Phase Shift

- Rigorous pulse propagation and SPM penalty calculation must be done by solving nonlinear Shrödinger equation

$$\frac{\partial E}{\partial z}+\frac{1}{2}\alpha E+\frac{i}{2}\beta_2\frac{\partial^2 E}{\partial \tau^2}-i\gamma E\left|E\right|^2=0$$

$$\gamma=\frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}$$

$$\beta_2=-\frac{\lambda^2}{2\pi c}D$$

- SPM penalty becomes significant when nonlinear phase ϕ_{NL} becomes comparable to π

$$\phi_{NL}=\int_0^L \gamma_{NL}(z)P(z)dz=\frac{2\pi}{\lambda}\int_0^L\frac{n_2(z)}{A_{eff}(z)}P_{in}(z)dz$$

Self Phase Modulation (SPM) as *combined* effect of nonlinearity and dispersion

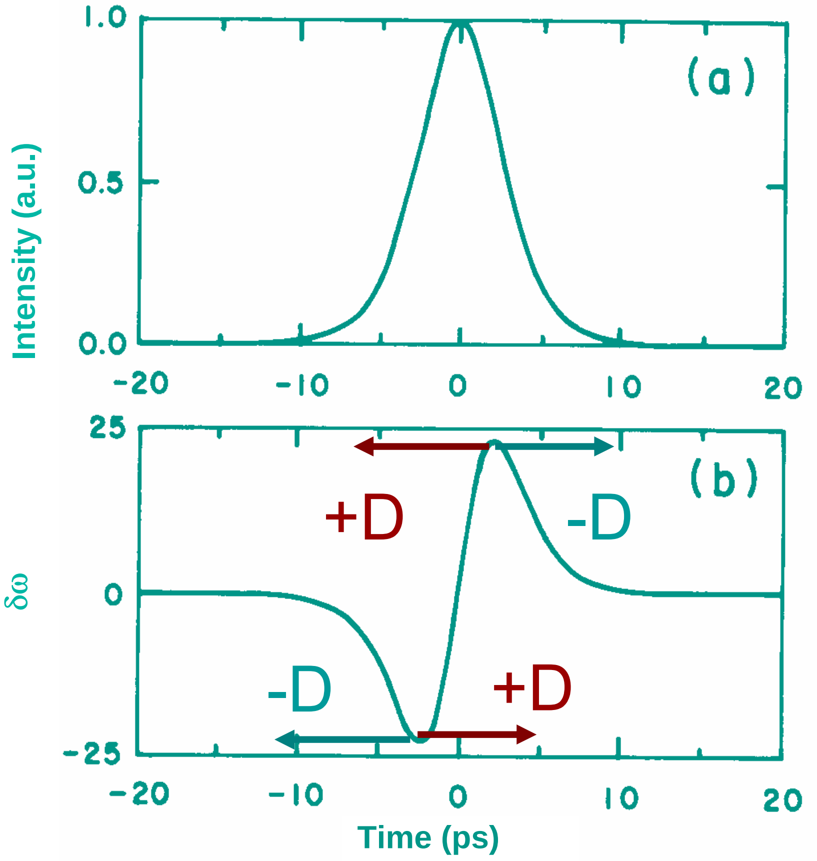
Step 1: Phase distortion

Nonlinearity creates phase modulation

$$\Delta\Phi(t) = \frac{2\pi}{\lambda} L_{eff} \frac{n_2}{A_{eff}} P$$

Step 2: Conversion to AM

Dispersion converts phase modulation in amplitude modulation

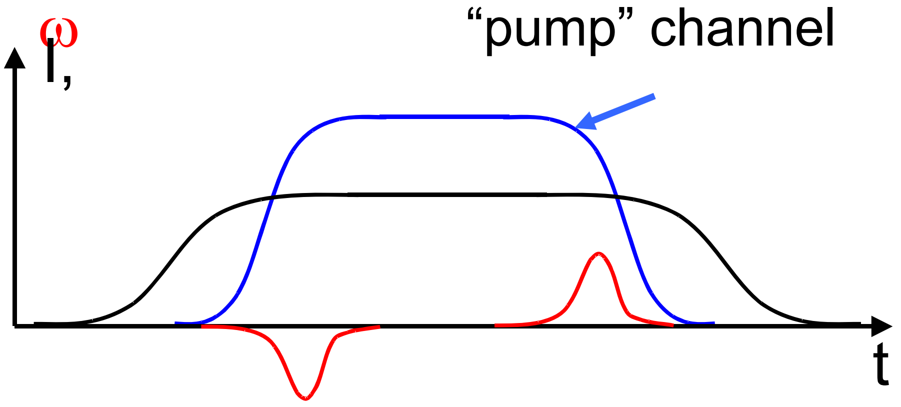


from G.P. Agrawal, Nonlinear Fiber Optics

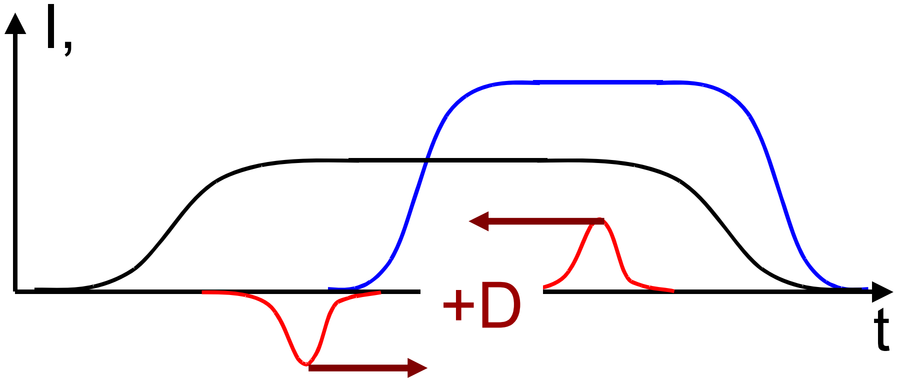
- SPM and linear dispersion can pull pulse apart (in –D fibers) or compensate linear broadening (in +D fibers) leading to a formation of *classical soliton*

Cross Phase Modulation (XPM)

Step 1: Phase distortion



Step 2: Conversion to AM



$$\Delta\Phi(t) = \frac{2\pi}{\lambda} L_{eff} \frac{n_2}{A_{eff}} 2P(t)$$

$$\omega(t) = -\frac{\partial \Delta\Phi(t)}{\partial t} = -\frac{2\pi}{\lambda} L_{eff} \frac{n_2}{A_{eff}} 2 \frac{\partial P(t)}{\partial t}$$

- XPM is similar to SPM except the fact that phase distortion is created by adjacent channels

Four Wave Mixing

(FWM)

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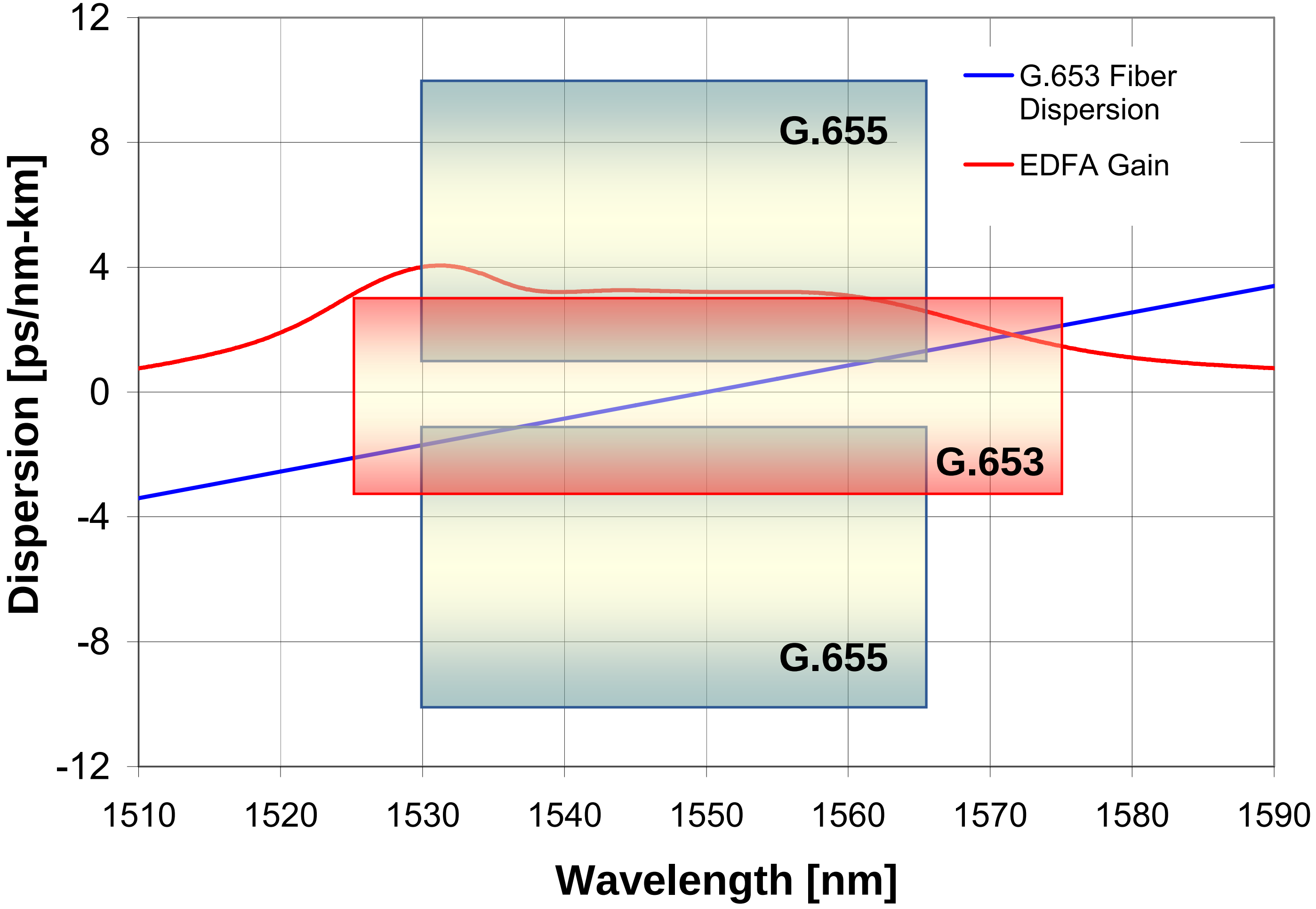
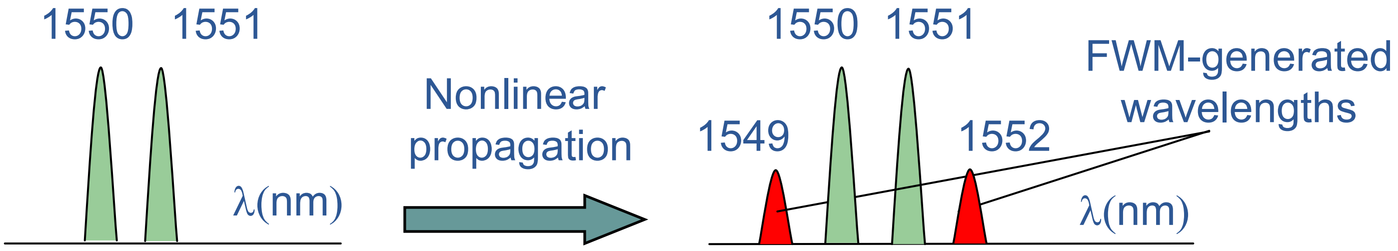
G.653 and G.655 Fiber Types



Four-Wave-Mixing (FWM)

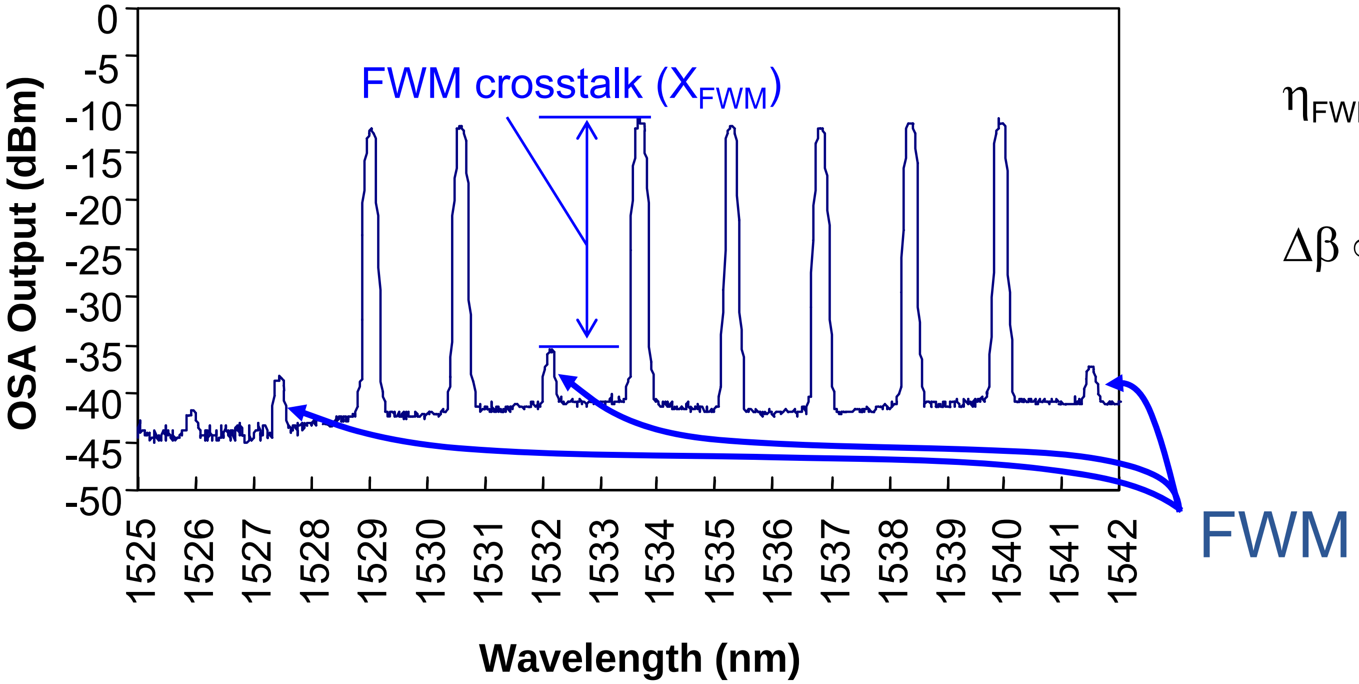
Experimental Observation



$$X_{FWM} \propto \left(\frac{2\pi n_2}{\lambda A_{eff}} P\right)^2 \eta_{FWM}$$

$$\eta_{FWM} = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}$$

$$\Delta\beta \propto \frac{\lambda^2}{c}(\Delta f)^2 D(\lambda)$$



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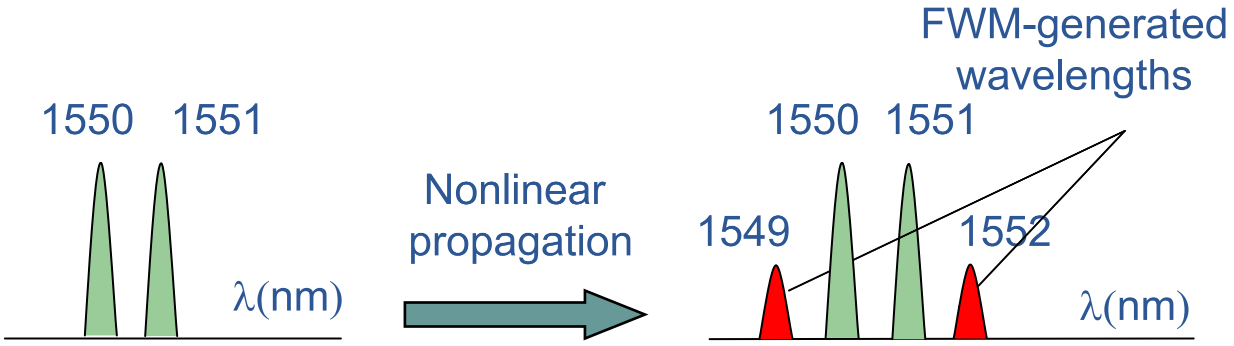
Four-Wave-Mixing (FWM)

Dependencies on Fiber/System Parameters



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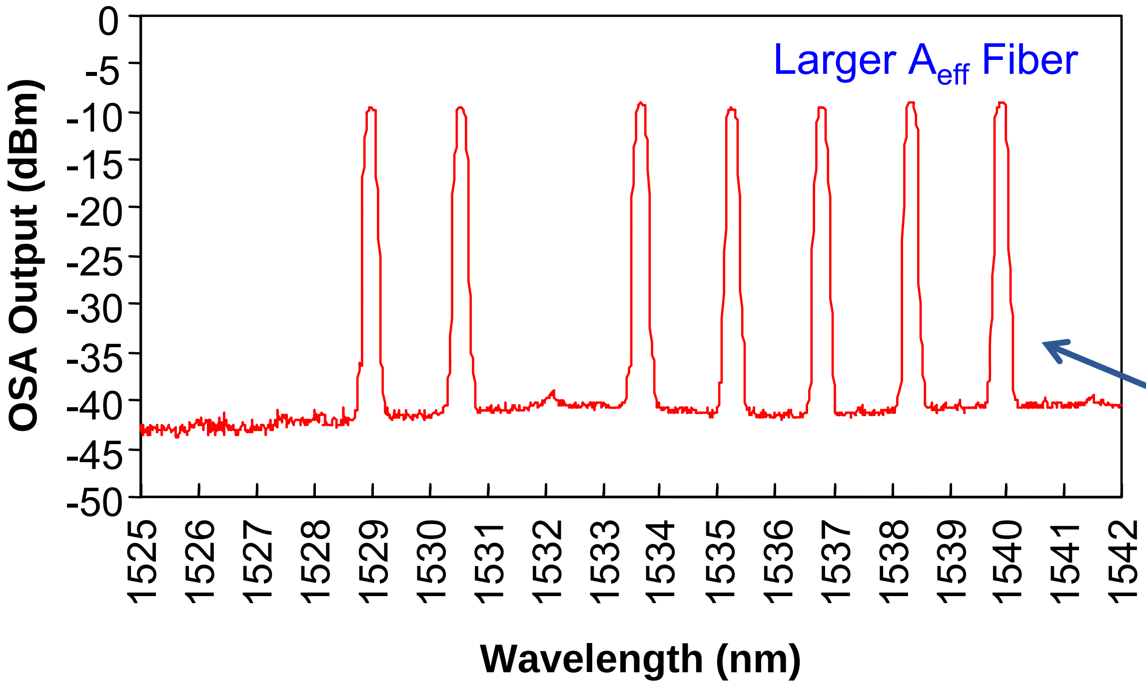
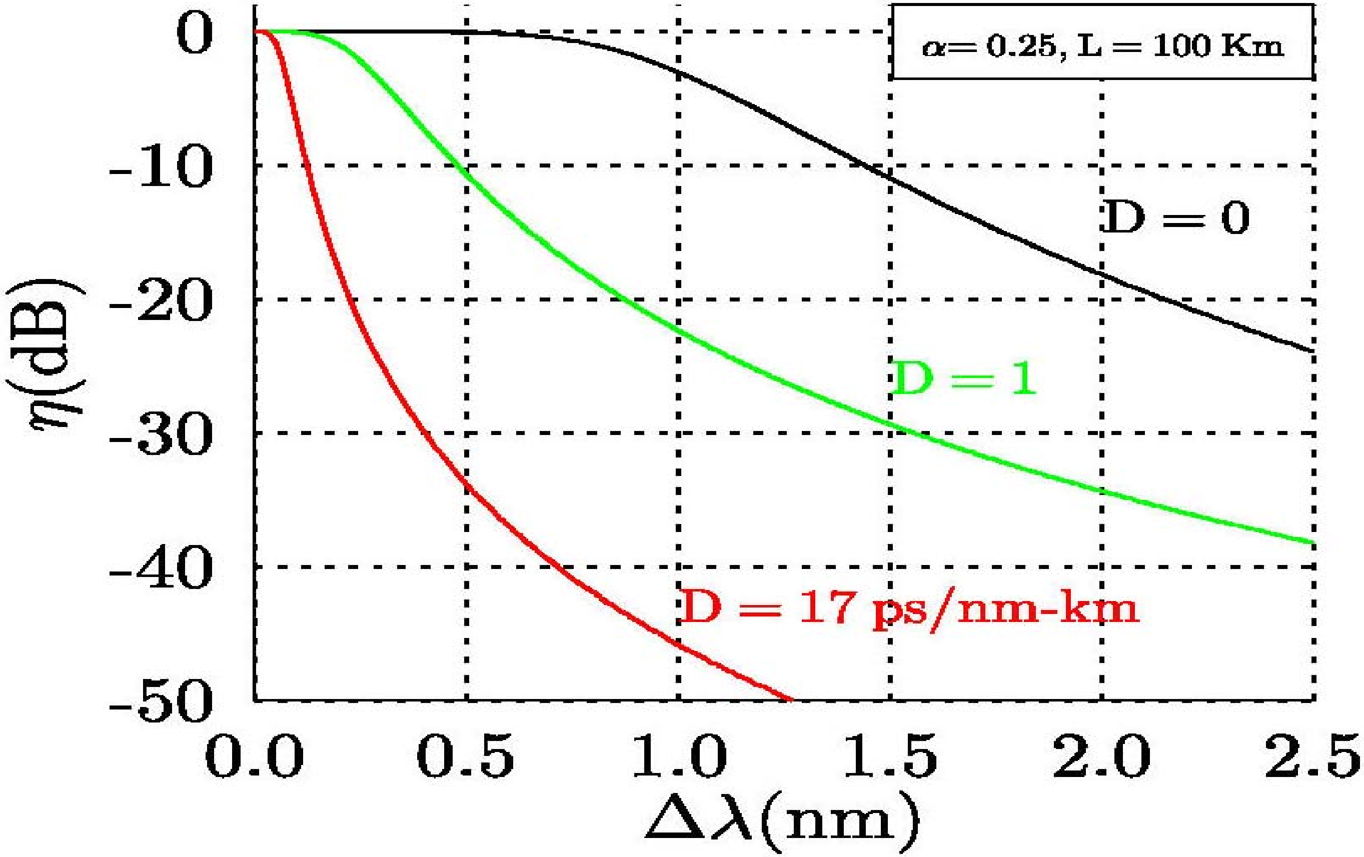


- X_{FWM} increases P_{ch}^2
- X_{FWM} decreases as 4th power of channel spacing
- X_{FWM} decreases quadratically with dispersion and A_{eff}

FWM Efficiency as a function of Dispersion and Channel Spacing



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Stimulated Brillouin Scattering	PON	Limits launched optical power, increases noise. Impairs video signal through CNR, CSO and CTB degradation
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Thank you!

Questions?

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