VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Raman, Brillouin and Rayleigh scattering

Fiber 4

Developed in cooperation with
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Communications lab – RF engineering

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Module Prerequisites

- **Fiber 1: Basics of Fiber Propagation**

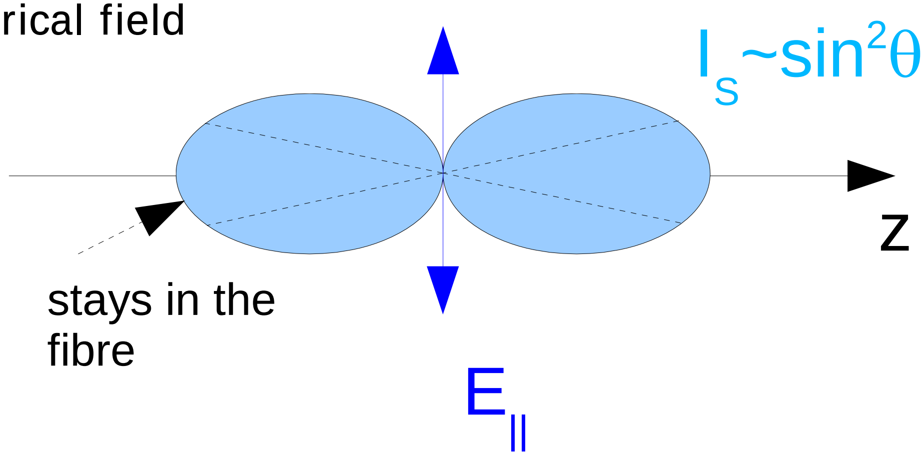
Module Objectives

- Rayleigh scattering
- Nonlinear effects in optical fibers
- Raman scattering
- Brillouin scattering
- Conclusion

Rayleigh scattering

Rayleigh scattering

- Optical field interacts with non-propagating density fluctuations in the fiber:
  - Microscopic defects in the amorphous structure of glass ($d \ll \lambda$)
    - Scattering of light ($P_r \sim \lambda^{-4}$)
      - Fiber attenuation (approx. 0.12 dB/km for SSMF @ 1550 nm)
      - Characterized by the fiber parameter: Rayleigh backscattering coefficient (-82 dB for SSMF @ 1550 nm and 1 ns pulse width)
    - Rayleigh scattering can be modeled as a radiating dipole
      - Radiation is rotationally symmetric to the polarization of the electrical field



Applications and System considerations

Applications:

- Optical Time Domain Reflectometry (OTDR)
- Sensing

System considerations:

- Rayleigh scattering can degrade system performance of a fiber optical transmission system
  - Converts the phase noise of the source into amplitude noise at the receiver
  - Two possible system constellations:
    - Back scattered light in bidirectional optical links
    - Double back scattered light in unidirectional link
  - Ghost pulses in loop configurations

Nonlinear effects in optical fibers

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Nonlinear effects

Stimulated scattering

Stimulated Raman Scattering (SRS)

Stimulated Brillouin Scattering (SBS)

- Above threshold power
- Can be used for optical amplification

Optical Kerr effect

changes refractive index in the fiber

Self Phase Modulation (SPM)

Cross Phase Modulation (XPM)

Four Wave Mixing (FWM)

Covered in more detail in lecture “Fiber 2“

Nonlinear effects

- dependencies
  - Material
  - Field distribution inside waveguide → power density

- nonlinear coefficient γ

  n_2: nonlinear-index coefficient

  A_{eff}: effective core Area

$$\gamma = \frac{k_0 n_2}{A_{eff}}$$

Common values for different fiber types:

Parameter/Fiber Type	SSMF	DSF	DCF
γ / W^{-1} km^{-1}	1,2	1,76	8,3

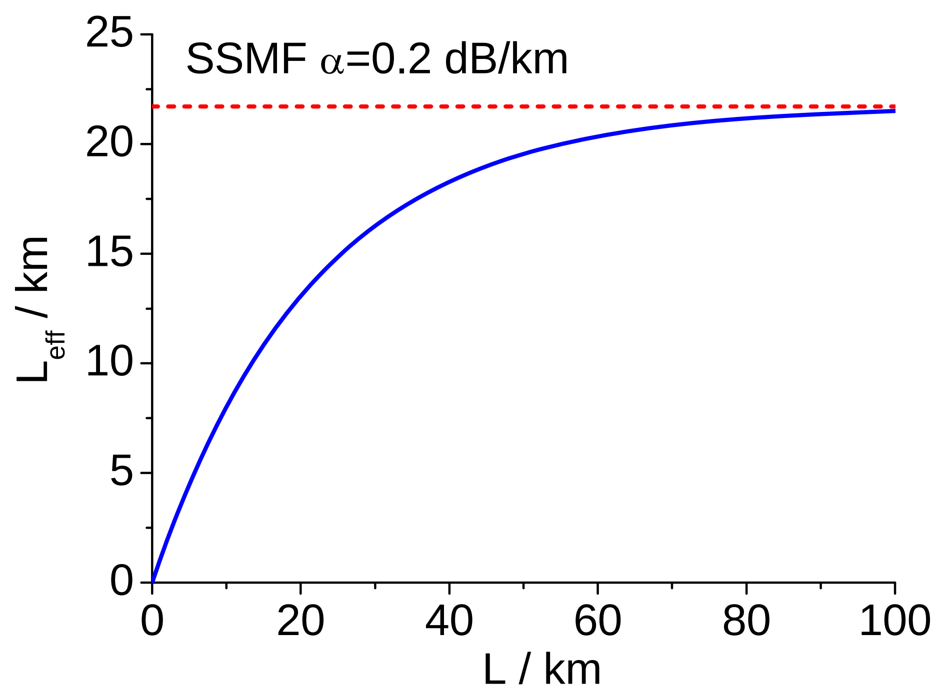
Nonlinear effects

- Effective length L_{eff}

$$L_{eff} = \frac{1-e^{-\alpha' L}}{\alpha'},$$

$$\alpha'[km^{-1}] = \ln\left(10^{\frac{\alpha[dB/km]}{10}}\right),$$

$$\lim_{L\to\infty} L_{eff} = \frac{1}{\alpha'}$$



- A fiber without attenuation and an effective length of L_{eff} has the same nonlinear behavior as a fiber with attenuation a and length of L

Nonlinear effects

- Effective core Area:
  - "Reciprocal" overlap integral for the considered mode of the fiber

$$A_{eff} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |F(x,y)|^2 \, dxdy \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |F(x,y)|^2 \, dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |F(x,y)|^2 |F(x,y)|^2 dxdy}$$

  - *F(x,y)* fiber mode field distribution
  - Common values for different fiber types:

Parameter/Fiber Type	SSMF	DSF	DCF
A_{eff} / µm²	80	54	21

Raman scattering

Raman scattering

- Spontaneous Raman scattering discovered by Raman → Nobel prize 1930

- Optical field interacts with molecules:
  - Bound electrons oscillate at the frequency of the incident optical light
  - Induced oscillating dipole moment produces optical radiation with same frequency + phase shift

→ phase causes refractive index of the medium

Raman scattering

- Molecular structure oscillates at various frequencies of molecular vibrations
  - Oscillation due to optical field contains sum and difference frequency terms between optical frequencies and vibrational frequencies
  - Sum and difference terms ➔ **Raman scattered light**

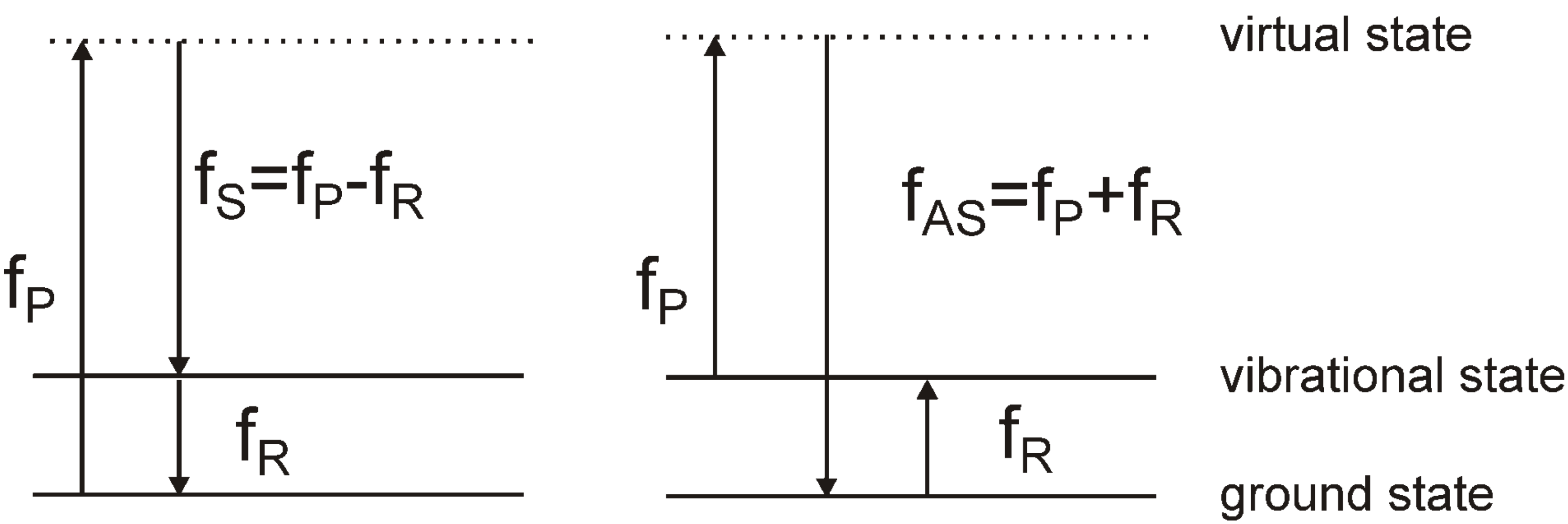
- Inelastic scattering (energy transfer from/to lattice)
  - **Optical Phonons are used to quantify loss/gain**
  - Photon energy is lost → lattice is heated
  - Photon energy is gained → lattice is cooled

Stimulated Raman scattering
Stokes, Anti-Stokes

- Scattered light shifted to lower frequencies
  → Stokes lines
- Scattered light shifted to higher frequencies
  → Anti-Stokes lines

- Anti-Stokes: orders of magnitude weaker than Stokes
  → not relevant for communications applications

Stimulated Raman scattering Stokes, Anti-Stokes



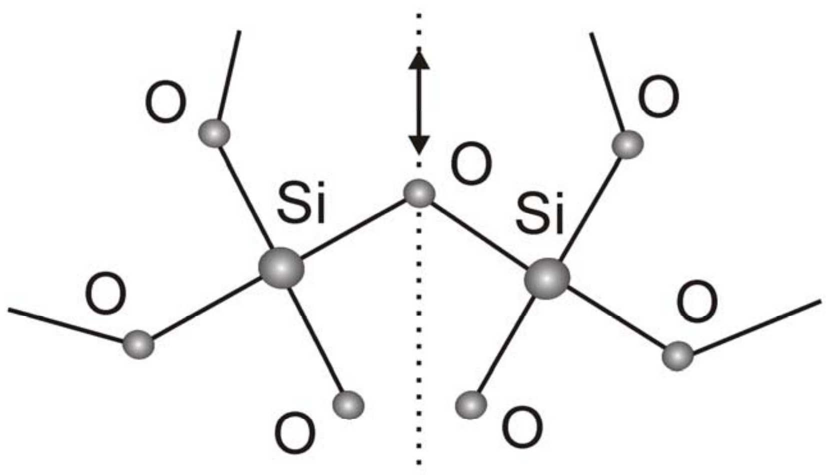
Stokes-wave generation

Anti-Stokes-wave generation

Stimulated Raman scattering (Anti-)Stokes frequency shift

- Frequency shift is determined by the frequency of the lattice phonon

- Silica glass:
  dominant Raman line due to bending motion of Si-O-Si bond



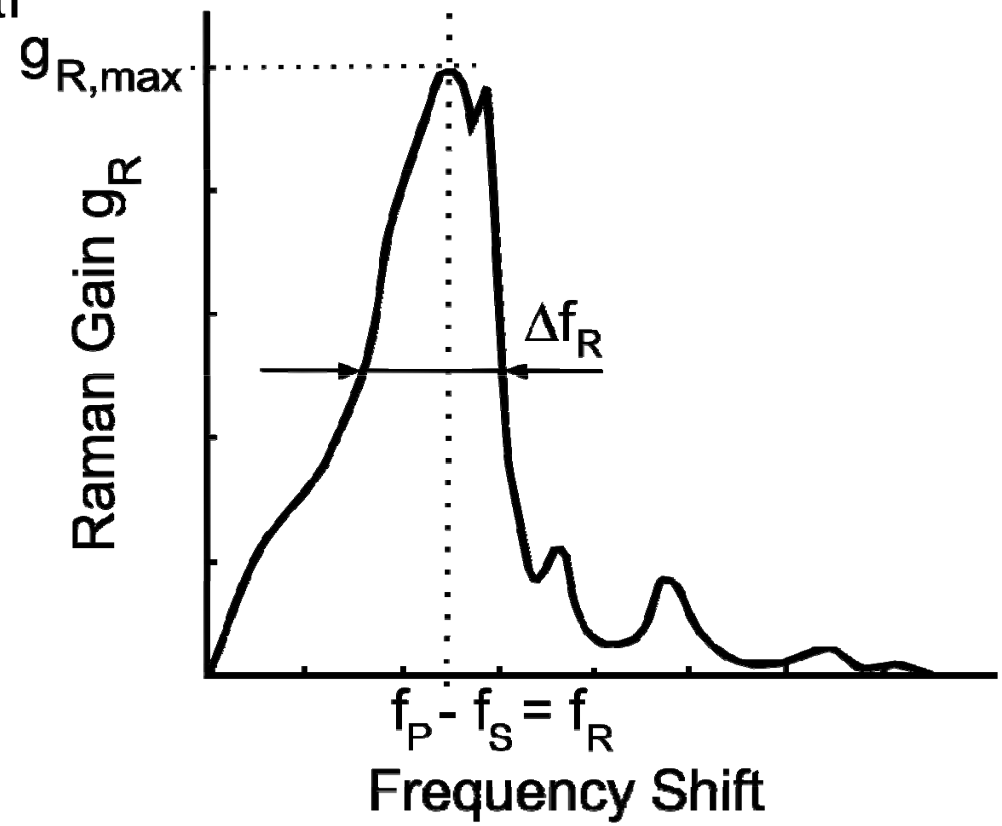
Stimulated Raman scattering

- Stimulation by pump with appropriate frequency shift with respect to signal light (determined by material)
  ➔ **amplification**

- Pump and signal are coherently coupled by Raman process

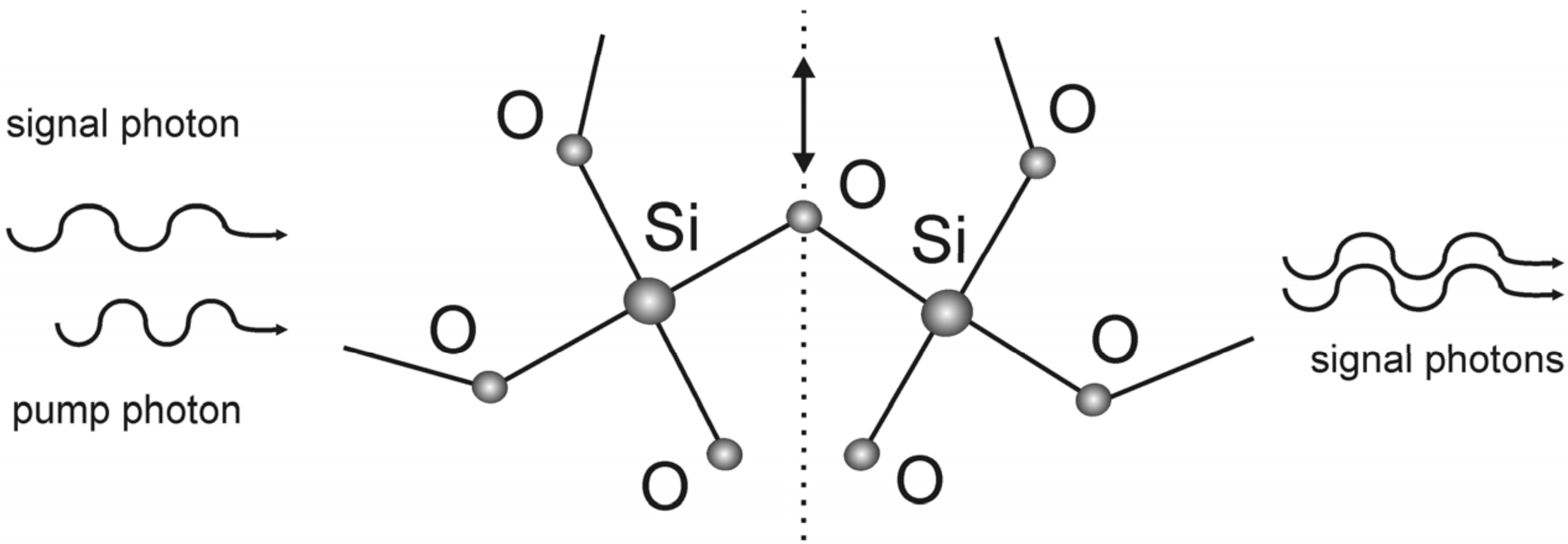
Stimulated Raman scattering

- Raman gain g_R is determined by frequency separation between pump and signal
  - Silica fibers:
    - g_R=1x10^{-13} m/W
    - f_R=13 THz, Δf_R=6 THz
    - @ λ=1 µm
  - SSMF:
    - g_R=3.1x10^{-14} m/W
    - @ λ=1.55 µm



Values from: T. Schneider, **Nonlinear Optics in Telecommunications**, Springer-Verlag Berlin, 2004
W. Glaser, **Photonik für Ingenieure,** Verlag Technik Berlin, 1997

Stimulated Raman scattering



- Inelastic scattering (energy transfer from / to lattice)
  - Photon energy is lost (pump photon) → lattice is heated, bending motion of Si-O-Si bonds
  - Photon energy is gained (signal photon) → lattice is cooled

Stimulated Raman scattering

- SRS is non-resonant
  - Upper state is virtual
    - No long upper-state lifetimes
    - No buffering effect for pump fluctuations but averaging over fiber length (several kms for efficiency reasons) possible
  - Fast process: sub-picosecond
- Polarization dependent
  - Peak coupling strength is an order of magnitude stronger when co-polarized than if orthogonally polarized
- Application → Raman amplifiers

Applications

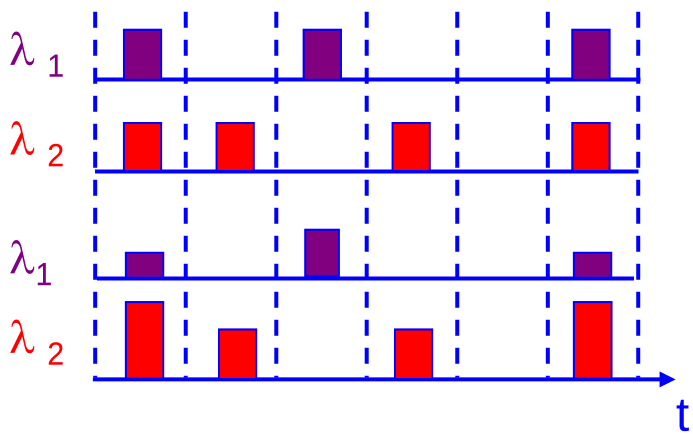
- Stimulated Raman Scattering
  - Raman lasers
  - Raman amplifiers

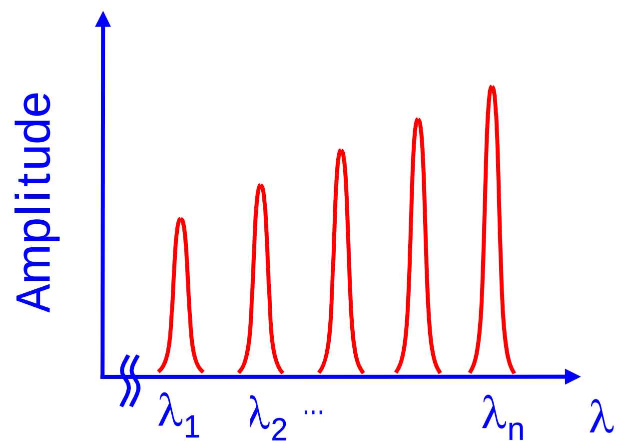
- Spontaneous Raman Scattering
  - Raman spectroscopy
    (sometimes also using Stimulated Raman Scattering)

System considerations
Raman tilt

- Amplification of higher wavelength channels at the expense of lower wavelength channels due to Raman scattering
- **Time domain:** amplification or attenuation of single bits

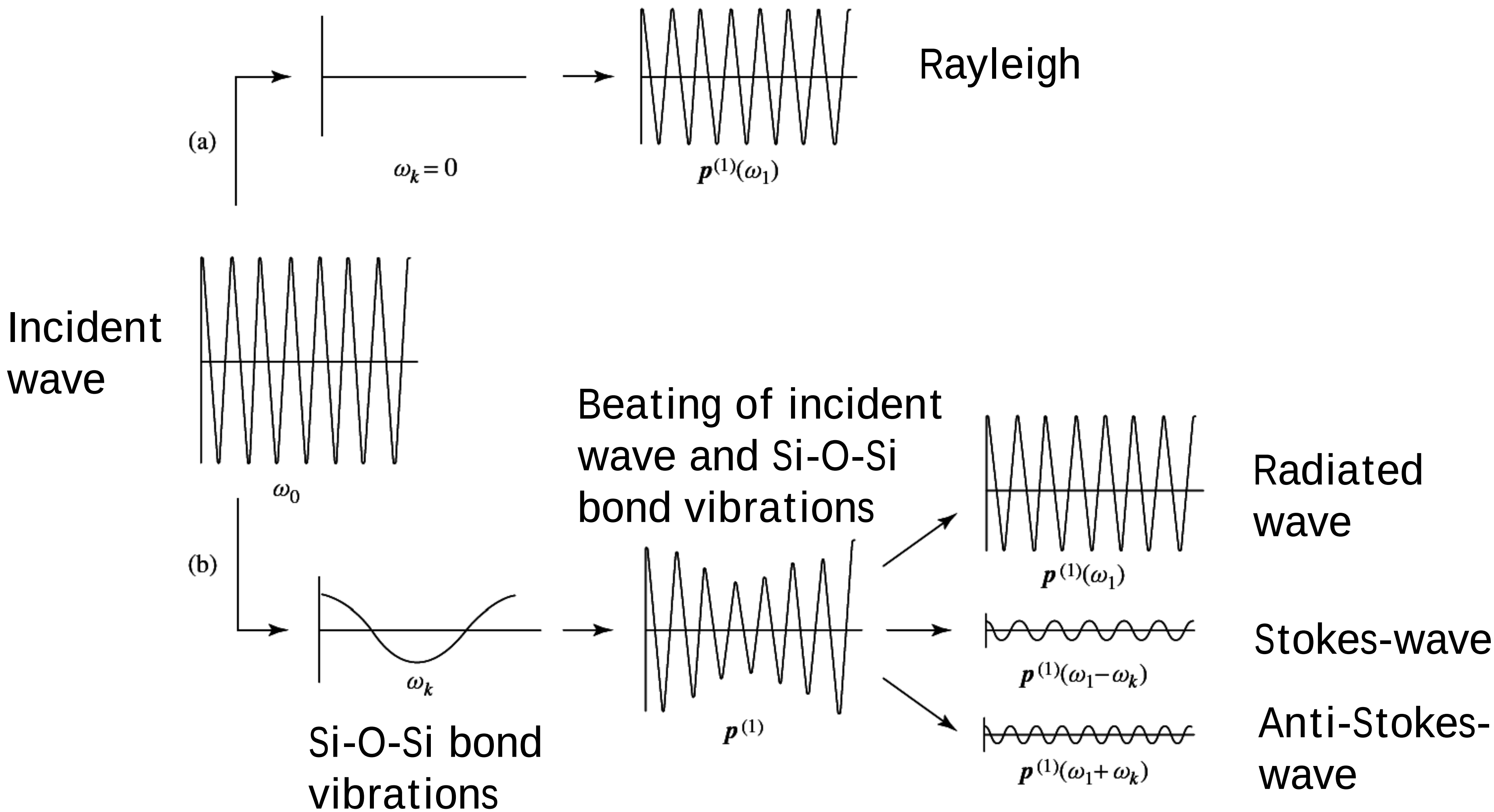
  Frequency domain: tilted WDM spectrum





References: T. Schneider, **Nonlinear Optics in Telecommunications**, Springer-Verlag Berlin, 2004
G.P. Agrawal, **Nonlinear Fiber Optics**, Academic Press, 2007
J. Bromage, **Raman Amplification for Fiber Communications Systems**, JLT, 2004

Raman and Rayleigh – a wave approach



Reference: Giordano Bruno, **Classical Theory of Rayleigh and Raman Scattering**

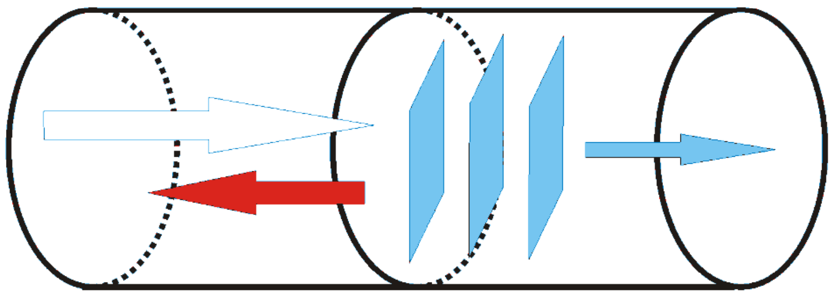
Brillouin scattering

Brillouin scattering

- Brillouin scattering discovered by Léon Brillouin
- Optical field interacts with propagating density fluctuations in the fiber:
  - Thermal fluctuations of fiber density due to thermo-elastic motions of the molecules
  - Density fluctuations can be regarded as acoustic waves
    - Travel through the fiber at the speed of sound
  - Results in modulation of the refractive index of the fiber

➔ **Scattering of light on the resulting refractive index grating**

Brillouin scattering

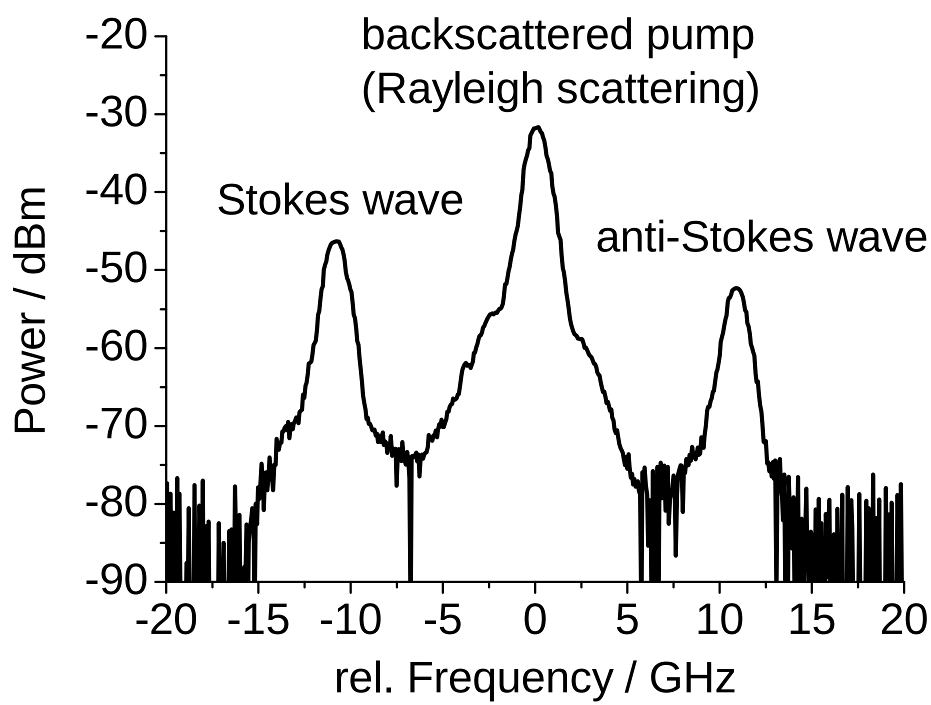


- Frequency shift of the back scattered wave for
  - Pump wavelength λ_P = 1550 nm
  - Refractive index n = 1.45
  - Sound velocity υ_a = 5.96 km/s

$$f_B = \frac{2\upsilon_a n}{\lambda_P} = 11.15\ \text{GHz}$$

Brillouin scattering
Stokes, Anti-Stokes

- Down shifted → Stokes wave
  - $f_S=f_P-f_B$
  - Acoustic wave propagates in the direction of the incident wave
- Up shifted → anti-Stokes wave
  - $f_S=f_P+f_B$
  - Acoustic wave propagates in the opposite direction of the incident wave



Brillouin scattering

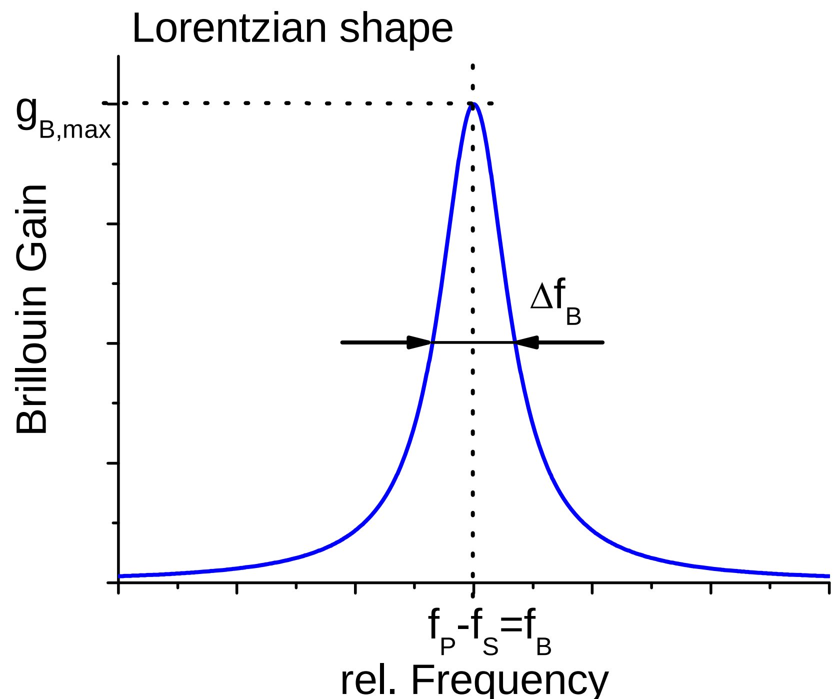
Brillouin gain:

- Lorentzian shape
  (low gain region)

$$g_B(f) = \frac{1}{1+\left[(f - f_B)/(\Delta f_B/2)\right]^2} g_{B,\max}$$

- Gaussian shape
  (high gain region)

$$g_B(f) = g_{B,\max} e^{-\ln(2)\frac{(f-f_B)^2}{(\Delta f_B/2)^2}}$$



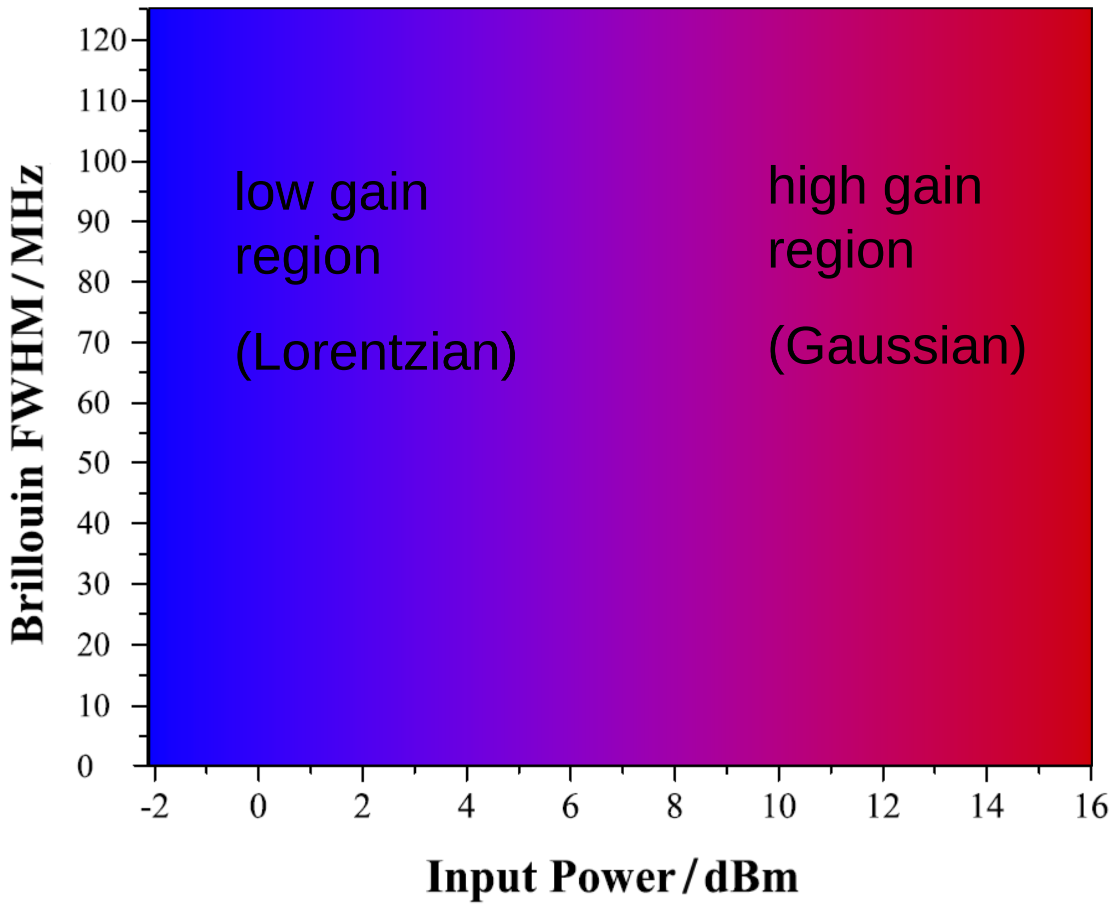
SSMF:

- λ = 1.55 µm
- Δf_B=35 MHz
- $g_B=2\times10^{-11}$ m/W
- $f_B=f_P-f_S$=11.15 GHz

Values from: T. Schneider, **Nonlinear Optics in Telecommunications**, Springer-Verlag Berlin, 2004

• Full width half maximum (FWHM) depends on the pump power

• NZ-DSF fiber



Reference: A. Boh Ruffin, Stimulated Brillouin Scattering: An Overview of Measurements, System Impairments, and Applications

Stimulated Brillouin scattering

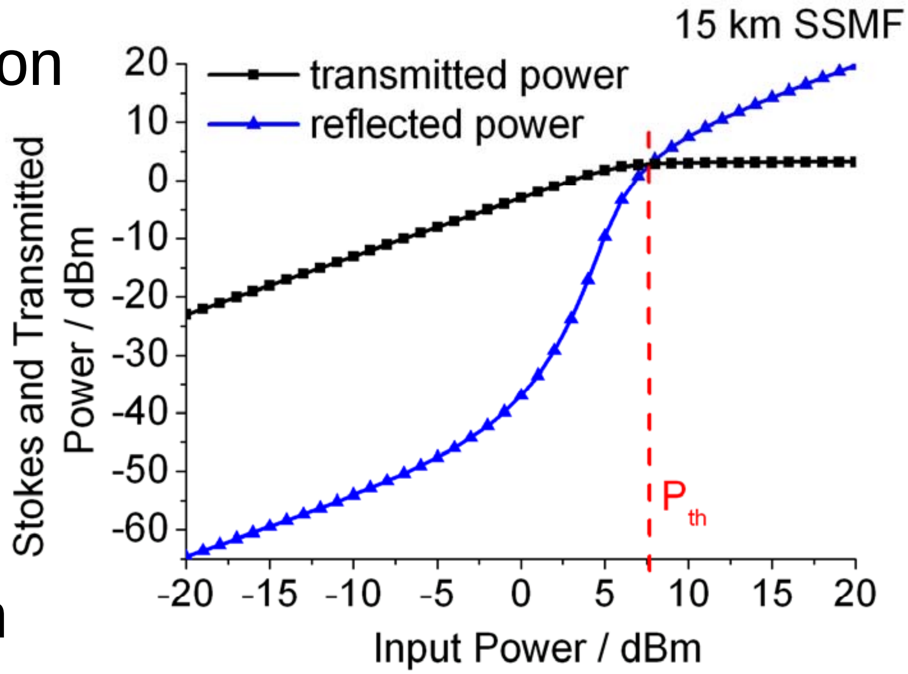
- Superposition between Stokes wave and incident wave (pump wave) leads to a fading with the beating frequency $\Delta f = f_P - f_S = f_B$
- Amplification of the propagating refractive index grating due to electrostriction
- Increase of the scattered Stokes wave power
- Exponential growth of the scattered power → stimulated scattering

Stimulated Brillouin scattering

Threshold power:

- L >> L_{eff}
- Neglected pump depletion

$$P_{th} \approx 21 \frac{K \cdot A_{eff}}{g_B \cdot L_{eff}} \frac{\Delta f_B \otimes \Delta f_P}{\Delta f_B}$$



- K – polarization adjustment factor
- Convolution ⊗ between the pulses

$$\Delta f_B \otimes \Delta f_P = \begin{cases} \sqrt{\Delta f_B^2 + \Delta f_P^2} & \text{Gaussian shape} \\ \Delta f_B + \Delta f_P & \text{Lorentzian shape} \end{cases}$$

Applications

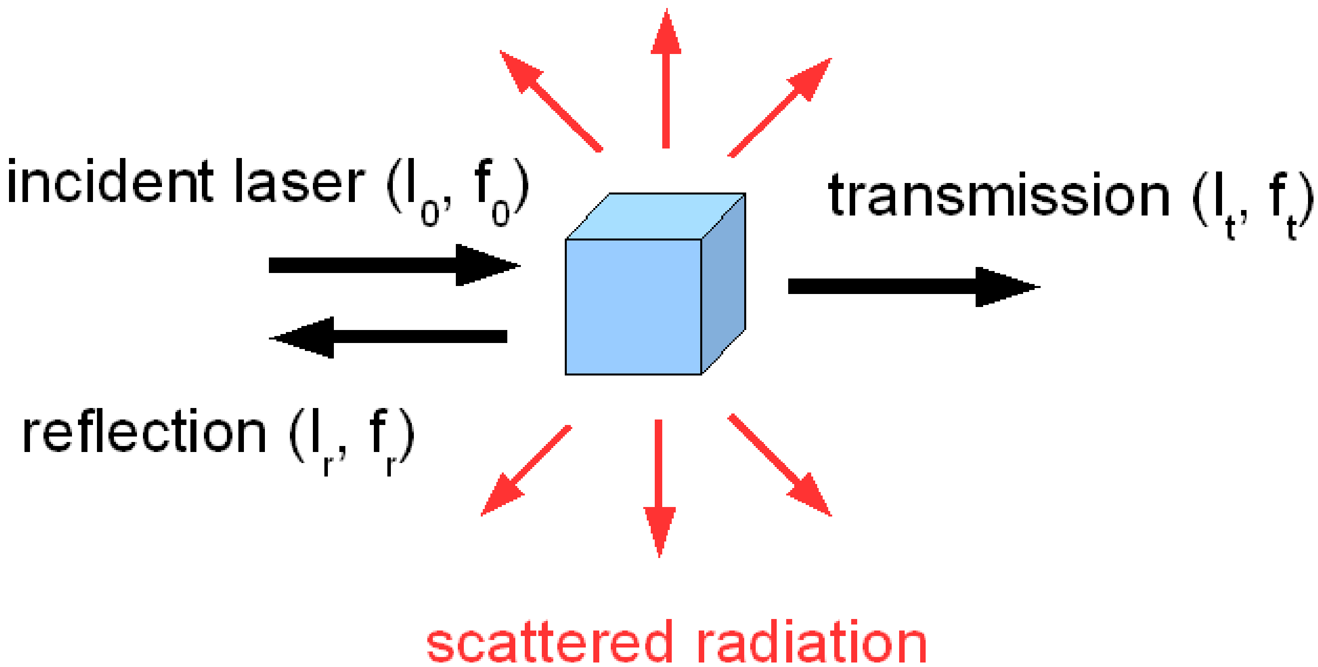
- Brillouin Amplifier
- Brillouin Laser
- Optical filter
- Brillouin optical spectrum analyzer (BOSA)
- Sensors (temperature, strain, …)
- Slow and fast light

System considerations

- The signal transfers optical power to the backscattered wave → degradation of the SNR at the receiver
- Maximal optical power which can be transmitted through one channel in a fiber is limited (… but very high)
- Performance degradations in bidirectional optical links due to the backscattered wave

References: T. Schneider, **Nonlinear Optics in Telecommunications**, Springer-Verlag Berlin, 2004
G.P. Agrawal, **Nonlinear Fiber Optics**, Academic Press, 2007

Conclusion



Rayleigh

(f_0)

- Particles
- Local refractive index variations

Brillouin

($f_0 \pm f_B$)

- Density fluctuations
- Acoustic waves
- f_B ~ GHz

Raman

($f_0 \pm f_R$)

- Molecules
- Electrons
- f_R ~ THz