Fiber Optics Communications

Week 5

Fiber Optics Non-Linear Effect

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Topics of Previous Lecture (Week- 4)

- Introduction to Optical Signal Dispersion
- Types of Optical Signal Dispersion
- Phase Velocity and Group Velocity
- Chromatic Dispersion
- Polarization-Modes Dispersion
- Modal Dispersion

Week-5: Lecture Learning Outcomes

1. Define and explain the concept of non-linear effects in optical fibers and their significance in fiber optic communication.
2. Identify the main types of non-linear effects, including Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM), Stimulated Raman Scattering (SRS), and Stimulated Brillouin Scattering (SBS).
3. Analyze the impact of fiber non-linearities on signal quality and system performance.
4. Calculate the phase shifts associated with specific non-linear effects in optical fibers.
5. Apply knowledge of non-linear effects to practical scenarios, such as wavelength-division multiplexing (WDM) and long-haul fiber optic links.

Week-5: Fiber Optics Non-Linear Effect

Outline

- Introduction to Fiber Optics Non-Linear Effect
- Types Nonlinear Effects in Optical Fibers
- Origin of Nonlinear Effects
- Stimulated Raman Scattering (SRS)
- Stimulated Brillouin Scattering (SBS)
- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)
- Four-Wave Mixing (FWM)

Introduction to Fiber Optics Non-Linear Effect

- Up to now, we have considered the fiber optic as linear medium; however, in reality, it is **nonlinear.**
- The study of fiber nonlinearities started around **1970s** after low-loss fibers were invented [1].
- Later in **1990s,** Much attention was given for fiber optics non-linear effect due to the emergence of multi-channel (WDM) optical communication system.
- **Fiber Optics Nonlinearity** arises due to two major **reasons,** which are:

  - **Scattering Related:** Presence of nonlinear inelastic scattering processes.
  - **Refractive Index Related:** Variation of the fiber's refractive index with Optical signal intensity, which is known as **Kerr Nonlinearity**.

Introduction to Fiber Optics Non-Linear Effect

- Therefore, fiber optics nonlinearities can be categorized as **scattering related** and **refractive index related nonlinearities**
- There are different types of fiber optics nonlinearities both in scattering and refractive index related categories:

Scattering Related

- Stimulated Raman Scattering (SRS)
- Stimulated Brillouin Scattering (SBS)

Refractive Index Related

- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)
- Four-Wave Mixing (FWM)

Scattering Related Fiber Optics Nonlinearities

Stimulated Raman Scattering (SRS)

- Stimulated Raman scattering arises due to the interaction between light-waves and the vibrational modes of silica molecules.
- An Incident Photon on a vibrating molecule will lose part of its energy to the vibrating molecule
- Let the incident photon before interaction has an energy E_{P1} given by:

$$E_{p1} = hv_1 \qquad (1)$$

Where:

h Is Planck's constant

v_1 Photon frequency before interacting

- After interacting with the vibrating molecule, the photon will scatter and posses lower frequency v_2 and lower energy E_{p2} given by:

$$E_{p2} = hv_2 \qquad (2)$$

Where:

$$E_{p1} > E_{p2} = E_{p1} - \Delta E$$

Stimulated Raman Scattering (SRS) Cont.

- The photon lost energy equal to ΔE after interacting with the vibrating molecule

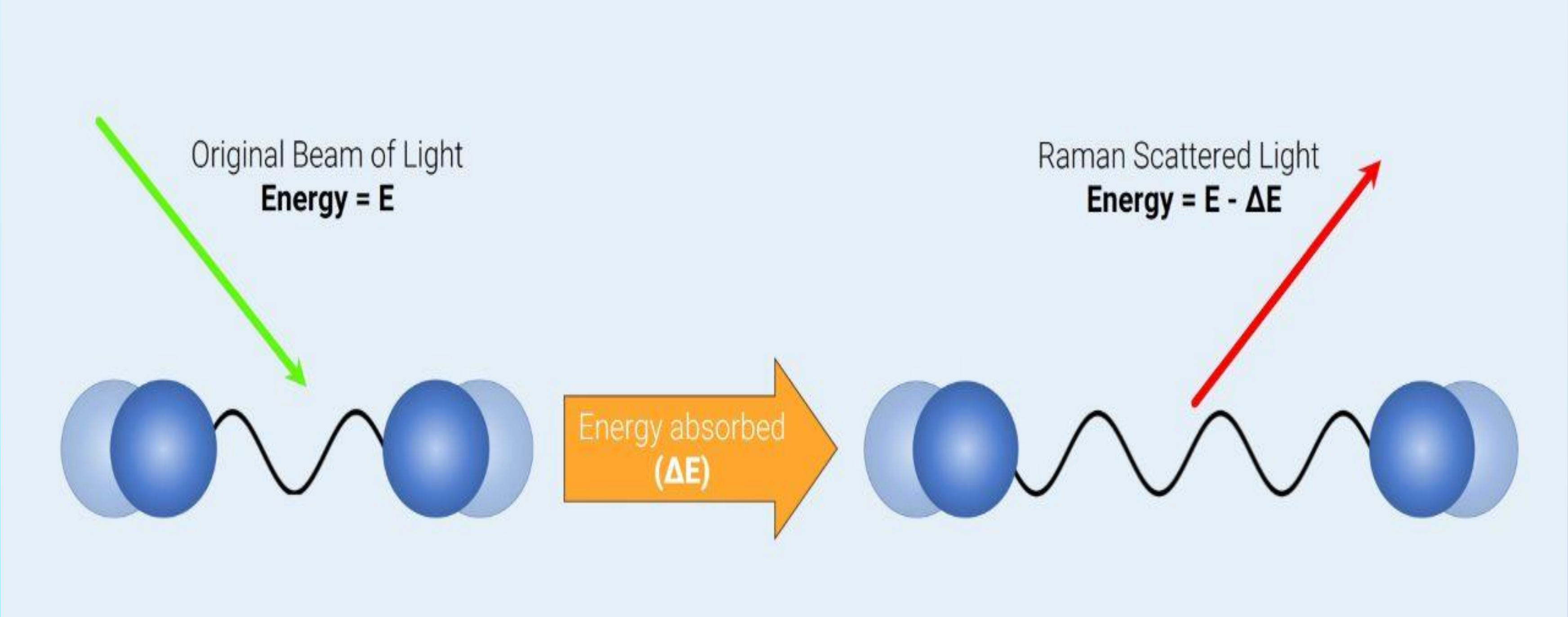


Figure 1: Photon interaction with vibrating molecules

Source: Bruker, "What is Raman spectroscopy?," in Guide to Raman Spectroscopy. https://www.bruker.com/pl/products-and-solutions/raman-spectroscopy/raman-basics/what-is-raman-spectroscopy/_jcr_content/root/sections/section_copy_1317658455/sectionpar/twocolumns_773106001_1315762341/contentpar-1/image_2091660955.coreimg.82.1280.jpeg/1733919189130/picture3.jpeg

Stimulated Raman Scattering (SRS) Cont.

- The modified photon due to the interaction is called a **Stokes photon**.
- The **injected optical signal wave** in a fiber, known as the **pump wave**, serves as the source of interacting photons
- In Stimulated Raman Scattering (SRS), the generated scattered light has a longer wavelength than the incident light, extending up to **125 nm** [2].

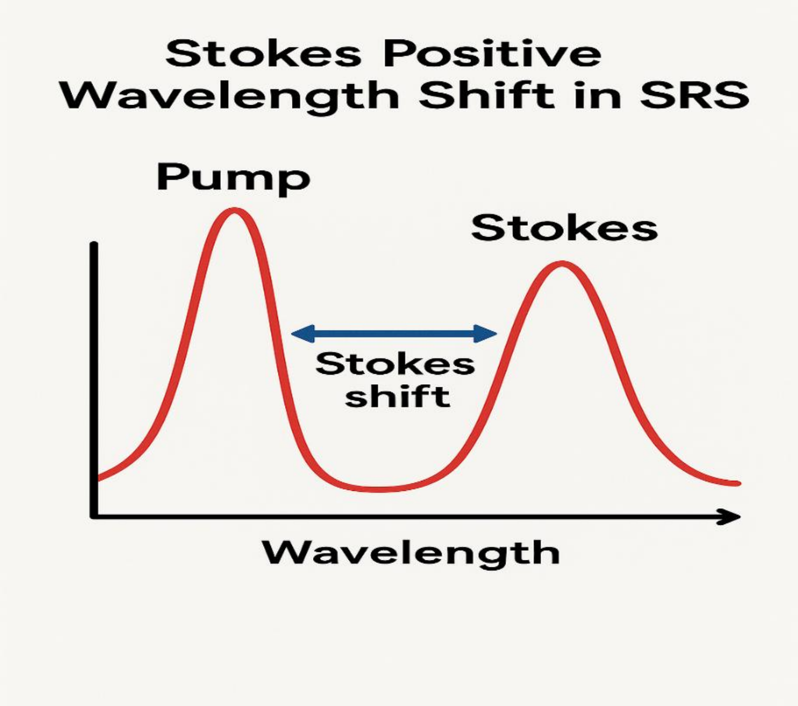


Figure 2: Stokes wavelength shift

Source: OpenAI, *"stoke positive wavelength shift in SRS,"* Sora. https://sora.chatgpt.com/g/gen_01k60z3j0kfpzs4evnn4dp7pdz

Stimulated Raman Scattering (SRS) Cont.

- When a shorter and longer-wavelength signal are propagating together in the fiber, SRS amplifies the longer wavelength signal while reducing the shorter wavelength pump signal power.

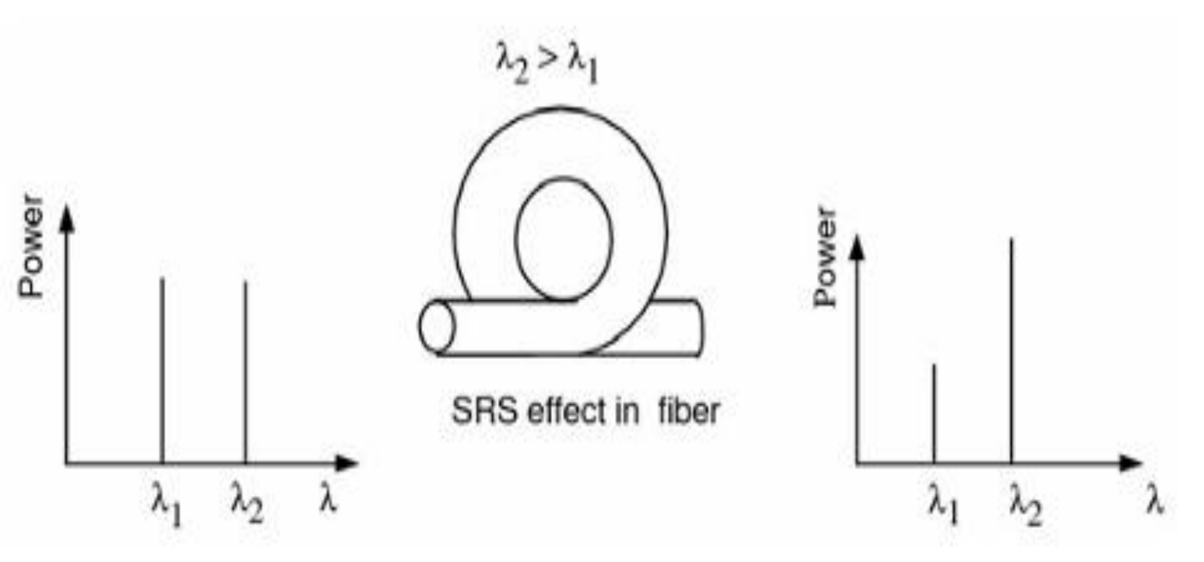


Figure 3: SRS effect in fiber

Source: S. Iyer, S. P. Singh, S. Kar, and V. K. Jain, "Study on Mitigation of Transmission Impairments and Issues and Challenges with PLIA-RWA in Optical WDM Networks,“ Journal of Optical Communications,2012. https://www.researchgate.net/publication/272421361_Study_on_Mitigation_of_Transmission_Impairments_and_Issues_and_Challenges_with_PLIA-RWA_in_Optical_WDM_Networks/figures?lo=1

Stimulated Raman Scattering (SRS) Cont.

- In multichannel optical systems (WDM), SRS reduces performance by transferring energy from shorter-wavelength channels to adjacent longer-wavelength channels
- In WDM systems, channels spaced up to 16 THz (≈125 nm) can interact via the SRS effect.

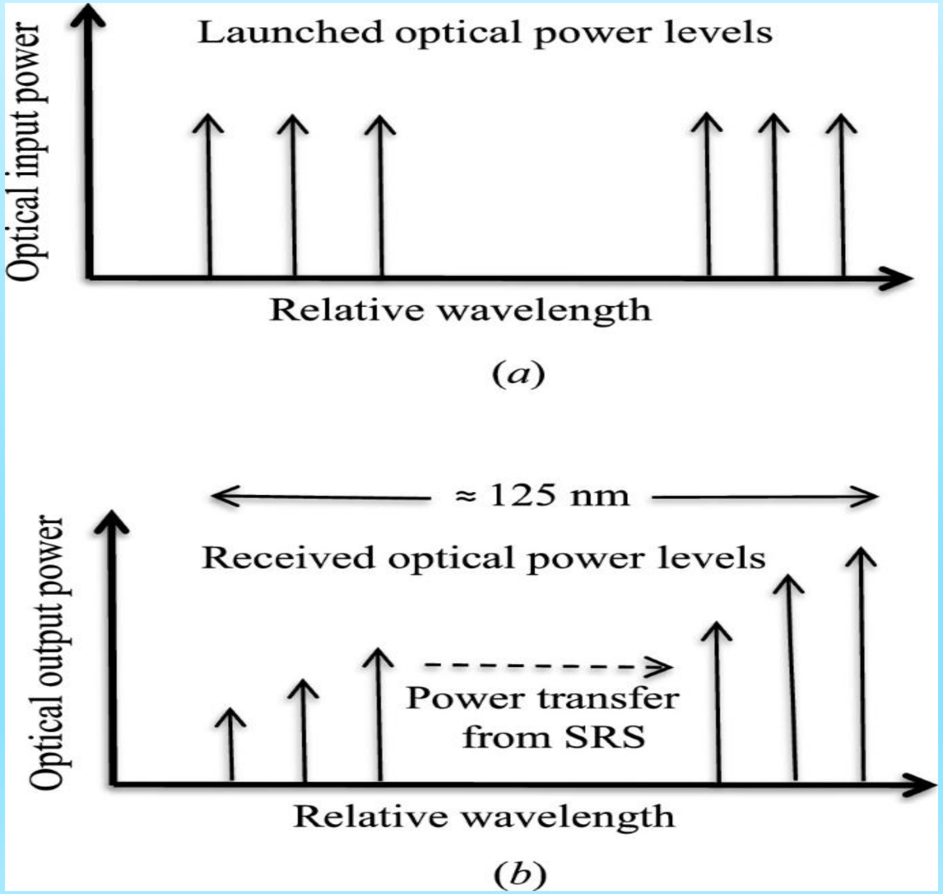


Figure 4: WDM channels interaction through SRS

Source: Keiser, G., *“Nonlinear Processes in Optical Fibers,”* in Fiber Optic Communications. Springer, Singapore, 2021. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_12/MediaObjects/495048_1_En_12_Fig4_HTML.png

Raman Gain Coefficient

- The Raman gain coefficient measures the strength of SRS in optical fibers, describing how pump wave power is transferred to a stokes wave power
- The Raman gain coefficient, g_R , is the function of the channel separation, Δv_s , in WDM system

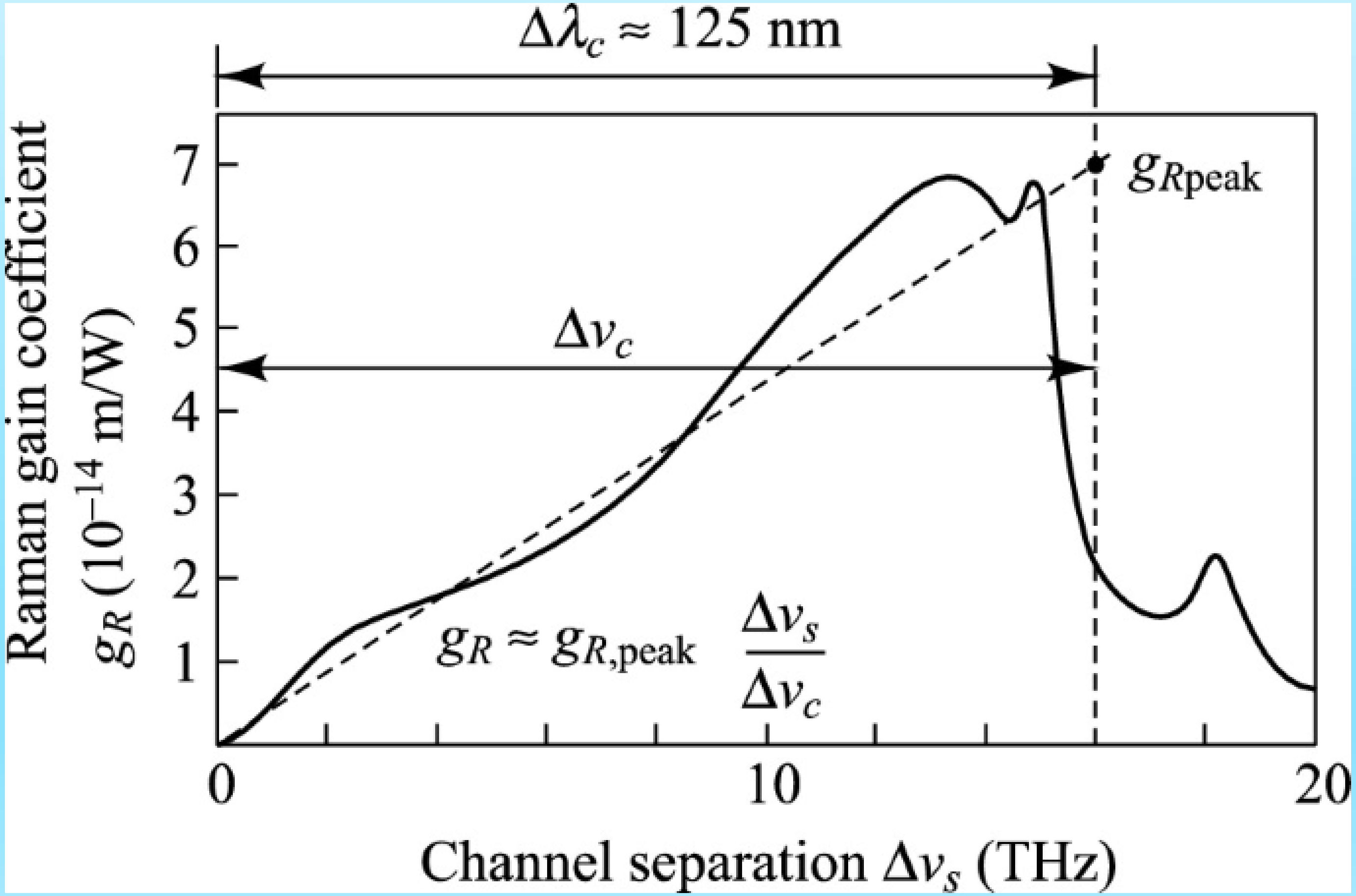


Figure 5: Raman gain coefficient

Source: Keiser, G., *“Nonlinear Processes in Optical Fibers,”* in Fiber Optic Communications. Springer, Singapore, 2021. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_12/MediaObjects/495048_1_En_12_Fig5_HTML.png

Effect of Raman Gain

- In WDM systems, Raman gain results in inter-channel crosstalk in WDM systems
- Reducing channel power minimizes crosstalk
- However, crosstalk mitigation through channels’ power reduction limits the number of channels
- Reducing the number of channels has a direct impact on the capacity of the fiber optic system.
- Raman gain supports Raman amplifier realization in WDM systems which is the positive side of SRS.
- The distributed nature of Raman amplification lowers the system noise and enable the system to achieve long distance transmission.

Stimulated Brillouin Scattering (SBS)

- SBS is a nonlinear effect in optical fibers that occurs at much lower input power than SRS
- SBS arises from a phenomena called **electrostriction**, where materials compress due to an applied electric field.
- An oscillating electric field at pump frequency (ν_p) generates an acoustic wave at frequency (ν_a) and variation of material's refractive index
- The material compression due to the **electrostriction** results in change of the material density [3].
- Change of material's refractive index will occur due to the induced material density variation
- The refractive Index variations cause the light waves to scatter backward along the fiber
- The frequency of back Scattered light with wave length (λ) experiences a Doppler shift ν_B due to the acoustic wave as:

$$\nu_B = \frac{2nV_s}{\lambda} \qquad (3)$$

Where:

n Refractive index

V_s velocity of acoustic wave

Stimulated Brillouin Scattering (SBS) Cont.

- SBS introduce both pump signal power reduction and frequency shift
- Most of the power launched into a single-mode fiber is reflected backward if it exceeds the SBS threshold (approximately 5 mW for long fiber)

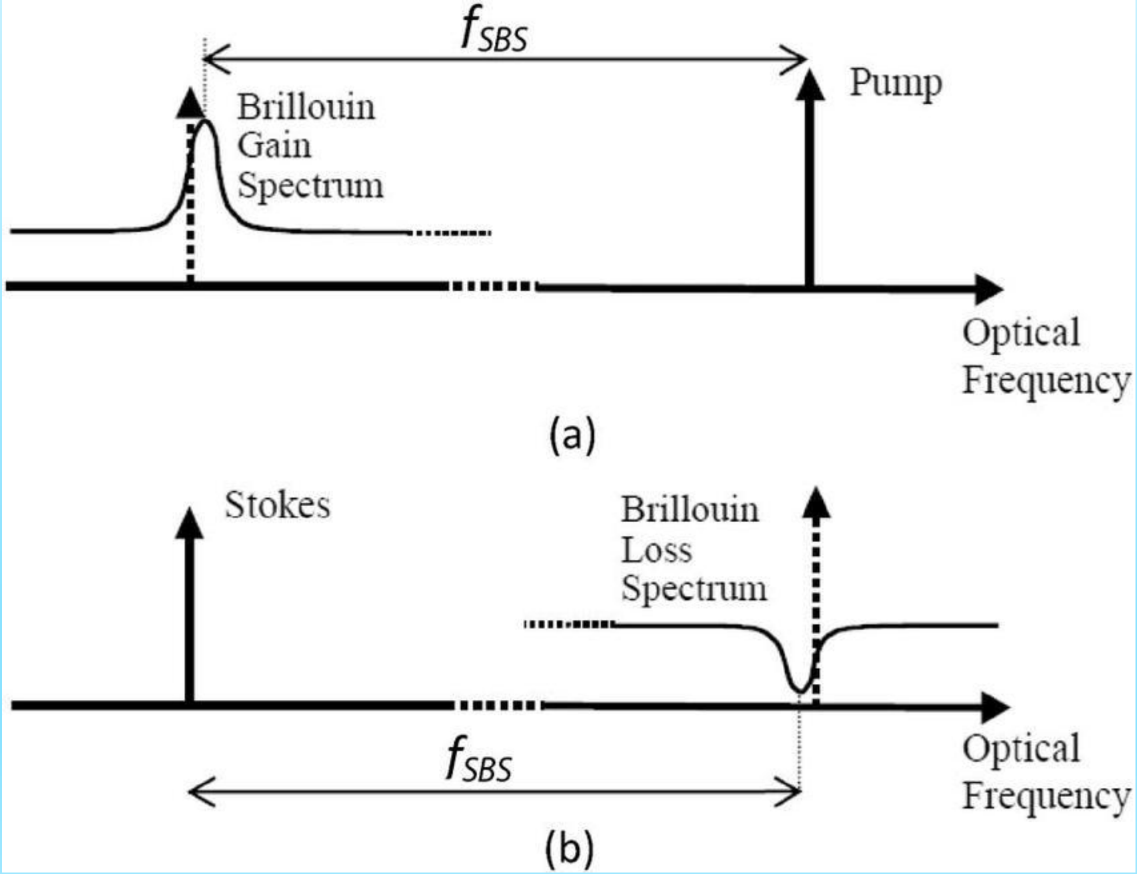


Figure 6: SBS induced **f**requency shift

Source: E. H. W. Chan and R. A. Minasian, *"All-Optical Frequency Shifter Based on Stimulated Brillouin Scattering in an Optical Fiber," IEEE Photonics Journal*, 2014. https://www.researchgate.net/profile/Erwin-Chan-2/publication/261410681/figure/fig3/AS:832901386088448@1575590573392/Generation-of-a-Brillouin-gain-spectrum-and-b-Brillouin-loss-spectrum-due-to-the.ppm

Impact of Stimulated Brillouin Scattering (SBS)

- In WDM systems, SBS is not that much a concern since channel powers are kept low (~1 mW) in practical fiber optics systems.
- SBS is a major issue in high-power fiber lasers and Yb (Ytterbium) -doped fiber amplifiers.
- SBS must be mitigated in parametric and Raman amplifiers that use high pump powers (>100 mW)
- On the other hand, Its narrow gain bandwidth can be used for channel selection in some applications.

Kerr Effect Related Fiber Optics Nonlinearities

Self-Phase Modulation (SPM)

- The refractive index (n) of many optical materials weakly depends on the optical intensity (I).
- The dependency of n on I is related to the optical power per effective area in the fiber as:

$$n = n_0 + I(t)n_2 = n_0 + n_2 \frac{P(t)}{A_{eff}} \qquad (4)$$

Where:

n_0	The linear refractive index
n_2	The non-linear refractive index coefficient
P	Optical power of the signal
A_{eff}	Optical power effective area in the fiber

- The refractive index non-linearity in Eq(4) is called **Kerr Nonlinearity**
- Kerr nonlinearity produces a non-linear phase modulation which is called the **Kerr effect.**

Self-Phase Modulation (SPM) Cont.

- In Sigle channel fiber optics communication, Kerr effect introduce **Self Phase Modulation**- a spurious **phase modulation.**
- From Eq(4), The propagation constant (β) is given by:

$$\beta = kn = \frac{2\pi}{\lambda}\left(n_0 + n_2\frac{P(t)}{A_{eff}}\right) = \frac{2\pi n_0}{\lambda} + P(t)\left(\frac{2\pi n_2}{\lambda A_{eff}}\right) \qquad (5)$$

- From Eq(5), **the nonlinear coefficient (γ)**, which represents the strength of the nonlinear effect in SPM can be obtained from the second term:

$$\gamma = \frac{2\pi}{\lambda}\left(\frac{n_2}{A_{eff}}\right) \qquad (6)$$

Where: λ Is the free space wavelength

Self-Phase Modulation (SPM) Cont.

- The optical field wave equation oscillating with ω_0 and propagating a total distance L in the fiber is given by:

$$E(L,t) = E_0 e^{-j(\omega_0 t - \beta L)} = E_0 e^{-j\left(\omega_0 t - L\left(\frac{2\pi n_0}{\lambda} + P(t)\left(\frac{2\pi n_2}{\lambda A_{eff}}\right)\right)\right)} \qquad (7)$$

- From Eq(7), the phase of the light wave φ given by:

$$\varphi = \omega_0 t - L\frac{2\pi n_0}{\lambda} - P(t)L\left(\frac{2\pi n_2}{\lambda A_{eff}}\right)$$

$$= \omega_0 t - L\frac{2\pi n_0}{\lambda} - LI(t)\frac{2\pi n_2}{\lambda} \qquad (8)$$

Where:

$I(t)$ The instantaneous light intensity in the optical fiber

Self-Phase Modulation (SPM) Cont.

- From Eq(8), It is known that the optical wave experiences both linear and non-linear phase shift.

$$\varphi = \omega_0 t - Lkn_0 - LI(t)kn_2$$

$$= \omega_0 t - \Delta\varphi_L - \Delta\varphi_{NL} = \omega_0 t - \Delta\varphi_T \qquad (9)$$

Where:

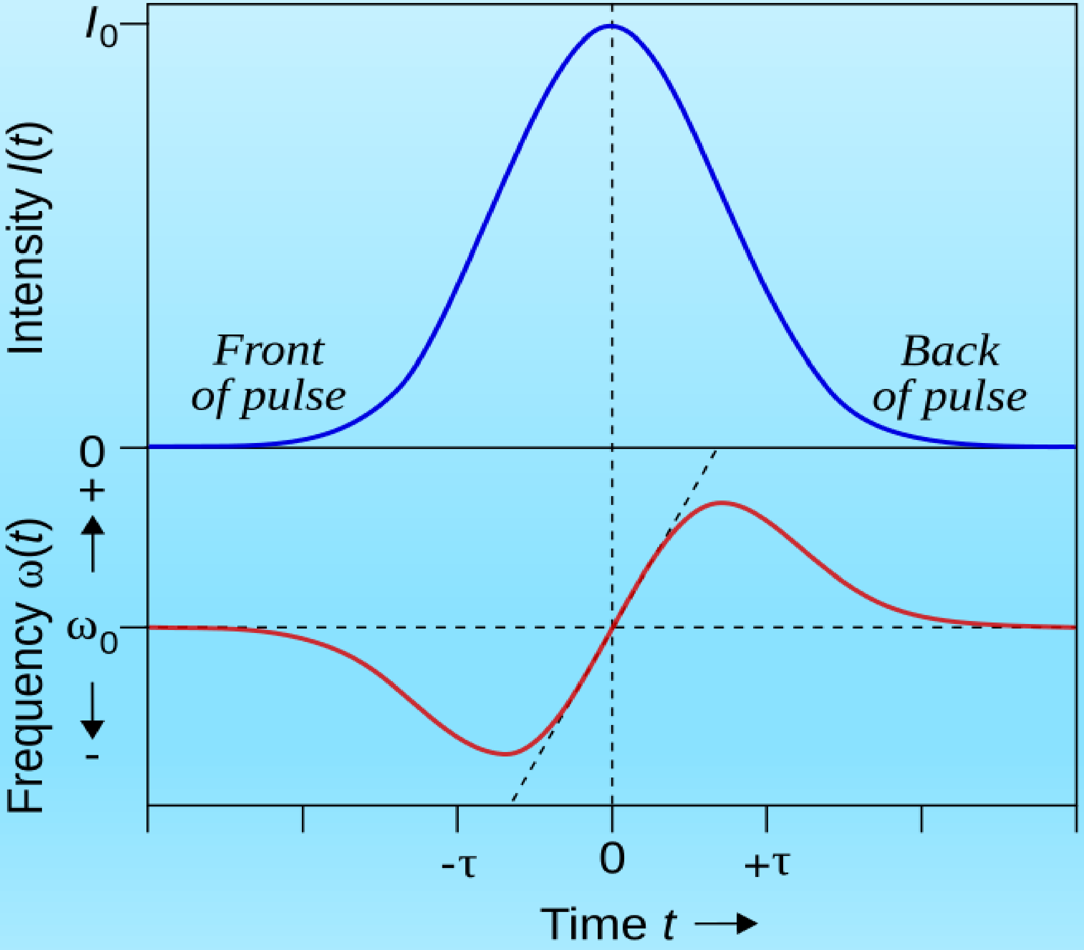
$k = \dfrac{2\pi}{\lambda}$	Propagation constant in vacuum
$\Delta\varphi_T$	Total phase shift
$\Delta\varphi_{NL}$	Non-linear phase shift
$\Delta\varphi_N$	Linear phase shift

- Considering the instantons frequency, the non linear phase shift introduces non linear frequency shift or **frequency chirp.**

Self-Phase Modulation (SPM) Cont.

- The frequency shift $\Delta\omega$ can be obtained from instantaneous frequency ω as

$$\omega = \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial t}\left(\omega_0 t - Lkn_0 - LI(t)kn_2\right) = \omega_0 - Lkn_2 \frac{\partial I(t)}{\partial t} = \omega_0 + \Delta\omega \qquad (10)$$



Slop of tangential line at different values of $I(t)$

Figure 7: SPM induced **f**requency shift

Source: E. Boutet, *"Self-phase modulation,"* Wikimedia Commons, 2014. https://upload.wikimedia.org/wikipedia/commons/thumb/d/d0/Self-phase-modulation-en.svg/668px-Self-phase-modulation-en.svg.png?20070329203335

Self-Phase Modulation (SPM): Spectral Broadening

- Eq(10) revealed that the frequency shift $\Delta\omega$ is given by:

$$\Delta\omega = -Lkn_2 \frac{\partial I(t)}{\partial t} \qquad (11)$$

- The $\Delta\omega$ and $\frac{\partial I(t)}{\partial t}$ term have opposite sign for Front of the pulse and back of the pulse.

Front of the Pulse

$\frac{\partial I(t)}{\partial t} > 0$ **and** $\Delta\omega < 0$

Center of the Pulse

$\frac{\partial I(t)}{\partial t} = 0$**,** $\Delta\omega = 0$ **, and**

$\Delta\varphi_T = \Delta\varphi_{\max}$

Back of the Pulse

$\frac{\partial I(t)}{\partial t} < 0$ **and** $\Delta\omega > 0$

- Due to the frequency chirp introduced by non-linear phase shift,

  SPM introduce spectral broadening on the Lightwave spectrum

Self-Phase Modulation (SPM): Spectral Broadening

- Figure (7) shows the spectral broadening effect for different value of phase shifts

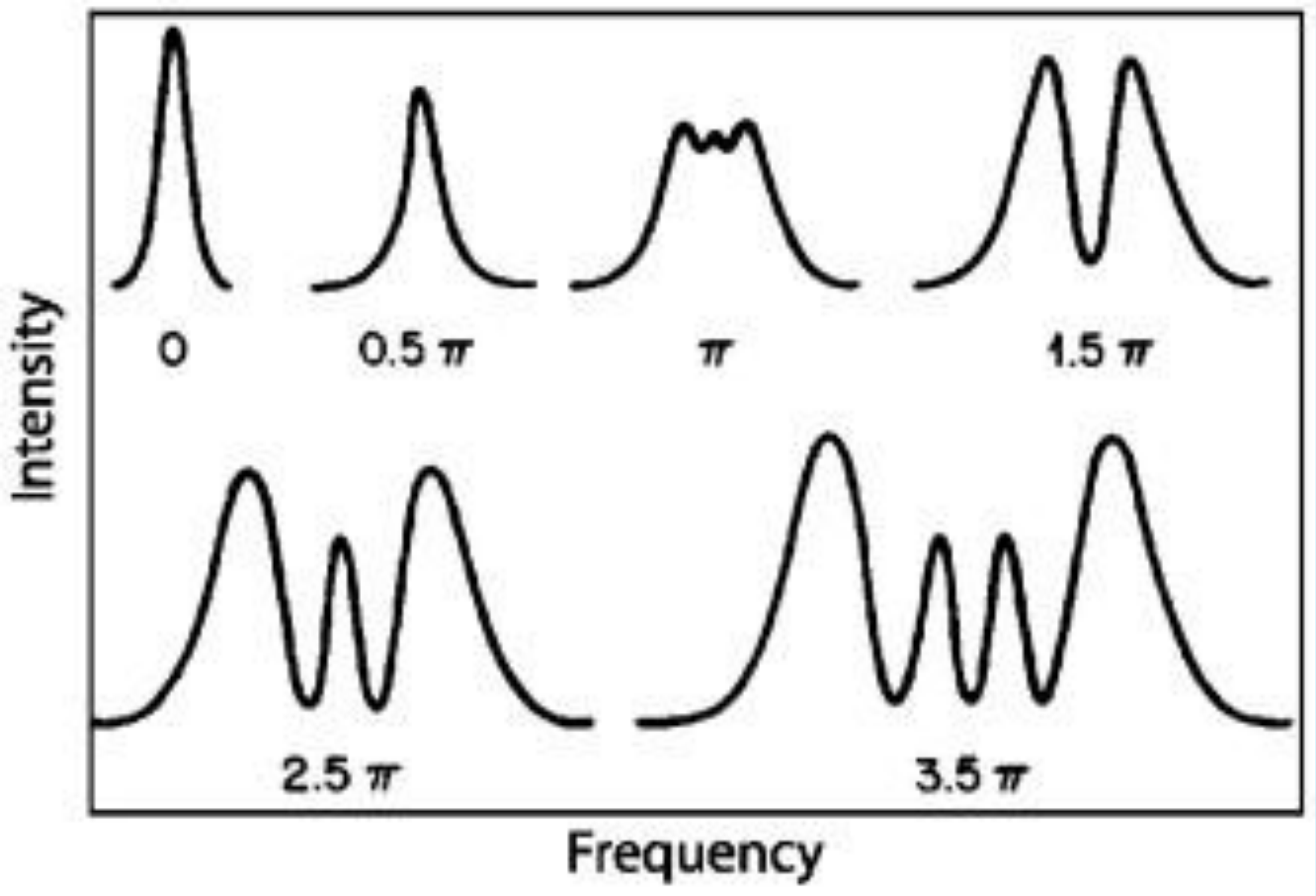


Figure 7: Spectral broadening

Source: *"Spectral Broadening,"* Engineering Topics, ScienceDirect. https://ars.els-cdn.com/content/image/3-s2.0-B9780123970237000048-f04-02-9780123970237.jpg

Self-Phase Modulation (SPM): Frequency Chirp

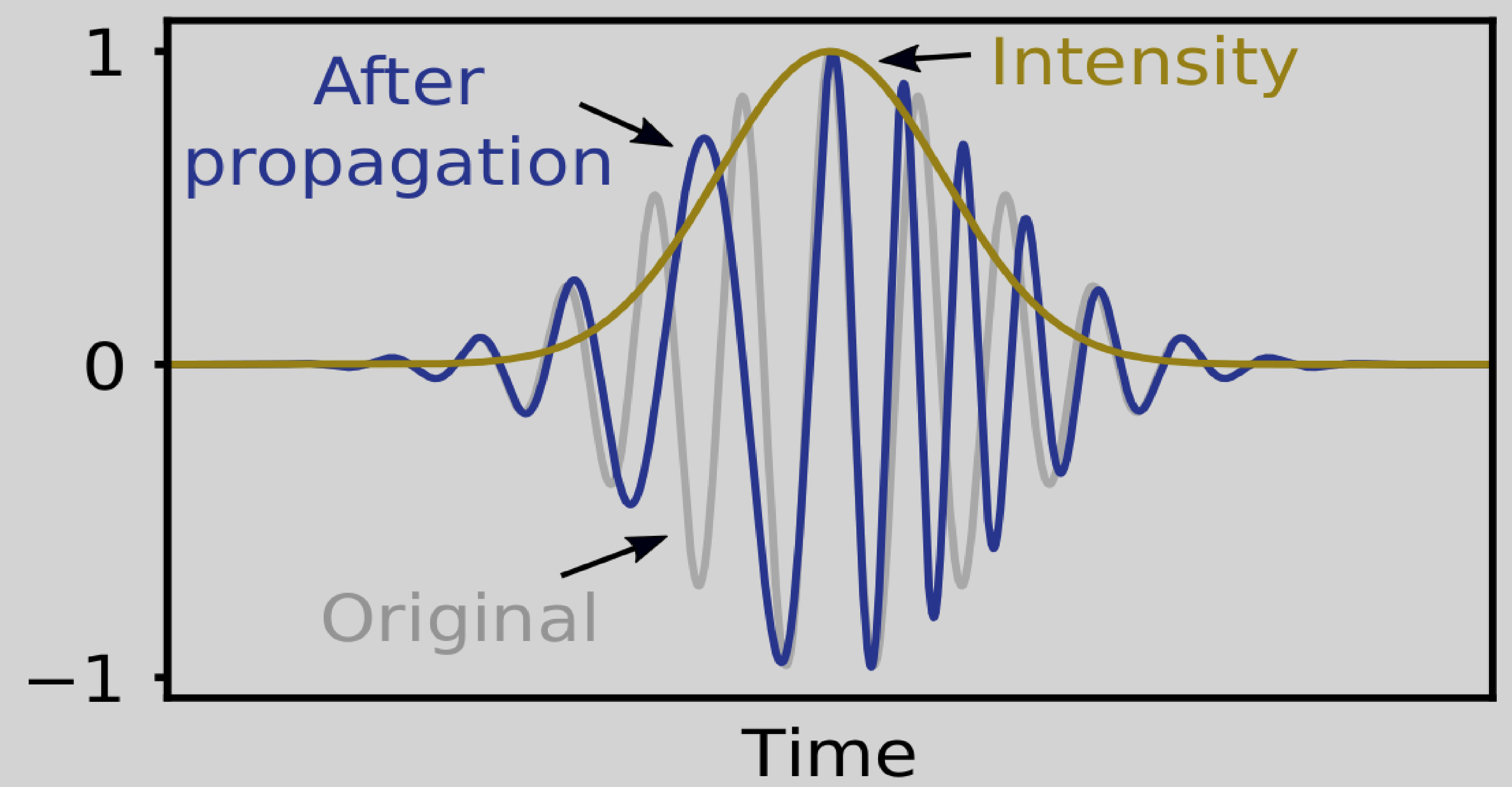


Figure 8: SPM induced Frequency chirp

Source: *“How to Model Chirp in Laser Pulse,”* Physics StackExchange. https://i.sstatic.net/PyCbe.png

Self-Phase Modulation (SPM): Chirp

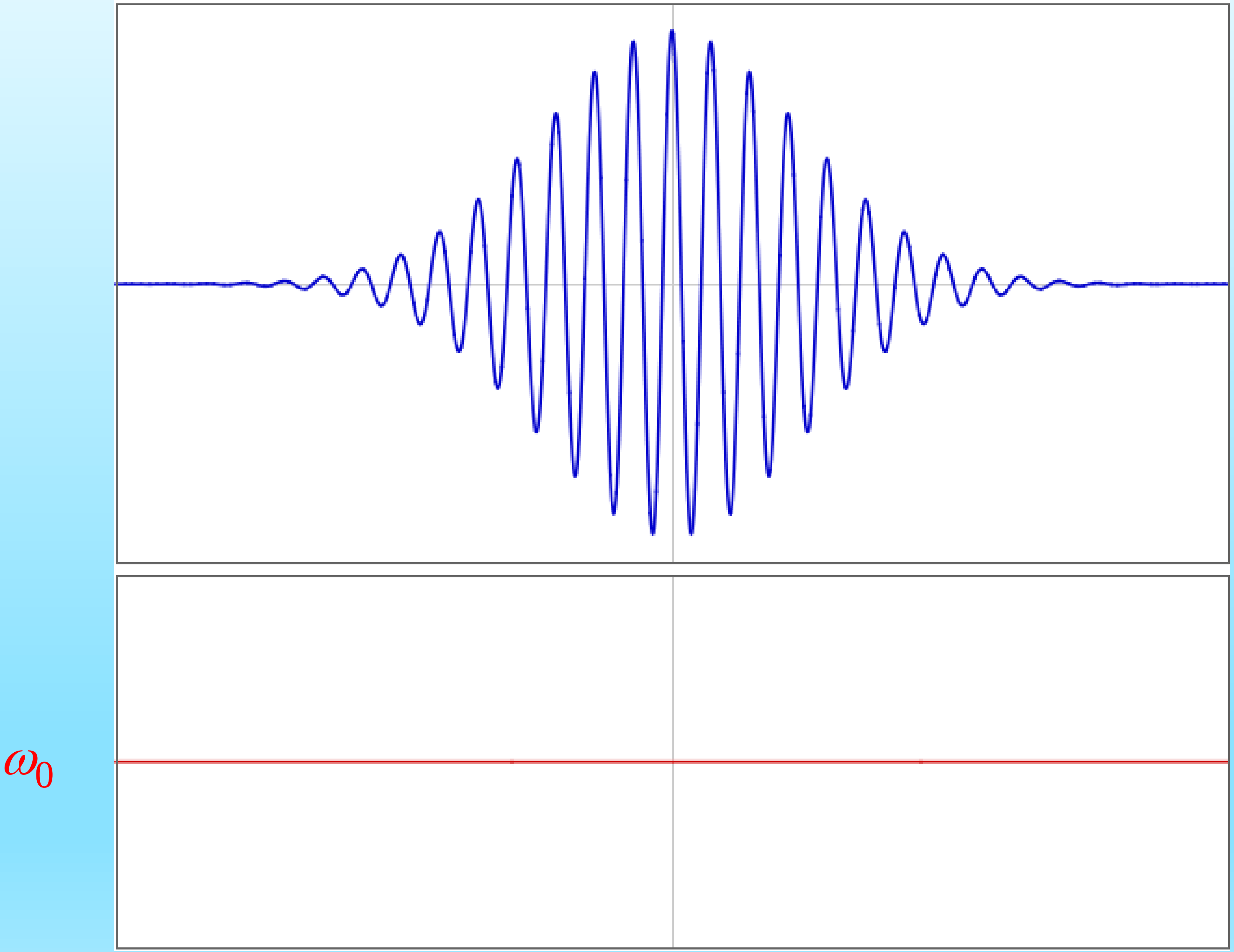


Figure 9: Frequency chirp

Source: *“Self-phase modulation induced spectral broadening,”* Physics StackExchange. https://i.sstatic.net/2KYyK.gif

SPM Induced Spectral Broadening Impact

- SPM-induced spectral broadening can degrade performance of a fiber optics communications system by increasing the Bit Error Rate (BER)
- SPM increase the system noise and introduce modulation instability
- On the other hand, SPM can be used for pulse compression applications

Cross-Phase Modulation (XPM)

- In our previous analysis of SPM, our focus was on optical pulses centered at a single wavelength.
- However, when multiple pulses at different wavelengths propagate together in a fiber, they interact through fiber nonlinearity.
- Cross-phase modulation (XPM) appears in multi-channel (WDM) systems [4] and has a similar origin as SPM.
- Due to the refractive index nonlinearity, the optical intensity fluctuation in one particular channel introduces phase fluctuation in the co-propagating adjacent channel.
- The non linear phase shift $\Delta\varphi_j^{NL}$ experienced by jth channel is given by:

$$\Delta\varphi_j^{NL} = \frac{\partial}{\partial t}\left(L\left(\frac{2\pi n_2}{\lambda A_{eff}}\right)\left[P_j(t) + 2\sum_{m\neq j} P_m(t)\right]\right) = \gamma L\left[\underbrace{\frac{\partial P_j(t)}{\partial t}}_{\text{SPM}} + \underbrace{2\sum_{m\neq j}\frac{\partial P_m(t)}{\partial t}}_{\text{XPM}}\right] \qquad (12)$$

Cross-Phase Modulation (XPM): Spectral Broadening

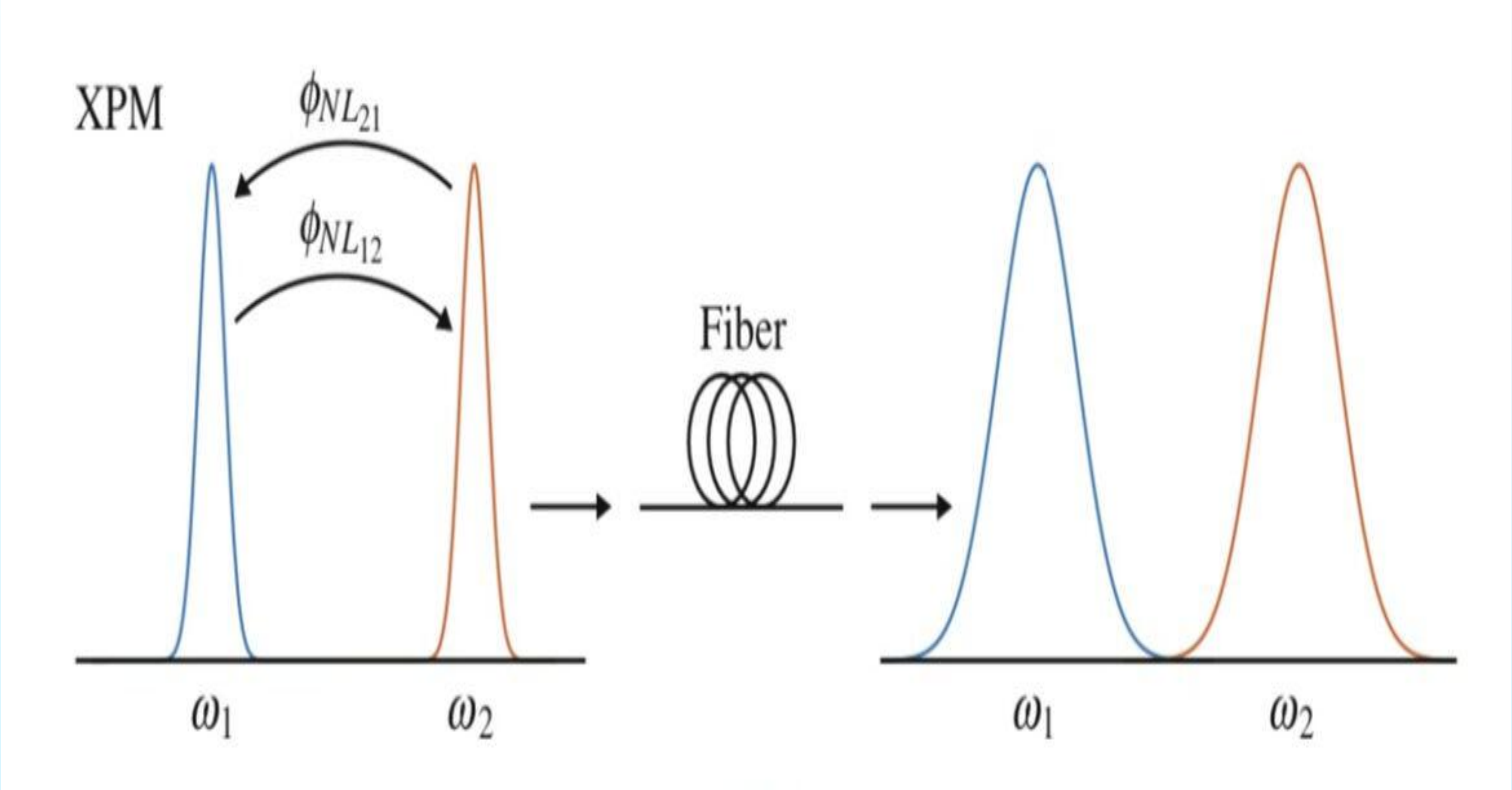


Figure 9: XPM induced spectral broadening

Source: *“Cross-Phase Modulation (XPM) in DWDM Networks,”* MapYourTech. https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcQOquLuCRtE11hSqdS0DTMqovxY37ZDLZyy1wuC1LDcY2rdar-rMDGTtLgI83OmNmdokLE&usqp=CAU

Cross-Phase Modulation (XPM): Other Effects

Crosstalk Between Channels

- The intensity fluctuations of one channel induce phase modulation in the other channels
- Introduce SINR degradation

Pattern Dependence

- XPM-induced phase distortion is influenced by the data patterns of neighboring channels
- XPM can cause significant performance degradation, especially in systems using phase-sensitive modulation formats such as QPSK or QAM.

Four Wave Mixing (FWM)

- Long-distance transmission of high-capacity dense WDM channels requires operation in the 1550-nm window of dispersion-shifted fiber
- High-speed long-distance systems require high optical launch powers per channel to achieve adequate signal-to-noise ratio(SNR)
- High launch power and low dispersion are critical, thus wavelength of channels operate near the zero-dispersion point.
- Near the zero-dispersion point, three optical frequencies $(\omega_i, \omega_j, \omega_k)$ can mix to generate a fourth intermodulation product (ω_{ijk}) as:

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k \quad \text{with } i, j \neq k \qquad (13)$$

- If the new frequencies lie within the transmission window of the original signals, it can lead to severe crosstalk.

Four Wave Mixing (FWM)

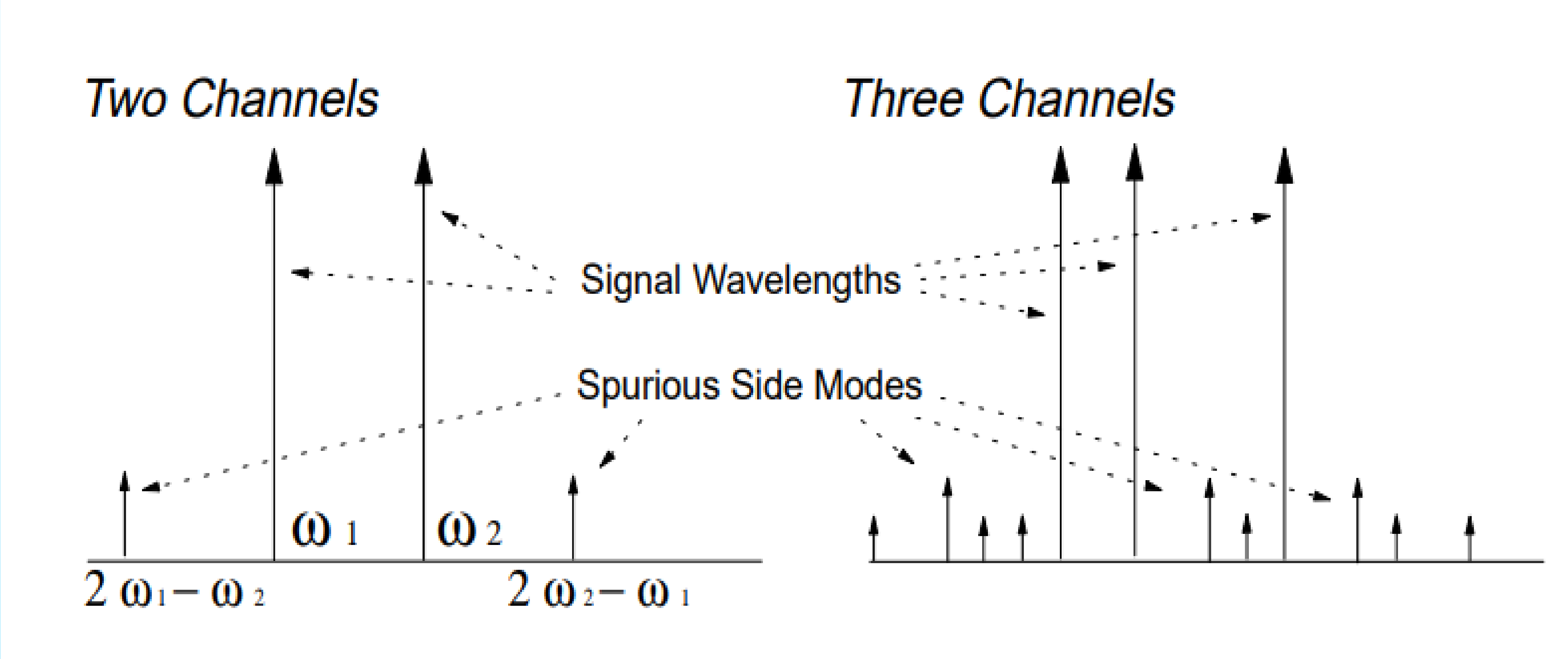


Figure 10: Spurious side modes due to FWM

Source: Prajapatijaimin, *"Define Four-Wave Mixing (FWM) with Diagram,"* 2022. https://i.imgur.com/mEVtGKN.png

Impact of Four Wave Mixing (FWM)

- FWM results in inter-channel crosstalk in WDM systems
- It generates additional noise and degrades system performance
- On the other hand FWM can be used for application which require wavelength conversion

Summary

- **Fiber Optics Nonlinear Effects:** Cause signal distortion, spectral broadening, and crosstalk, affecting communication quality.
- **Types of Nonlinear Effects in Optical Fibers:** Kerr effect-based (SPM, XPM, FWM) and Scattering-based (SRS, SBS)
- **Origin of Nonlinear Effects:** Caused by the intensity-dependent refractive index of the fiber material (Kerr effect) and interaction of light with the medium.
- Nonlinear effects become prominent when:
  - ✓ Optical power is high
  - ✓ Fiber length is long
  - ✓ Pulse width is short (high peak power)

References

[1] Govind P. Agrawal,*‘’ NONLINEAR FIBER OPTICS”,* Elsevier, 6th ed., Pp.1, 2019.

[2] Gerd Keiser, *“Fiber Optic Communications”,* Springer, Pp.481, 2021.

[3] Govind P. Agrawal,‘’ FIBER-OPTIC COMMUNICATION SYSTEMS’’, John Wiley & Sons, 5th ed., Pp.49, 2021.

[4] Shiva Kumar and M. Jamal Deen, ‘’ Fiber Optic Communication Systems’’, Wiley, Pp.439, 2014.

Thank You !