Course EE5134: Optical Communications and Networks

Assignment 2 Report

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Question 1

(a) An optical fiber communication link has an attenuation of 0.45 dB/km, laser input optical power of 1.2 mW, and receiver sensitivity of 60 µW. Calculate the maximum transmission distance of this fiber link. (5 marks)

Solution:

The maximum distance is limited by the total allowable power loss, which is the different between the transmitted power and the minimum detectable power (receiver sensitivity). Attenuation in dB/km quantifies how much power is lost per kilometer.

Steps:

1. Convert power values to the same unit: Transmission Power $\mathrm{P}_{\mathrm{tr}} = 1.2$ mW, Receiver sensitivity $\mathrm{P}_{\mathrm{rec}} = 0.06$ mW
2. Total attenuation: $\mathrm{L} = 10\log_{10}(\frac{1.2}{0.06}) \approx 13$ dB
3. Maximum transmission distance: $d_{max} = \frac{\text{total attenuation}}{\text{attenuation per km}} = \frac{13}{0.45} \approx$ **28.9 km.**

(b) An optical fiber has core and cladding refractive index of 1.46 and 1.44, respectively.

(i) Calculate the critical angle at core-cladding interface. (5 marks)

Solution:

The critical angle θ_c is the minimum angel of incidence at the core-cladding interface for total internal reflection (TIR) to occur. Beyond this angle, the light escape into the cladding. Using Snell's Law:

$$n_1 \sin\theta_c = n_2 \sin 90°$$

$$\Rightarrow \theta_c = \arcsin\frac{n_2}{n_1} = \arcsin\frac{1.44}{1.46} \approx 80.6°$$

where n_1 is the core index, n_2 is the cladding index. The critical angle is **80.6°**. Light must strike the core-cladding interface at angle $\geq$80.6° to ensure TIR.

(ii) Calculate its acceptance angle and NA. (5 marks)

Solution:

The acceptance angle θ_a defines the maximum external angle at which light can enter the fiber and still undergo TIR. Using Snell's Law:

$$n_0 \sin\theta_a = n_1 \sin\theta_r = n_1 \sin(90° - \theta_c)$$

$$\Rightarrow \theta_a = \arcsin(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}) \approx 14°$$

where n_0 is the air refractive index, n_1 is the core index.

The numerical aperture (NA) quantifies the light-gathering ability of the fiber. The formulas are:

$$\mathrm{NA} = n_0 \sin\theta_a|_{\max} = \sqrt{n_1^2 - n_2^2} = \sqrt{1.46^2 - 1.44^2} \approx \mathbf{0.241}$$

Higher NA means better light collection and light entering at angle $\leq$**14**° will propagate via TIR.

(c) Explain the difference between Rayleigh Scattering and Raman Scattering in optical fiber. (hint: can use figures/drawings to explain) (5 marks)

Solution:

In fiber communications, Rayleigh scattering causes inherent **wavelength-dependent** attenuation ($\propto \lambda^{-4}$), limiting signal reach, while Raman scattering induces nonlinear **power-dependent** effects like crosstalk but enables amplification through energy transfer between wavelengths. They are different in terms of **physical mechanism** and **impact** in fiber optics:

Rayleigh scattering is an important component of the scattering of optical signals in optical fibers. Silica fibers are glasses, disordered materials with microscopic variations of density and refractive index. Rayleigh scattering arises from **density fluctuations** in silica fibers, with scattered loss coefficient $\alpha_{\text{Rayleigh}} \propto \frac{1}{\lambda^4}$. This wavelength-dependent attenuation limits fiber reach. Shorter wavelengths scatter much more strongly than longer wavelengths.

Rayleigh scattering can be considered to be **elastic** scattering since the energy of the scattered photons is not changed. Photon wavelength remains **unchanged** after scattering and molecular energy states are unaffected (no transition between energy levels).

Raman scattering is conceptualized as involving a virtual electronic energy level which corresponds to the energy of the exciting laser photons. Absorption of a photon excites the molecule to the imaginary state and re-emission leads to Raman (involves energy exchange) or Rayleigh scattering (without energy exchange) [1]. It is possible for the incident photons to **interact with the molecules** in such a way that energy is either gained or lost so that the scattered photons are **shifted in frequency**. Such **inelastic** scattering is called Raman scattering.

Stokes and anti-Stokes scattering are the two fundamental forms of Raman scattering. For Stokes scattering, it occurs when a photon transfer energy to a molecule, exciting it to a higher vibrational state, so the scattered photons has lower energy (longer wavelength) than the incident photon. While anti-Stokes scattering involves the molecule donating energy to the photon, returning to a lower vibrational state, so the scattered photon has higher energy (shorter wavelength). Raman scattering enables broadband amplification via stimulated Raman scattering (e.g., Raman amplifiers) but introduces power-dependent crosstalk in dense WDM system.

Furthermore, the frequency characteristics of Rayleigh and Raman scattering are fundamentally distinct, governed by their energy exchange mechanisms with matter. For Rayleigh scattering, the scattered light retains the same frequency as the incident light, and the spectral intensity scales as λ^{-4}, making it highly wavelength-dependent, which causes strong attenuation of blue light ($\lambda \approx 400$ nm) in optical fibers compared to infrared light ($\lambda \approx 1550$ nm). Raman scattering produces symmetrically shifted bands (Stokes/anti-Stokes) encoding molecular vibrational information, with frequency shift by about 13 THz and gain spectra spanning 20-30 THz.

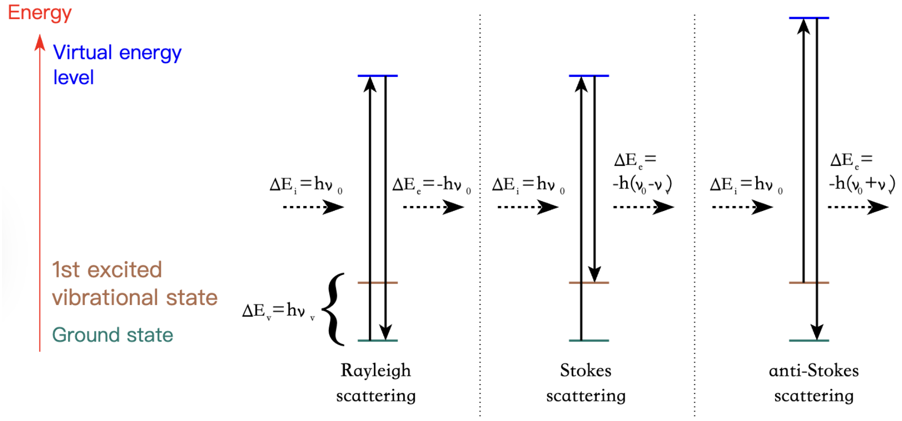

Figure 1: Rayleigh and Raman scattering

Question 2

(a) Modulator based on electro-absorption effect is one type of external optical modulator for lightwave system.

(i) Explain the mechanism and advantages of Electro-absorption Modulator (EAM). (5 marks)

Solution:

The Electro-Absorption Modulator (EAM) operates based on the Franz-Keldysh effect in semiconductors. Here's the working principle:

1. Franz-Keldysh effect: When an electric field is applied to a semiconductor (e.g., InP), its effective bandgap energy decreases, enabling photons with energy slightly below the original bandgap to be absorbed. The effect modulates the absorption coefficient of the semiconductor: with zero/low E-field, material is transparent to incident light (bandgap > photon energy); with high E-field, bandgap shrinks, allowing photon absorption (bandgap $\leq$ photon energy). The light intensity is varied by adjusting the reverse bias voltage.

2. Device structure: EAMs are typically integrated with a DFB laser on the same InP substrate, forming a compact chip (called an Electriabsorption-Modulated Laser, EML). Light from the DFB laser passes through the EAM section, where its intensity is modulated by the applied voltage.

Advantages of EAM:

1. Compact size: EAMs are integrated with DFB lasers and ideal for dense optical systems.

2. High-speed modulation: EAMs support multi-GHz modulation speeds, suitable for high-bandwidth applications linke coherent comunications and 5G networks.

3. Low chirp: EAMs exhibit negative chirp, which can compensate for fiber dispersion in certain scenarios.

4. Low insertion loss: By sharing the same InP substrate as the laser, coupling losses between between the laser and modulator are minimized, unlike $LiNbO_3$ modulators that suffer from fiber-waveguide coupling losses.

5. Low drive voltage: Requires low reverse bias voltage (1-3 V) for full modulation, reducing power consumption compared to $LiNbO_3$ modulators needing higher voltages (about 5-10 V).

(ii) What are the limiting factors on the performance of modulator-integrated DFB laser? (5 marks)

Solution:

The performance of modulator-integrated DFB lasers (e.g., electroabsorption-modulated lasers, EMLs) is limited by several key factors arising from the tight integration of the laser and modulator on a single chip:

1. Electrical crosstalk contributed by the leakage from modulator contact to laser contact affects the bias voltage of the DFB laser in a periodic manner, leading to frequency chirping. This degrades signal integrity in high-speed systems.

2. Optical crosstalk contributed by the residual reflectivity at the output facet creates optical feedback into the laser cavity. This induces time-dependent wavelength instability and exacerbates frequency chirping.

(b) A photodiode has a responsivity of 0.86 A/W and a saturated input power of 1.8 mW.

(i) If the incident light power is 1.2 mW, calculate its photocurrent and provide the answer in mA. (5 marks)

Solution:

Photocurrent is proportional to incident power below saturation:

$$\mathrm{I_p} = \mathrm{R} \cdot \mathrm{P_{in}} = 0.86\mathrm{A/W} * 1.3\mathrm{mW} = \mathbf{1.032}\ \mathrm{mA}$$

(ii) If the incident light power is 2.4 mW, can we calculate its photocurrent? (if yes, please provide the photocurrent in mA; if no, please provide the reason behind) (5 marks)

Solution:

The photodiode's saturation input power is 1.8 mW. Beyond this, the photocurrent no longer scales linearly due to carrier velocity saturation or space-charge effects. At 2.4 mW, the photodiode is saturated and the photocurrent **cannot** be calculated using $\mathrm{I_p} = \mathrm{R} \cdot \mathrm{P_{in}}$.

Appendix

Speed of light in vacuum = 3×10^8 m/s,
Electric charge = 1.6×10^{-19} C,
1eV = 1.6×10^{-19} J,
Planck's constant = 6.63×10^{-34} J·s,
Boltzmann constant = 1.38×10^{-23} J/K,
Room temperature = 300K,
Air refractive index = 1

References

[1] Wikipedia contributors, “Raman scattering — Wikipedia, the free encyclopedia,” 2025. [Online; accessed 5-April-2025].