EEE 333 - Optical Communication Devices

Lecture 1
Introduction

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1 Reference

Optical Fiber Communications: Principles and Practice , by John M. Senior 3$^{\text{th}}$ Edition

2 Introduction

Remember :

$$f = \frac{c}{\lambda}$$

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1. Q **What is the difference between (optical) and (visible)?**

1. A **Optical is more generic term than visible, optical range includes the visible range, ultraviolet range and infrared range**

Visible light range is 400 nm - 700 nm

Note that visible light does not propagate in optical fiber

3 Visible light communication (VLC)

is the use of visible light as a transmission medium.

the light may be modulated via (intensity modulation / direct detection (IM/DD)) which is the simplest form of modulation for optical system.

This modulation works as follow: the output optical power is directly proportional with the input current

$$P_{\text{opt}} \propto I_{\text{in}}$$

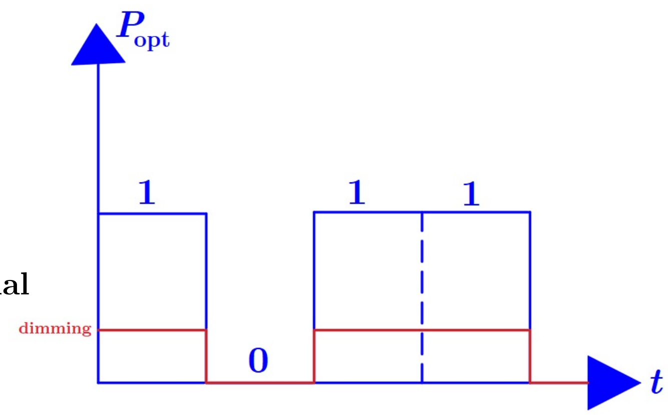

Figure 1: Sending of bits over time via VLC, not that dimming is the study of communication techniques while the user wants to turn the lights of without losing the connection

2. Q What is the difference between RF and IM?

In RF (radio frequency) the electric field is modulated, not the power

$$\underbrace{s(t)}_{\text{electric field}} = Am(t)\cos(\omega t + \phi)$$

In IM (Intensity modulation) the optical power is modulated imperceptibly [1]

Direct detection:

The detection of the optical signal via a photo detector

$$I_p \propto P_{opt}$$

$$I_p = RP_{opt}$$

Where R is the responsivity (A/W)

Light sources should be forward biased, and light detectors should be reverse biased, note that the are diodes at all

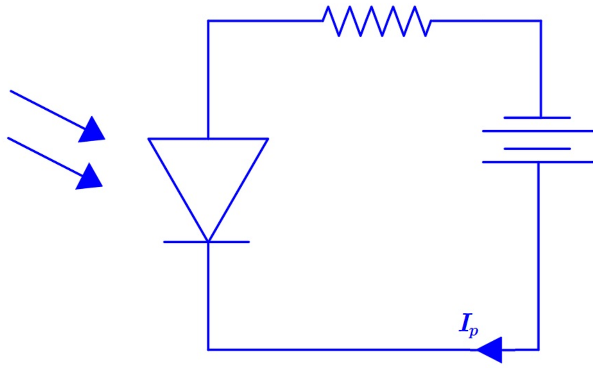

Figure 2: The photo detector diode is reverse biased, to block the current when P_{opt} = zero

4 Optical Fiber Communication (OFC)

is a method of transmitting information from one place to another by sending pulses of infrared light through an optical fiber.

Windows of communication (Bands to transmitt the signal)

1st window : 850 nm

2nd window : 1310 nm

3rd window : 1550 nm

Why specifically these ranges? to avoid attenuation caused by many reasons, e.g. (OH^- ion) dissolved in the glass.

[1] so slight, gradual, or subtle as not to be perceived by human eye

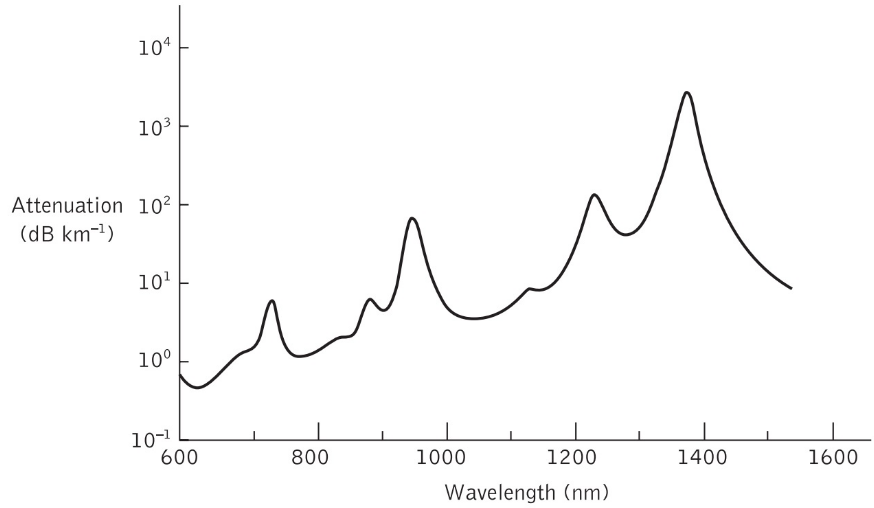

Figure 3: The absorption spectrum for the hydroxyl (OH) group in silica

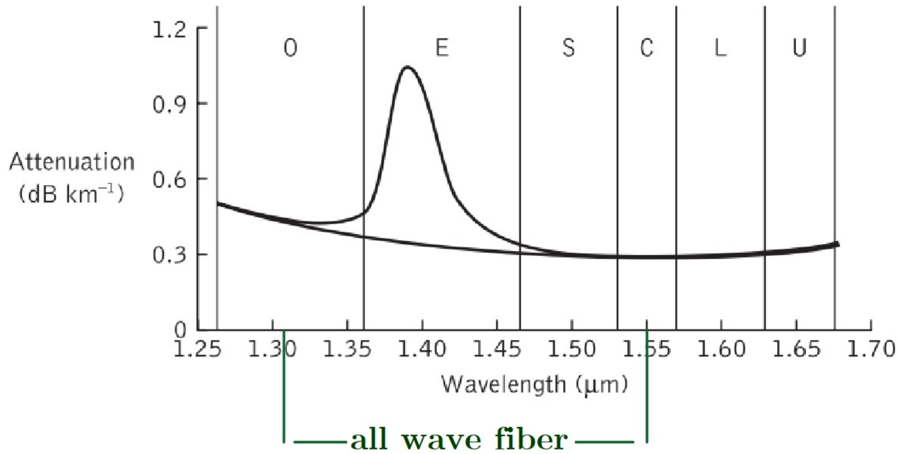

Figure 4: Fiber attenuation spectra, some technologies are use to eliminate the attentuation in the range of (1310 nm 1550 nm) (called the All wave fiber) leades to the use of the **2**$^{\text{nd}}$ window and **3**$^{\text{rd}}$ window

5 Dispersion

Dispersion is the spreading out of a light pulse in time as it propagates down the fiber due to the deviation of the wavelength range the transmitted signal, which means that the signal components arrives not in the same time
One advantage of laser (LD) over LEDs is the the wavelength range of laser is narrower than the wavelength range of LEDs, leads to smaller line width. which leads to less dispersion.
Note that the dispersion affects add up when the length of channels increases, as illustrated in the next figure

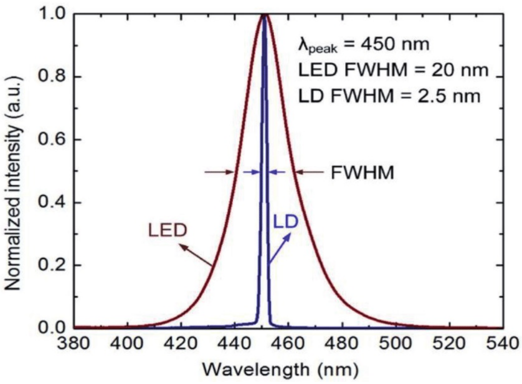

Figure 5: FWHM (Full Width at Half Maximum) of LED compared to Laser (LD)

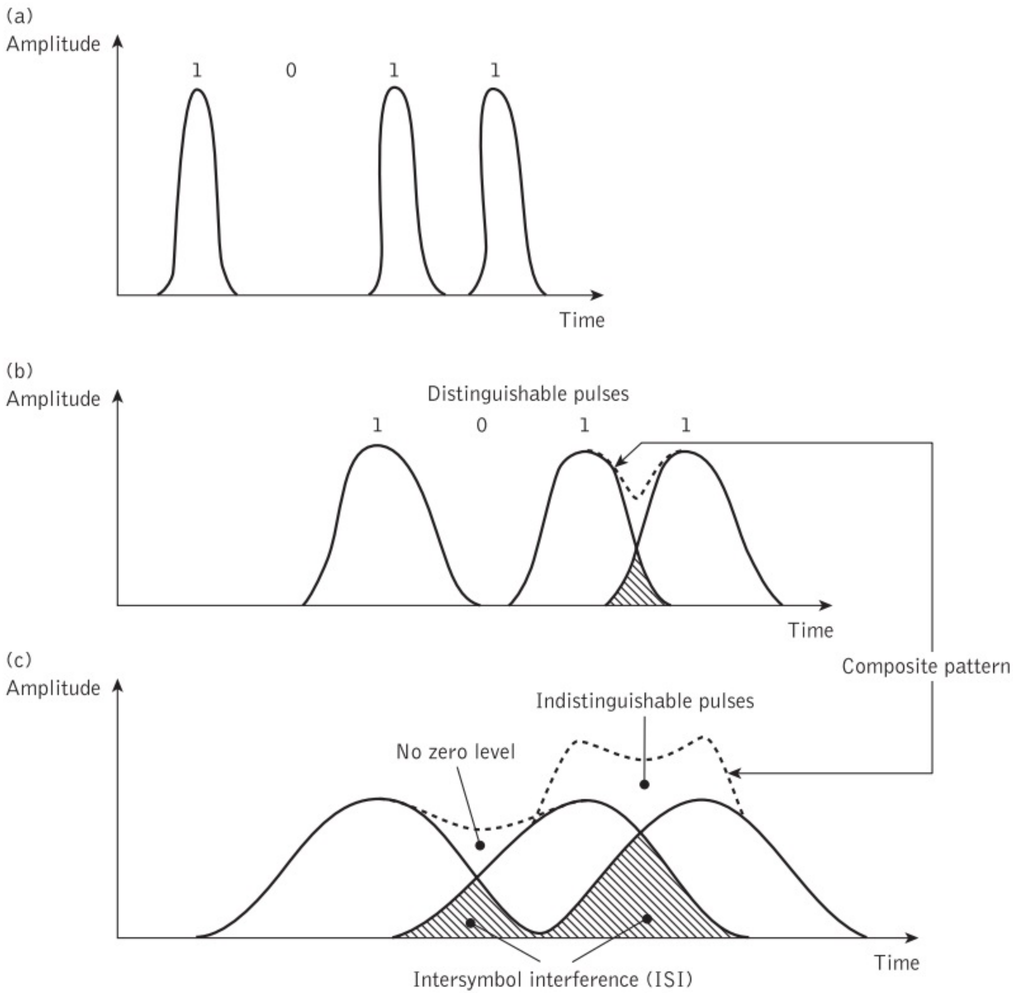

Figure 6: An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance L_1; (c) fiber output at a distance $L_2 > L_1$

6 LASER

LASER as an acronym for Light Amplification by Stimulated Emission of Radiation. The interaction of light with matter takes place in discrete packets of energy or quanta, called photons. Furthermore, the quantum theory suggests that atoms exist only in certain discrete energy states such that absorption and emission of light causes them to make a transition from one discrete energy state to another. The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the higher energy state E_2 and the lower energy state E_1 by the expression:

$$E = E_2 - E_1 = hf$$

where $h = 6.62610^{-34} Js$ is Planck's constant.

spontaneous emission is the dominant in the case of LEDs , while stimulated emission is the dominant in the case of Laser

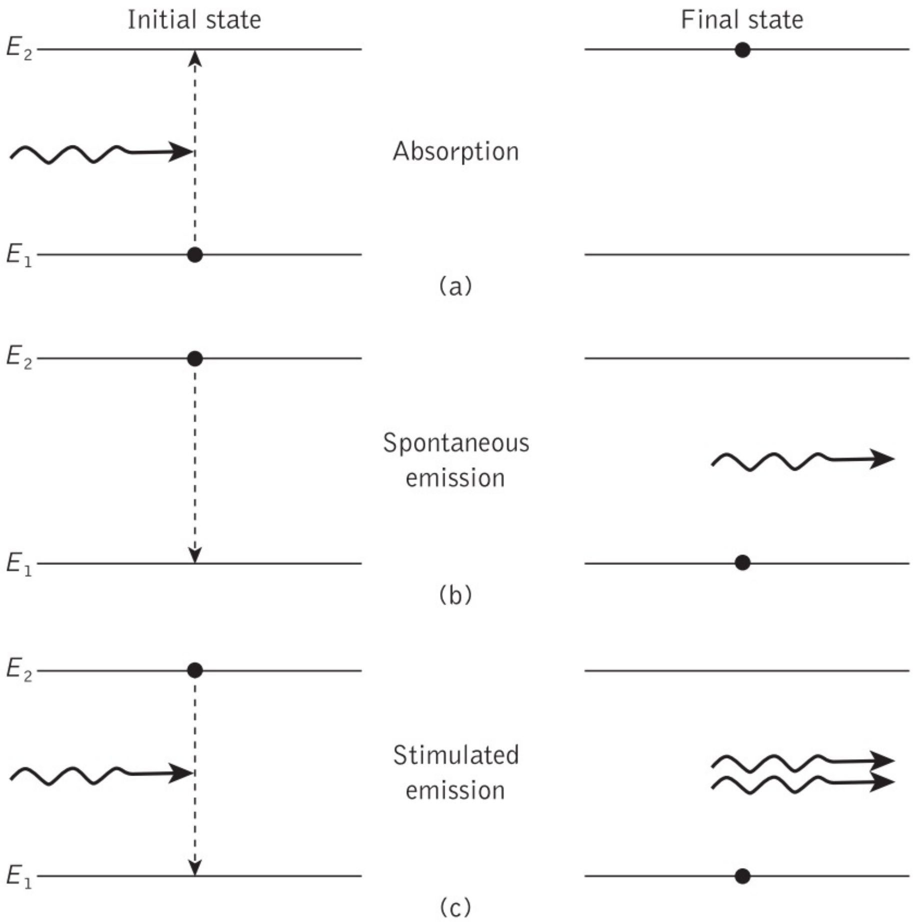

Figure 7: Energy state diagram showing: (a) absorption; (b) spontaneous emission; (c) stimulated emission. The black dot indicates the state of the atom before and after a transition takes place

3. Q Why silicon is not suitable for fabrication of light emitting diodes

3. A Since Silicon is an Indirect Band Gap semiconductor so electron cannot fall directly to the valence band but must undergo a momentum change as well as a change in energy. So, energy is released as heat along with the light. Hence, silicon is not suitable for the fabrication of LEDs.

Therefore, Gallium arsenide (GaAs) is more suitable, because it is more suitable because it is direct Band Gap semiconductor

7 The Einstein relations

7.1 Absorption

the upward transition rate R_{12} (indicating an electron transition from level 1 to level 2) may be written as:

$$R_{12} \propto N_1 \rho_f$$

$$R_{12} = B_{12} N_1 \rho_f$$

Where

R_{12} : electron transition from level 1 to level 2

ρ_f : spectral density

N_1 : represent the density of atoms in energy levels E_1

B_{12} : Einstein coefficient of absorption.

7.2 spontaneous emission

R_{21} (indicating an electron transition from level 2 to level 1) in case of spontaneous emission

$$R_{21} \propto N_2$$
$$R_1 = A_{21} N_2$$

Where

R_{12} **: electron transition from level 2 to level 1**

N_2 **: represent the density of atoms in energy levels** E_2

A_{21} **: Einstein coefficient of spontaneous emission**

7.3 stimulated emission

R_{21} **(indicating an electron transition from level 2 to level 1) in case of stimulated emission**

$$R_{21} \propto N_2 \rho_f$$
$$R_{21} = B_{21} N_2 \rho_f$$

Where

R_{21} **: electron transition from level 2 to level 1**

ρ_f **: spectral density**

N_2 **: represent the density of atoms in energy levels** E_2

B_{21} **: Einstein coefficient of absorption.**

the sum of the spontaneous and stimulated contributions

$$R_{21} = N_2 A_{21} + B_{21} N_2 \rho_f$$

For a system in thermal equilibrium, the upward and downward transition rates must be equal and therefore$R_{12} = R_{21}$, or

$$B_{12} N_1 \rho_f = N_2 A_{21} + B_{21} N_2 \rho_f$$

It follows that:

$$\rho_f = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

and:

$$\rho_f = \frac{A_{21}/B_{21}}{(B_{12} N_1 / B_{21} N_2) - 1} \tag{1}$$

considering the atomic system to be in thermal equilibrium such that the rate of the upward transitions must equal the rate of the downward transitions. The population of the two energy levels of such a system is described by Boltzmann statistics which give:

$$\begin{aligned}\frac{N_1}{N_2} &= \frac{g_1 \exp\left(-E_1/KT\right)}{g_2 \exp\left(-E_2/KT\right)} \\ &= \frac{g_1}{g_2} \exp\left(E_2 - E_1/KT\right) \\ &= \frac{g_1}{g_2} \exp(hf/KT)\end{aligned} \tag{2}$$

from the equation, we notice that $E_2 > E_1$, therefore $\dfrac{N_1}{N_2} \uparrow\uparrow$, therefore $N_1 >> N_2$.

Substituting Eq. (2) into Eq. (1) gives:

$$\rho_f = \frac{A_{21}/B_{21}}{[(g_1 B_{12}/g_2 B_{21}) \exp(hf/KT)] - 1} \tag{3}$$

To emit laser, we need $N_2 > N_1$, which introduce us to the mechanism of population inversion (next lecture)

However, since the atomic system under consideration is in thermal equilibrium it produces a radiation density which is identical to black body radiation. Planck showed that the radiation spectral density for a black body is given by :

$$\rho_f = \frac{8\pi h f^3}{c^3}\left[\frac{1}{\exp(hf/KT)-1}\right] \tag{4}$$

Comparing Eq. (4) with Eq. (3) we obtain the Einstein relations:

$$B_{12} = \left(\frac{g_2}{g_1}\right) B_{21} \tag{5}$$

and:

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{c^3}$$

It may be observed from Eq. (5) that when the degeneracies of the two levels are equal ($g_1 = g_2$), then the probabilities of absorption and stimulated emission are equal. Furthermore, the ratio of the stimulated emission rate to the spontaneous emission rate is given by:

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{\exp(hf/KT)-1}$$

This indicates indicates that for systems in thermal equilibrium spontaneous emission is by far the dominant mechanism.

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4. Q How to increase stimulated emission compared to spontaneous emission ?

4. A Increase number of incoming photons

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5. Q How to increase stimulated emission compared to absorbtion ?

5. A By Population inversion (make $N_2 > N_1$)

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6. Q Calculate the ratio of the stimulated emission rate to the spontaneous emission rate for an incandescent lamp operating at a temperature of 1000 K. It may be assumed that the average operating wavelength is 0.5μm.

6. A The average operating frequency is given by:

$$f = \frac{c}{\lambda} = \frac{2.998 \times 10^8}{0.5 \times 10^{-6}} \simeq 6.0 \times 10^{14} \text{ Hz}$$

Using Eq. (6.11) the ratio is:

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{1}{\exp\left(\frac{6.626\times10^{-34}\times6\times10^{14}}{1.381\times10^{-23}\times1000}\right)}$$

$$= \exp(-28.8)$$

$$= 3.1\times10^{-13}$$

MCQ Questions

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1. Q **What is the wavelength range of visible light?**

(a) 200 nm - 400 nm

(b) 400 nm - 700 nm

(c) 700 nm - 1000 nm

(d) 1000 nm - 1300 nm

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2. Q **Which bias should be applied to a light source?**

(a) Reverse bias

(b) No bias

(c) Forward bias

(d) Both forward and reverse bias

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3. Q **Which bias should be applied to a light detector?**

(a) Reverse bias

(b) No bias

(c) Forward bias

(d) Both forward and reverse bias

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4. Q **What is the unit of responsivity?**

(a) Watts per Volts

(b) Amperes per Volts

(c) Volts per Watt

(d) Amperes per Watt

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5. Q

Which of the following is the most suitable wavelength for fiber optic communication in the first window?

(a) **500 nm**

(b) **850 nm**

(c) **1300 nm**

(d) **1550 nm**

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6. Q **Which of the following is the most commonly used wavelength in the second window for fiber optic communication?**

(a) **850 nm**

(b) **1310 nm**

(c) **1550 nm**

(d) **2000 nm**

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7. Q **What does the acronym LASER stand for?**

(a) **Light Absorption by Saturated Emission of Radiation**

(b) **Light Amplification by Saturated Emission of Refraction**

(c) **Light Absorption and Stimulated Emission of Refraction**

(d) **Light Amplification by Stimulated Emission of Radiation**

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8. Q **Einstein coefficient of spontaneous emission**

(a) $\boldsymbol{A_{21}}$

(b) $\boldsymbol{E_{21}}$

(c) $\boldsymbol{B_{21}}$

(d) $\boldsymbol{N_{21}}$

9. Q **In Population inversion**

(a) $N_2 < N_1$

(b) $N_2 > N_1$

(c) $N_2 = N_1$

(d) None of the above

10. Q **Population inversion is a mechanism to :**

(a) increase stimulated emission compared to spontaneous emission

(b) increase absorption compared to increase stimulated

(c) increase spontaneous emission compared to absorption

(d) increase stimulated emission compared to absorption

11. Q **Increasing the number of incoming photons leads to**

(a) increase stimulated emission compared to spontaneous emission

(b) increase absorption compared to increase stimulated

(c) increase spontaneous emission compared to absorption

(d) increase stimulated emission compared to absorption

Answers :

$\boxed{\textbf{1. A}}$ (b)

$\boxed{\textbf{2. A}}$ (c)

$\boxed{\textbf{3. A}}$ (a)

$\boxed{\textbf{4. A}}$ (d)

$\boxed{\textbf{5. A}}$ (b)

$\boxed{\textbf{6. A}}$ (b)

$\boxed{\textbf{7. A}}$ (d)

$\boxed{\textbf{8. A}}$ (a)

$\boxed{\textbf{9. A}}$ (b)

$\boxed{\textbf{10. A}}$ (d)

$\boxed{\textbf{11. A}}$ (a)