Test Device Physics –
Photonic Devices
Bachelor (2) *(EE)(EEMCS)*

Module/course code: module 7a/201400430
Date: April 8th 2016
Time: 13:45 – 15:15 *(+25% for students who may use extra time)*
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Instructor: Sonia M. Garcia Blanco, Jeroen Korterik, Michiel de Goede, Pablo Munoz Galindo
Allowed aids during the test: (Scientific) calculator

Exercise 1: Photonics

[1 point] What is photonics? Give examples of two photonics devices to generate light, two devices to manipulate/route light and two devices to detect light. Explain briefly how those devices operate.

Exercise 2: Transmission in optical waveguides

Consider the two designs of slab waveguides shown in Fig 1.

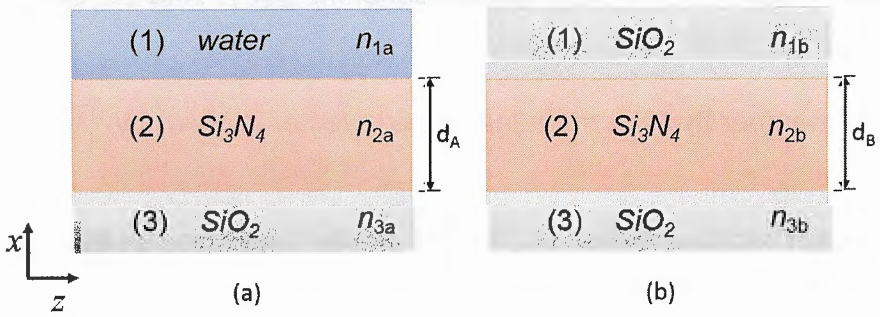


Figure 1 - Asymmetric (a) and Symmetric (b) Slab waveguides

Both structures are infinite in the "y" direction. The parameters of the design and the value of the refractive index of the different materials are given in the table below. Follow the different sections (A-D) in order to study these structures by applying the ray optics approach.

λ_0 = 785 (nm)	n_{water} (785 nm) ≈ 1.33
d_A = 5 (µm)	n_{Si3N4} (785 nm) ≈ 2
d_B = 1 (µm)	n_{SiO2} (785 nm) ≈ 1.45

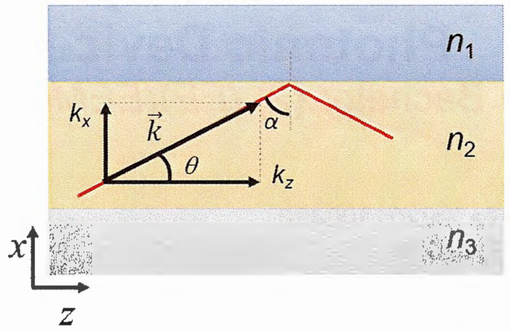


Figure 2 – k vector of a waveguide traveling inside a slab waveguide

A) [0.5 points] Calculate the critical angles (α_{c1}, α_{c2}) for the interfaces between the different media of the waveguide shown in Fig 1a. The angles are described in Figure 2. What is the condition for having total internal reflection at both interfaces simultaneously in this structure?

B) [0.5 points] A representation of the k-vector ($\vec{k}$) of a wave traveling inside the core of the waveguide structure can be seen in Fig 2. Find the expressions of the different components of the k-vector depending on the incidence angle (θ). What is the expression of the propagation constant $\beta(\theta)$? And the expression of the effective refractive index n_{eff} (θ) ?

Hint: remember that the modulus of the k-vector is given by $|\vec{k}| = n_2 \cdot k_0$

C) [1 points] Calculate the number of TE modes supported by the waveguide represented in Fig 1b.

Hint 1: *The transverse resonance condition is given by:*

$$[1] \quad \Delta\Phi = 2 \cdot d \cdot k_x - \varphi_1 - \varphi_3 = m\, 2\pi \quad ; \quad m = 0,1,2, \ldots N$$

Hint 2: *The phase delay introduced after reflection in the interface of the medium 2 and the medium 1/3 (φ_1 , φ_3) for a TE mode is given by:*

$$[2] \quad \varphi_i = 2 \cdot \tan^{-1}\left(\frac{\sqrt{{n_2}^2 sin^2\alpha - {n_i}^2}}{n_2 cos\alpha}\right)$$

Hint 3: *Start by making $\alpha = \alpha_c$ (cutoff condition) in expressions [1] and [2]. The number of TE modes (N) must be an integer. Round the result to the nearest integer up, if necessary.*

D) [1 points] The Self-consistency condition for the previous structure (for TE modes) is given by the following expression:

$$[3]\quad tan\left(\pi\frac{d\ \cdot n_2\cdot\sin\theta}{\lambda_0}-m\frac{\pi}{2}\right)=\sqrt{\frac{\sin^2\theta_c}{\sin^2\theta}-1}$$

(Where you can notice that $\theta_C+\alpha_C=\frac{\pi}{2}$). By solving this equation, it is possible to calculate the angles (θ) for the different TE modes that can travel through the waveguide. Unfortunately, it is not possible to find an analytical solution to this equation. Thus, a graphical solution is often the preferred method in order to solve the equation and find the different values of sin(θ). The graphical solution, in case of the slab waveguide of this exercise, can be seen in Fig 3. The different solutions have been labeled for your convenience.

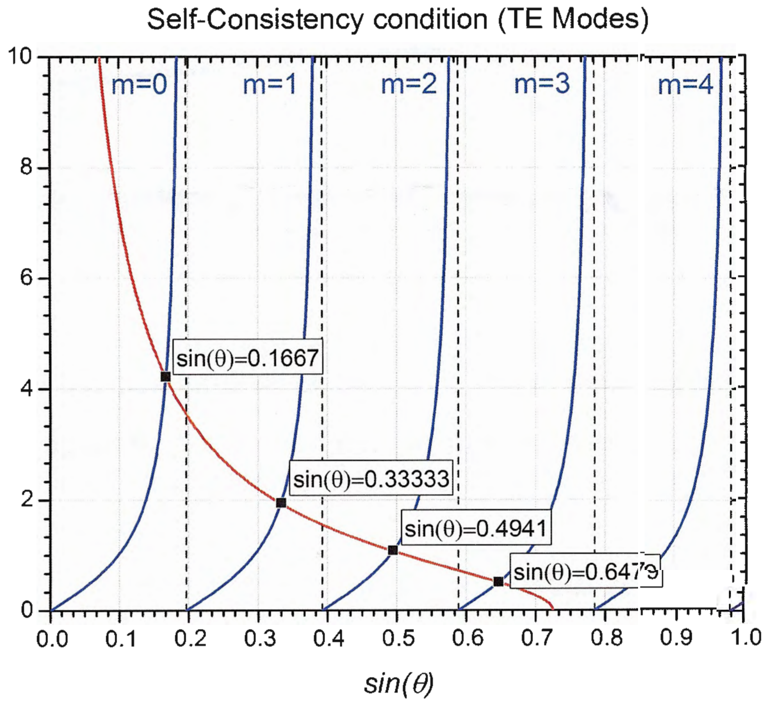


Figure 3 – Self consistency condition for the slab waveguide (for TE modes)

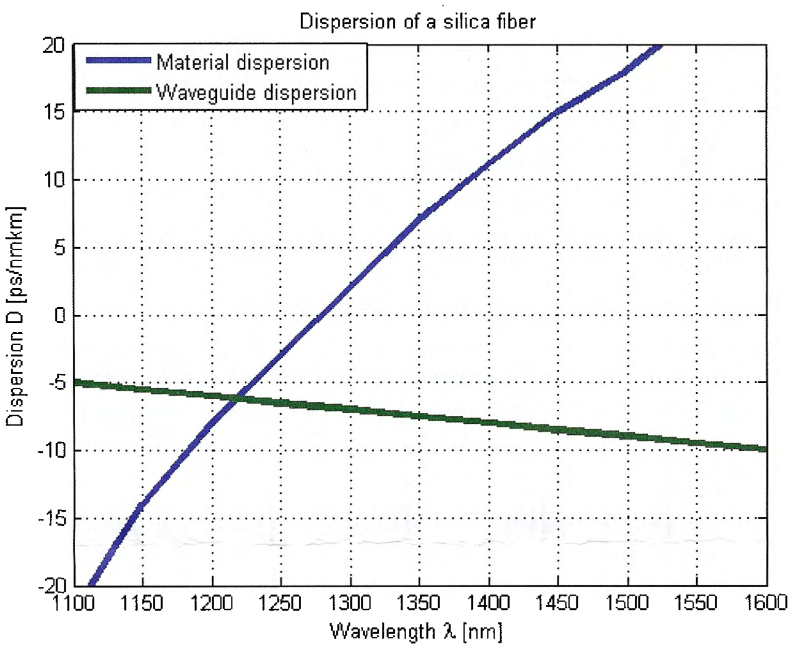
For each mode, calculate:

- Bounce angle (θ_i)
- Effective refractive index ($n_{eff,i}$)

E) [0.5 point] From the modes that you calculated in the previous question, which mode travels the fastest through the waveguide? Which one travels the slowest?

F) [0.5 point] What is the meaning of intermodal dispersion in a multi-mode waveguide? How does it affect the rate of data transfer through the waveguide?

G) [0.5 point] Consider the following typical dispersion diagram of a single-mode silica waveguide:



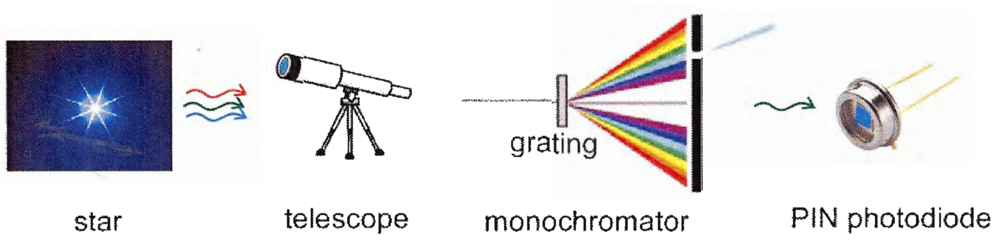
At what wavelength would you achieve the highest data transfer rate? What other effects not included in this graph would limit the actual data transfer?

H) [0.5 point] Estimate the highest data transfer rate through a 3 km long silica single-mode waveguide (fiber) that is operated with a 1170 nm LED with a 20 nm bandwith.

<u>Exercise 3: Photodetectors</u>

The measurement of the (optical) radiation spectrum of a star is a very useful method in astronomy as it tells something about the chemical composition of the star and about its (relative) speed.

Below is a schematic representation of a possible setup to perform this measurement:



The spectrum coming from the star is captured by a telescope, the monochromator only transmits 1 wavelength (color of light) at a time and this signal is measured in the example on a simple PIN photodiode. Next, another wavelength is selected by the monochromator, it's measured again and so on until all wavelengths of interest are measured.

A) [1 point] Consider a passive load for the PIN photodiode: a resistor connected between the anode and cathode of the photodiode and no external bias voltage applied to the diode. What gives the best linearity in the measurement: a low value resistance or a high value resistance for this load? Explain this by drawing current vs. voltage curves (VI curves) of the diode at different light levels and drawing the load lines for the different resistance values.

B) [1 point] Why could biasing the photodiode lead to a better linearity in our measurement? Explain this by drawing the load line in the current vs. voltage diagram again.

The photodiode datasheet mentions the following specifications:

NEP : 10fW / $\sqrt{Hz}$ @ 800nm
Quantum efficiency : 80% @ 800nm
Responsivity : 0.3 A/W @ 600 nm

C) [1 point] Calculate the NEP at 600nm

D) [1 point] If the load resistor and/or electronics that are used to process the photodiode current suffer from too much noise to measure the signal at the desired speed, what alternatives we can use instead of the photodiode plus load resistor? Give one example of a photodetector and explain what mechanism helps us to improve the overall signal to noise ratio in that case.

<u>Useful values</u>:

speed of light: 3.0×10^8 m/s
electron charge: 1.6×10^-19 C
h (Planck's constant): 6.6×10^-34 Js