UNIVERSITE PARIS SUD **Année 2015-2016**
CENTRE SCIENTIFIQUE D'ORSAY 16 février 2016

Optoelectronics

Duration: 3 hours

- Documents and calculators are not allowed. A calculator will be provided if needed.
- Please turn off your mobile phones.
- Please write your response of parts A, B and C on separate copies

Part A

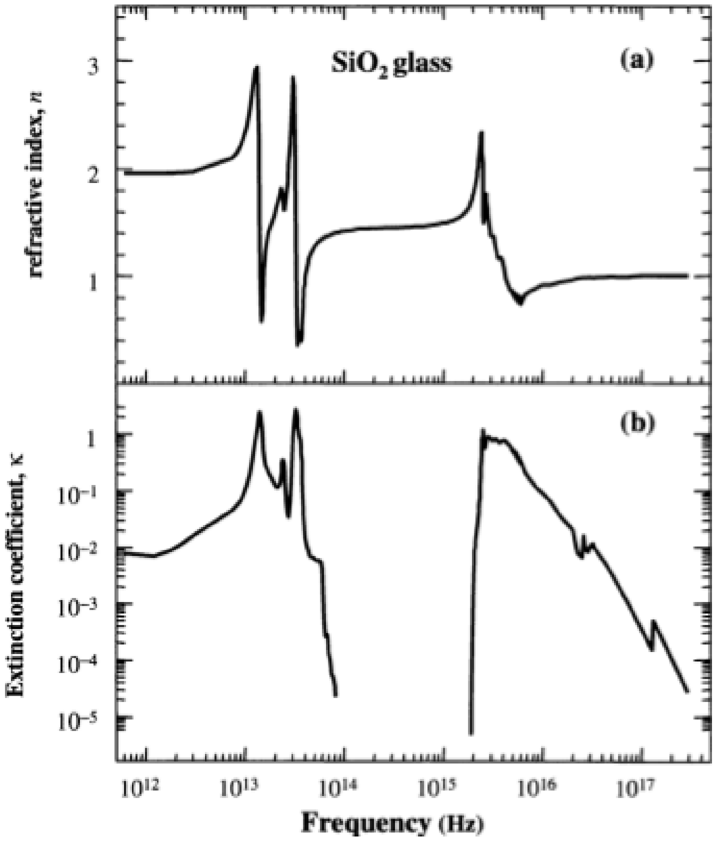
Materials for optoelectronics:

1) What can you say about the silicon as a material for optoelectronics ? Give the real and imaginary part of the refractive index of silicon at a wavelength of 1.55 µm.

2) What is the main application of lithium niobate in optoelectronics. Why ?

3) Give the name of a family of semiconductors that can be used for light emission at telecommunication wavelength of 1.55 µm. How the emission wavelength can be tuned ?

Light-matter interaction:



The previous figure represents the measured real and imaginary part of the refractive index of silica. Near the frequencies 10^{13} Hz and $3.5\text{x}10^{13}$ Hz, a particular pattern appears twice.

4) What is the name of a classical model that describes atom-light interaction and explains this particular pattern ?

5) What are the hypotheses of this classical model ? What are the limitations of this model ?

6) On these curves, the maxima of absorption correspond to a rapid variation of the real part of the refractive index. This particular behavior is related to the Kramers-Kronig relations. Explain what are these relations. In particular, what is the general physical principle that implies the Kramers Kronig relations ?

7) What is the necessary condition, known as the Bernard-Durrafourg condition, to get optical gain in a semi-conductor such as GaAs ?

8) What are the main characteristics of semiconductor amplifiers? How they compare to other amplifiers that you know ?

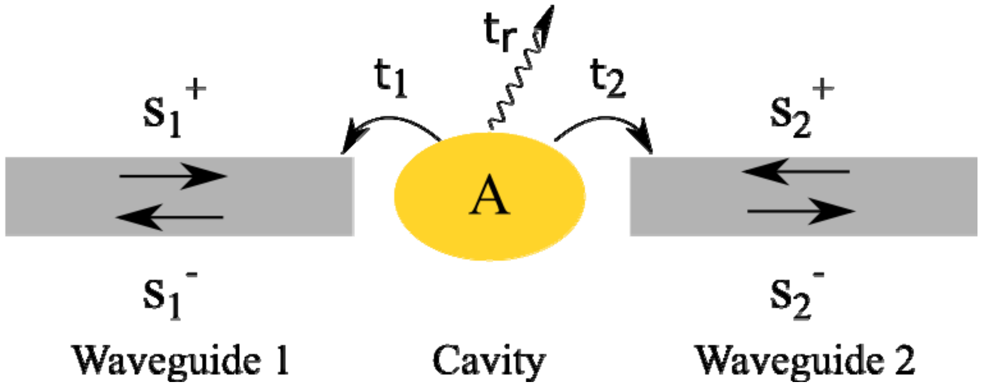
Waveguides

9) Draw a schematic view of a ridge waveguide and a rib waveguide.made in silicon on insulator. Give their typical sizes for a wavelength of 1.55 µm

10) Give the typical value of the losses of the two waveguides when they are fabricated in silicon. Explain the origin of the loss difference. What can you say about the bending losses of the two kinds of waveguide ?

Problem: Cavities

We consider a cavity coupled to two access waveguides as shown on the following figure.



The incident field in the waveguide 1 has a pulsation ◆. The cavity resonance pulsation is ω_0. We note $\Delta\omega=\omega_0-\omega$

A is the slowly varying amplitude of the electric field of the resonant mode normalized such that $|A|^2$ is the energy stored in the cavity (in Joule unit).

t_r, t_1, t_2, are respectively the characteristic coupling time of the cavity to free space, waveguide 1 and waveguide 2. They characterize the different channel of losses of the cavity (to free space, to the waveguide 1 and to the waveguide 2).

$|S^+_i|^2$ and $|S^-_i|^2$ are respectively the incident and reflected power in the waveguide i (with i=1, 2).

It can be shown that the evolution of the amplitude inside the cavity can be described by the two equations:

$$\frac{dA}{dt} = i\Delta\omega A - \left(\frac{A}{2t_1} + \frac{A}{2t_2} + \frac{A}{2t_r}\right) + \frac{s_1^+}{\sqrt{t_1}} + \frac{s_2^+}{\sqrt{t_2}} \text{ and } s_i^- = -s_i^+ + \frac{A}{\sqrt{t_i}}$$

First, we suppose that there is no light incident on the cavity but that there is some energy stored in it. In this case we have $\Delta\omega=0$. The quality factor of a cavity is defined as

$$Q = 2\pi \frac{\text{energy stored in the cavity}}{\text{energy lost per cycle}}$$

11) Show that $Q=\omega_0 t_{eq}$ with t_{eq} a time that you will define. (Hint: you can calculate $\frac{d|A|^2}{dt}$ as a function of $|A|^2$)

We now consider the steady state ($\frac{dA}{dt} = 0$), when light is incident from waveguide 1 to the cavity with a pulsation ω. Note that $s_2^+ = 0$. We also consider the following simplification: $t_1=t_2$.

12) Calculate the energy stored in the cavity as a function of the incident power.

13) Calculate the power in the waveguide 2 as a function of the stored energy in the cavity.

14) Calculate the transmission spectrum $T(\omega) = \left|\frac{s_2^-}{s_1^+}\right|^2$. What is the value of the maximum of the transmission? How the full width at half maximum of the transmission spectrum is related to the Q factor?

15) Calculate the value of $\left|s_1^-\right|^2$, i.e. the reflected power from the cavity back to the waveguide 1 as a function of $\Delta\omega$, t_1 and t_{eq} and s_1^+ .

We consider now the particular case $\frac{1}{t_1} = \frac{1}{t_r}$ and $\Delta\omega=0$.

16) What is the expression for the reflected power in the waveguide 1. How do you interpret this particular condition known as critical coupling?

We are interested in determining experimentally the energy stored in the cavity. Experimentally, we cannot directly measure the coupling time t_r or t_1. However, we can measure the Q factor, the maximum of the transmission spectrum and the incident power in the waveguide 1.

17) These three values can be measured but the measurement of the power circulating inside the waveguides need a particular care. Can you explain what is the origin of this difficulty ?

18) Show that the energy in the cavity can be deduced from ω_0, the Q factor, the maximum of the transmission spectrum and the power $\left|s_1^+\right|^2$. Write a similar expression where the power in the waveguide 1 is replaced by the power in the waveguide 2.

Because the energy stored in the cavity is particularly high, a nonlinear effect occurs. This nonlinear effect is responsible for the appearance of the supplementary loss term equal to $-\beta\left|A\right|^2 A$ where β is an unknown constant.

19) Without any calculation explain why the energy in the cavity cannot be deduced experimentally from the incident power (hint: what can you say about the reflected power ? About the critical coupling ?)

20) Write the new differential equation verified by A and show that the energy stored in the cavity is equal to a constant times the power circulating in the output waveguide 2, $\left|s_1^-\right|^2$. Show that this constant can be deduced from the measurement of the Q factor, and of the transmission maximum measured at very low power.

Part B

Diode lasers

1. Can you explain in a simple schematics the different phenomenon that we can observe in light matter interaction (you can take a system with two levels of energies E_1 and E_2). Which phenomenon give rise to laser emission, what can you say about the emitted photons?
2. What are the three elementary parts needed to build a laser cavity.
3. Can you explain in a simple schematics the difference between direct band gap and indirect band gap semiconductors? Please give an example of semiconductors used for laser diode active regions. Why do we use this type of semiconductors?

   Figure B-1 is a typical optical output as function of the drive current of a laser diode.

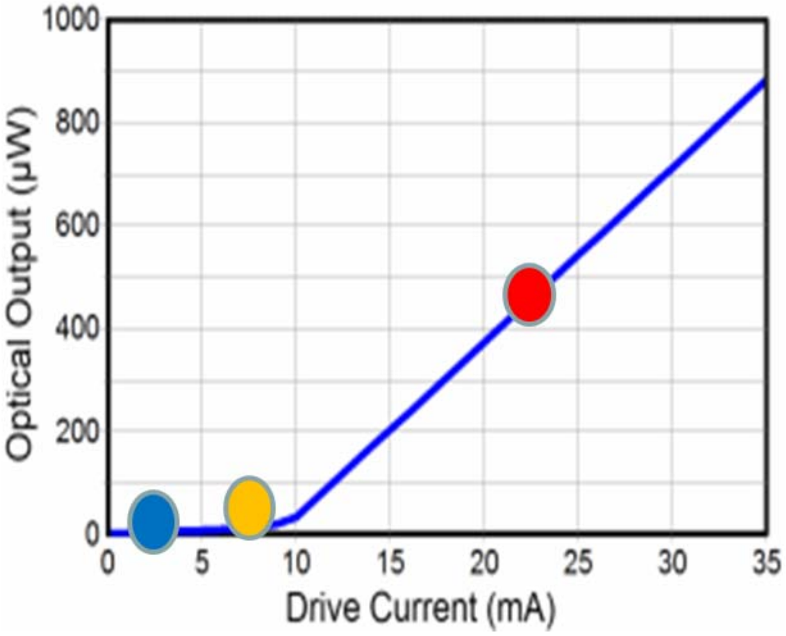


Figure B-1

4. Can you comment on the three colorized zones of this curve?
5. What is the threshold of this laser? What is the value of the wall plug efficiency (dP/dI)?
6. How the threshold and the wall plug efficiency changes if the mirror losses became higher?
7. What happens if the waveguide losses became higher?

Quantum Cascade Lasers

8. What is the wavelength range of Mid-Infrared, which are the main applications?
9. What are the main sources that exist in this range of wavelength?
10. What is the main difference between diode lasers and quantum cascade lasers.
11. Explain the operating principle of a quantum cascade laser, how can we tune the operating wavelength?
12. What are typical now days quantum cascade lasers features in the mid-Infrared (wavelength, maximum operating temperature, maximum power…)

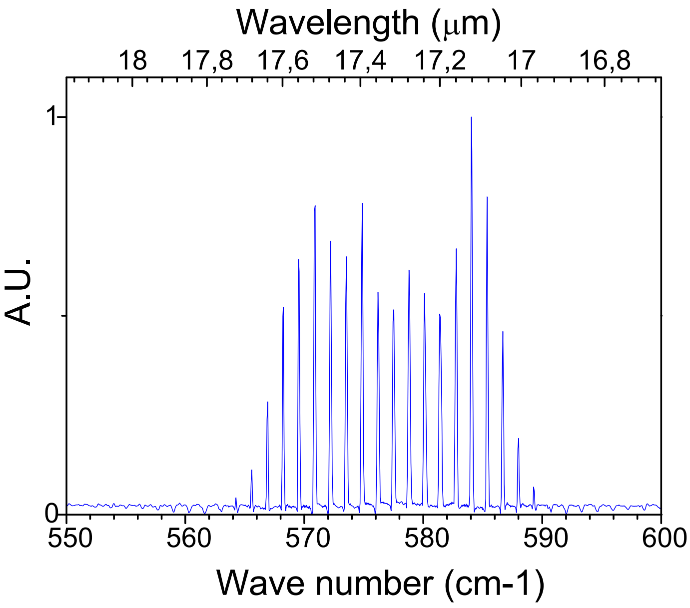


Figure B-2

Figure B-2 gives the collected spectrum of a quantum cascade laser

13. At which wavelength this laser operate?
14. From the given spectrum, what is the type of the laser cavity? Explain the longitudinal mode selection in this type of cavity (you can provide a simple schematics).
15. If we assume that the index group velocity is ng_{eff}= 3.6, what is the cavity length of this laser.

The Figure B-3 is a colorized scanning electronic microscopy of an emission facet of quantum cascade laser.

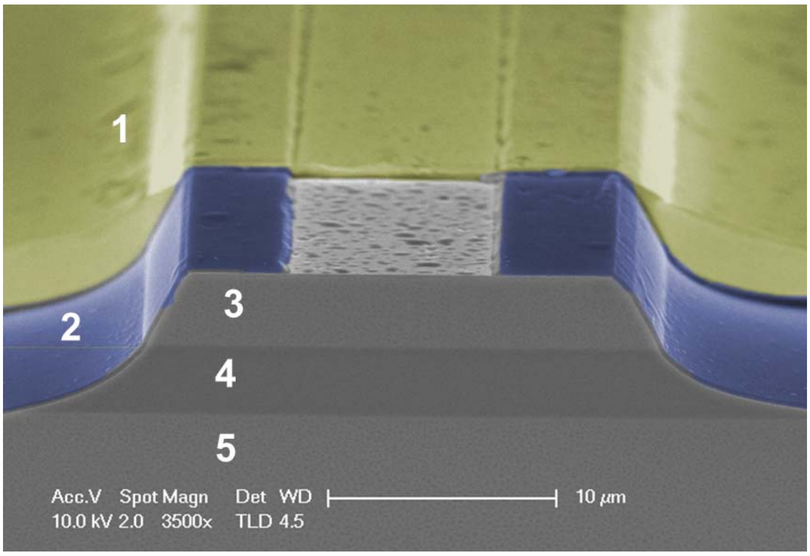


Figure B-3

16. From this image what can you tell about the laser type mirror cavity, the optical waveguide and the vertical mode confinement?
17. What are the zones 1, 2, 3, 4 and 5 of the image?
18. Enumerate the different fabrication steps to get the quantum cascade laser shown if the figure B-3?

Quantum Well Infrared Photodetector

19. What are the main families of existing detectors in the mid-infrared? Explain the principle of operation of each family.
20. Explain using a schematics the principle of operation of a quantum well infrared photodetector. What is the dark current? How does it change as function of the temperature? And as function of doping level?
21. What is the definition of the responsivity? In which units is it given?

The Figure B-4 give the normalized responsivity of GaAs/AlGaAs based quantum well infrared photodetector.

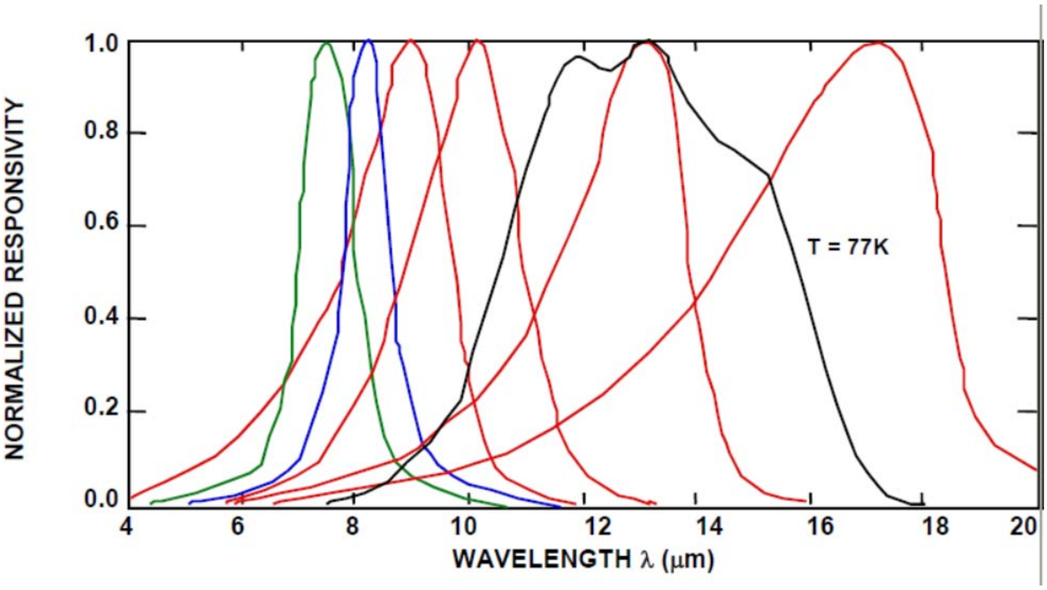


Figure B-4

22. How could we obtain the wavelength tuning response in the GaAs/AlGaAs system?
23. What is the typical full width at half maximum (FWHM)? What is the physical origin of the FWHM? Can we expect to have larger FWHM? How?
24. Explain the principle of operation of a quantum cascade photodetector. What is the difference with a quantum well infrared photodetector?

Part C

Exercise: dynamics of a high-speed semiconductor laser

1. The semiconductor laser is an important element in fiber optic links since it generates the coherent optical wave that carries the signal. To this end, direct modulation of semiconductor lasers is a promising solution for all-optical access networks. Fig. 1 shows the modulation response of a directly-modulated quantum well (QW) laser measured for various pump currents ranging from 1 to 4 mA.

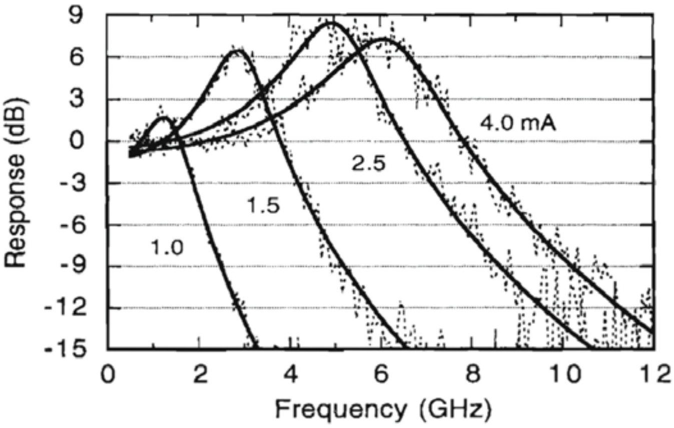


Figure 1

Briefly comment Fig. 1 and discuss what is important for high-speed applications.

2. The semiconductor laser is traditionally modeled by the following rate equations

$$\frac{dp}{dt} = \left[G_N(N - Nt) - \frac{1}{\tau_P} \right] p \tag{1}$$

$$\frac{dN}{dt} = \frac{J}{e} - \frac{N}{\tau_s} - G_N(N - N_t)\,p \tag{2}$$

with N the carrier density, N_t the carrier density at the optical transparency, p the output power, J the pump current, G_N the differential gain (or dynamic gain), τ_P the photon lifetime, τ_s the carrier lifetime and e the elementary charge of the electron.
a) Using the steady-state conditions (d/dt=0), show that the carrier density at threshold is given by,

$$N_{th} = N_t + \frac{1}{G_N \tau_P} \tag{3}$$

b) Verify that the steady state power can be expressed such as,

$$p_0 = \tau_P \left[\frac{J}{e} - \frac{N_{th}}{\tau_s} \right] \tag{4}$$

3. Using a small-signal analysis, it is possible to extract from the rate equations the relaxation oscillation (RO) frequency of the laser which is given by,

$$f_R = \frac{1}{2\pi} \sqrt{\frac{G_N p_0}{\tau_P}} \tag{5}$$

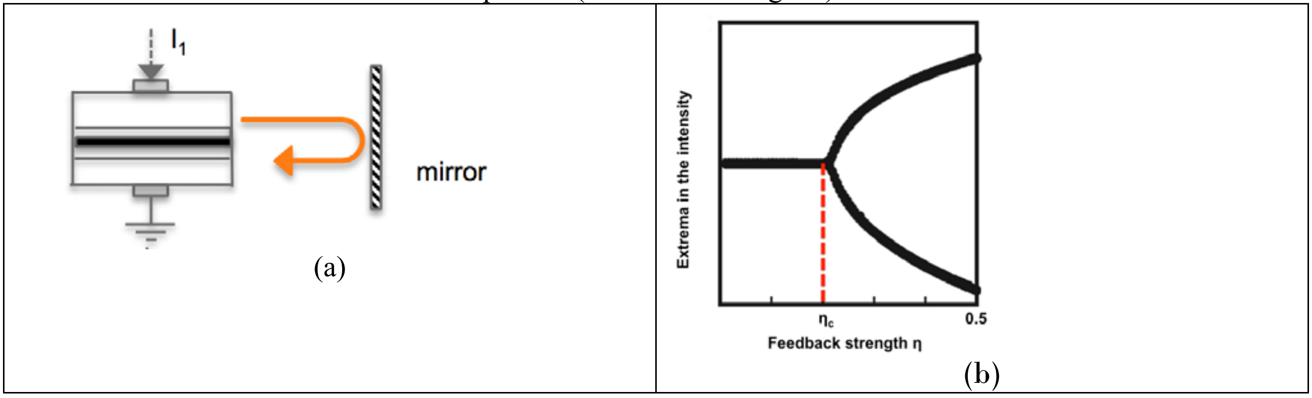
Based on (5) explain qualitatively and in a few sentences some straightforward ways to increase the RO frequency either by changing the material or the device properties.

4. Assuming that a large electron density N_t is not needed to achieve optical transparency, show that the RO frequency can be reformulated as,

$$f_R = \frac{1}{2\pi}\sqrt{\frac{1}{\tau_P \tau_S}\left(\frac{J}{J_{th}} - 1\right)} \tag{6}$$

with J_{th} the pump current at threshold.
Considering $J/J_{th}=1.3$, $\tau_P=1$ ps, $\tau_P=1$ ns, calculate the RO frequency of the laser in GHz. How will change the modulation response in case of a strong damping rate Γ ($\Gamma >> f_R$).

5. Now it is assumed that a small part of the emitted light from the semiconductor laser is fed-back into the cavity (Fig. 2a). The strength of the optical feedback is controlled by the parameter η that is defined as the ratio between the reflected and emitted powers (not shown in Fig. 2a).



(a)

(b)

Figure 2

a) Fig. 2b depicts the bifurcation diagram of the laser. Extrema of the intensity output I(t) are plotted as a function of η which is progressively changed from small to large values. Comment the bifurcation diagram and plot the time traces of I(t) for $\eta < \eta_c$ and $\eta > \eta_c$.
b) Beyond a certain feedback level, the laser enters within the coherence collapse regime. Explain in a few sentences the signification of this regime and its consequences on a communication system.
c) The optical linewidth of the laser subject to optical feedback can be expressed as follows,

$$\Delta\nu = \frac{\Delta\nu_0}{\left[1+\eta\cos\left(\varphi+\tan^{-1}\left(\alpha_H\right)\right)\right]^2} \tag{7}$$

with $\Delta\nu_0$ the optical linewidth of the laser without feedback, α_H the linewidth broadening factor, and φ the phase of the delayed field. From (7), find the conditions leading to the maximum and minimum optical linewidths [$\Delta\nu_m$, $\Delta\nu_M$]. Considering $\eta=0.2$ and $\Delta\nu_0 = 5$MHz, determine $\Delta\nu_m$ and $\Delta\nu_M$.