Centre Scientifique d'Orsay **Année 2016-2017**

Université Paris-Sud

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Université Paris Saclay

Optoelectronics

M2 Nanosciences: nano-dispositifs
M2 Composants et Antennes pour les Telecoms
M2 Réseaux Optiques et Systèmes Photoniques

Duration: 3 hours

- Documents and calculator 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 and report your anonymous number on each copy.**

Part A

Materials for optoelectronics:

1) Define the bandgap of a semiconductor. What is a direct band gap and an indirect band gap ? Give an example of semiconductors of each kind. In optoelectronics applications, what is the crucial difference between a direct and an indirect band gap semiconductor ?

2) Give the name of two wide-band gap semiconductors. What can are the applications of such wide-band gap semiconductors.

3) What silicon compatible material is used to produce high performance photodetectors in "silicon" photonics? Why ?

Light-matter interaction:

4) Give the name of two models that can describe atom-light interaction. What are the strengths and limitations of these models ?

5) Explain with words what are the Kramers-Kronig relations. What is the general physical principle that implies these Kramers-Kronig relations ? What are their main consequence in optoelectronics ?

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

Waveguides, cavities and couplers :

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

8) 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 ?

9) Why is it difficult to inject light into an integrated optical waveguide from a standard optical fiber? Give two technical solutions, which you will explain with the help of diagrams, to remedy this problem.

10) Describe the operation of an optical modulator made of $LiNbO_3$ (lithium niobate). What is the physical effect used to get an interaction between the optical wave and the electrical signal ?

11) Draw a schematic view of a directional coupler. Explain with words its functioning.

12) An integrated circuit:

a) What is the integrated circuit represented on the scanning electron microscope image below ? Explain its functioning. In particular, why are there two rings ?

b) Sometimes, some electrical wires are added above the rings (figure below right). When an electrical current circulates in these wires, heat is generated on top of the ring resonator. What can be the effects of this heating on the silicon ring? On the whole circuit?

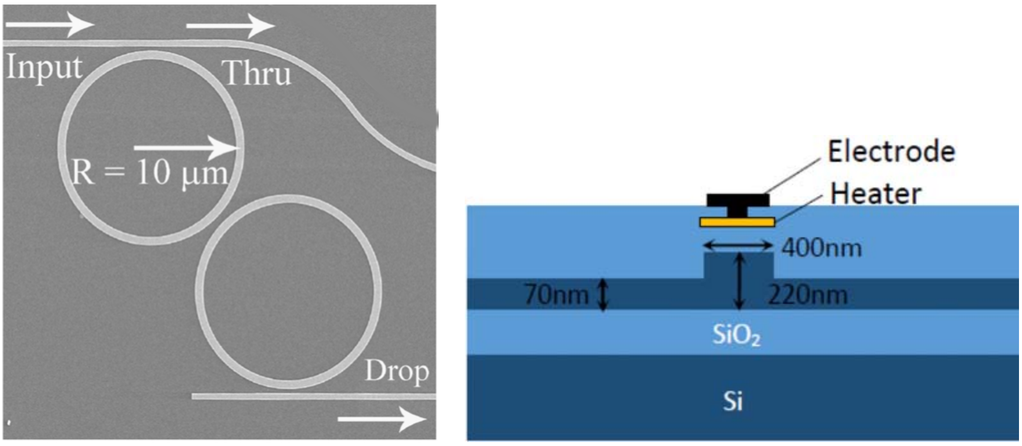


Figure 1 : (left) scanning electron microscope (SEM) view of an integrated circuit (without heaters). Right : schematic view of an electric heater on top of an optical waveguide.

Problem: Optical amplifier

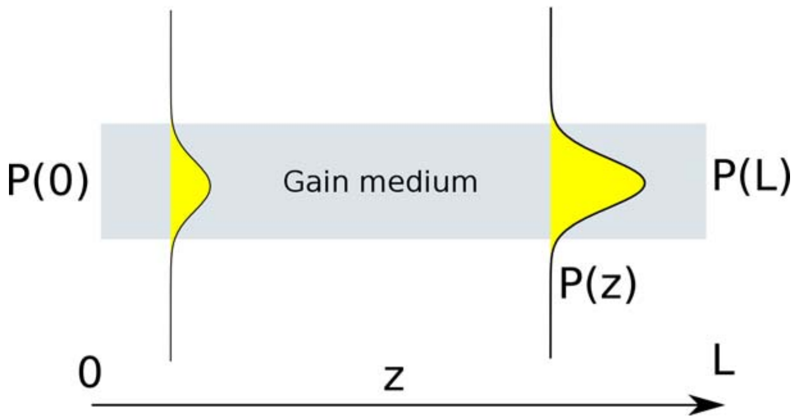
13) Give the name of two kinds of optical amplifiers. For each kind of amplifier, give a remarkable property and application.

We are interested in the optical bandwidth of an amplifier. To simplify the calculations, we assume a spectral dependence of the gain of the amplifying medium of the form :

$$g_0(\nu) = \frac{C_0}{1 + (2\pi T_2)^2(\nu - \nu_0)^2}$$

14) What is the optical bandwidth $\Delta\nu_g$ of this gain medium as a function of T_2?

During the propagation in an amplifier of length L made using the preceding amplifying medium, a continuous signal has its power P amplified from P(0) to P(L) according to $\frac{dP}{dz} = g_0(\nu)P$ where P(z) designates the power circulating in the amplifier. The effects of saturation are neglected here.



15) Give the power P(L) as a function of the parameters of the problem. Deduce the gain G = P(L) / P(0) of the amplifier. For which frequency is the gain of the amplifier maximum?

16) Show that the amplifier bandwidth $\Delta\nu_G$ depends on the gain coefficient bandwidth $\Delta\nu_g$ as :

$$\Delta\nu_G = \Delta\nu_g \sqrt{\frac{\ln(2)}{\ln\left(G_0/2\right)}}$$

where $G_0=\exp(C_0L)$.

17) Comment the value of the two bandwidths in the case where the gain G_0 = 30 dB. Schematically draw the gain of the medium and of the amplifier as a function of frequency.

The saturation power of the medium is now taken into account so that the gain of the amplifying medium is given by:

$$g(\nu) = \frac{g_0(\nu)}{1+P/P_s(\nu)}$$

with P the optical power circulating in the optical waveguide and P_s the saturation power.

18) Explain the origin of gain saturation. Give an important application of this effect in the case of semiconductor amplifiers.

19) We suppose that the power at the entrance of the amplifier, P(0), is large as compared to P_s. Calculate the power P(L) at the output of the amplifier.

20) What can you say about the amplifier bandwidth in this case ?

Part B

Diode lasers

1) Comment the data of **Figure 1**. What are the magnitudes on the "X" and "Y" axis? What relationships exist between the different magnitudes? What is the interest of the various semiconductor materials mentioned for the emission.

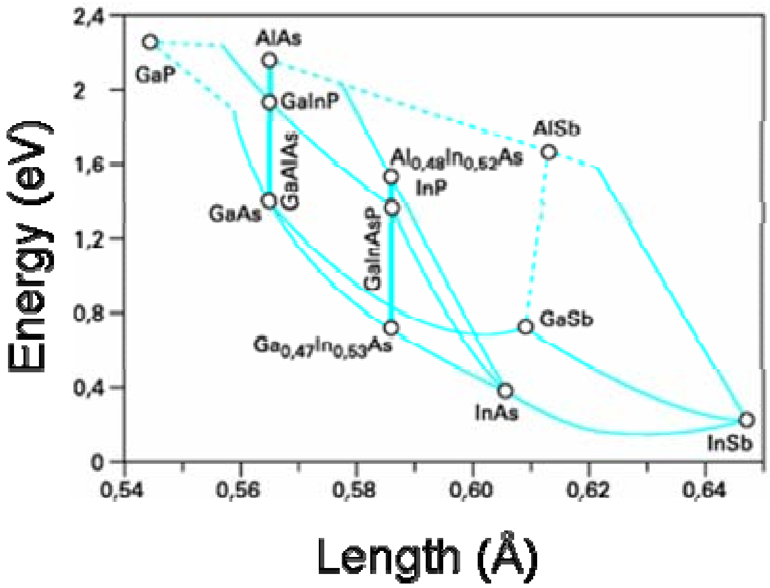


Figure B-1

2) We want to design an active region (Quantum well heterostructure) operating at wavelength λ = 1.55 µm.

a)- At which energy do it correspond? "*h*" (Planck constant) = 4.135667×10^{-15} eV.s, "*c*" (The speed of light in vacuum)=3×10^{8} m.s^{-1}

b)- What type of material can be considered and why?

3) We will consider the following alloy to design our quantum wells "$Ga_x In_{1-x} As_y P_{1-y}$". where "x" and "y" are real numbers ($0 \le x \le 1$, $0 \le y \le 1$) which express the fraction of concentrations of Ga and As respectively. For lattice match considerations with InP substrate, the concentrations of Ga and As has to respect the two following conditions:

-$y/x \approx 2,20$

-$0 \le x \le 0,47$

- The Energy band-gap follows the empirical law : Eg (eV) = $1,35-0,72y+0,12y^2$. Give the corresponding fraction concentrations (x and y) for a laser emission around λ = 1.55 µm.

4) What does the acronym LASER mean? Describe its operating principle. How many components are needed and how are they done in the case of a LASER diode?

5) What is the population inversion, how can we obtain it in LASER diode.

6) We Consider a Fabry-Pérot cavity of length "L" whose constituent medium has an optical refractive index "n" and whose two mirrors have a the same power reflection coefficient "R" respectively.

a)- Make a simple schematics to explain the principle of selection of optical frequencies.

b)- Draw the shape of the transmission curve through the cavity as a function of the photon energy (or wavelength).

7) The following equation gives the gain condition to have laser effect on the Fabry-Pérot optical cavity:

$$g_{threshold} = \frac{1}{\Gamma}\left(\alpha_w - \frac{1}{2nL}\ln\left(R_1 R_2\right)\right)$$

a)- Comment on the gain condition (you can use a small schematic)

b)- What is "Γ"?

c)- What is the expression of mirror losses?

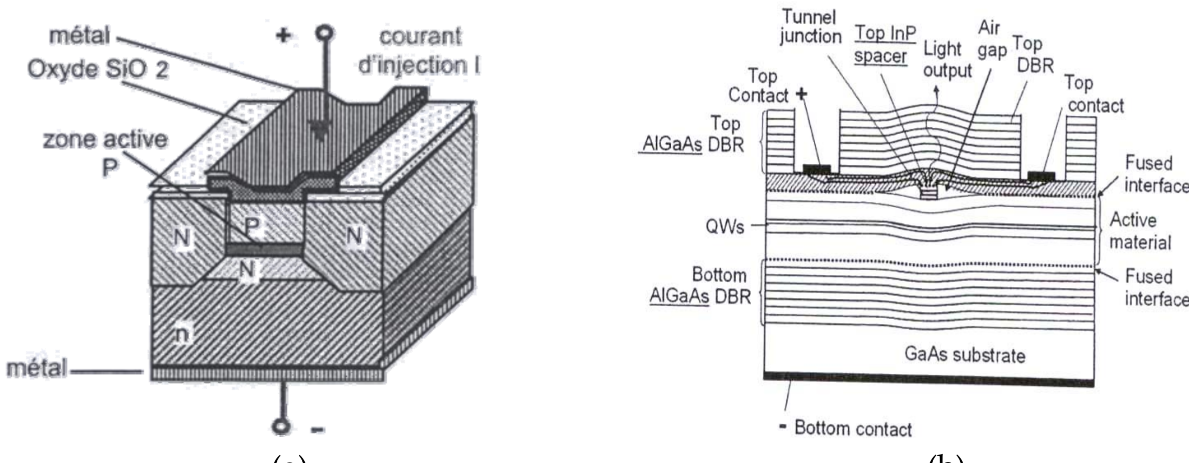
d)- Calculate the total optical losses in (cm^{-1}) if we consider the waveguide losses of $3cm^{-1}$ and (L=1.5mm) (R_1=R_2=0.3) (n=3.5).

8) In **Figure 2** we consider two semiconductor diode laser Fabry-Pérot cavities.

a)- Identify the main elements of the LASER diode.

b)-What is the interest of the two structures represented?

c)-What generic processing techniques are used to fabricate this diode?



(a) (b)

Figure B-2: (a) Diode LASER in ridge cavity, (b) vertical cavity surface emitting diode laser (VCSEL).

Quantum Cascade Lasers

1)- General questions:

a)- Where is located the Mid-Infrared range? What are the main applications?

b)- What are the main sources that exist in this wavelength range?

c)- Explain the operating principle of a quantum cascade laser, how can one set the operating wavelength range? What are the advantages of quantum cascade lasers compared to other existing sources?

d)- Explain how population inversion is achieved in a quantum cascade laser. What is the use of resonant tunneling in the active region?

2)- The figures bellow show the features of a quantum cascade laser at different sets of operating temperatures.

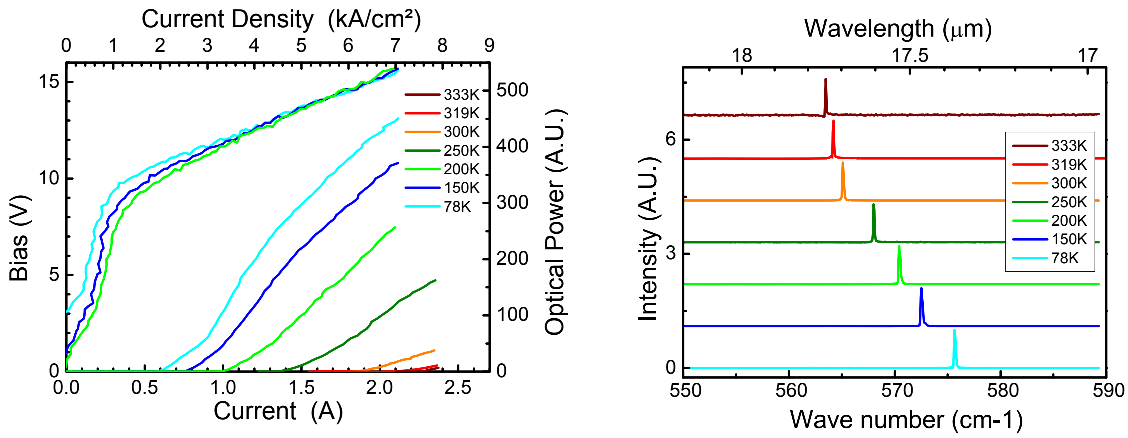


Figure B-3

a)-What are representing this two figures?

b)-Explain the physical reasons for the shape of the Bias curve as a function of the injected current.

c)- What is the threshold current density of this laser at room temperature?

d)- What is the operating wavelength range?

e)- Explain the shape of the spectra emitted by this laser (longitudinal modes).

f)- What can be deduced from the emitted spectra on the optical cavity of this laser? Explain the frequency selection rules in this cavity.

g) What solutions can be used to increase the wavelength tuning range (views in progress).

h)- What is typical now days quantum cascade lasers features in the mid-Infrared (wavelength, maximum operating temperature, maximum power ...)

Quantum Well Infrared Photodetector

1)- General questions:

a)- What are the main families of existing detectors in the mid-infrared? Explain the principle of operation of each family.

b)-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?

c)-What is the definition of the responsivity? In which units is it given?

2) We want to design a Mid-Infrared QWIP active region heterostructure using GaAs/AlGaAs material system.

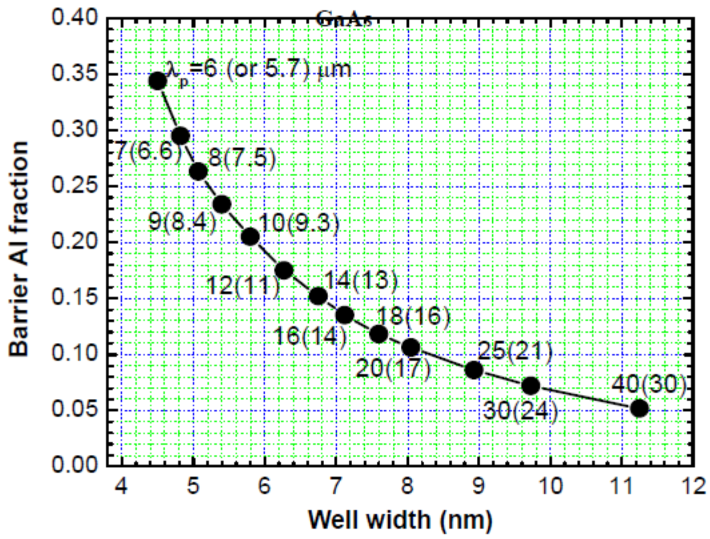


Figure B-4 the wavelength in between brackets is for doped wells

a)- What dose the figure B-4 represent?

b)- What is the thickness and alloy x fraction concetration $Al_xGa_{1-x}As$ that should be used to construct a detector operating at 14 µm (for an non-doped heterostructure)?

Part C

Exercise: modulation dynamics of a semiconductor laser

We consider a distributed feedback (DFB) semiconductor laser. The cavity is 300-µm long. The width and thickness of the active area is 1.2-µm and 0.2-µm respectively. The internal loss is given by the coefficient α_i=40 cm^{-1}, and the reflectivity (in intensity) of each facet is R_1=R_2=0.3.

1- The corpuscular equations describing the evolution of carrier and photon numbers within the laser cavity are given by:

$$\frac{dS}{dt}=\left[A(N-N_t)-\frac{1}{\tau_p}\right]S \quad (1)$$

$$\frac{dN}{dt}=\frac{I}{e}-\frac{N}{\tau_s}-A(N-N_t)S \quad (2)$$

with S the photon number, N the carrier number, I the pump current, τ_p the photon lifetime, τ_s the carrier lifetime and e =1.6 × 10^{-19}C the elementary charge of the electron. We assume a linear gain dependence such as g=A× (N-N_t) with A=1.4 ×10^4 s^{-1} a temporal coefficient of differential gain and N_t =7.2 × 10^7 the carrier number at the optical transparency. The group index is n_g=4. The speed of light is c=3 × 10^8 m/s.

a) Calculate the photon lifetime.
b) Calculate the carrier number N_0 at threshold.
c) Calculate the threshold current I_0 for τ_s =1 ns.
d) Express the photon number S_0 as a function of the pump current. Calculate S_0 for I/I_0=2.
e) Applying a small-signal analysis on Eqs. (1)-(2) allows retrieving the so-called relaxation oscillation (RO) frequency of the laser such as,

$$f_r=\frac{1}{2\pi}\sqrt{\frac{AS_0}{\tau_p}} \quad (3)$$

Calculate the RO frequency for I/I_0=2.
Explain qualitatively possible ways to increase the RO frequency.

2. Figure 1 gives the squared RO frequency (circles) as a function of the total output power (mW). The dashed line is for guiding eyes only. Explain why Eq. (3) can not reproduce the data set shown in Figure 1. Why is that?

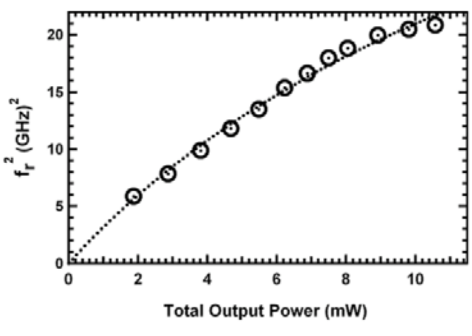


Figure 1

3. Figure 2 shows the evolution of the damping rate γ_{fr} (squares) as a function of the squared RO frequency.

Extract the carrier lifetime. Compare the extracted value to that used in the corpuscular equations. Conclusions. Lastly, briefly explain why the slope is important for high-speed applications.

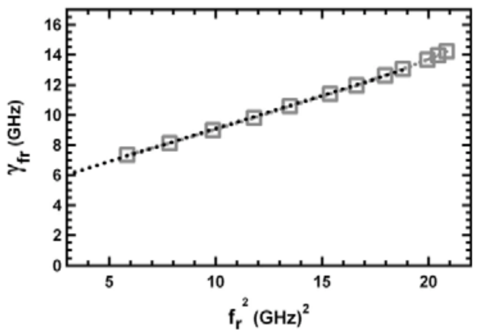


Figure 2

Exercise: Feedback response of a semiconductor laser

In 1986, Tkach and Chraplyvy from Bell Labs unveiled the first cartography of a DFB semiconductor laser operating under external optical feedback, representing the spectral behavior of the laser as a function of the two feedback parameters that are the feedback power ratio, defined as the ratio between reinjected and emitted powers, and the external cavity length. As shown in Figure 3, they identified five distinct feedback regimes.

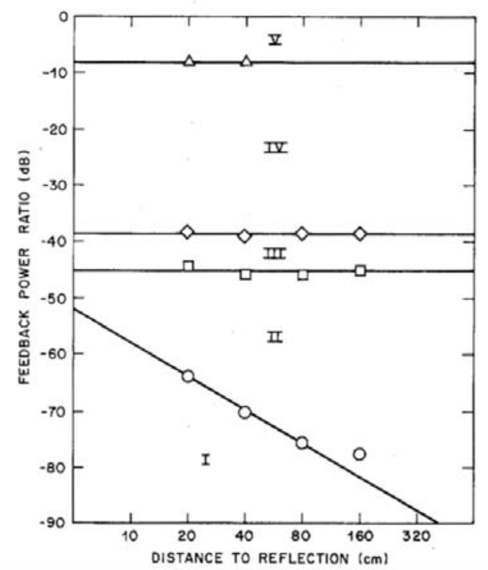


Figure 3

a) Describe the feedback regimes. In particular, emphasize those that are unstable.
b) Explain how to realize a secured communication channel.
c) A parasitic feedback from a fiber changes the optical linewidth $\Delta\nu$ of the lasing mode such as,

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

with $\Delta\nu_0$ the optical linewidth of the solitary laser (w/o external optical feedback), η the intensity feedback into the laser, φ the phase of the delayed field. Retrieve the value of $\Delta\nu_0$ assuming a maximum broadening of 4 MHz at η=0.4.