Centre Scientifique d'Orsay **Année 2018-2019**

Université Paris-Sud 26 Février 2019
Université Paris Saclay

Optoelectronics

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

Duration: 3 hours

- Documents 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 semiconductor 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 be the applications of such wide-band gap semiconductors.

3) What are the main applications of germanium in optoelectronics ? Is it a direct or an indirect bandgap semiconductor ? Why germanium is said to be a silicon compatible material ?

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 consequences 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 their typical sizes for a wavelength of 1.55 µm.

8) Give the typical value of the propagation losses for 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) Recall the value of the refractive index of silicon and silica at 1.55 µm. Schematically draw the dispersion curves of a planar dielectric waveguide made in silicon on silica. What are the slope of these curves at very short wavelengths and at very long wavelengths ?

10) Define the group index n_g . Show that $n_g = n_{eff} - \lambda\, dn_{eff}/d\lambda$, where n_{eff} is the effective refractive index of the waveguide.

11) Give the definition of the quality (Q) factor of a cavity. What is called the free spectral range of a cavity. In the case of a ring resonator of radius R, give the expression of this free spectral range. Introduce and define any necessary parameters appearing in the formula.

12) Describe the operation of an optical modulator made of $LiNbO_3$ (lithium niobate). What is the physical effect used to get the modulation of the optical wave by the electrical signal ? Give one physical effect that can be used to modulate light in a silicon modulator.

13) Draw a schematic view of a Bragg mirror in integrated optics. Explain with words its functioning.

14) 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 ?

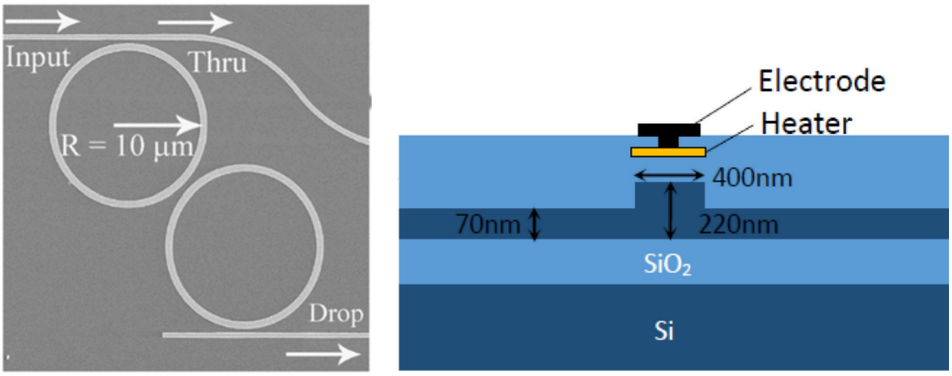
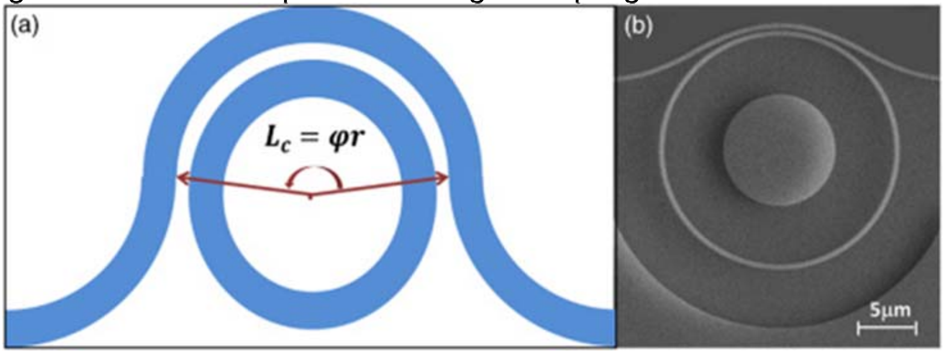


Figure A 1 : (left) scanning electron microscope (SEM) view of an integrated circuit (without heaters). Right : schematic view of an electric heater on top of an optical waveguide.

15) What could be, in your opinion, the interest of the following pulley type coupling to a microring resonator as compared to straight coupling.



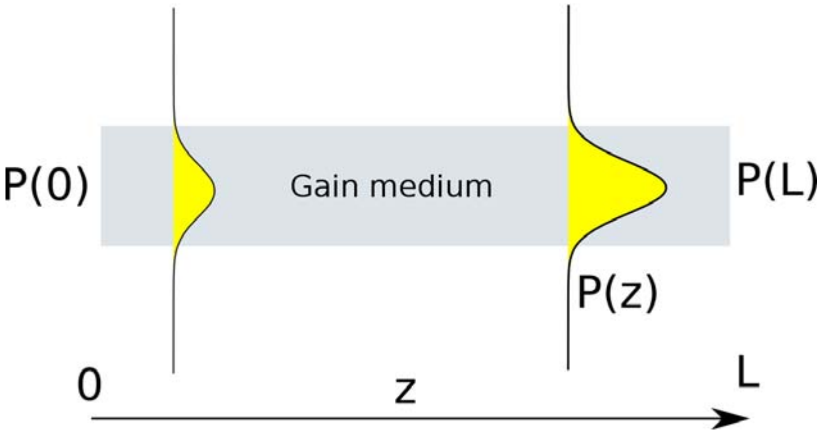
16) Define what are EDFA and SOA amplifiers. For each kind of amplifier, give a remarkable property and application.

Optical amplifier

We assume a spectral dependence of the gain of the amplifying medium of the form :

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

During the propagation in an amplifier of length L made using the previous 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 optical power circulating in the amplifier. The effects of saturation are first neglected here.



17) Give the power P(L) as a function of the parameters of the problem. Deduce the total gain G = P(L) / P(0) of the amplifier.

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) 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.

19) Compare and comment the amplifier gain in the two cases ?

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.
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.

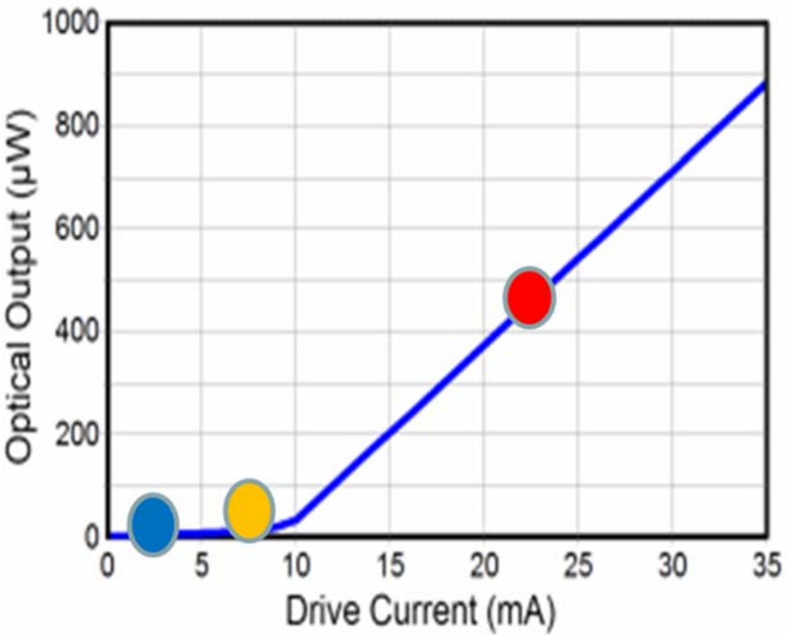


Figure B-1

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 will happen (Threshold, dP/dI) if the waveguide losses became higher?
8. What will happen (Threshold, dP/dI) if the mirror losses became higher?

Quantum Cascade Lasers

9. What is the wavelength range of Mid-Infrared, what are the main applications?
10. What are the main sources that exist in this range of wavelength?
11. What is the main difference between diode lasers and quantum cascade lasers.

12. Explain the operating principle of a quantum cascade laser, how can we tune the operating wavelength?
13. What are typical now days quantum cascade lasers features in the mid-Infrared (maximum operating temperature, maximum power…)

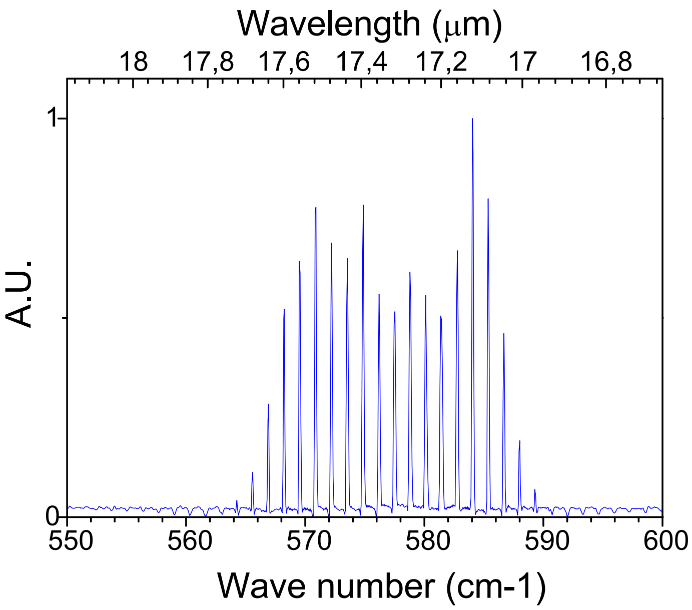


Figure B-2

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

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}= 3.9, what is the cavity length "L" of this laser (we remind you that the free spectral range FSR is given $FSR = \frac{\lambda^2}{2ng_{eff}L}$).

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

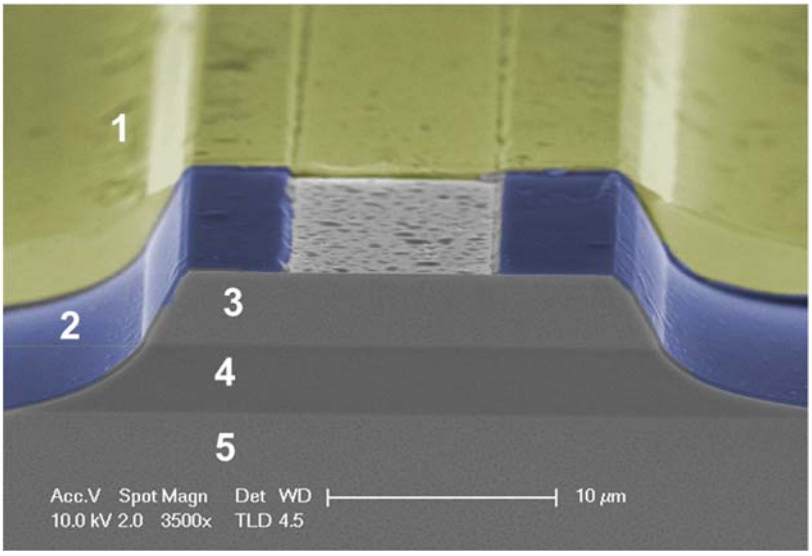


Figure B-3

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 ?

Quantum Well Infrared Photodetector

18. What are the main families of existing detectors in the mid-infrared?
19. Explain using a schematic the principle of operation of a quantum well infrared photodetector.
20. 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.

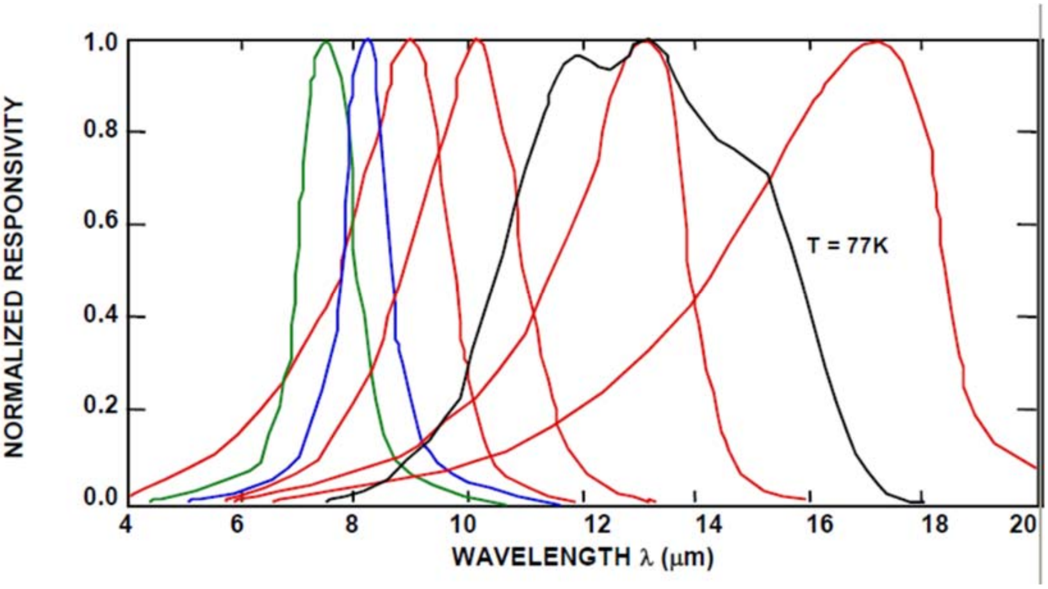


Figure B-4

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 1

The transition matrix of the semiconductor laser gives insight on rates of evolution of each state variable (complex electric field and carrier population). By performing a linear stability analysis of the steady-state conditions, the transition matrix can be expressed as follows,

$$J = \begin{pmatrix} -\frac{1}{\tau_s} - G_N S & 0 & -\frac{1}{\tau_p} \\ 0 & 0 & \frac{\alpha G_N}{2} \\ G_N S & 0 & 0 \end{pmatrix}$$

with G_N the semiconductor laser's dynamic gain (or differential gain), τ_S the carrier lifetime, τ_p the photon lifetime, α the linewidth enhancement factor and S the photon density in the cavity.

Q1. Explain why the transition matrix has a dimension of three.
Q2. What is the linewidth enhancement factor?
Q3. Demonstrate that the characteristic polynomial reads,

$$\lambda\left[\lambda^2 + \left(\frac{1}{\tau_s} + G_N S\right)\lambda + \frac{G_N S}{\tau_p}\right] = 0$$

Q4. Show that the eigenvalues of the third-order characteristic polynomial can be written as

$$\lambda_\pm = -\Gamma \pm \sqrt{\Gamma^2 - \omega_R^2}$$

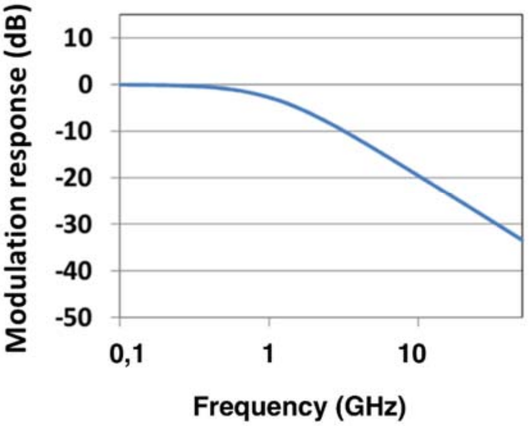
Express Γ and ω_R as a function of G_N, τ_S, τ_p and S.

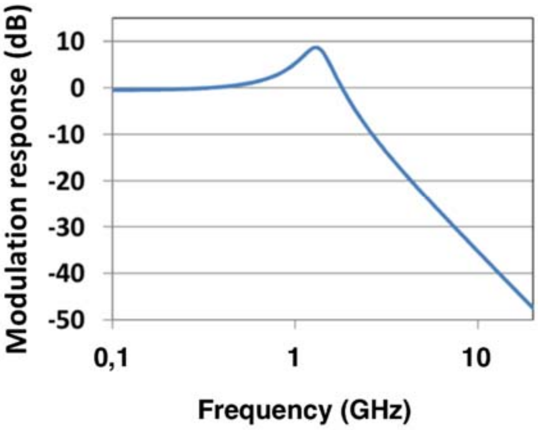
Q5. Give the physical meanings associated to Γ and ω_R?

Q6. Assuming $\Gamma << \omega_R$ show that the eigenvalues are complex numbers. Conclusions.

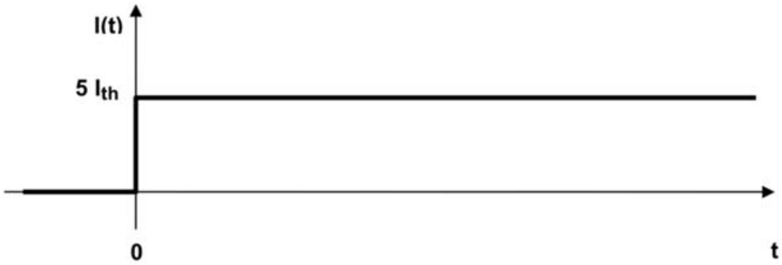
Q7. Assuming $\Gamma >> \omega_R$ show that the eigenvalues are real numbers. Conclusions.

Q8. The figures depicted hereinafter show a measurement of the modulation response (transfer function) performed on two semiconductor lasers. Using Q6 & Q7, discuss and explain the results.





Q9. We now look at the turn on transient of the semiconductor laser in time assuming $\Gamma << \omega_R$. The idea is to see how the semiconductor laser would perform in a digital optical communication system. The input current to the laser has the form shown below. It is a step function given by: $I(t)= 5\times I_{th}$ with I_{th} the threshold current of the laser.



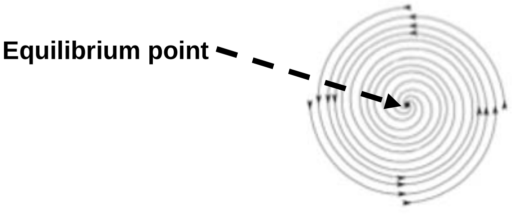
Represent qualitatively the evolution carrier density N(t) and photon density S(t) as a function of time $t \geq 0$. Assuming that the carrier lifetime is about 1 ns, what would be the maximum data rate (in GBits/sec) at which this laser can be reliably used in an optical communication system in which a logical "1" corresponds to light present and a logical "0" corresponds to no light present.

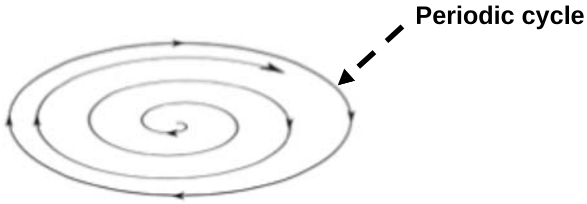
Exercise 2

Q1. What are the main fingerprints of chaos in deterministic continuous systems?

Q2. Quickly remind the Poincaré-Bendixon theorem.

Q3. The figures below show the solution curves of a deterministic continuous system (as for a semiconductor diode laser) represented in the phase-space. The solution either asymptotically converges to an equilibrium point (left) or to a periodic cycle (right). In one sentence, and based on Q2, use your intuition to explain why a continuous system exhibiting a 2-dimensional phase-space dynamic cannot experience a chaotic divergence.





Q4. Explain why a semiconductor diode laser cannot spontaneously exhibit chaos?

Q5. Give solutions for chaos generation in semiconductor diode lasers.

Q6. In a few sentences, explain and discuss the purpose of the experimental setup shown below.