MASTER 1 EMIMEO - EXAMINATION December 2020

Power Amplifier

We consider a power transistor having the following I / V characteristics. (Fig 1)

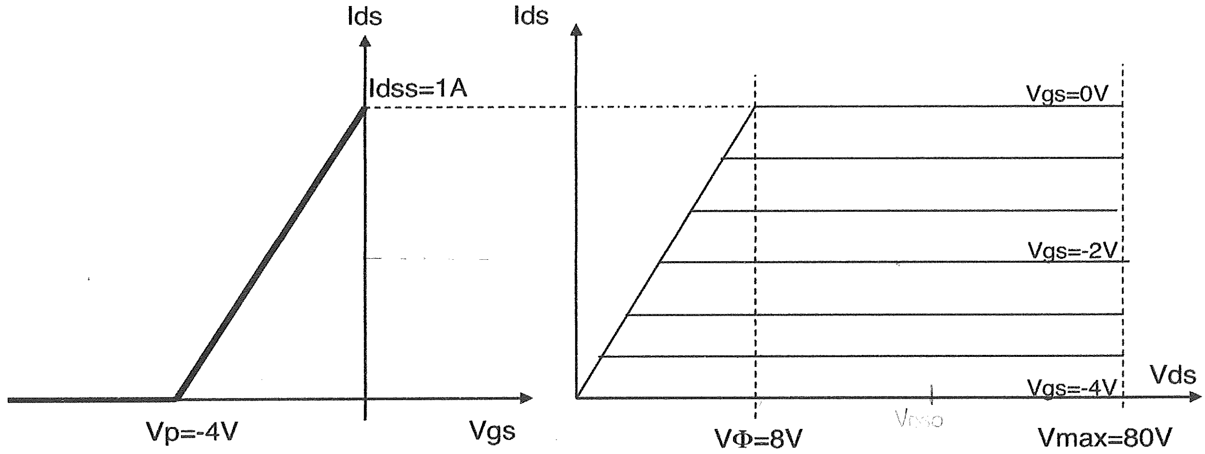


Fig 1

Rg = 4Ω , Cgs=5pF , Fo=3.6 Ghz , Cds = 0.6 pF

The gate source bias voltage Vgs0 is chosen so that we have an aperture angle of 110 ° when the RF input voltage Vgs1 is at its maximum value.

The following required relationships are given:

$$Ids0 = \frac{Ip}{\pi} \cdot \frac{\sin\varphi - \varphi\cos\varphi}{1-\cos\varphi} \qquad Ids1 = \frac{Ip}{\pi} \cdot \frac{\varphi - \sin\varphi\cos\varphi}{1-\cos\varphi}$$

$\gamma = 110°$

A] In this first part A , we want to reach the maximum output power performance .

1) Calculate the values of Vgs0 , Vds0

2) Calculate the load impedance (real part and imaginary part) that must be connected at the drain port of the transistor

3) Determine the value of the output power and the power added efficiency.

4) We want to design the output matching networks following the circuit topology of Fig 2

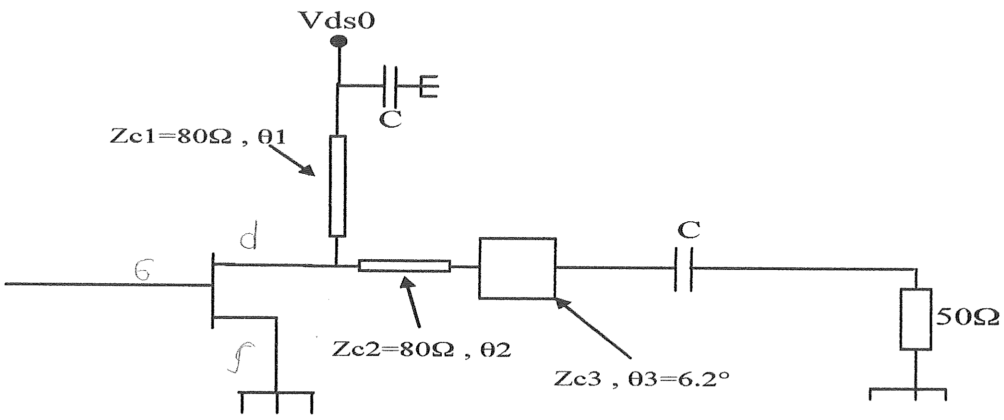


Fig 2

4a) What is the purpose of the distributed lines connected in the drain bias circuit .

4b) Determine the value of the electrical delay $\theta 1$

4c) Determine the values of $\theta 2$ and Zc3

B] In this second part B ,we keep the same load impedance and the same gate bias voltage Vgs0 determined in part A .The value of Vgs1 is now set to Vgs1=+2V .The value of Vds0 is decreased.

1) What is the value of Vds0 required to reach the saturation regime of the transistor at Vgs1 = +2V.

2) What are the corresponding values of the output power and power added efficiency

4a) Bias Tee & Impedance matching.
- Bias Tee doubles as a filter for the even harmonics
- BIAS Tee for the $\frac{\lambda}{4}$ → connected to the DC Power
- Impedance matching for the lines connected to the load

The bias tee part doesn't interact with the impedance matching part because it is seen as an open circuit at the fundamental frequency

180 π
6.2 x

Master 1 EMIMEO - Active Non linear circuits - January 2021
2nd Session Examination – (Power amplifier)

Let us consider a Field Effect Transistor having the static I/V characteristics plotted in figure 1 and the equivalent large signal circuit model given in figure 2.

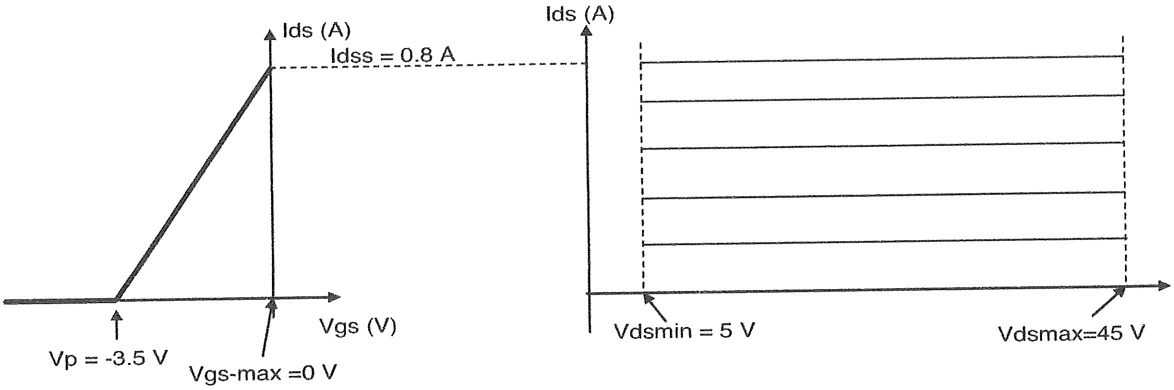


Figure 1

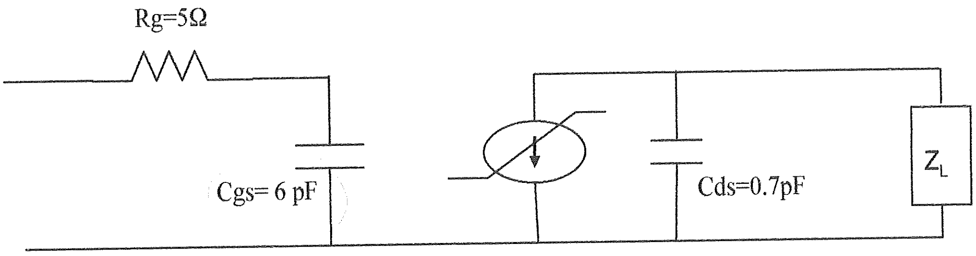


Figure 2

The gate - source bias voltage is Vgs0= - 2.5 V and the RF operating frequency is F0= 4 Ghz
We want to reach the maximum output power performances of the transistor.

<u>First part: Only one transistor is used .</u>

1) What is the value of the aperture angle φ

2) What is the value of the optimal load impedance Z_L: real and imaginary parts

3) What are the values of the maximum output power and the corresponding power added efficiency

<u>Second part : N similar transistors are connected in parallel .</u>

N transistors are now connected in parallel as shown in figure 3 .

Each one of these N transistors is the same as the one studied in the first part and DC biasing conditions remain the same.

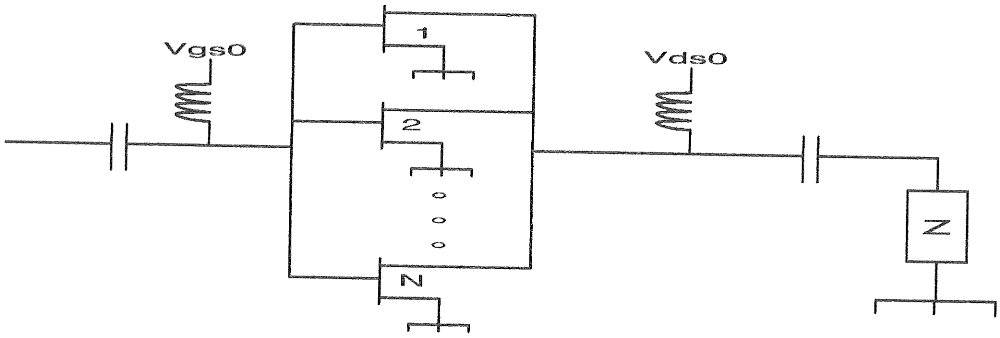


Figure 3

4) As we want to have an amplifier providing at least 30 W output power , what is the required value of N

5) What is the value of the load impedance Z

6) What is the value of the power added efficiency at the maximum output power that can be delivered into the load impedance Z

7) We consider now that input and output matching circuits have been designed and connected to the N transistors as shown in figure 4.
These matching circuits have respectively 1 dB and 0.5 dB losses.

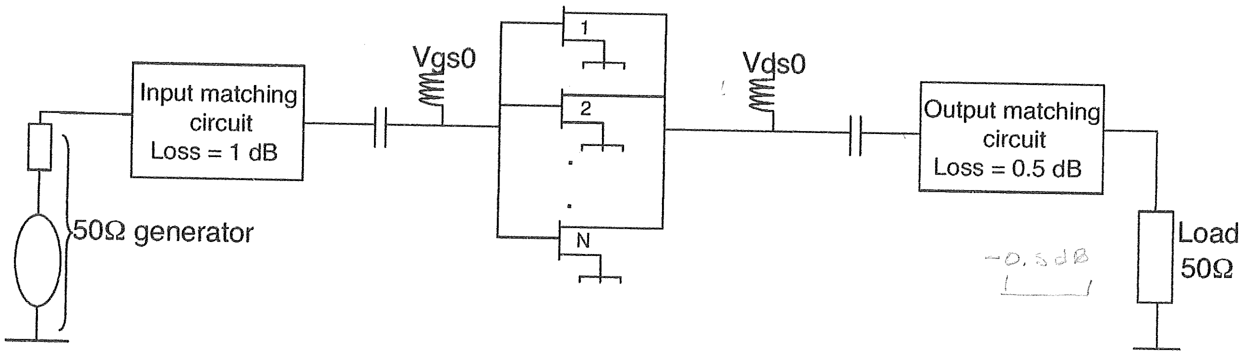


Figure 4

7-a) What is the value of the maximum output power delivered into the load impedance

7-b) What is the value of the corresponding input power (delivered by the input generator)

7-c) What is the power added efficiency of the overall power amplifier .

Faculté des Sciences & Techniques — Université de Limoges — EMIMEO Erasmus Mundus

1st session – December 11, 2020

Master 1 EMIMEO - Exam of "Basics of active and nonlinear electronics" (M. Campovecchio)

A- Narrow-band power amplifier (2 stages)

Specifications:

Output Power $P_{OUT} > 2$ W ; Center frequency $f_0 = 20$ GHz ;

Total power gain $G_P > 20$ dB ; Source and Load resistors $R_G = R_L = R_{50} = 50\ \Omega$

MMIC technology (0.25 µm GaAs HEMT foundry) :

Power density **PD** = 1 W/mm ; Measured maximum gain @ 20 GHz $G_{MAX(@20GHz)} = 16$ dB ≈ 40 ;

Maximum drain current $I_{DSmax} = 800$ mA/mm; Limits of V_{DS} voltage (V_{DSmin}=1 V and V_{DSmax}=11 V)

Optimum power resistance: $R_{OPT} = 12{,}5\ \Omega$.mm

Linear electrical model : $C_{GS} = 2{,}7$ pF/mm ; $C_{DS} = 0{,}6$ pF/mm ; $Ri = 1\ \Omega$.mm ; $R_{DS} = 125\ \Omega$.mm

Selected transistor (unitary size **T1 of 0.6mm**) @ 20 GHz = **8x75 µm** GaAs HEMT

In the problem (C_{GS1} ; C_{DS1} ; Ri_1 ; R_{IN1} ; R_{DS1} ; R_{OPT1}) stand for the values of transistor **T1** = 8x75µm = **0.6 mm**

In this problem, **each stage has to be matched to its optimum power load** R_{OPT_A} **and** R_{OPT_B}

1) Using scaling rules, calculate the numerical values (C_{GS1} ; C_{DS1} ; Ri_1 ; R_{DS1} ; R_{OPT1}; R_{IN1} @ 20GHz) of T1.

2) Power gain :

- $G_P(R_{OPT})$ is the power gain of a transistor T when it is loaded by its optimum power load ($L_{OPT}//R_{OPT}$).
- $G_{MAX} = G_P(R_{DS})$ is the maximum power gain of T when it is loaded by its optimum gain load ($L_{OPT}//R_{DS}$).

  In both cases, $L_{OPT} = 1/(C_{DS}\,\omega^2)$.

  It can be demonstrated that the power gain $G_P(R_{OPT})$ can be expressed as a function of G_{MAX} by:

$$G_P(R_{OPT}) = R_{OPT}\left[\frac{R_{DS}}{R_{DS}+R_{OPT}}\right]^2 \frac{g_m^2}{R_i\, C_{GS}^2\, \omega^2} = 4\, R_{OPT}\, \frac{R_{DS}}{[R_{DS}+R_{OPT}]^2}\, G_{MAX}$$

Using this equation and the measured value of $G_{MAX(@20GHz)}$=16dB=40, determine the expression of $G_{P1}(R_{OPT1})$ for the transistor T1 when it is matched to its optimum power load R_{OPT1}. Demonstrate that the numerical value of G_{P1} at 20GHz is $G_{P1(@20GHz)}$ =13,2=11,2dB.

3) Using the specifications of output power and the technological data of power density, determine the sizing of the 2-stage amplifier (**size** of each stage with numbers n_B and n_A of transistors T1 per stage / optimum load resistance required by each stage R_{L_B} and R_{L_A} as a function of R_{OPT1} / output power P_{OUT} of 2nd stage/ gain of 2nd stage $G_{P_B} = G_{P_1}$/ inter-stage power $P_{IN_B} = P_{OUT_A}$ / gain of 1st stage $G_{P_A} = G_{P_1}$/ input power $P_{IN} = P_{IN_A}$).

4) On the amplifier schematic (next page), indicate the numerical values of each stage when the amplifier operates at the maximum output power of the last stage.

5) Input and inter-stage matching

   a) Calculate the equivalent series input resistances R_{i_A} and R_{i_B} of each stage.

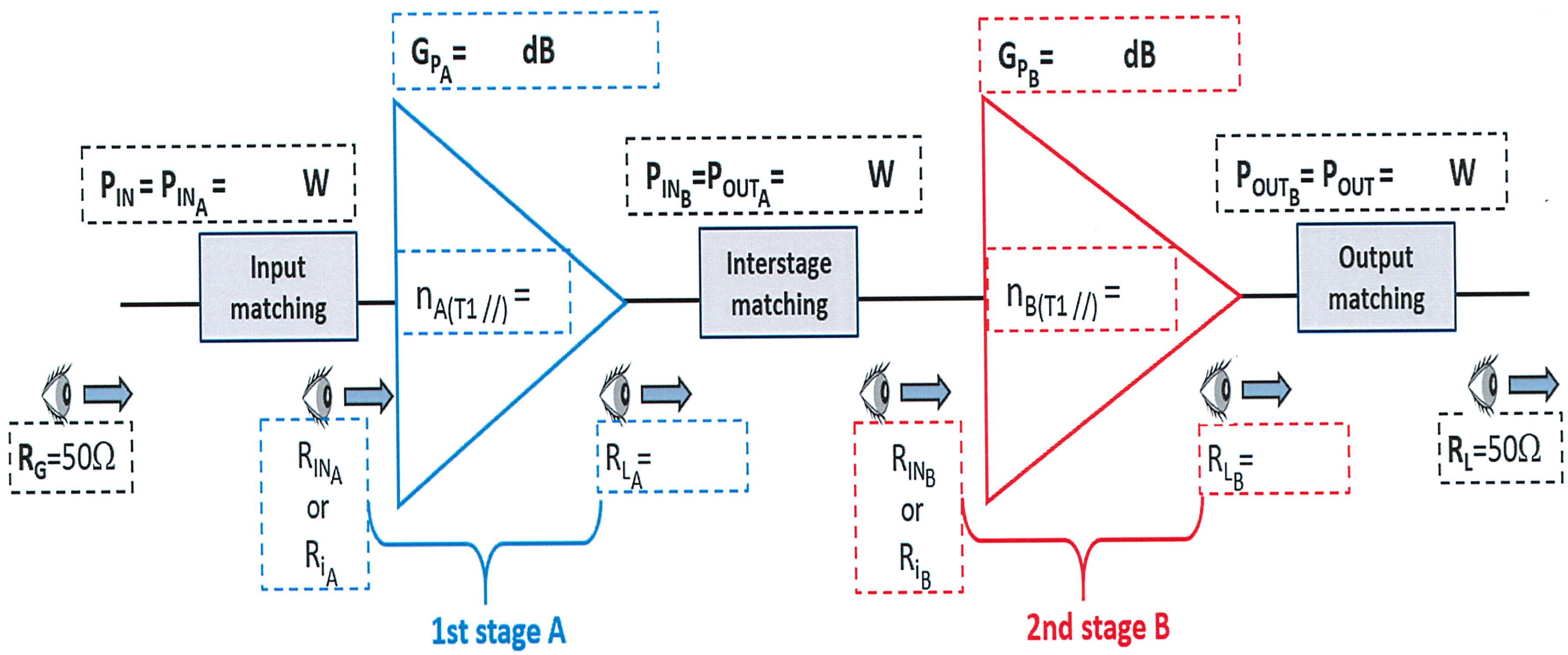
   b) Calculate the equivalent parallel input resistances R_{IN_A} and R_{IN_B} of each stage at 20GHz.

6) Draw the electrical matching circuits (inductors and transformers) of the two-stage amplifier when matched to $R_G = R_L = 50\Omega$ and determine the expression of matching elements **without calculating numerical values**. For the sake of simplicity, you can use the notations:

$$L_1 = 1/(C_{GS1}\,\omega_0^2) \text{ and } L_2 = 1/(C_{DS1}\,\omega_0^2)$$

7) If both stages operate in class-A, calculate the total DC power to determine the maximum PAE of the amplifier? Why is-it less than 50%?

Name:



$G_{P_A}=$ dB
$G_{P_B}=$ dB
$P_{IN} = P_{IN_A} =$ W
$P_{IN_B}=P_{OUT_A}=$ W
$P_{OUT_B}= P_{OUT}=$ W
Input matching
Interstage matching
Output matching
$n_{A(T1\,//)} =$
$n_{B(T1\,//)} =$
$R_G=50\Omega$
R_{IN_A} or R_{i_A}
$R_{L_A}=$
R_{IN_B} or R_{i_B}
$R_{L_B}=$
$R_L=50\Omega$
1st stage A
2nd stage B

Semester S1 – Module 3

Fundamentals of coherent photonics

EXAMINATION

LASERS

January 2021

Duration: 40 minutes

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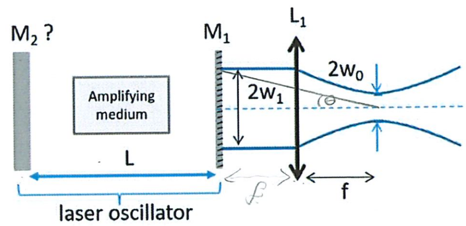
Let us consider a laser chain made of an amplifier seeded by the radiation from an oscillator. The first part of the exercise is dedicated to the free space propagation oscillator and the second one to the fiber amplifier.

Part 1: Laser resonator

The laser oscillator of Fabry-Perot type delivers P_0 = 20mW at wavelength λ = 1064nm and operates in the continuous wave regime.

The laser beam from the oscillator has a Gaussian profile of radius ω_0 = 5µm (at e^{-1} maximum) measured in the focal plane of the lens L_1 (focal length f = 12mm on the figure). Some specifications of the two mirrors are missing: the reflectivity R_1 of the output coupler is unknown as well as the radius of curvature of rear mirror M_2. M_1 is a plane mirror and M_2 has a reflectivity R_2 = 1. The cavity length is L = 1m.



1) Considering that the laser wavefront is flat between L_1 and M_1, compute ω_1 the radius of the Gaussian beam on mirror M_1.

2) Calculate the radius of curvature R_{c2} of mirror M_2 so that the Gaussian beam considered is a transverse mode of the cavity. Is mirror M_2 convex or concave?

3) What is the diameter of the beam in the M_2 plane?

4) The intracavity power is P = 0.8W.

✓ **a.** Establish a relation between P and P_0, and deduce the reflectivity R_1 of the output coupler. We will consider that the power is constant at any plane of the cavity.

b. In the weak pumping regime considered here, the small signal gain coefficient γ_0 (cm^{-1}) is proportional to the pumping rate W_P: $\gamma_0 = K.W_P$. α_t will be the intracavity losses coefficient (cm^{-1}).

- First, the laser operates at threshold. What does it mean?
- What is the pumping rate $W_{P,th}$, according to K and α_t, required to reach the laser threshold?

c. Now, the laser operates above threshold, with a pump power so that $W_P = X.W_{P,th}$.

- Describe the evolution of γ(P) during the transient regime.
- Determine an expression for P/P_{sat} according to X. (P_{sat}: saturation power)

d. Considering that P_{sat} = 0.2W, compute X.

5) Describe the general features of the laser emission (continuous wave regime) in the spectral and temporal domains. The spectral bandwidth of emission is named $\Delta\nu$.

Reminder: $\omega^2(z) = \omega_0^2(z)\left[1+\frac{z^2}{\alpha^2}\right]$, $R(z) = z+\frac{\alpha^2}{z}$, $\alpha = \frac{\pi\omega_0^2}{\lambda}$

Part 2: Fiber amplifiers

We consider an Yb^{3+}-doped fiber amplifier forward-pumped at 968 nm and seeded by the radiation from the resonator studied in Part 1. The absorption cross-section (σ_a) and emission cross-section (σ_e) of Yb^{3+} ions are shown in Fig. 1.

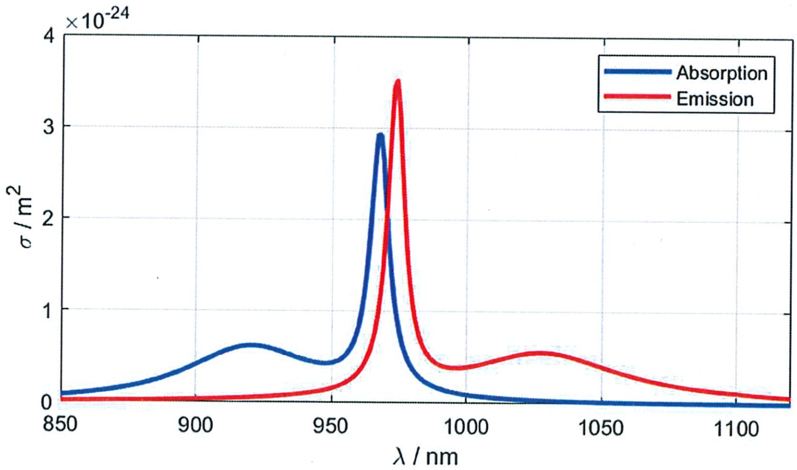


Fig. 1: Emission and absorption cross-sections of Yb^{3+} ions diluted in silica matrix.

At the two relevant wavelengths:

λ = 968 nm, $\sigma_a = 2.92\times10^{-24}$ m² and $\sigma_e = 1.17\times10^{-24}$ m²

λ = 1064 nm, $\sigma_a = 1.44\times10^{-26}$ m² and $\sigma_e = 2.89\times10^{-25}$ m²

The pump beam carries a continuous wave power of 5 W at 968 nm while the signal power is 20 mW at the fiber input. Fig. 3 shows the results of numerical simulations for the Ytterbium ring-doped fiber.

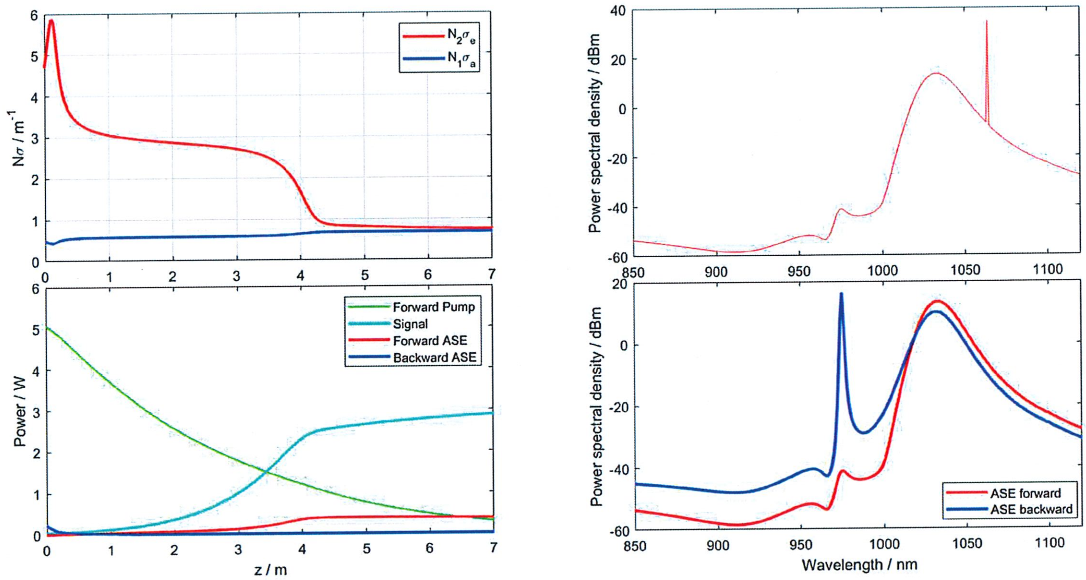


Fig. 3: Results from numerical modeling of forward pumped Ytterbium ring-doped fiber amplifier: Left-hand side panels: longitudinal evolution of the population densities (top) and powers (bottom). Right-hand side panels: spectral evolution of the power densities.

5) Give the equation for the longitudinal evolution of the signal power. By referring to question 1, explain the behavior of the amplifier for the two regions:
   a. $z < 4$ m
   b. $z \geq 4$ m.

6) We now consider the evolution of the power spectral densities versus wavelength for the 7-m long amplifier. Explain:
   a. The profile of the noise in the top panel.
   b. The profile of the backward ASE noise in the bottom panel.

1) Is Yb^{3+} ion pumped at 968 nm and emitting at 1064 nm a three-level system or a quasi-four-level system? Justify.

The schematic of the set-up is shown in Fig. 2.

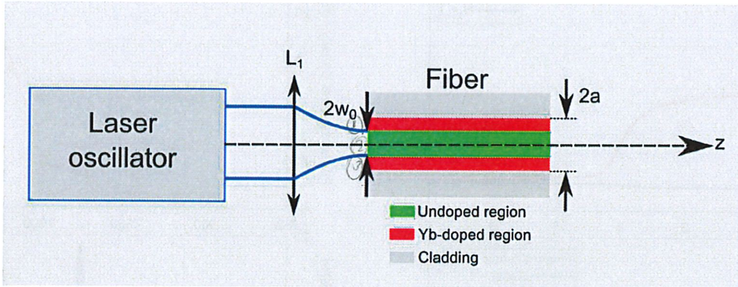


Fig. 2: Schematic of the set-up.

We consider the Gaussian approximation for the field distribution $\psi(r,\theta)$ of the radiation at the focal plane of lens L_1:

$$\psi(r,\theta) = \frac{1}{w_0}\sqrt{\frac{2}{\pi}}e^{-\frac{r^2}{w_0^2}} \tag{1}$$

where w_0 is the field radius defined at 1/e of the peak amplitude.

The multiplying factor $\frac{1}{w_0}\sqrt{\frac{2}{\pi}}$ is chosen to normalize $\psi(r,\theta)$ so that $1 = \int_0^{2\pi}\int_0^{\infty}\psi^2(r,\theta)rdrd\theta$, where $\psi^2(r,\theta)$ corresponds to the field intensity.

The Yb^{3+}-doped fiber is cylindrically symmetric and singlemode. We therefore also consider that the guided mode of the fiber follows the canonical form given in Eq.1.

✓ **2)** The fiber is described by its numerical aperture NA and core radius a. Considering that the NA is 0.09, what is the core radius a ensuring singlemode operation at the signal wavelength.

3) The fiber mode field radius w can be calculated from Eq.2:

$$w = a \times (0.65 + 1.615/V^{1.5} + 2.879/V^6) \tag{2}$$

✓ What is the mode field radius at the signal wavelength?
Comment on the coupling efficiency between the resonator and the fiber amplifier.

— **4)** The Yb-doping with concentration N_{Yb} follows the form:

$$N_{Yb}(r) = 5\times10^{25}\text{m}^{-3} \text{ for } a_{d1} \le |r| \le a_{d2}$$
$$N_{Yb}(r) = 0 \text{ elsewhere}$$

Recalling that $\left(e^{ax^2}\right)' = 2axe^{ax^2}$, calculate the overlap factor Γ between the light intensity distribution and the doped region for $a_{d1} = a/2$ et $a_{d2} = a$.

Semester S1 –Module 3
Module Fundamentals of coherent photonics

EXAMINATION
GUIDED OPTICS
January 4th 2021

Estimated duration : 40 minutes

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Please clearly explain and justify your answers as often as possible

Data and curves that can be useful for this exercise are provided at the end (pages 4 and 5)

The aim of this exercise is to study the propagation features of an optical fiber and to evaluate its suitability for high bit rate communications. The only known information concerning the optogeometrical characteristics of this fiber are the following:

- this fiber is a cylindrical step index fiber;
- the cladding (diameter 125 μm) is made of pure silica SiO_2, of refractive index $n_2(\lambda)$;
- the central cylindrical core is made of Ge doped silica (refractive index $n_1(\lambda)$);
- the numerical aperture is NA = 0.12. It is constant over the entire range of wavelengths [400 nm, 2000 nm].
-

1. Verify that the transverse modes of this fiber can be considered as LP modes. What does "LP" mean ?

2. Thanks to a suitable imaging device, we can observe the intensity pattern exiting the fiber in the plane of the output face. First, a beam from a laser diode LD1 emitting at λ_1 = 450 nm is launched in a piece of this fiber. With a particular setting of the injection, we can observe the intensity pattern shown in Fig. 1, corresponding to one particular pure $LP_{m,n}$ mode.

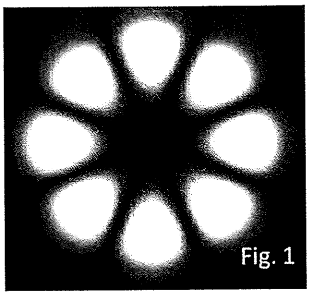


Fig. 1

   a) What is this pure LP mode (m = ?, n = ?) ?

   b) From this observation, what condition C1 can you deduce concerning the core radius a ?

   c) The Fig. 2 proposes six different maps of the electric field in this LP mode (i.e. electric field orientation in the lobes). Indicate that (those) which can actually exist in this LP mode in a given cross section of the fiber, at a given time, and justify your answer.

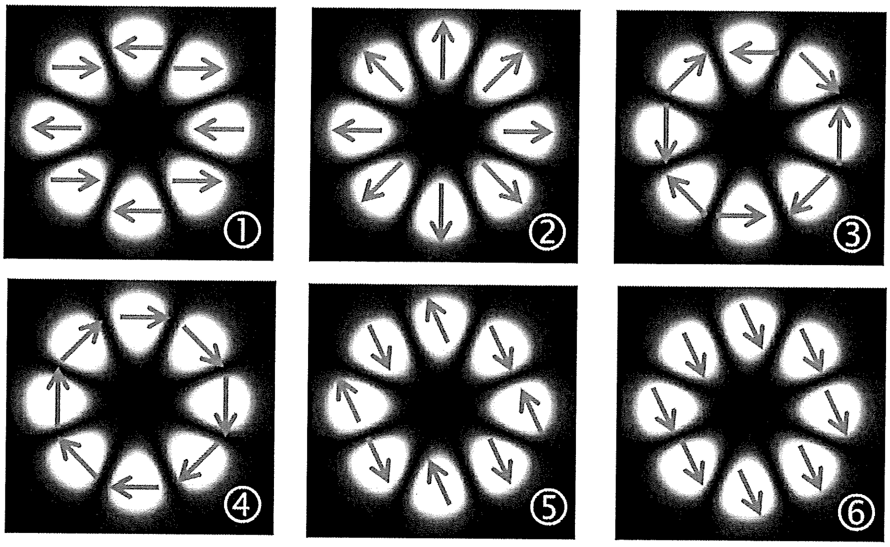


Fig. 2

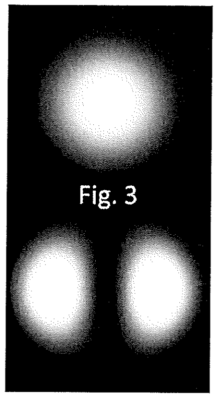


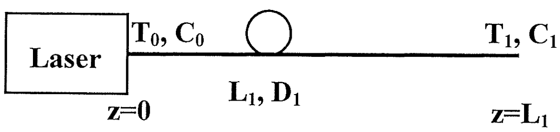
Fig. 3

3. The laser diode LD1 is replaced by another laser diode LD2 emitting at $\lambda_2 = 780$ nm. With this source, whatever our effort, we can only observe patterns corresponding to one of the two modes shown in Fig. 3, or corresponding to a combination of these two modes, and we cannot observe other modes.
   a) What new condition C2 can you deduce concerning the core radius ?
   b) From C1 and C2, determine the core radius with a precision of $\pm$ 0.1 µm.

4. The diameter of the core of the fiber is exactly d = 7.8 µm. Finally, the fiber will be used at $\lambda_3 = 1550$ nm.
   a) Only with considerations on the guided modes, is this fiber potentially suitable for applications to long haul high bit rate transmission links?
   b) Using the set of curves provided in the appendix part, evaluate with the best possible precision the dispersion coefficient of the material D_m at λ_3.
   c) The dispersion coefficient of the guide for the fundamental mode at λ_3 is $D_g = -\ 6$ ps/(nm.km). From the above information, calculate the chromatic dispersion coefficient of the fiber at λ_3. This coefficient will be noted D_1 in the following.

We now consider that the chromatic dispersion coefficient D_1 of the fiber is equal to 16 ps nm^{-1} km^{-1}. A laser pulse at λ_3 propagates in this fiber whose length is noted L_1. Its half-pulsewidth at 1/e of the maximal intensity is T_0=10 ps. A spectral measurement showed a half-spectral bandwidth at 1/e of the maximal intensity $\Delta\nu_0$= 50.33 GHz.

Fiber F_1



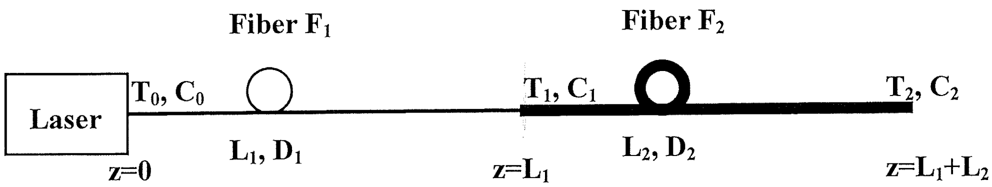
5. Calculate the possible values of the chirp parameter C_0 of the pulse emitted by the laser.

6. Calculate the lowest pulsewidth T_m that this pulse may reach during an in-fiber propagation.

7. After propagation in the L_1-long fiber, the half-pulsewidth at 1/e of the maximal intensity is T_1=3.1622 ps. Calculate the fiber length L_1.

8. Determine the sign of the chirp value C_0.

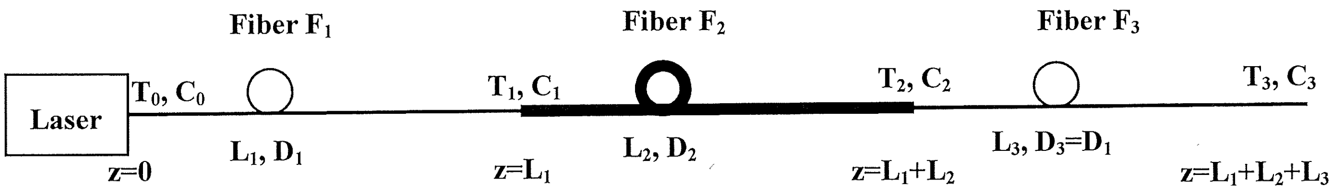
A second fiber (F_2) is connected to the fiber F_1. Its length is L_2=100 m. At the F_2 fiber output, the half-pulsewidth at 1/e of the maximal intensity is T_2=5 ps



9. Determine the possible values of the chromatic dispersion coefficient D_2 of the fiber F_2.

10. Plot the half-pulsewidth T(z) and the chirp parameter evolution C(z) along this optical fiber line for the different possible values of D_2.

A third fiber (F_3) with identical properties as the fiber F_1 is connected after the fiber F_2. Its length is L_3=100 m.



11. Explain simply (a justified graphical analysis is sufficient) how the insertion of this last fiber in the system can help us to deduce the real value of D_2. We assume that we can measure and that we know the value of T_3 at the output of the global optical line.

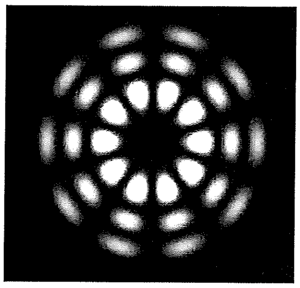
****

<u>Data and curves which may be useful/necessary for this exercise (pages 4 and 5)</u>

π=3.14159 *Celerity of light in the vacuum*: c = 3.10^8 m.s^{-1}

Function →	$J_0(x)$	$J_1(x)$	$J_2(x)$	$J_3(x)$	$J_4(x)$
first zero for x = →	2,405	0	0	0	0
second zero for x = →	5,52	3,83	5,14	6,38	7,59
third zero for x= →	8,65	7,02	8,42	9,76	11,06

First zeros of few Bessel functions of the first kind



intensity pattern of the $LP_{5,3}$ mode

<u>Formulas</u> :

Modulus of the wave vector at the wavelength λ in the vacuum : $k_0 = \frac{2\pi}{\lambda}$

numerical aperture of a fiber : $NA = \sqrt{n_1^2 - n_2^2}$

relative index difference : $\Delta = \frac{NA^2}{2n_1^2}$ normalized spatial frequency : $V = k_0.a.NA$

normalized propagation constant of a mode : $B = \frac{\beta^2 - k_0^2.n_2^2}{k_0^2.(n_1^2 - n_2^2)}$ where β is the propagation constant of this mode

dispersion of the material $D_m = -\frac{\lambda}{c}\frac{d^2n}{\lambda^2}$

dispersion of the guide for a mode which dispersion curve is B=f(V) : $D_g = -\frac{n_1.\Delta}{c.\lambda}.V.\frac{d^2(VB)}{dV^2}$

Gaussian pulse invariant function

$$\frac{T(z)^2}{1 + C(z)^2} = \frac{1}{4\pi^2\Delta\nu^2}$$

Chirp parameter evolution

$$C(z) = C_0 + \frac{\beta_2 z}{T_m^2}$$

Second derivative of the propagation constant β

B

$$\beta_2 = -\frac{\lambda^2 D}{2\pi c}$$

$n_{eff} = \frac{\beta}{k_0}$

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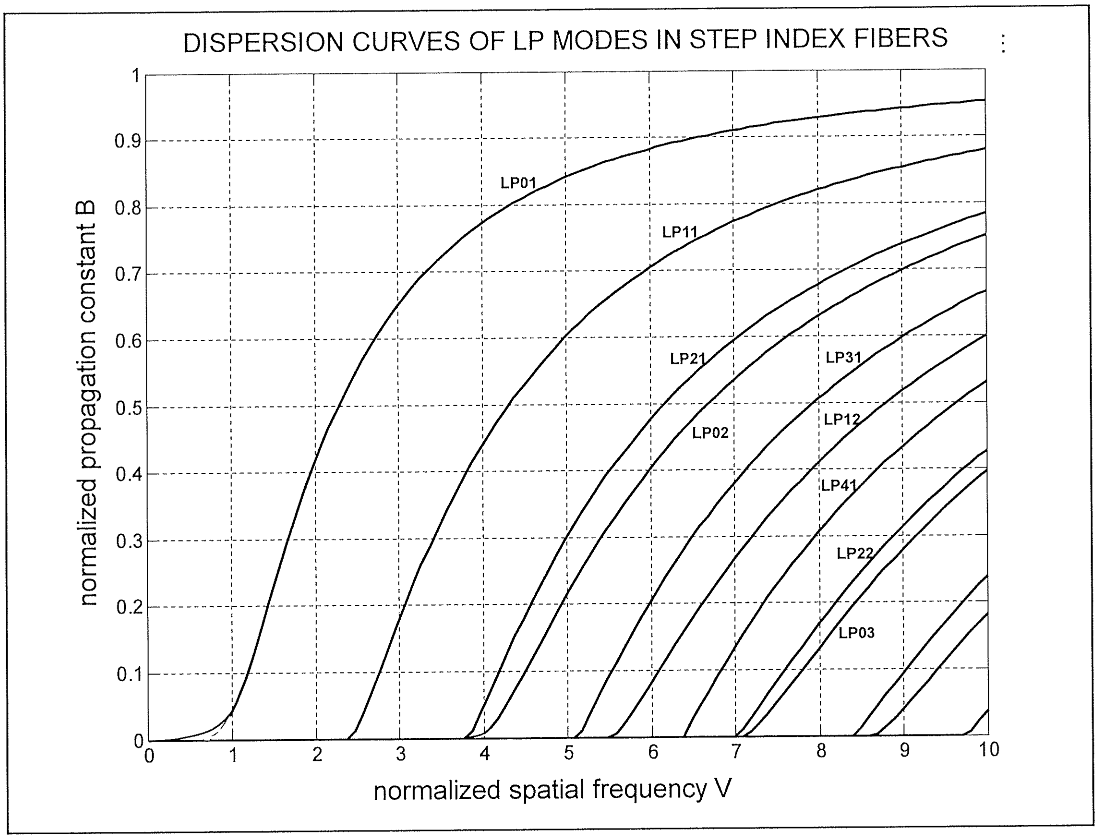
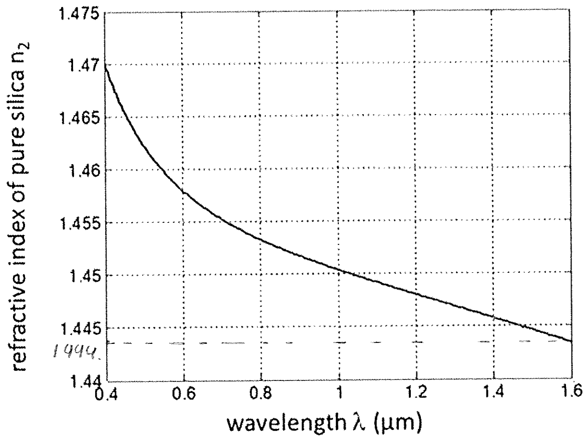
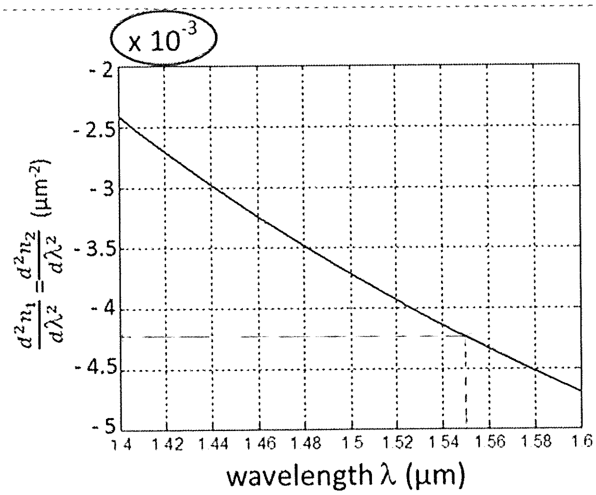

DISPERSION CURVES OF LP MODES IN STEP INDEX FIBERS
normalized propagation constant B
normalized spatial frequency V
LP01
LP11
LP21
LP02
LP31
LP12
LP41
LP22
LP03
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0 1 2 3 4 5 6 7 8 9 10


refractive index of pure silica n_2
wavelength λ (µm)
1.475
1.47
1.465
1.46
1.455
1.45
1.445
1.444
1.44
0.4 0.6 0.8 1 1.2 1.4 1.6


x 10^{-3}
$\frac{d^2 n_1}{d\lambda^2} = \frac{d^2 n_2}{d\lambda^2}$ (μm^{-2})
wavelength λ (µm)
- 2
- 2.5
- 3
- 3.5
- 4
- 4.5
- 5
1.4 1.42 1.44 1.46 1.48 1.5 1.52 1.54 1.56 1.58 1.6

Semester S1 -COHERENT PHOTONICS
PROPAGATION IN OPTICAL WAVEGUIDE

EXAMINATION

GUIDED OPTICS

February 5th 2021

Estimated duration: 1 hour

No document of any kind allowed

Please clearly explain and justify your answers to the questions as often as possible

Exercice I (Data and curves that can be useful for this exercise are provided page 2)

Two pieces of step index optical fiber, respectively called F_1 and F_2, have been drawn from the same preform. For that reason, they have the same core index n_c and the same cladding index n_g, but they can have different outer diameters and thus different core radii. The core radii of fibers F_1 and F_2 are called a_1 and a_2 respectively.

1. What does "step index" fiber mean?
2. We assume that the weak guidance approximation (WGA) applies in these fibers. What information can you deduce concerning the transverse modes of these fibers?

Experimental measurements show that the LP_{11} mode in the fiber F_1 and the LP_{02} mode in the fiber F_2 have the same cutoff wavelength noted λ_{cc}.

3. a) By means of two large drawings (at least 5cm X 5cm each), plot the intensity pattern, in the plane (xOy) perpendicular to the propagation axis z, corresponding to the LP_{11} mode and that corresponding to the LP_{02} mode. O is the center of the core.
   b) On each of these patterns, add five arrows representing the possible electric field (direction and amplitude) at five different points (M_i (x,y), (i = 1 to 5)) of the cross section of the core, at a given time.
   c) Below each pattern, plot the shape of the curve I = f(x) along the diameter Ox, I being the light intensity. Add comments/explanations on this shape if possible.

4. Express λ_{cc} with the data provided in the exercise, in the fiber F_1.
5. Likewise, express λ_{cc} with the data provided in the exercise, in the fiber F_2.
6. From the above results, deduce a simple relationship between a_1 and a_2.
7. We know that $a_2 = a_1 + 2.37$ µm. Calculate a_1 and a_2 (you should find $a_1 = 4$ µm)
8. We measure $\lambda_{cc} = 1254$ nm. Calculate the numerical aperture of the fibers F_1 and F_2 to the nearest 10^{-3} (you should find NA ≈ 0.120)

We now work with the fiber F_1, at $\lambda_T = 1550$ nm. At λ_T the index of the cladding is $n_g(\lambda_T) = 1.444$.

9. Is the fiber F_1 suitable for application in a high bit rate transmission system at λ_T ? Justify your answer.
10. Using the data and curves provided in the appendix part, evaluate the effective index of the fundamental mode in the fiber F_1, at λ_T.
11. Calculate the phase velocity of the fundamental mode in the fiber F_1, at λ_T.

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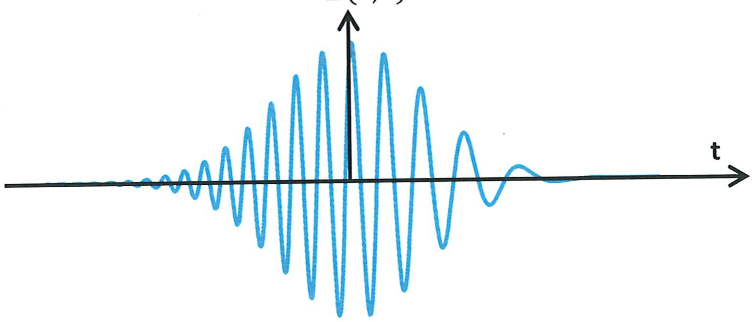
Exercice II

The following figure describes the time domain evolution of the electric field E(z,t) of an optical Gaussian pulse.



1. Does this pulse present a null, positive or negative chirp ?
2. What must be the sign of the chromatic dispersion coefficient D experienced by this pulse along its propagation in a singlemode optical fiber in order to reach the minimal achievable pulsewidth at the output?

Exercice III

A laser emits optical Gaussian pulses with center wavelength λ=1.5 μm. The values of initial half pulsewidth T_0 and chirp parameter C_0 are unknown. A spectral measurement has shown that the half spectral width $\Delta\nu_0$ is 100 GHz.
This laser is connected to an optical fiber F_1 with length L_1=100 m and chromatic dispersion coefficient D_1=100 ps/nm/km.
At the output of the fiber F_1 the half pulsewidth T_1 is equal to 5 ps.

1. Calculate the minimal half pulsewidth T_m of the pulse that may be reached during the propagation.
2. Calculate the possible values of the chirp parameter C_1 after propagation along the fiber F_1.
3. Establish the relationship between C_0 and C_1 and calculate the possible numerical values of C_0.
4. Establish the relationship between T_0 and C_0 and calculate the possible numerical values of T_0.

A second fiber F_2 with properties identical to fiber F_1 and length L_2 is connected after the fiber F_1.
After the propagation along both fibers, the half pulsewidth T_2 at the output of fiber F_2 is measured equal to T_1. We call C_2 the chirp parameter value associated to T_2 at fiber F_2 output.

5. What is the simple relationship between C_1 and C_2?
6. Plot the possible evolutions of C(z) and T(z) in this optical line including both fibers.
7. Determine the real values of C_0, C_1 and C_2.
8. Calculate the length L_2
9. Calculate the real value of T_0.

Appendix :

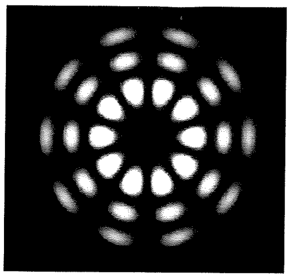
$$\beta_2 = -\frac{\lambda^2 D}{2\pi c}$$

Data and curves which may be useful/necessary for Exercise 1

π=3.14159 *celerity of light in the vacuum*: c = 3.10^8 m.s^{-1}

Function →	$J_0(x)$	$J_1(x)$	$J_2(x)$	$J_3(x)$	$J_4(x)$
first zero for x = →	2,405	0	0	0	0
second zero for x = →	5,52	3,83	5,14	6,38	7,59
third zero for x= →	8,65	7,02	8,42	9,76	11,06

First zeros of few Bessel functions of the first kind



intensity pattern of the $LP_{5,3}$ mode

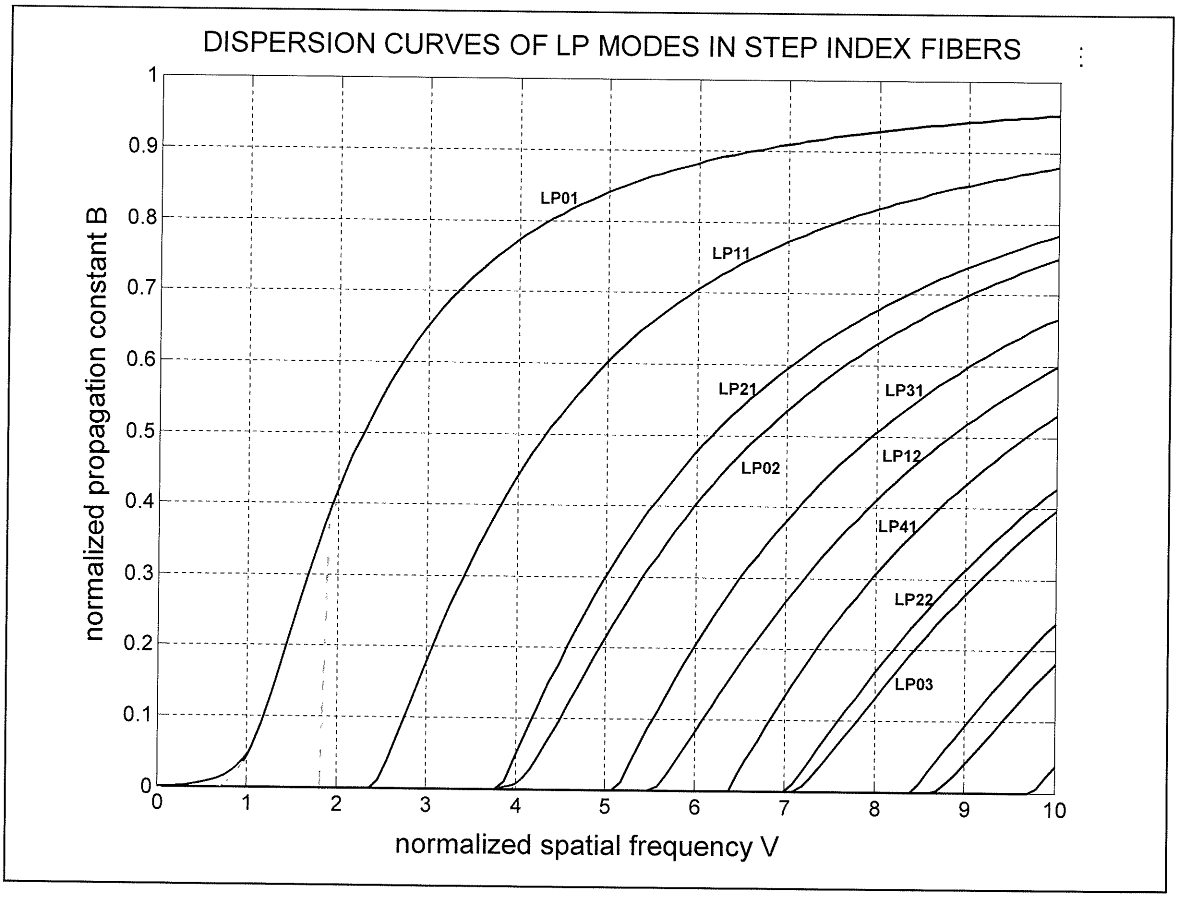
Formulas for an optical fiber which core index = n_1 and cladding index = n_2 :

Modulus of the wave vector at the wavelength λ in the vacuum: $k_0 = \dfrac{2\pi}{\lambda}$

numerical aperture of a fiber $NA = \sqrt{n_1^2 - n_2^2}$

relative index difference : $\Delta = \dfrac{NA^2}{2n_1^2}$ normalized spatial frequency: $V = k_0.a.NA$

normalized propagation constant of a mode: $B = \dfrac{\beta^2 - k_0^2.n_2^2}{k_0^2.(n_1^2 - n_2^2)}$ where β is the propagation constant of this mode



Examination – O. Tantot's part (Smith Chart)

Exercise #1

A transmission line ($\nu = c$; $\lambda = c/f$) with a characteristic impedance $Z_C = 36\ \Omega$ is terminated with an impedance $\underline{Z}_L$ such that s = VSWR = 3 and the phase of the reflection coefficient $\varphi_L = 16°$. The working frequency is 3 GHz.

1) Using the Smith chart, give the modulus of the reflection coefficient $|\Gamma_L|$ and the complex value of $\underline{Z}_L$.
2) A short-circuited stub is used to match this impedance (figure 1). Give the value of d and l_s if $Z_{CS} = Z_C$ and $d/\lambda < 0.25$.

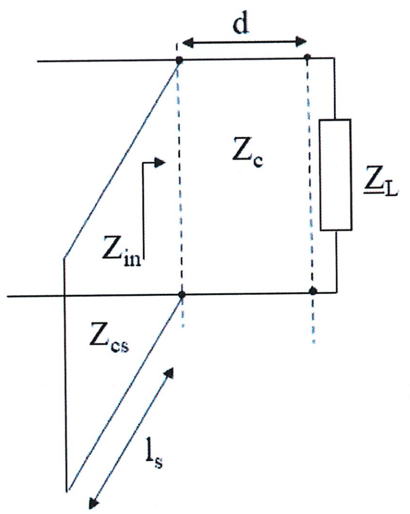


Figure 1: stub short-circuited at a distance d from the load $\underline{Z}_L$

3) This device is now is connected to a generator with an internal impedance Zg = 50 Ω. A section of line is inserted between the generator and the device (figure 2). Give the value of the characteristic impedance Z_{C1} and the dimension l_1 so that all the energy is absorbed in the device.

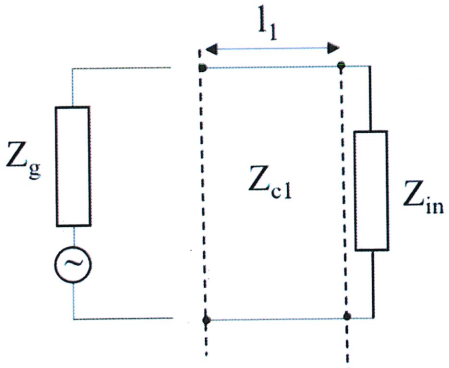


Figure 2: generator, section of line l_1 and the device

Exercise #2

A transmission line ($v = c$; $\lambda = c/f$) with a characteristic impedance $Z_{C1} = 40\ \Omega$ and length $d_1 = \lambda_0/8$, is terminated with a normalized admittance $\underline{y}_L = 4 + j$. The working frequency is $f_0 = 6$ GHz. A second transmission line is added, with characteristic impedance Z_{C2} and length d_2. A capacity $C = 0.663$ pF is inserted in parallel between the two transmission lines (figure 3).

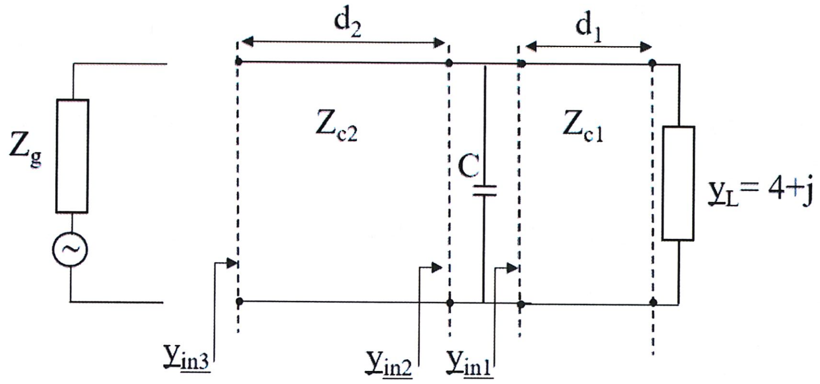


Figure 3

If the internal impedance of the generator is equal to $Zg = 50\ \Omega$, calculate Z_{c2} and d_2 so that $Z_{in3} = Z_g$.

Exercise #3

$\underline{Z}_L$ is the normalized impedance of load equal to $\underline{Z}_L = 4 - j$. The characteristic impedance of the two line is $Z_C = 40\ \Omega$ and their lengths $d_1 = d_2 = \lambda_0/8$ (figure 4). The working frequency is $f_0 = 6$ GHz. Calculate the value of L in nH so that the normalized input impedance is $z_{in3} = 1 + j$.

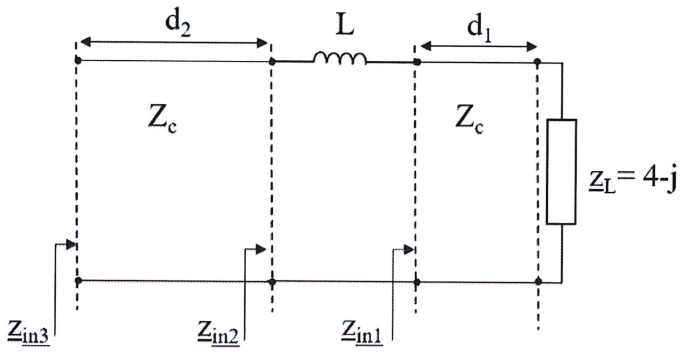


Figure 4