<u>Exercice 1</u> : propagation of LP modes in step index fibers

Data and curves likely to be used in this exercise are given at the end .

Step index fibers are constituted of a cylindrical core (refractive index $n_1(\lambda)$), surrounded by a cladding (refractive index $n_2(\lambda)$). Most of the time, the cladding is made of pure silica and the core is made of silica doped with germanium.

1/ a- what is the meaning of the expression "step index" ?
b- what is the role of germanium in the core ?
c- in what range of wavelengths are optical fibers used for telecommunication systems? Why ?

A manufacturer of silica fibers receives an order for a step index fiber which must fulfill the three following conditions:

<u>c 1</u> : the numerical aperture, which is assumed to be independent of the wavelength, must be equal to NA = 0.12 ;

<u>c 2</u> : the fiber must be single mode @ λ = 800 nm ;

<u>c 3</u> : the fiber must be able to guide at least two LP modes @ λ = 750 nm

This manufacturer has 5 different fibers described in the following table:

	Fiber 1	Fiber 2	Fiber 3	Fiber 4	Fiber 5
index n_1 (@ 800 nm)	1.456	1.456	1.458	1.458	1.46
Core diameter (µm)	5	6	5	6	5

2/ a- verify that the weak guidance approximation can be used for these fibers. What kind of transverse modes can be considered in this case ?
b- what are the two fibers which fulfill the condition c1?
c- determine the limit values of the diameter of the core (maximal value and minimal value) imposed by the conditions c 2 and c 3. Deduce that the Fiber 3 only fulfills all the conditions required by the custumer.

3/ A blue light beam from an argon laser emitting @ λ_A = 457 nm is launched in a piece of Fiber 3.
a- what are the LP modes able to propagate in the fiber at this wavelength ?
b- sketch a schematic representation of the energy distribution in each of these modes;
c- with any injection conditions, what can we observe on a screen set in front of the output face of the fiber ?
d- Fibre 3 is spliced to a fiber $F_{M,}$ single mode @ λ_A, and one measures the power at the output of this second fiber. What do we note if we handle the Fiber 3 ? Justify your answer. What do we note if we handle the Fiber $F_{M,}$ without touching Fiber 3 ? Justify your answer.

4/ We now work with the Fibre 3 only (Fiber F_M is removed), @ λ_T = 800 nm.
a- Using the provided information, evaluate the propagation constant β of the fundamental LP mode @ $\lambda_{T.}$
b- deduce the phase velocity of a continuous wave carried by this fundamental mode.
c- why is the velocity of a pulse propagating in the fiber lower than this phase velocity ?

5/ In fact, the core of the fiber is elliptical, the axis of the ellipse being oriented along two perpendicular directions x and y. The modes HE_{11x} and HE_{11y} composing the LP_{01} mode, respectively polarized along x and y, are no longer degenerated.

a- What does this expression means : " the modes HE_{11x} and HE_{11y} are no longer degenerated " ?

b- At the wavelength λ_T, the effective indices of the two modes are n_{ex}=1.45549 for the HE_{11x} mode and n_{ey}=1.45551 for the HE_{11y} mode. Show that, at this wavelength, the two modes in phase periodically along their propagation, every 4 cm (= spatial period).

c- What precaution should we take to ensure that a linearly polarized wave, launched at the input of a few meter long piece of fiber, remains linearly polarized at the output ?

<u>Data and curves likely to be useful for the exercise</u>

π=3,14159 V= k_0.a.NA is the normalized spatial frequency

Relative index difference : $\Delta = \dfrac{n_1^2 - n_2^2}{2.n_1^2}$

Group velocity : $v_g = \dfrac{d\omega}{d\beta}$

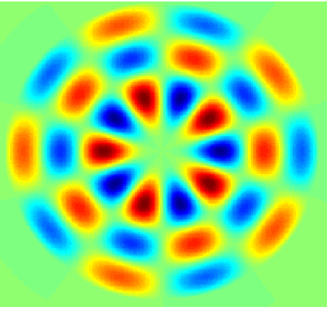
Group index : $n_g = n_e - \lambda \dfrac{dn_e}{d\lambda}$

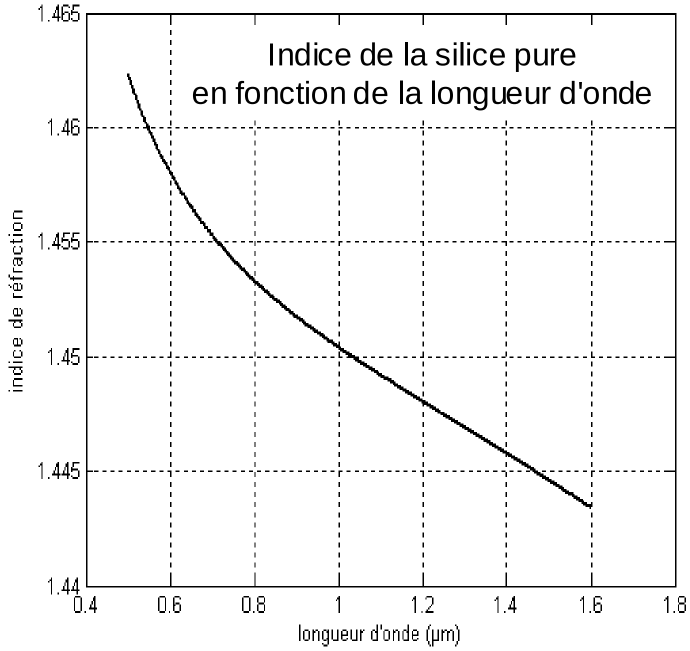
Normalized propagation constant of a given mode : $B = \dfrac{\beta^2 - k_0^2.n_2^2}{k_0^2.(n_1^2 - n_2^2)}$ (β is the propagation constant of the mode)

Fonction →	$J_0(x)$	$J_1(x)$	$J_2(x)$	$J_3(x)$	$J_4(x)$
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	7,01	8,42	9,76	11,06

First zeros of the first Bessel functions of first order (including the zero at the origin if there is)

Distribution of the linearly polarized field in the $LP_{5,3}$ mode :





Curve of $n_{sil} = f(\lambda)$ where n_{sil} is the refractive index of the pure silica

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Curves B=f(V) for the first LP modes (modes of lowest orders), where V is the normalized spatial frequency, and $B = \dfrac{\beta^2 - k_0^2.n_2^2}{k_0^2.(n_1^2 - n_2^2)}$, β being the propagation constant of the considered mode.