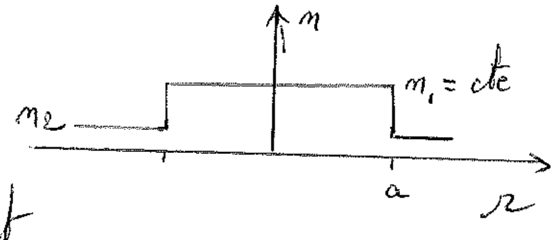
ENIMEO 

# Fundamentals on coherent optics: linear propagation in optical waveguides.

## exercice 1 correction

1- a "step index" means that the refractive index in the core is constant (independent of the distance to the axis)




b Ge is a dopant of silica ($SiO_2$) which effect is to increase its refractive index in order to fulfill the condition : Ge doped Silica → index $n_1$ > index $n_2$ ← pure silica

c. The three main ranges of wavelengths used for telecommunications in optical fiber are around 850 nm, 1300 nm and 1550 nm which are the three spectral windows corresponding to the better transparency of silica (lowest attenuation).

2. a. Weak Guidance approximation applies if $\Delta = \frac{NA^2}{2 n_1^2} < 10^{-2}$

highest $\Delta$ for the 5 fibers $\Delta \leqslant \frac{0.12^2}{2 . 1.456^2} \simeq 3,34\ 10^{-3} < 10^{-2}$

← lowest $n_1$ for the 5 fibers

$\Delta < 10^{-2} \Rightarrow$ WGA applies → the considered transverse modes are LP (linearly polarized) modes.

b) NA = 0.12 and $n_2$ (800 nm) $\simeq$ 1.453 (read on the graph $n = f(\lambda)$)

knowing that $NA = (n_1^2 - n_2^2)^{1/2} \Rightarrow n_1 = (NA^2 + n_2^2)^{1/2} = 1.458$

Fiber 3 and Fiber 4 would be suitable

c) condition C2 : fiber single mode at $\lambda_1 = 800$ nm

$$\Rightarrow \frac{2\pi}{\lambda_1} a \, NA < 2.405 \Rightarrow a < \frac{2.405 \, \lambda_1}{2\pi \, NA} \quad (1)$$

condition C3 : fiber is two mode (at least) at $\lambda_2 = 750$ nm

$$\Rightarrow \frac{2\pi}{\lambda_2} a \, NA > 2.405 \Rightarrow a > \frac{2.405 \, \lambda_2}{2\pi \, NA} \quad (2)$$

(1) and (2) $\Rightarrow$ $$\frac{2.405 \, \lambda_2}{2\pi \, NA} < a < \frac{2.405 \, \lambda_1}{2\pi \, NA} \Rightarrow 2.4 < a < 2.55 \ \mu m$$

$$\Rightarrow 4.8 < \phi < 5.1 \ \mu m$$

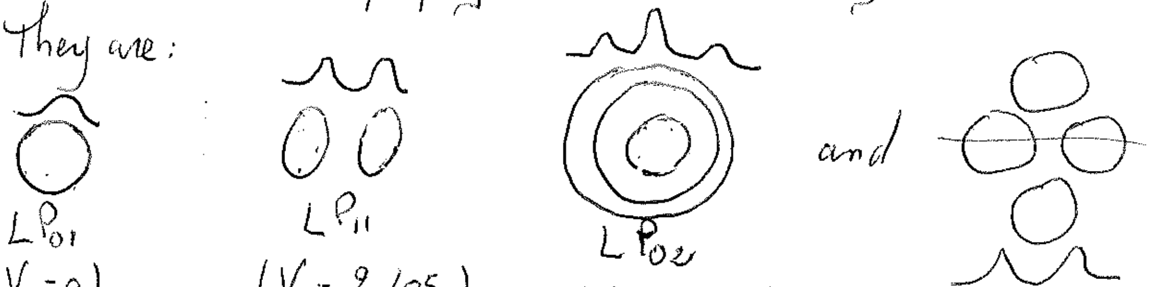
Fiber 3 only fulfills the conditions $4.8 < \phi < 5.1 \ \mu m$ and $n_1 = 1.458$

3/ a) $V = \frac{2\pi}{0.457} \times 2.5 \times 0.12 = 4.12$

The modes able to propagate are those having their $V_c < 4.12$

They are:

b)



$LP_{01}$ ($V_c = 0$)

$LP_{11}$ ($V_c = 2.405$)

$LP_{02}$ ($V_c = 3.83$)

and

$LP_{21}$ ($V_c = 3.83$)

c) one can see a superimposition of these 4 modes, with any phase relation between them, and a "weight" of each of them depending on the input beam and on mode coupling along the propagation

$\Rightarrow$ "speckle" with large grains (only few low order modes)

d) Fiber 3 is handled $\Rightarrow$ speckle at the output changes

$\Rightarrow$ excitation coefficient of $LP_{01}$ mode in $F_1$ changes

$\Rightarrow$ fluctuations of power at the output end of $F_1$

$F_M$ is handled. It only propagates the fundamental ($LP_{01}$) mode
→ the transverse distribution of light and the power at the output remain stable if the perturbations are not too severe.
Note that if very tight bendings are applied, loss occurs at these bendings.

4/a) $\lambda_T = 0.8\,\mu m$ $\quad V = \frac{2\pi}{\lambda_T} a\, NA = 2.36$ (single mode)

- We can read on the curve $B = f(V)$ for the fundamental mode:
$B(2.36) \simeq 0.5$

$$B = \frac{\beta^2 - k_0^2 n_2^2}{k_0^2 \underbrace{(n_1^2 - n_2^2)}_{NA^2}} \Rightarrow \beta = k_0 [B\, NA^2 + n_2^2]^{1/2} = 11.43\ 10^6\ m^{-1}$$

$n_2 = 1.453$

b) $v_\varphi = \frac{c}{n_e} = \frac{c}{(\beta/k_0)}$ with $\frac{\beta}{k_0} = n_e = [B\, NA^2 + n_2^2]^{1/2}$
$= [0.5 \times 0.12^2 + 1.453^2]^{1/2} = 1,45548$

$$v_\varphi = \frac{3\ 10^8}{1.45548} = 2.061\ 10^8\ m\,s^{-1}$$

c) velocity of a pulse = group velocity $= \frac{c}{n_g}$ with $n_g = n_e - \lambda \frac{dn_e}{d\lambda}$

$\frac{dn_e}{d\lambda} < 0 \Rightarrow n_g > n_e \Rightarrow v_g < v_\varphi$

5/a) $HE_{11x}$ and $HE_{11y}$ are not degenerated means that their propagation constants are different ($\beta_x \neq \beta_y$)

b) $\left.\begin{array}{l} \varphi_x = \beta_x z = \frac{2\pi}{\lambda} n_{ex} z \\ \varphi_y = \beta_y z = \frac{2\pi}{\lambda} n_{ey} z \end{array}\right\} \Delta\varphi = |\varphi_x - \varphi_y| = \frac{2\pi}{\lambda} z\, |n_{ex} - n_{ey}|$

modes in phase again when $\Delta\varphi = 2\pi$, for $L$ such that $\frac{2\pi}{\lambda} L\, |n_{ex} - n_{ey}| = 2\pi$

$$\Rightarrow L = \frac{\lambda}{|n_{ex} - n_{ey}|} = \frac{800\ 10^{-9}}{1.455549 - 1.455551} = 0,04\ m = 4\ cm \text{ (beat length } L_B)$$

c) The polarization of the beam at the input must be linear, and oriented along one eigenaxes of the fiber: either along $x$ (excitation of $HE_{11x}$ only) or along $y$ (excitation of $HE_{11y}$ only).

Z.