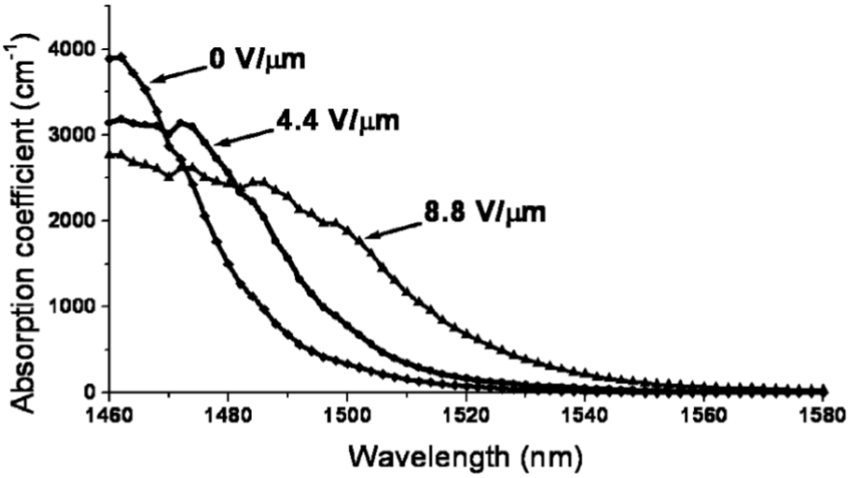
Exercise 1

We want to operate an electro-absorption modulator AM operating at $\lambda = 1520$ nm . the device is based on InGasAsP/InP and the absorption as been experimentally characterized. The results are given in the following graph which shows the absorption as a function of wavelength for different values of electric field in the active region (from Helman et al. JSTQE 2005). The active region is 350 nm wide and 100 μm long and you can assume that when you apply a voltage across the width of the device, and that the entire voltage drops in this region only.



(a) What are the voltages required to obtain the three curves shown in the graph ?

(b) Calculate the transmission of the modulator for 0 V and for the maximum voltage found in part (a).

(c) What is the insertion loss of the device in dB (light loss even when the device is at 0 V) ?

(d) What is the extinction ratio of the device ?

Exercise 2

A lithium niobate ($LiNbO_3$) Mach-Zehnder modulator has an electrode length of L = 1.5 cm and an electrode gap of $d = 10$ µm.

For the specific crystal orientation and polarization of our device, we have:

- Operation wavelength is 1550 nm
- Refractive index of $LiNbO_3$ of 2.2
- Pockels coefficient 30 pm/V

(a) Calculate V_π for the given parameters

(b) If the modulator is driven by a voltage source of 5 V peak-to-peak , what is the resulting phase shift of the MZI ?

We upgrade the modulator to a **push-pull operation: it** operates by applying equal and opposite voltage changes to the two arms of the interferometer.

(c) Derive the equation describing the relation between output field E_{out2} and input field E_{in}

(d) Show that the output power is given by: $P_{out} = P_{in}\cos^2\left(\frac{\Delta\phi}{2}\right)$ with$\Delta\phi = \phi_1 - \phi_2 - \pi\frac{V}{2V_\pi}$

(e) What can you say about the chirp $-d\phi_{out}/dt$? Compare to the single arm modulator.

Exercise 3

We have seen in class that modulators can be integrated on a chip. One of the elements required is a power coupler where light can go from one waveguide to another. A coupler can be made from simply putting two waveguides side by side: if two waveguides are sufficiently close such that their fields overlap, light can couple from one into the other.

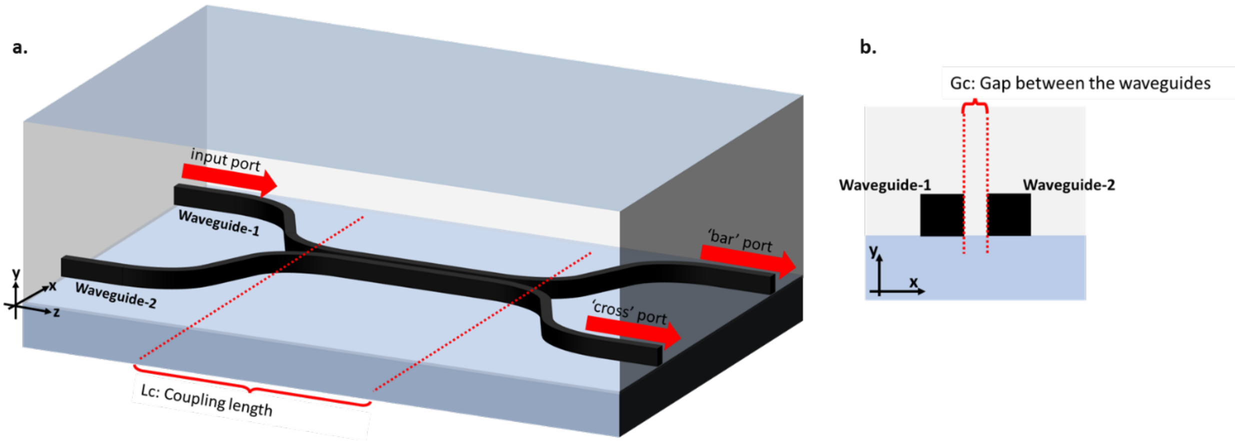


Figure 1 a. Schematic for the integrated coupler where BOX-oxide(light blue), cladding(grey) and waveguides(black). b. Cross-sectional view of the waveguide in the coupling region

By using coupled mode theory, transmitted power at each port can be determined:

$$P_{bar}(z) = \left((\cos(gz))^2 + \frac{\Delta\beta}{2}\frac{(\sin(gz))^2}{g^2}\right)P_{in}$$

$$P_{cross}(z) = \kappa^2\frac{(\sin(gz))^2}{g^2}P_{in}$$

$$g^2 = \kappa^2 + \left(\frac{\Delta\beta}{2}\right)^2$$

Where κ is the coupling coefficient, $\Delta\beta = \beta_2 - \beta_1$ is the phase mismatch per unit length, z is the propagation length within the coupling region.

κ is large when the gap between the waveguides (Gc) is small and also depends on how confined the light is within the waveguide. $\Delta\beta$ is determined by dispersion properties of each waveguide. When two waveguides are identical, the coupler is said to be phase-matched as $\Delta\beta$ is zero.

(a) For κ = 0.1 µm^{-1}, using matlab plot the power versus coupling length in the 'bar' port and in the 'cross' port for the incidence power of 1 mW.

(b) For this configuration, pinpoint the minimum coupling length (L_c) to obtain a 3-dB coupler?

(c) For this configuration, pinpoint the minimum coupling length (L_c) to obtain a complete optical switch, i.e. the transmission from input port to the 'cross' port is 100%?

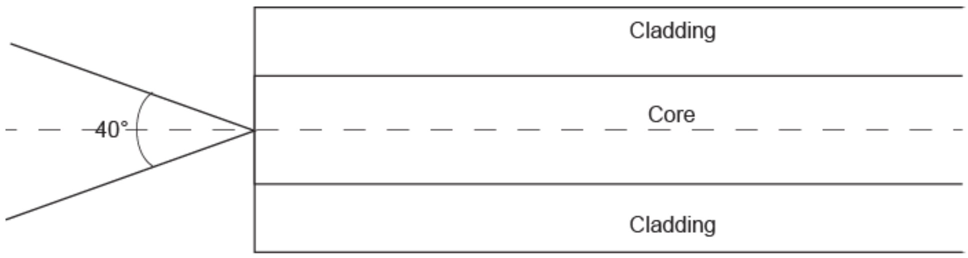
Many optical components require specific dispersion properties, and the waveguide dimensions may not be altered easily. In the next subsection, we investigate the response when the waveguides within the coupler have different dimensions. When β_2 and β_1 are not identical, this is called phase mismatched configuration.

(d) Repeat part (d) where β_1 is 8.1 μm^{-1} and β_2 is 8.5 μm^{-1}.

(e) Comment on whether it is possible to use this phase-mismatched coupler as a complete switch.

Exercise 4

You need a step-index multi-mode fiber that can guide all incoming light (via total internal reflection) within a cone of 40 degrees and transmit a 10 Mb/s signal 500 m. The refractive index of the core is 1.5 and the medium outside the fiber is air.



(a) Choose a value for the refractive index of the cladding to satisfy the coupling condition.

(b) Let's estimate the pulse broadening ΔT due to the multimode propagation in a fiber of L, a core index n_1, a cladding index n_2 and critical angle θ_c. Based on the incident angles leading to the shortest and longest path, show that the ΔT (if assumed equivalent to the difference in time between the two path and that the velocity of propagation is c_0/n_1) is given by:

$$\Delta T = \frac{L}{c_0}\frac{n_1^2}{n_2}\Delta$$

(c) Can this fiber fulfill the transmission criteria you require, assuming that such intermodal broadening dominates?

Exercise 5

A 2.5 Gb/s data link is set up on an optical fiber with 0.25 dB/ km attenuation. The light source used has a spectral width of 6 nm.

(a) If the mean optical power at the input is 1 mW, what is the mean optical power of the light signal after a 28 km transmission distance?

(b) If 25 km is the maximum reliable transmission distance, estimate the dispersion parameter of the optical fiber used in the system

(c) Near the zero-dispersion wavelength λ_0, the dispersion parameter of the fiber can be expressed as a function of the dispersion slope S_0: $D(\lambda) = S_0(\lambda - \lambda_0)$. Given that $\lambda_0 = 1550\ \mathrm{nm}$ and $S_0 = 0.1\ \mathrm{ps/(nm^2 \cdot km)}$, estimate the center wavelength of the light source.

Graded Exercise

We are given a step-index fiber of radius 5 μm with $n_1 = 1.468$, $n_2 = 1.462$ at a wavelength of 1400 nm.

(a) What is numerical aperture, and total acceptance angle of the fiber?

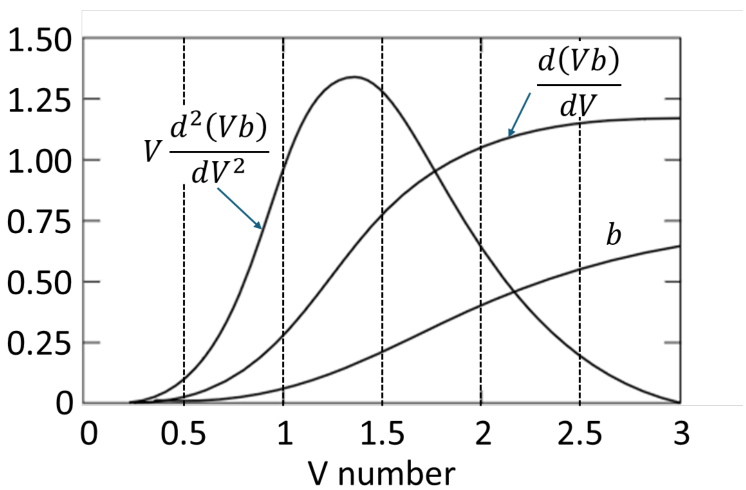
(b) How many modes can exist approximately in this fiber?

(c) What is the cut-off wavelength of this fiber (wavelength for single mode operation)?

(d) We define the normalized propagation constant of the fiber as $b \approx \frac{n_{\mathrm{eff}} - n_2}{n_1 - n_2}$, with $n_{\mathrm{eff}} = {}^{\beta}/_{k}$. This approximation is valid for small index difference $\Delta = \left(\frac{n_1 - n_2}{n_1}\right)$. Given that the group velocity due to waveguide effects can be expressed as $\frac{1}{v_{g,eff}} \approx \frac{n_2}{c}\left[1 + \Delta \frac{d(bV)}{dV}\right]$, show that the waveguide dispersion is:

$$D_W \approx -\frac{n_2 \Delta}{c_0 \lambda} V \left[\frac{d^2(bV)}{dV^2}\right]$$

(e) We use our previous step index fiber but with a source at 2000 nm. The material dispersion at this wavelength is found to be $D_M = 30\ \mathrm{ps/(nm \cdot km)}$. Using the answer from part (d) and the following graph, what is the total dispersion of this fiber at 2000 nm?



(f) We wanted to have zero dispersion at 2000nm. What should have been the radius of the fiber?