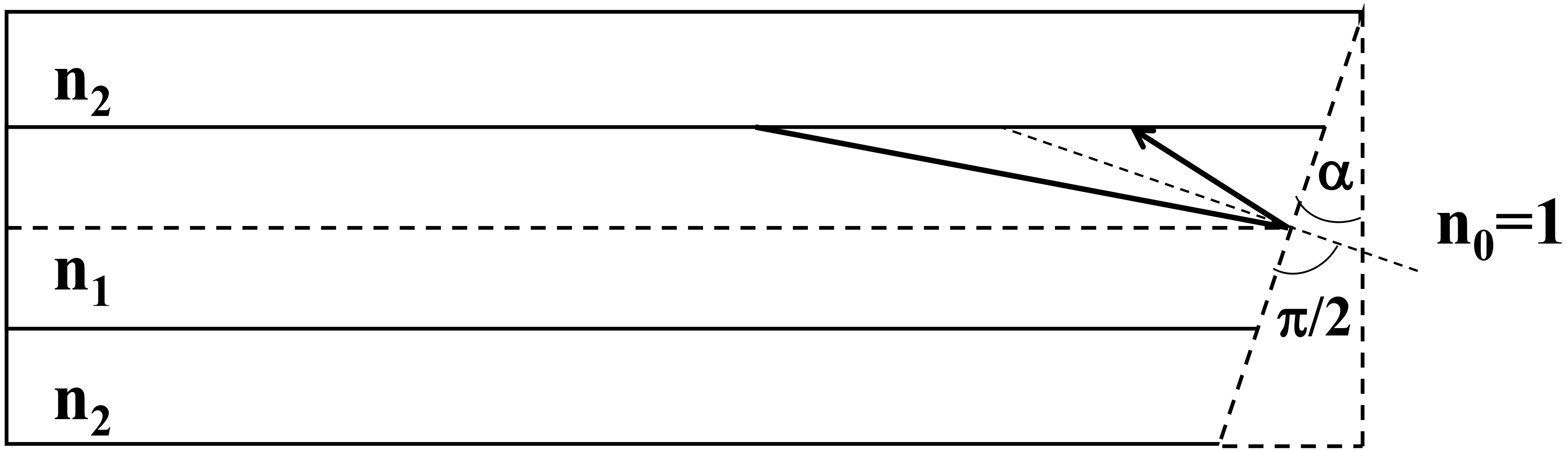
Exercise 2.1

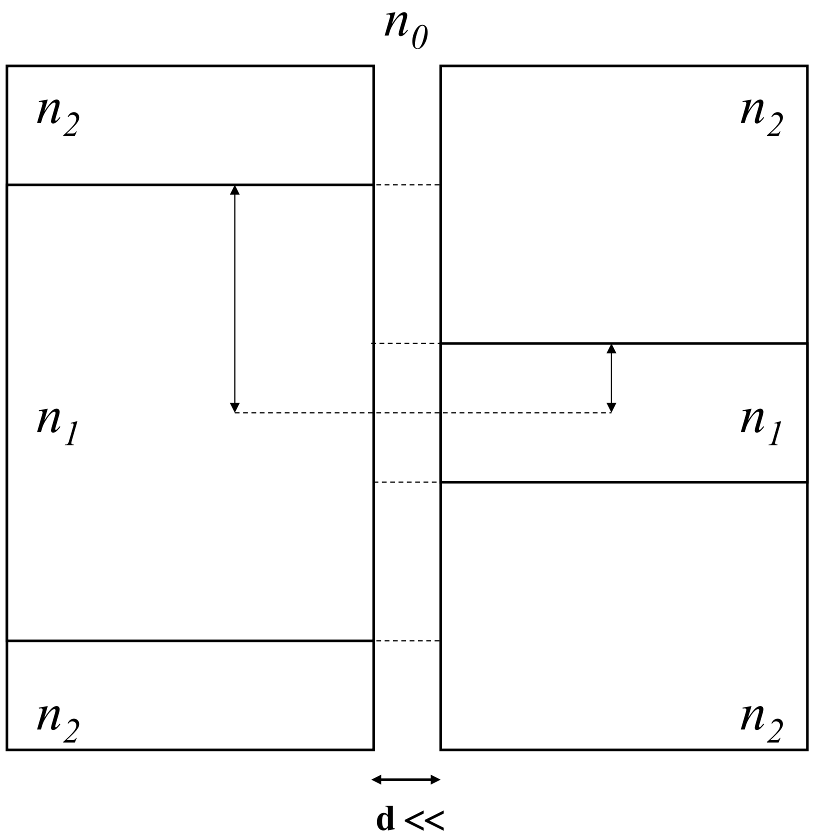
To avoid the reflected rays at the fiber's output to become guided in the backwards direction, the end surface is cut non-perpendicular to the fiber axis (see figure). This is usually referred to as angled physical contact (APC) connectors. If the fiber has the core index $n_1 = 1.47$ and cladding index $n_2 = 1.46$, find the minimum angle α such that all possible reflected rays wont be guided.



Solution: $\alpha > 6.7^o$

Exercise 2.2

Estimate the losses in a connection between 2 optical fibers with a core diameter mismatch (see figure). Assume that the optical power is uniformly distributed all over the core of the transmitting fiber. Make the calculations in both directions (from the larger core to the smaller core and vice versa). Consider a standard single mode fiber and a standard multimode fiber for the calculations.



$$a_1 = 25\mu m$$

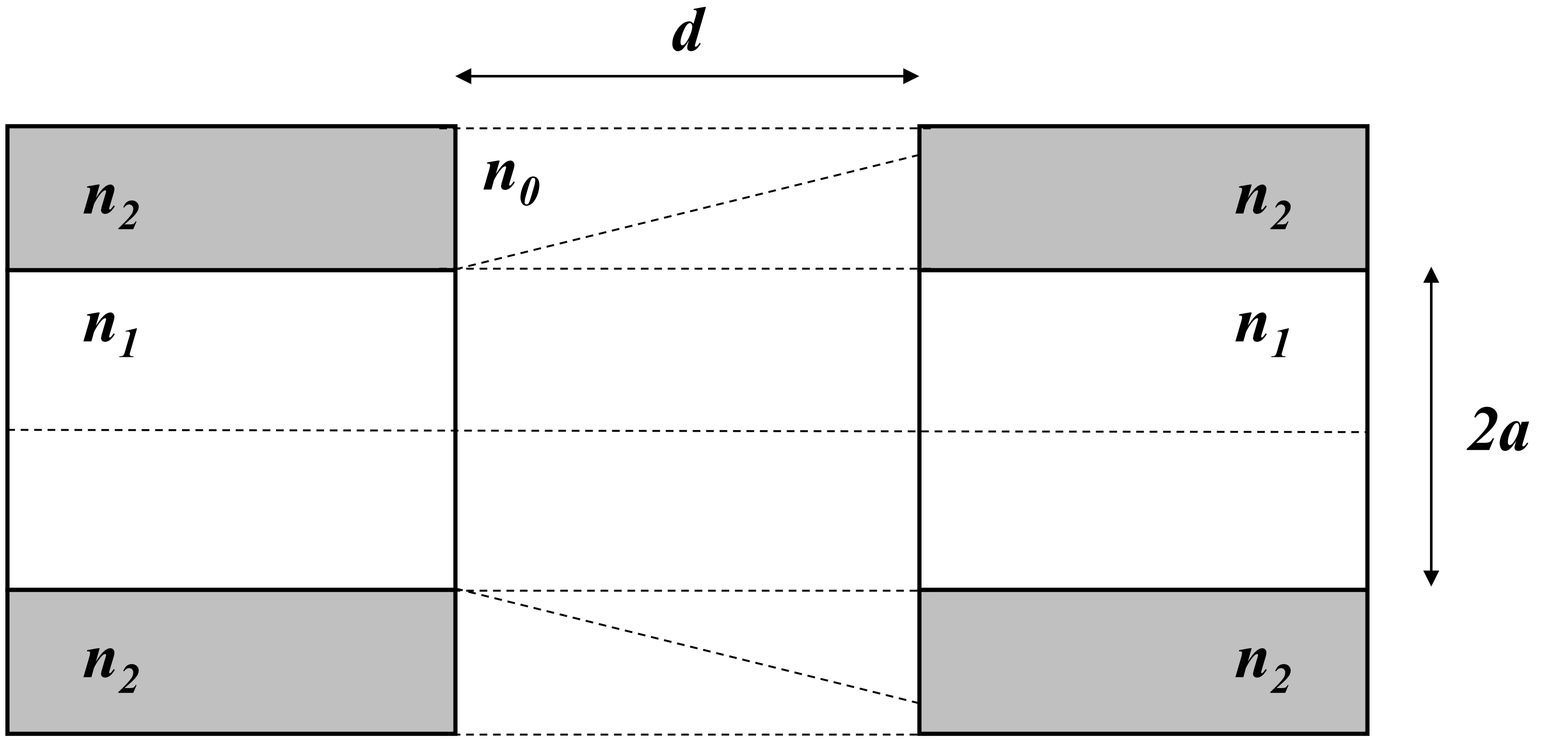
$$a_2 = 5\mu m$$

$$n_1 = 1.45$$

Solution: $L \approx -14.3\ dB$

Exercise 2.3

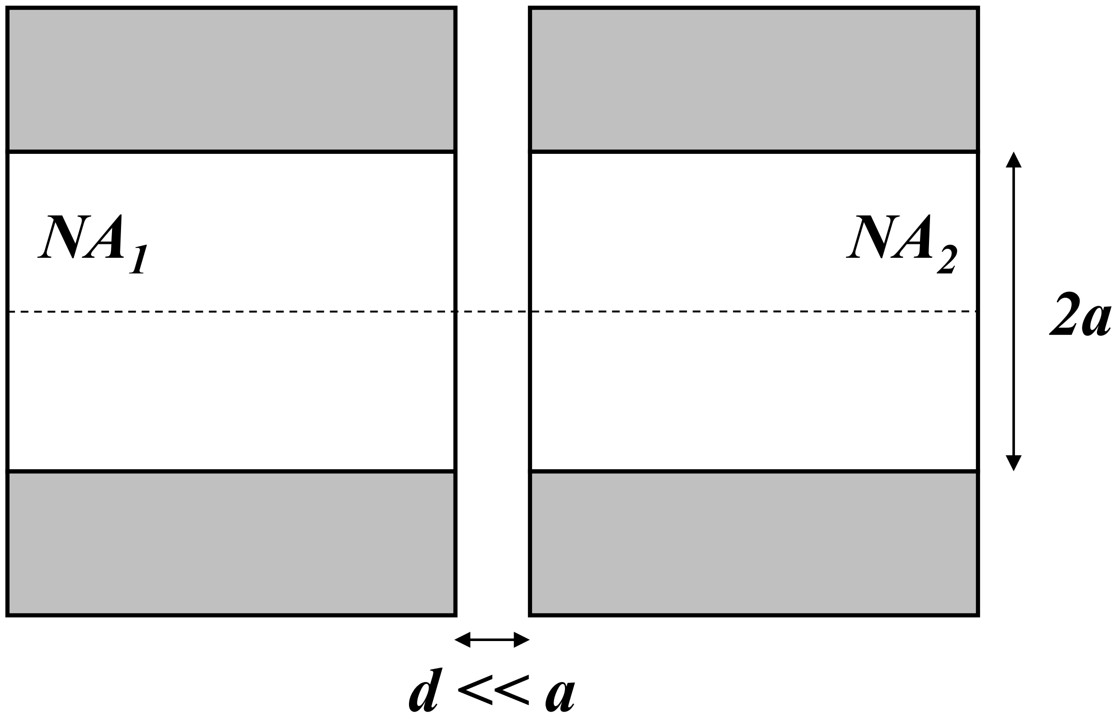
Estimate the losses in a connection between 2 identical optical fibers with numerical aperture $NA = 0.2$ and a separation distance $d = 2a$ (see figure). Assume that the optical power is uniformly distributed all over the core of the transmitting fiber as well as the projected light spot. Neglect reflection losses.



Solution: $L \approx -1.5\ dB$

Exercise 2.4

Estimate the losses in a connection between 2 identical optical fibers except the numerical apertures (see figure). Neglect reflection losses.



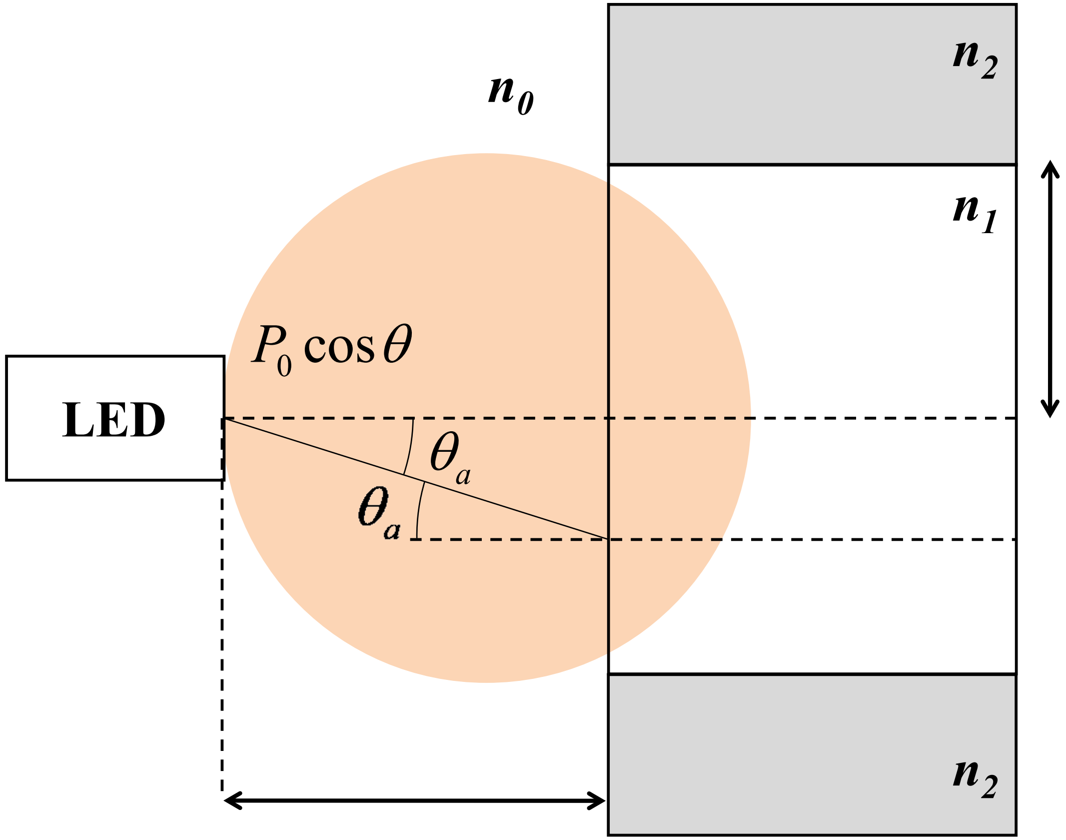
$$\frac{NA_1}{NA_2} = 2$$

Solution: $L \approx -6\ dB$

Exercise 2.5

Estimate the coupling efficiency from an LED source into an optical fiber with numerical aperture $NA = 0.1$. Assume a Lambertian radiation pattern for the LED $P(\theta) = P_0 \cos\theta$. Assume the separation distance to be much smaller than the core's radius (see figure). Neglect any reflection losses.

Find the coupling efficiency improvement if the LED is replaced by a laser with a very directive radiation pattern $P(\theta) = P_0 \cos^{100}\theta$.



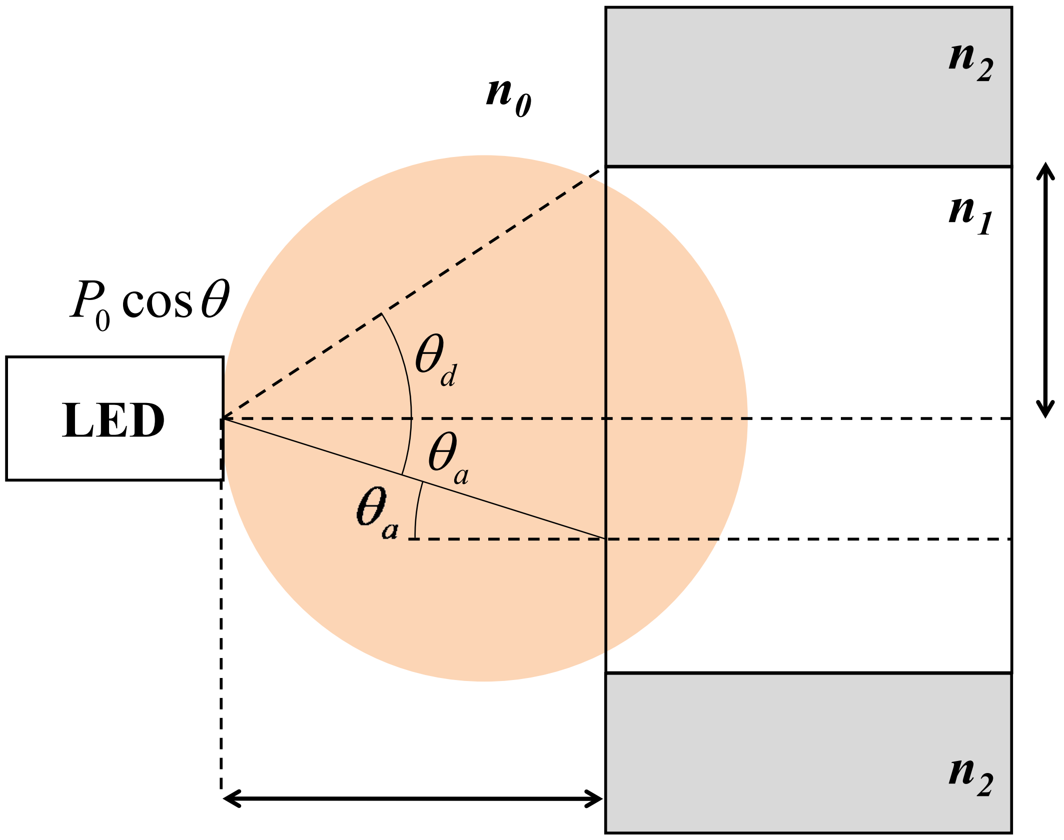
Solution: $\eta_{LED} \approx -20\ dB$, $\eta_{laser} \approx -4\ dB$

Exercise 2.6

An LED is located at a certain distance from an optical fiber (see figure) with numerical aperture $NA = 0.1$ and core radius $a = 25\ \mu m$.

a) Find the distance above which the coupling efficiencies are limited by the vision angle rather then the fiber's acceptance angle.

b) Estimate the coupling efficiency at two times such distance. Assume a Lambertian radiation pattern for the LED $P(\theta) = P_0 \cos\theta$. Neglect any re-flection losses.



Solution: $d = 250\ \mu m$, $\eta \approx -26\ dB$

Exercise 2.7

For the 3 types of standard fibers: step-index multimode, graded-index multimode and single-mode.

a) Find the normalized frequency (V).

b) Calculate the corresponding cutoff wavelength (λ_c).

c) Calculate the approximate number of modes (M).

d) Estimate the optical power concentration inside the core (P_{core}/P_{tot}).

Consider the following reference parameters:

step-index multimode	$a = 31.25\,\mu m$ $NA = 0.2$ $\lambda = 1300\,nm$ $\alpha = \infty$
graded-index multimode	$a = 25\,\mu m$ $NA = 0.2$ $\lambda = 1300\,nm$ $\alpha = 2$
step-index single-mode	$a = 4.5\,\mu m$ $NA = 0.1$ $\lambda = 1550\,nm$ $\alpha = \infty$

Solution: $V \approx 30.21\,,\, 24.17\,,\, 1.82$ $\quad M \approx 456\,,\, 146\,,\, 1$

$\lambda_c \approx 16.3\mu m\,,\, 13.1\mu m\,,\, 1.82$ $\quad P_{core} \approx 94\%\,,\, -\,,\, 85\%$

Exercise 2.8

Consider the standard step-index multimode fibers.

a) Calculate the coupling losses from an LED with Lambertian radiation pattern for the LED $P(\theta) = P_0 \cos\theta$. Assume the LED-fiber separation to be negligible.

b) If the normalized frequency must be kept constant, calculate the required core radius for the coupling efficiency to be -6 dB.

Consider the following reference parameters:

step-index multimode

$$a = 31.25\,\mu m$$
$$NA = 0.2$$
$$\lambda = 1300\,nm$$
$$\alpha = \infty$$

Solution: $\eta_c = -14dB$, $a' = 12.5\ \mu m$

Exercise 2.9

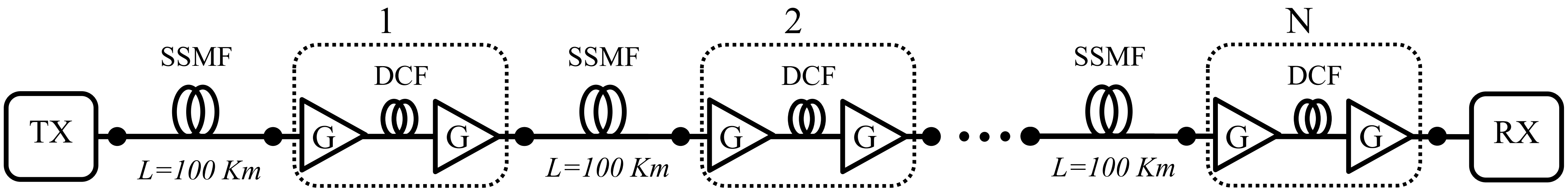
a) Plot the maximum transmission distance (L_{max}) limited by attenuation versus the bit rate (R_b) for standard single/multi-mode fibers at 1550 nm ($\alpha = 0.2\, dB/km$). Assume a transmission power $P_{tx} = 10\, mW$ and a receiver sensitivity at 10 Gb/s of $S_{10G} = -40\, dBm$. Use the log scale for the R_b axis.

b) Plot the maximum transmission distance (L_{max}) limited by modal dispersion versus the bit rate (R_b) for standard multi-mode fibers ($n_1 = 1.45$, $\Delta = 2\%$). Consider both step-index and ideal graded-index profiles. Use the log scale for both L_{max} and R_b axis.

c) Plot the maximum transmission distance (L_{max}) limited by chromatic dispersion versus the bit rate (R_b) for standard single/multi-mode fibers at 1550 nm ($D = 17\, ps/(nm \cdot km)$). Use the log scale for both L_{max} and R_b axis.

d) Determine which is the limiting factor (attenuation, modal dispersion or chromatic dispersion) in each region. To facilitate the calculations, use the approximation $\ln(1+x) \approx x$ (valid for $-1 < x \leq 1$) in the attenuation limit .

Exercise 2.10



Design a 5000 km link (see figure) using SSMF fibers ($\alpha_{SSMF} = 0.2\, dB/km$, $D_{SSMF} = 17\, ps/(nm \cdot km)$ @ $1550\, nm$), ideal optical amplifiers and DCF fibers ($\alpha_{DCF} = 0.5\, dB/km$, $D_{SSMF} = -85\, ps/(nm \cdot km)$ @ 1550 nm). The SSMF fiber spans must be of $100\, km$ and DCF fibers don't compute in transmission distance. Determine the following parameters:

a) Length of the DCF fibers and number of spans.

b) Gain of the amplifiers if they have to completely compensate for the losses of the previous fiber.

c) The slope of the dispersion parameter for SSMF and DCF fibers is $S_{SSMF} = 2\, ps/(nm^2 \cdot km)$ and $S_{DCF} = -9.8\, ps/(nm^2 \cdot km)$, respectively. Calculate the accumulated dispersion (in ps/nm) at the end of the link for a channel 16 nm away from the central channel (1550 nm).