Solution to Problem Set 9
Optical Waveguides and Fibers (OWF)

Exercise 1: LP-modes, hybrid modes and cut-off frequencies

The facet of a Corning SMF-28 fiber is illuminated with a green laser (wavelength of 532 nm). You can find all relevant parameters of the fiber in its datasheet:
(http://www.corning.com/media/worldwide/coc/documents/Fiber/PI1450_3-2015.pdf).

a) How many LP-mode families are guided?

Solution: The normalized frequency V can be calculated from the data given in the datasheet:

$$V = ak_0\sqrt{n_1^2 - n_2^2} = ak_0 A_N = 6.78$$

Now the crossings of the dispersion diagram with $V = 6.78$ can be counted. This yields 7 guided mode families.

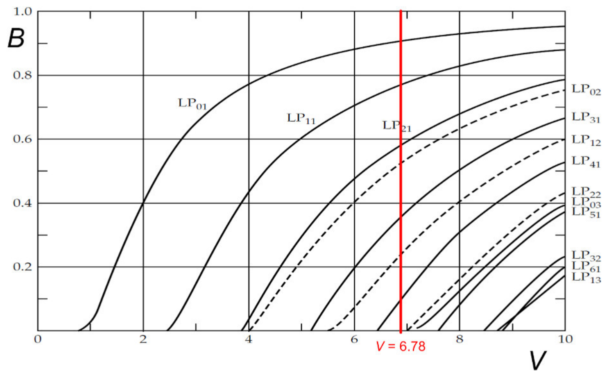

Figure 1: Dispersion diagram of LP-modes in a step-index fiber

b) How many different modes are guided by the fiber?

Solution: Taking into account the degeneracies of the mode families the total number of guided modes can be calculated. $LP_{\nu\mu}$mode families with $\nu = 0$ are two-fold degenerate, whereas all the others are four-fold degenerate. In total there are 24 modes.

This can be compared to the estimated value for step-index fibers $M_g \approx {V^2}/{2} \approx 23$. It can be seen that the rough estimate is quite reasonable.

c) Sketch the intensity profile of all the guided mode families.

Solution:

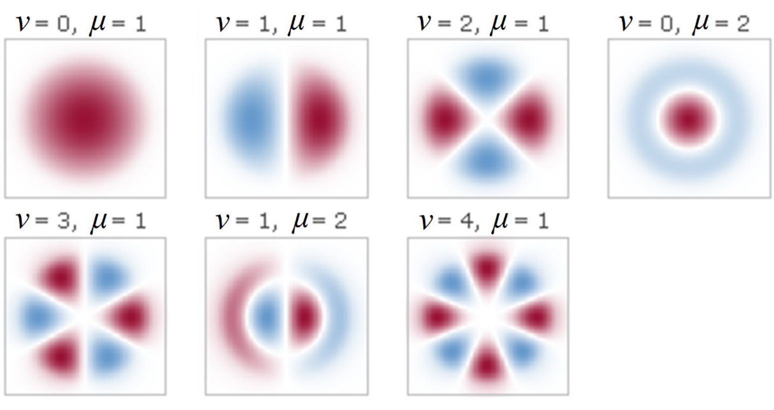

Figure 2: Mode profiles of the seven guided mode families of a standard SMF at $\lambda = 532$ nm.

Exercise 2: Photonic wire bonds and cut-off frequencies

Fig. 3 shows so-called photonic wire bonds connecting two silicon-on-insulator (SOI) waveguides, a four-core multicore fiber and SOI waveguides, and a horizontal-cavity surface-emitting laser (HCSEL) and an SOI waveguide. Taper structures are used to match the modes of the SOI waveguides, the multi-core fiber, and the HCSEL to the modes of the photonic wire bonds. The bond consists of a polymer (trade name IP-Dip, a commercially available photoresist), and has a refractive index of 1.53 at $\lambda = 1550\,\text{nm}$. The structure is surrounded by air. In the following you can assume that the wire bond waveguide has a circular cross section, and that the bend radius is large compared to the bond diameter, such that the structure can be approximated by a straight waveguide.

a) Which condition must the diameter of the bond fulfill, such that the bond is a single-mode waveguide at a wavelength of1550 nm?

Solution: For a single-mode waveguide the normalized frequency needs to fulfil the condition $V \leq 2.405$. With the values given for the index contrast ($n_1 = 1.53$, $n_2 = 1$) and wavelength ($\lambda = 1.55\,\mu\text{m}$) it can be deduced that:

$$a = \frac{V\lambda}{2\pi\sqrt{n_1^2 - n_2^2}} \leq 0.512\,\mu\text{m}\,.$$

b) Does the LP-mode model apply in this case?

Solution: No the LP-mode model only holds for small index contrast waveguides, which is not the case here. The estimation made in part a) is however not based on this model, and therefore the result is valid.

c) Discuss ways to increase the diameter and thus mechanical stability.

Solution: Cover the wirebond with a cladding material; in that way the refractive index contrast will be decreased, and the wirebond will become more weakly guided. This would however increase bend losses, and thus requires a larger minimum bend radius. Increasing the diameter without lowering the refractive index contrast would make the wirebond multi-mode at our desired wavelength of 1550 nm. Using larger wavelengths where the wirebond might still be single-mode would not be an option, as it is not compatible with existing standards. Namely, due to the availability of cheap semiconductor lasers, low loss fibers and amplifiers 1.55 μm is the standard telecommunication wavelength.

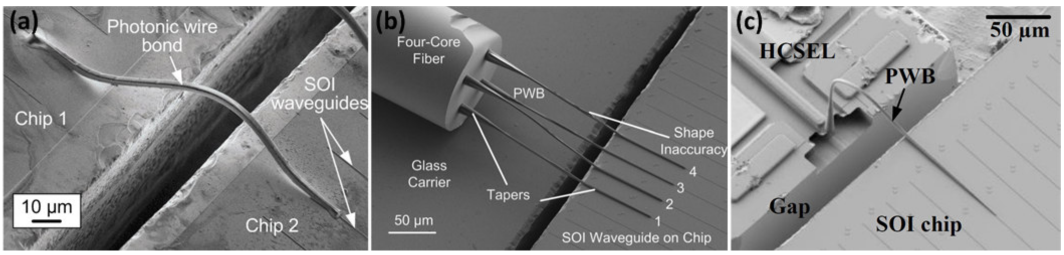

Figure 3: (a) A photonic wire bond between two silicon waveguides [1]; (b) Four photonic wire bonds between four cores of a multi core fiber and four SOI waveguides [2]; (c) A photonic wire bond between a HCSEL and an SOI waveguide [3]

[1] Lindenmann et al., "Photonic wire bonding: a novel concept for chip-scale interconnects", *Optics Express*, vol. 10, no. 16, pp 17667-17677, 2012.
[2] Lindenmann et al., "Connecting Silicon Photonic Circuits to Multicore Fibers by Photonic Wire Bonding", *Journal of Lightwave Technology*, vol. 33, no. 4, pp 755-760, 2015.
[3] Billah et al., Multi-Chip Integration of Lasers and Silicon Photonics by Photonic Wire Bonding ", in CLEO: 2015, OSA Technical Digest (online) (Optical Society of America, 2015), paper STu2F.2.

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