EE234 Photonics Laboratory, Lab 4

Laser-to-Fiber Coupling

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Abstract

In this lab, we were trying to couple light from a Fabry-Perot semiconductor diode laser into a single-mode fiber using an imaging telescope. Furthermore, we tried to measure the mode size of the optical fiber and the spectrum of the emitted light. It turned out that even though launching light into a single-mode fiber is a challenging task, the theoretically predicted coupling efficiency could be achieved.

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1 Procedure, Results, Analysis, and Discussion

1.1 Light source setup

Our first objective in this laboratory experiment was to assure parallel alignment of our light source, a Fabry-Perot semiconductor laser operating at a 1550 nm wavelength (Mitsubishi ML976H6F). This laser diode was mounted into a special mount (Newport 700C), which incorporated a collimating lens (Newport 700-42). The position of the laser inside the mount can be changed by adjusting two screws on the outside of the mount. Since the vertical and horizontal position of the lens is fixed, this adjustment allows us to change the angle of the emitted light. We will show in Section 1.2 that it is important to know the direction of the emitted light to within a few mrad. Therefore, we tried to align the beam parallel to the surface of the optical table and also parallel to a row of holes.

To do this, we used the common iterative procedure. An iris is placed close to the laser and adjusted, so that the beam passes through its center. Then, one displaces the iris as far along the beam as possible. At this position, the beam will most likely not hit the center of the iris anymore and the vertical axis of the diode laser has to be adjusted to bring the beam back to the center. Following this, one returns the iris to its initial position and adjusts its height again, etc. Going through these steps a couple of times should make the beam travel parallel to the optical table. A similar procedure can be used to make the beam travel parallel to a row of holes.

Since we wanted to operate at an output power of 2 mW, the diode driver (Newport 501AN) had to be set to 24.5 mA (see lab reports 1, 2, and 3).

1.2 Theoretical coupling efficiencies

Optimum coupling into a fiber depends crucially on the relative position of the fiber with respect to the laser beam. The following expressions give estimates for the coupling efficiencies for some cases of misalignment.

Axial Offset & Modematching If we want to couple an elliptical Gaussian beam into a single-mode fiber, we can express the coupling efficiency in the case of axial offset D as follows.

$$T = \frac{4\frac{\omega_{fiber}^2}{\omega_x \omega_y}}{\sqrt{\left(1+\frac{\omega_{fiber}^2}{\omega_x^2}\right)^2 + \frac{k^2\omega_{fiber}^2}{4R_x^2}}\sqrt{\left(1+\frac{\omega_{fiber}^2}{\omega_y^2}\right)^2 + \frac{k^2\omega_{fiber}^2}{4R_y^2}}}$$

with

$$\omega_{x,y} = \omega_{x_0,y_0}\left[1+\left(\frac{\lambda D}{\pi\omega_{x_0,y_0}^2}\right)^2\right]^{-1/2}, R_{x,y} = D\left[1+\left(\frac{\pi\omega_{x_0,y_0}^2}{\lambda D}\right)^2\right], \text{ and } k = \frac{2\pi}{\lambda}$$

Modematching In the case that we don't have any mechanical misalignment, we are still left with the problem of matching an elliptical Gaussian mode to the circular Gaussian mode of the fiber. We are therefore left with the following expression for the coupling efficiency.

$$T = \frac{4\omega_{fiber}^2\omega_x\omega_y}{\left(\omega_x^2+\omega_{fiber}^2\right)\left(\omega_y^2+\omega_{fiber}^2\right)} \tag{1}$$

Tilt In case the fiber axis is tilted with respect to the optical axis of the incoming beam, we get the following theoretical coupling efficiency.

$$T = \frac{4\omega_{fiber}^2\omega_x\omega_y}{\left(\omega_x^2+\omega_{fiber}^2\right)\left(\omega_y^2+\omega_{fiber}^2\right)}\exp\left[-\frac{2\pi^2\omega_{fiber}^2}{\lambda^2}\left(\frac{\omega_x^2\theta_x^2}{\omega_x^2+\omega_{fiber}^2}+\frac{\omega_y^2\theta_y^2}{\omega_y^2+\omega_{fiber}^2}\right)\right]$$

where $\theta_{x,y}$ are the tilt angles in the x and y direction, respectively.

Lateral Offset In case of later offset between the axis of the optical fiber and the optical axis of the incoming beam, the coupling coefficient computes to

$$T = \frac{4\omega_{fiber}^2\omega_x\omega_y}{\left(\omega_x^2+\omega_{fiber}^2\right)\left(\omega_y^2+\omega_{fiber}^2\right)}\exp\left[-\frac{2d_x^2}{\omega_x^2+\omega_{fiber}^2}-\frac{2d_y^2}{\omega_y^2+\omega_{fiber}^2}\right]$$

where $d_{x,y}$ denotes the lateral offset in the x and y direction, respectively.

Since we tried our best to align the fiber as well as possible, we are going to assume that we don't have any tilt or lateral offset between the incoming laser beam and the axis of the optical fiber. Therefore, we will only pay attention to the expression that deals with mode matching (Equation 1), since the mode of the laser beam is elliptical. We measured this mode in Lab 3 and found the following values for the beam waists;

$$\omega_x \approx 1.3\,\mu\text{m} \quad \text{and} \quad \omega_y \approx 1.32\,\mu\text{m}$$

The manufacturer of the laser diode doesn't quote the values for those two parameters, but gives the parallel and perpendicular divergence angles $\theta_x = 25°$ and $\theta_y = 30°$. It is not immediately obvious, whether those values denote the full divergence angles or

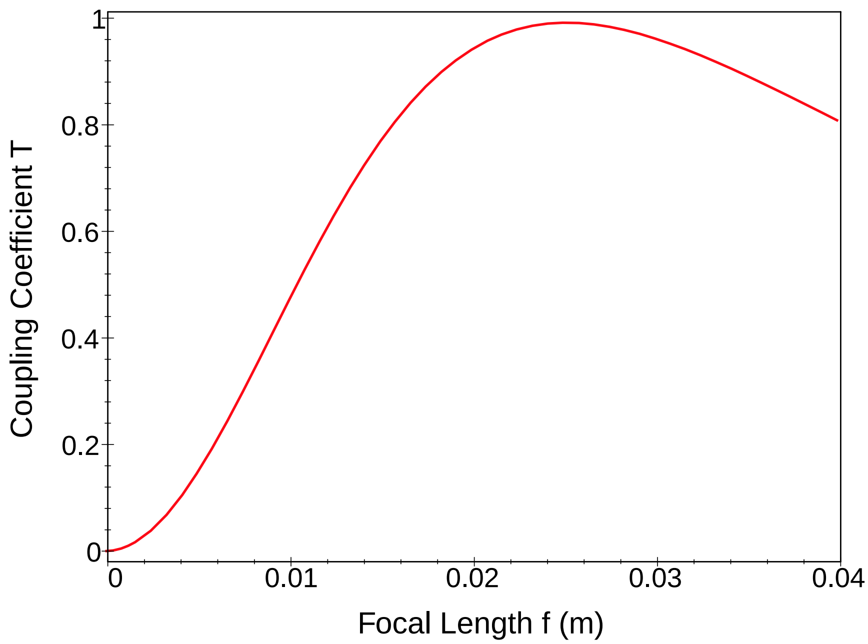

Figure 1. Coupling efficiency T as a function of focal length f for the case of modematching limited coupling.

the half angles. Looking at the specsheet available on the internet, a graph of the far field pattern can be found on the last page. Looking at this graph it becomes clear that $\theta_{x,y}$ denote the half angles, the same way the divergence angle is usually defined. This allows us to calculate the cross section of the laser diode's waveguide, assuming that we have a diffraction limited beam. With the relation

$$\theta_{x,y} = \frac{\lambda}{\pi \omega_{x,y}}$$

we find

$$\omega_x \approx 1.132\,\mu\text{m} \quad \text{and} \quad \omega_y \approx 0.942\,\mu\text{m}$$

For all future calculations, we will use these values for $\omega_{x,y}$. After propagation through the first lens with focal length 5 mm, the beam waists will be

$$\omega_x \approx 2.179\,\text{mm} \quad \text{and} \quad \omega_y \approx 2.619\,\text{mm}$$

according to

$$\omega_{x_2,y_2} = \frac{f\lambda}{\pi \omega_{x_1,y_1}} \tag{2}$$

To find the optimum focal length for the second lens in the telescope configuration, we simply insert Equation 2 into Equation 1, since we already know the mode size in

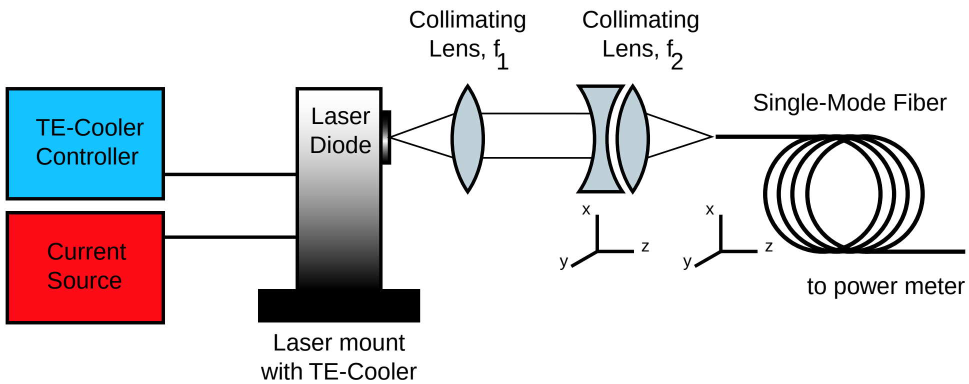

Figure 2. Setup for laser-to-fiber coupling experiment.

front of the second lens. We will assume that the beam waist lies one focal length in front of the second lens and that the fiber is placed one focal length after the second lens. The resulting expression depends only on the focal length f (ω_{fiber} is given to be 5.2 μm). A plot of this function can be seen in Figure 1. The maximum is located at $f = 25.18$ mm. At this point, the theoretical coupling efficiency is $T_{25} = 99.16\%$. Since we didn't have a lens with this focal length at the time of the experiment, we used a lens (Newport F-L10B) with a 12 mm focal length. The theoretical coupling efficiency using this lens is $T_{12} = 60.03\%$.

1.3 Experimental setup

After having gone through the initial alignment procedure, as described in Section 1.1, the fiber coupler was placed approximately 10 cm in front of the laser mount. We made sure that the axis of the coupler coincided with the axis of the laser beam. This is done easiest, when the collimating lens and the fiber are removed from the coupler. The built-in iris helps to achieve a fairly precise placement of the fixture.

Before installing the fiber (Corning SMF-28) into the fiber coupler, we had to cleave the fiber to assure an optically even surface (Fujikura CT-100B). Any residual roughness would result in diffuse surface reflection, reducing the coupling efficiency vehemently. One end of the fiber was placed inside the fiber coupler approximately one focal length away from the second collimating lens, the other end was brought in close contact with the power meter. To achieve close proximity with the diode inside the power head, we removed its attenuator and adjusted the settings of the power meter accordingly. A sketch of the setup is shown in Figure 2. To position the fiber with respect to the incoming laser beam, the fiber coupler allowed to shift the location of the negative lens, as well as the x-y-position of the fiber itself. The former allows for a fine adjustment of the incoming beam, while the latter can only be used for coarse adjustment, due to the nature of the screws that have been implemented. It turned out that backlash was a problem for either adjustable element. This problem can certainly be overcome by more sophisticated translational stages.

As we all know, theoretical predictions are one thing, acquiring experimental data is another thing. Launching light into a single-mode fiber is certainly one of the more complicated tasks and not far from being an art in itself. As so often, it takes perseverance and a fair amount of luck to achieve optimum results that fit the theoretical predications closely. It must have been our turn this time, considering the fact that the rest of the week was miserable enough. The maximum amount of light that we were able to couple into the optical fiber was

$$P = 1.16\,\mathrm{mW}$$

The transmittance of the second collimating lens is 94% at 1550 nm, according to the Newport catalog. Assuming no further losses, the total incident power should have been $P_0 = 1.88$ mW. This means that we achieved a coupling efficiency of 61.7%, which is slightly higher than the predicted theoretical value.

This result might be higher than initially expected, but there are some points that have to be taken into account, besides the ingenious experimental capabilities of ours.

1. We should not forget that the beam waists that we measured in Lab 3 were slightly larger than the ones that we used for the calculations of the theoretical coupling efficiency. Using those numbers, we calculate a maximum coupling efficiency of 77.7%, using a 12 mm focal length lens.

2. Furthermore, the mode size diameter of the fiber is specified only within $\pm 0.8\,\mu$m. Takin this uncertainty into account, the theoretical maximum coupling efficiency lies between 54.5% and 66.1%.

3. We have to take into account that we don't really know exactly how much power the laser diode was emitting at the moment of the measurement. Diode lasers are know to exhibit fluctuations from time to time. For future experiments it would be advisable to have a means of constantly monitoring the diode laser. This could be achieved by using a highly transmissive beam pick-off, which is placed directly in front of the laser diode.

4. Of minor concern is the fact that the theoretical expressions for the coupling efficiencies have been derived, assuming Gaussian mode propagation inside the fiber. This is certainly a fairly good approximation for the lowest order fiber mode and shouldn't cause major deviation from the exact values.

1.4 Mode size measurement

To measure the mode size diameter of the single-mode fiber, we used a setup similar to the one from Lab 3. We placed the tip of the fiber one focal length in front of a 11 mm focal length lens and placed the mechanical chopper one focal length after the lens. For convenience, we used the photodiode of the power head as the photoreceiver. We measured the rise-time and fall-time for two different frequencies and calculated the beam waist averaging those four values. Backing out the propagation of the light through the lens, we arrived the following erroneous results;

$$\omega_{x,y} \approx 0.85\,\mu\text{m}$$

This is wrong by a factor of 5, no matter how bad our measurements regarding the radius of the chopping wheel, the distance between the fiber and the lens, or the lens and the chopping wheel might have been. At this point, we don't have a satisfying explanation for this, but it is clear that a user error is most likely the culprit.

Repeating this measurement more carefully should deliver better results.

1.5 Laser diode spectrum

Let us turn our attention away from the mediocre result of the last section towards a more pleasing one. We fed the output of the fiber into an optical spectrum analyzer (OSA) and measured the laser diode's spectrum between 1522 nm and 1557 nm. The result can be seen in Figure 3. If there would have been any doubt, whether this diode is of the Fabry-Perot or DFB kind, there should be no doubt any more after looking at the plot. We are clearly seeing multimode operation, centered around 1540 nm. The roundish shape of the peaks is a result of the filter shape. Reducing the resolution bandwidth of the receiver (i.e. the OSA) should result in more pronounced peaks. Comparing this result with the data provided by the manufacturer, we notice very good agreement.

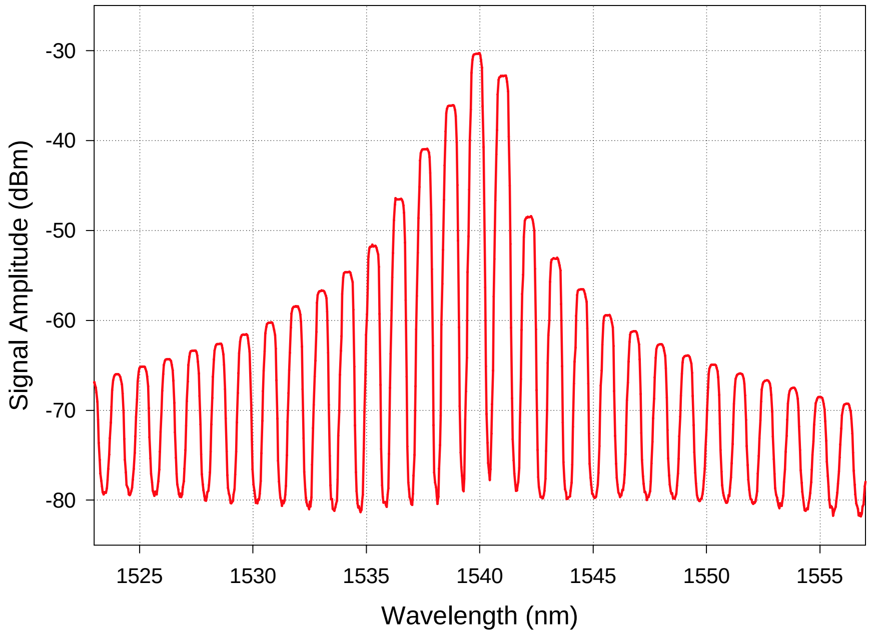

Figure 3. Spectrum of a Fabry-Perot laser diode as measured by an optical spectrum analyzer.

2 Conclusion

Coupling light into a single-mode fiber is a challenging experimental task. It depends on many factors, such as knowledge of the laser diode's and fiber's mode sizes, as well as endurance and persistence of the experimentalist. We were able to achieve a fairly high coupling efficiency, but didn't succeed in measuring the fiber's mode size diameter accurately within a reasonable experimental error. The spectrum of the laser diode showed us, that the diode is emitting several longitudinal modes, which is common for Fabry-Perot laser diodes. The acquired skill how to launch light into a fiber will help us in future experimental setups. The problems we had in achieving a high coupling efficiency makes the need for standardized and precise fiber coupling connectors apparent. It wouldn't be economically, if every single fiber had to be treated the way we did.