Improving Alignment of Free-Space Coupling of Multi-Mode Fibres using Off-Axis Digital Holography

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Off-axis digital holography is employed to align multi-mode fibers in a free-space optical setup that can be used for space-division multiplexing (SDM) transmission. We show that alignment based on power coupling measurements alone does not guarantee a low mode-dependent loss, limiting the system capacity. The alignment method we proposed previously enables reliable fiber coupling with low mode-dependent loss and cross-talk for few-mode to multimode fiber alignment, by using digital holography to capture the full complex optical field at the output of the fiber of interest. After capturing the full complex field, by means of digital demultiplexing, we can calculate relevant parameters such as mode-dependent loss and cross-talk. Here we extend these results with few-mode to few-mode fiber alignment measurements and look at alternative optimization metrics such as the cross-talk between the mode groups of interest and all guided modes. The proposed method allows for precise (automated) alignment of space-division multiplexing components, devices and subsystems.

Introduction

It has been demonstrated that space-division multiplexing (SDM) can largely increase the capacity of optical fiber communication[1]. For mode-division multiplexing (MDM), a subset of SDM, different modes in few-mode fibers (FMFs) and multi-mode fibers (MMFs) are used as independent spatial paths to increase the throughput with respect to single-mode fibers. However, as these modes have a complex spatial distribution, this has to be taken into account when coupling between SDM components. Using total coupled power as an optimization metric might disproportionately impact certain modes, resulting in increased impairments such as mode-dependent loss (MDL) and cross-talk (XT).

A complete description of the spatial distribution of light can be retrieved using digital holographic measurements. Off-axis digital holography (DH) measures the amplitude and phase for both polarizations of a free-space signal by recording the interference between the signal field and a flat-phase reference[2]–[4]. Analysis of the measured interference subsequently reveals important metrics for SDM systems such as MDL and XT.

Previously[5], we demonstrated the use of off-axis DH for the alignment of free-space coupling between a FMF and a MMF. Coupling was evaluated at various fiber positions. At each position, the total coupled power was measured and DH was used to calculate MDL and XT. In this work, we extend these results with additional measurements on FMF to FMF coupling and look at an additional optimization metric. It is shown that maximizing the total coupled optical power does not provide adequate coupling and MDL penalties of up to 20 dB are observed. Therefore, to ensure reliable coupling, the spatial distribution of the light must be taken into account when the coupling is optimized in SDM systems. Off-axis DH is demonstrated to provide the necessary measurements for reliable automated alignment of SDM devices and subsystems.

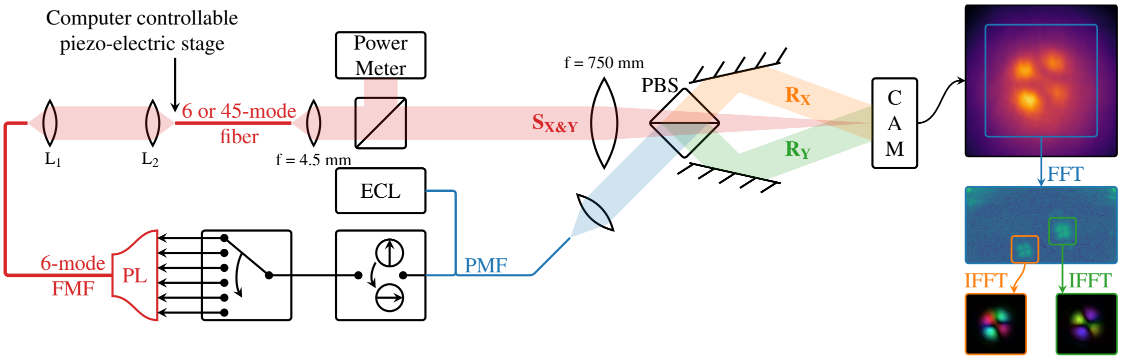

Fig. 1: Experimental setup. $S_{X\&Y}$ denotes the dual-polarization signal to be characterized, R_X and R_Y are the reference beam for x- and y-polarization, respectively. Note that the signal $S_{X\&Y}$ passes over the PBS.

Experimental setup

Fig. 1 shows the experimental free-space optical setup. A photonic lantern (PL)[6] multiplexes light from six single-mode fibers to a 6-mode FMF[7]. The light exiting the 6-mode FMF is coupled into a short piece of either 6-mode FMF or 45-mode MMF[8] in free space using collimator lenses mounted on computer-controllable piezo-electric 3-axis stages. The light exiting this fiber is collimated, split, and measured using a free-space power meter and off-axis DH. The DH setup is comprised of a lens for the signal beam $\mathbf{S_{X\&Y}}$, a large collimator for the reference beams $\mathbf{R}$, a polarization beam splitter (PBS), mirrors, and a camera. By interfering with the signal field with two off-axis flat-phase reference beams, this setup is capable of measuring the signal field in both amplitude and phase for both polarizations. The digital field extraction process is visually explained in Fig. 1. More details on the measurement technique can be found in[2],[3].

To optimize coupling, the x- and y-position of the 3-axis stage are swept. Coupling efficiency is measured using two methods. Firstly, light is inserted into one of the inputs of the PL and the total coupled optical power exiting the fiber is measured using the free-space power meter. Secondly, the light exiting the fiber is measured using off-axis DH, providing a full description of the signal light which is used for subsequent modal analysis. The modal decomposition of the signal light is obtained through *digital demultiplexing* into target mode fields, obtained for the employed FMF and MMF using a scalar numerical mode solver. This process is repeated for each input port and polarization of the PL to construct a complex-valued dual-polarization transfer matrix from PL input port to output mode. Analysis of this transfer matrix can be used to assess the quality of the transmission channel and free-space coupling therein.

Results

Fig. 2 shows the total coupled optical power measured using the free-space optical power meter when only the linearly polarized (LP) LP_{01} port of the PL is excited for both coupling to the FMF and MMF fiber. From Fig. 2a, for coupling to the FMF, it can be seen that there is a relatively broad optimum coupling position where the measured power stays constant. However, for coupling to the MMF, in Fig. 2b, there is no distinct optimum position visible for the measured range of 10 µm to 10 µm in both the horizontal and vertical direction. This can be explained by the fact that the LP_{01} mode will couple into the higher-order modes of the MMF, however, this results in severe MDL penalties not seen from these power measurements. As in both coupling scenarios, there is no significant variation of the metric over the variation of the fiber, it is not suitable for accurate alignment.

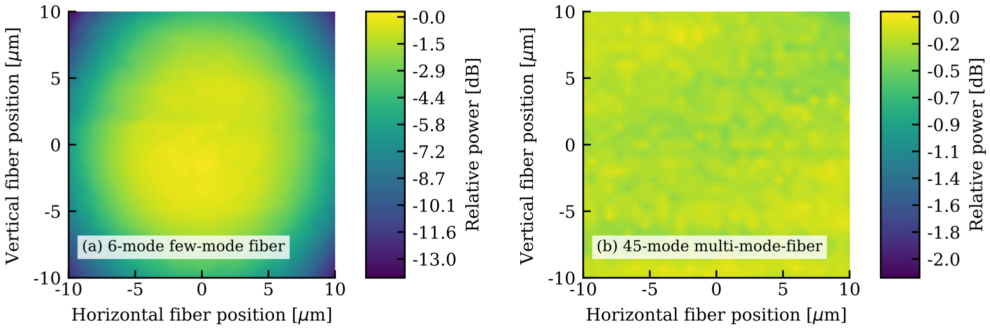

Fig. 2: Relative powers measured at the output of the two different fiber types when launching the LP_{01} mode. Powers are normalized to the maximum measured powers.

In Fig. 3 alignment metrics obtained using the DH setup are shown. Here MDL is calculated through singular value decomposition (SVD) of the complex-valued dual-polarization transfer matrix T from PL input port to MMF output mode:

$$\mathrm{MDL}\,[\mathrm{dB}] = 10 \cdot \log_{10}\left(\frac{\lambda_0}{\lambda_{2N_k-1}}\right)^2 \tag{1}$$

with λ_0 and λ_{2N_k-1} the largest and smallest singular value, respectively. The full transfer matrix T can be converted into a mode-group intensity transfer matrix $\hat{T}$, from which XT can be calculated using:

$$\mathrm{XT}\,[\mathrm{dB}] = 10 \cdot \log_{10}\left(\frac{\mathrm{tr}(\hat{T})}{\Sigma\hat{T} - \mathrm{tr}(\hat{T})}\right) \tag{2}$$

with tr the trace operator. This definition of XT describes the ratio between of power coupled to the intended mode-group and the other mode-groups. When coupling a FMF to a MMF, it is possible that modes will be coupled to higher order modes supported by the MMF, and therefore increasing MDL. Therefore, we also introduce the higher-order modes (HOM) XT, defined as the ratio between the power in the transmitted modes of the output fiber and the power in the other supported modes of the fiber-coupled into as

$$\mathrm{XT\ HOM}\,[\mathrm{dB}] = 10 \cdot \log_{10}\left(\frac{\Sigma_{i=0,j=0}^{n}\hat{t}_{i,j}}{\Sigma\hat{T} - \Sigma_{i=0,j=0}^{n}\hat{t}_{i,j}}\right). \tag{3}$$

Here, n is the number of transmitted modes. As for coupling to the FMF, the number of modes supported equals n, this metric is only evaluated for coupling into the MMF.

A clear optimum fiber position is observed for all metrics in Fig. 3 near zero offsets in both horizontal and vertical directions. For fiber position offsets within the large optimum power areas of Figs. 2a and 2b, Figs. 2b and 3b show an MDL penalty of up to 20 dB, demonstrating that power measurements only do not guarantee adequate coupling. Furthermore, Figs. 3a and 3d show the measured XT and a distinct optimal location for the fiber position is observed, which coincides with the optimum position obtained based on MDL for the FMF scenario, however for the MMF scenario, the optimum in Fig. 3c is slightly shifted with respect to Fig. 3e. However, for the HOM XT in Fig. 3d the optimum coincides with the one from Fig. 3e. Thus, both MDL and XT can be used as optimization metrics for alignment since they both directly measure the quality of coupling, however, when the supported modes in the fiber-coupled into is larger than the number of transmitted modes, the HOM XT is the more relevant metric.