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Alignment of Free-Space Coupling of Few-Mode Fibre to Multi-Mode Fibre using Digital Holography

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Abstract *Off-axis digital holography is used to align a few-mode fiber to a multi-mode fiber in a free-space optical setup. Alignment based on power coupling measurements alone cannot guarantee low mode-dependent loss. The proposed alignment method enables reliable fiber coupling with low mode-dependent loss and crosstalk. © 2022 The Author(s)*

Introduction

The potential of space-division multiplexing (SDM) to greatly increase optical fiber transmission data rates has been shown[1]. In mode-division multiplexing (MDM), a subset of SDM, the spatial diversity of few-mode fibers (FMFs) and multi-mode fibers (MMFs) is exploited by modulating data on fiber modes as independent spatial paths, increasing throughput with respect to conventional single-mode systems. Light in these fibers has a complex spatial distribution. Therefore, when coupling between SDM components optimized using total coupled power as an optimization metric, certain fiber modes may be disproportionately affected, leading to increased impairments such as mode-dependent loss (MDL) and cross-talk (XT). Hence, the spatial properties of coupling should be taken into account, requiring characterization tools able to provide such insight.

A full description of the spatial distribution of light can be obtained using digital holographic measurements. Off-axis digital holography (DH) measures the amplitude and phase for both polarizations of a free-space optical signal by recording the interference between the signal field and a flat-phase reference[2]–[7]. Subsequent analysis of the measured interference patterns can reveal important metrics for SDM transmission systems such as MDL and XT.

In this work, we demonstrate the use of off-axis DH for the alignment of free-space coupling of light between a FMF and a MMF. Coupling is evaluated at various fiber positions. At each position, the total coupled optical power is measured using a free-space power meter and a transfer matrix of the SDM subsystem is measured using DH, which is used to calculate MDL and XT. It is shown that only maximizing total coupled optical power does not provide adequate coupling and severe MDL penalties of up to 20 dB are observed. Therefore, to ensure reliable results, the spatial distribution of the light must be taken into account when 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.

Experimental setup

Fig. 1 shows the experimental free-space optical setup. A photonic lantern (PL)[8] multiplexes light from six single-mode fibers to a 6-mode FMF[9]. The light exiting the 6-mode FMF is coupled into a short piece of 45-mode MMF[10] in free space using collimator lenses mounted on computer controllable piezo-electric 3-axis stages. The light exiting the MMF is collimated, split, and measured using a free-space power meter and off-axis DH. The experimental DH setup is comprised of a lens for the signal beam $\mathbf{S}_{\mathbf{X\&Y}}$, a large collimator for the reference beams **R**, a polarization beam splitter (PBS), mirrors, and a camera. By interfering the

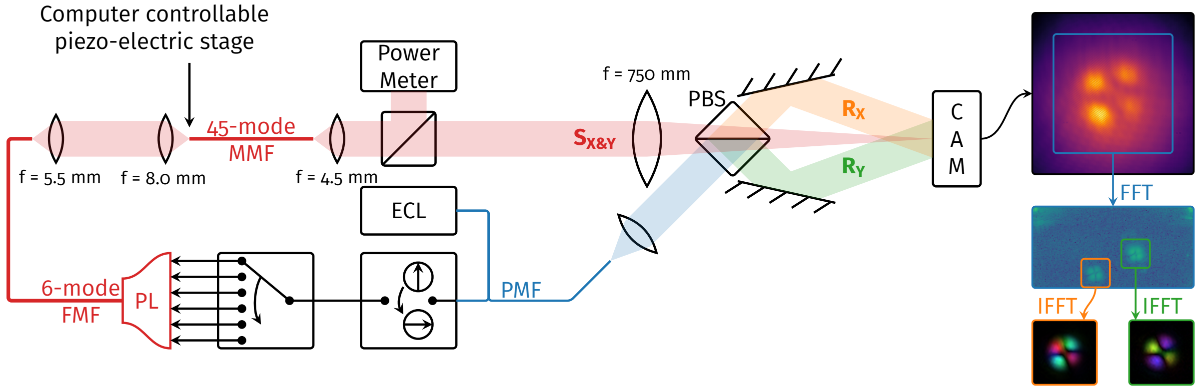

Fig. 1: Experimental setup. PL: photonic lantern, $S_{X\&Y}$: dual-polarization signal to be characterized, R_X and R_Y: reference beam for x- and y-polarization, FFT: fast Fourier transform, ECL: external cavity laser. Note that the signal $S_{X\&Y}$ passes over the PBS.

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 on the right. More details on the measurement technique, setup, and required digital signal processing (DSP) 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 optical power exiting the MMF is measured using the free-space power meter. Secondly, the light exiting the MMF 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 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 MMF output mode. Analysis of this transfer matrix reveals MDL and mode-group XT, which 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} or LP_{02} port of the PL is excited. As can be seen from this figure, no distinct optimum can be found using these power measurements. The coupled power stays constant within a range of 0.5 dB when exciting the LP_{01} mode, while the fiber is scanned over a range of $-10\,\mu m$ to $10\,\mu m$

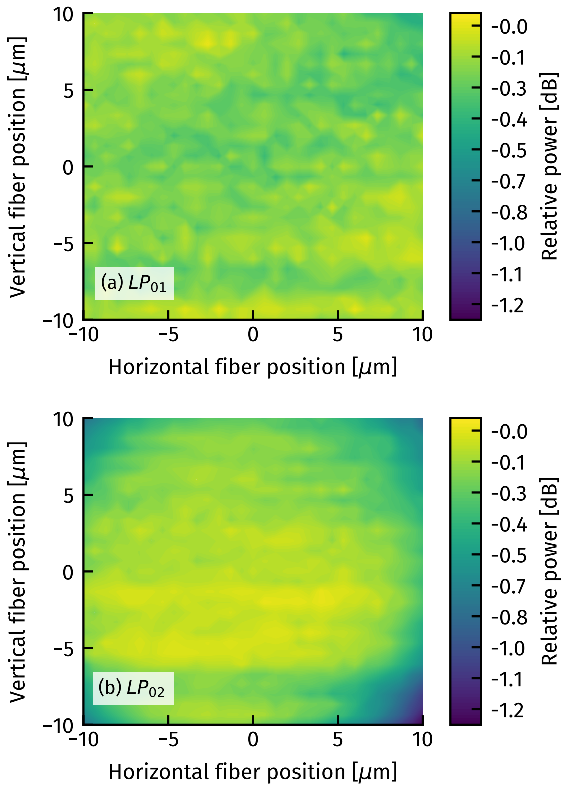

Fig. 2: Relative powers measured at output of the MMF. Powers are normalized to the maximum measured powers. (a) shows the power when launching the LP_{01} and LP_{02} mode, respectively

in both the horizontal and vertical direction. When exciting the LP_{02} mode using the PL, the coupled power is about 1.2 dB lower at large offsets, but constant at small offsets, similar to the LP_{01}. The slightly lower powers at large offsets are expected, as the LP_{02} mode couples with more difficulty into the MMF compared to the LP_{01} mode, making it more suitable to assess quality of alignment. However, since no variation of the metric is observed over significant variation of the fiber position, it is not suitable for accurate alignment.

Fig. 3 shows the MDL measured using the DH

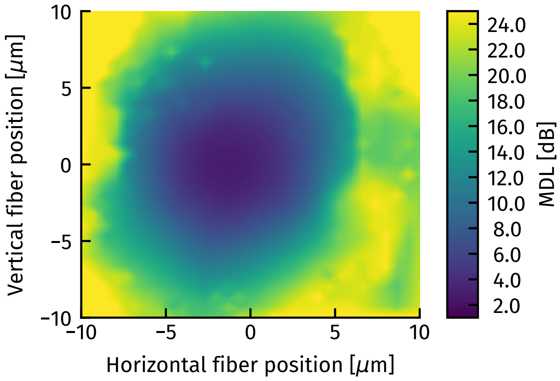

Fig. 3: MDL for different offsets of the 45-mode MMF.

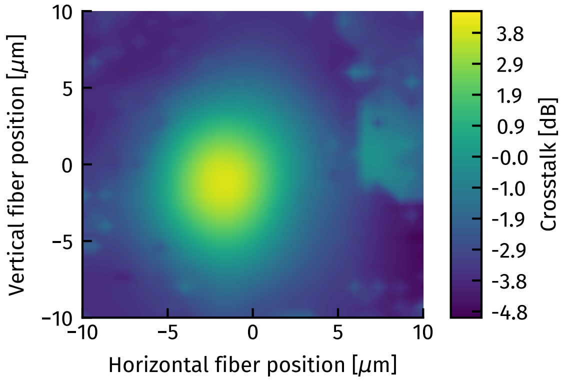

Fig. 4: XT for different offsets of the 45-mode MMF.

setup. 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:

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

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:

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

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. Thus, a higher value indicates more power on the diagonal of the matrix and less XT to other mode-groups.

A clear optimum fiber position is observed in Fig. 3 near zero offset in both horizontal and vertical direction. For fiber position offsets within the large optimum power area of Fig. 2b, Fig. 3 shows an MDL penalty of up to 20 dB, demonstrating that power measurements only do not guarantee adequate coupling. Furthermore, Fig. 4 shows the measured XT and a distinct optimal location for the fiber position is observed, which coincides with the optimum position obtained from Fig. 3. Thus, both MDL and XT can be used as optimization metrics for alignment since they both directly measure the quality of coupling.

Conclusions

Optimization of free-space coupling between a few-mode fiber and a multi-mode fiber is investigated. When only the total coupled optical power is maximized, the spatial distribution of the light is not taken into account and good coupling with low mode-dependent loss and cross-talk cannot be guaranteed. Off-axis digital holography provides a full description of optical fields and is demonstrated to provide relevant metrics for the investigated coupling scenario. The proposed method can be used for reliable automated alignment of SDM components, devices, and subsystems enabling the effective coupling of amplifiers and multiplexers into transmission fibers.

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