Digital few-mode fiber multiplexer using multiplane light conversion

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***Abstract*— We propose an all-optical data-driven technique for space division multiplexing in few-mode fibers. A digital twin was realized by multiplane light conversion and neural networks. It is promising for a digitally programmable multiplexer in fiber communication.**

***Keywords*— Optical networks / Space division multiplexing / Artificial intelligence / Digital Twin**

I. Introduction

Development of fiber optical networks as the backbone of the global infrastructure has driven exponential growth in data demands. Space division multiplexing (SDM) over few-mode fibers (FMF) spatial domain is proposed to enhance optical network capacity limits by orders of magnitude compared to state-of-the-art single mode fibers. Based on multiplane light conversion (MPLC), multiple input beams are converted to the FMF mode domain and launched into the fiber. Inside the MPLC the beams are modulated by a phase-changing element within several passages and are shaped in amplitude and phase due to diffraction. We use a spatial light modulator (SLM) for the implementation of the MPLC, whose programmability allows us to design digitally the MPLCs behavior and compensate on phase and polarization aberrations during operation [1-4]. Conventionally, phase masks are calculated in advance that carry out a spatial transformation between spatially distributed input spots and coaxial output modes. After calculation, phase masks are either printed on dielectric mirrors or displayed on diffractive optics. This process entails two-fold problems. First, the phase masks are calculated offline and inserted into the experiment later on, where small deviations cause enormous performance reductions. Second, phase mask printing can barely be adapted after fabrication. We propose a data-driven optimization of the displayed phase mask by using machine learning to overcome the hurdles of re-configurability and alignment. We use neural networks (NN) for digital calibration to ensure pixel-precise alignment. Our implementation of the MPLC with a SLM is mimicked as a digital twin by a NN, the Model-NN. In a second step, the fixed Model-NN is controlled by another neural network called Actor-NN. After the calibration, our Actor-Model scheme predicts phase patterns for the SLM based on the desired intensity distribution after the MPLC, i.e. the mode patterns of FMF. By digitally sampling and control of the MPLC behavior with NN, we improved the SLM beam-shaping quality without suffering from the SLM refresh rate limitations, depending on the available filling factor and spatial resolution. The adaptability of the SLM as a digital optical device allows further re-calibration during operation [4-6]. Due to the all-optical implementation, transmission and multiplexing of delicate quantum states for QKD-based physical layer security in fiber communication is proposed.

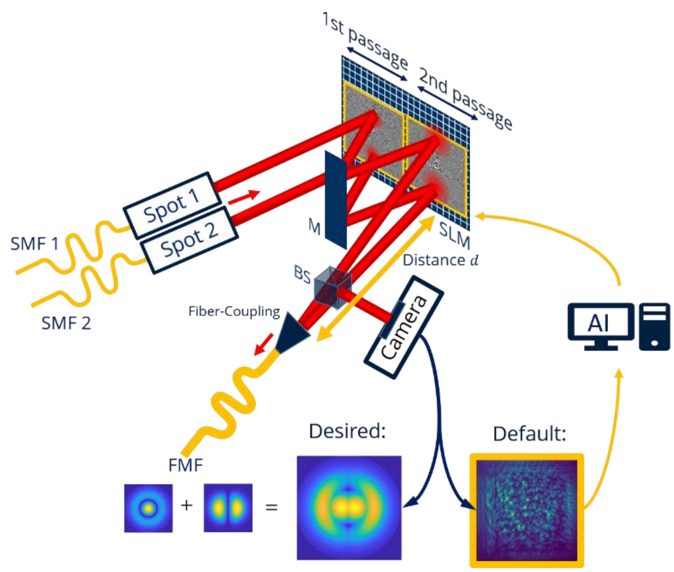

Fig. 1. Optical MPLC setup and AI-driven optimization scheme [6]

II. Method

In this paper, we present a method to advance the mode shaping procedure by a smart data-driven online calibration, where the entire MPLC apparatus is considered as a black box, see figure 1. By training an NN, we create a digital twin including all misalignments and tolerances of the setup, called Model-NN. With the Model-NN, we gain knowledge about the experimental environment. Afterwards, the Model-NN is kept static and another single-layer NN called Actor-NN is trained controlling the model. As training the Model was performed on all-experimental data, it contains knowledge on the system.

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This is used in the offline training of the Actor-NN to predict the required phase masks to perform the desired beam shaping task. Experimental tolerances are considered already in the calibration procedure, which advances the MPLC setup. The Actor-NN architecture is again the single-layer perceptron shown in Figure 2. In Figure 3 (left column), three desired intensity samples are shown. The corresponding phase mask prediction of the Actor-NN (see Fig. 3 middle left column) is forwarded to the Model-NN which predicts the MPLC output beam intensity. In the middle right column of Figure 3, three predictions from the Model-NN are shown. Mean-Squared-Error defines the loss function optimizing the Actor-NN to control the Model-NN which represents the experimental setup.

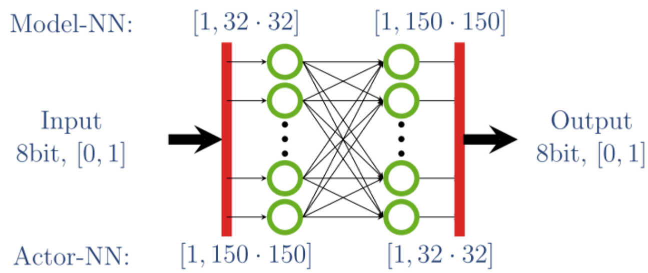

Fig. 2. Structure of Neural Networks for the digital twin [6]

III. Results

After training of the entire Actor-Model structure, the Actor-NN is frozen and is used to generate phase masks for the experiment. The phase masks provided by the Actor-NN are displayed on the SLM to run the MPLC. In Figure 3 (right column), three camera images capturing the MPLC output are shown. The images are taken after the setup was calibrated with the approach introduced. We achieve a correlation between the ground truth and the Model-NNs prediction of C = 0.7. For the measured intensity we achieve a correlation of C = 0.65 compared to the Model-NNs prediction and C = 0.6 to the ground truth.

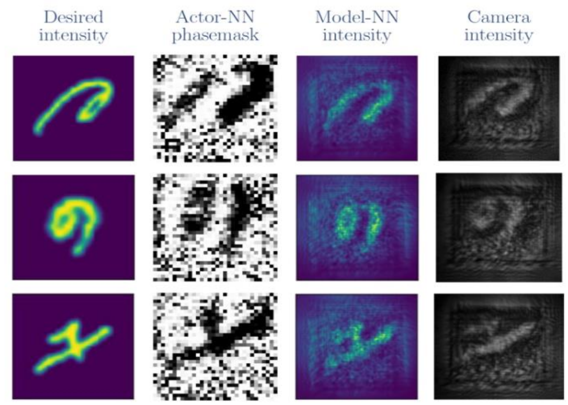

Fig. 3. Results from the Actor-Model approach. Left column: Ground truth, Middle left: Actor-NNs phase mask prediction, Middle right: Model-NNs intensity prediction, Right column: Experimental result [6]

IV. Conclusion

We have demonstrated an intelligent approach to calibrate an MPLC device using experimental data. Although we treat the entire light shaping system as black box, delicate knowledge about the experimental behavior is gained by using machine learning algorithms with C = 0.82. Here, we have shown that the Actor-Model approach is feasible for online calibration of an all-optical mode multiplexer based on MPLC. In contrast to an offline calculation of SLM phase masks, our approach does not suffer from mismatches between algorithm and experiment reducing the alignment effort dramatically. This is particularly beneficial for the advancement of SDM networks [7-8] or the transmission of fragile quantum states.

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