Beam Forming over 4.5 km 45 Mode Multi-Mode Fiber

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Abstract *We modulate the amplitude, phase and polarization of 45 parallel phase-stabilized inputs to a mode multiplexer, achieving full control over the optical field's space, time, polarization, and frequency at the output of a 4.5 km graded index multimode-fiber.*

Introduction

Beam forming is the process of transmitting a predistorted waveform through a scattering medium, so it arrives undistorted at the output side. This enables remote spectro-temporal focusing over multi-mode fibers (MMF) by synthesizing a transmitted multi-mode waveform corresponding to the inverse of the frequency fiber transfer matrix[1],[2]. Similarly, ultra-fast spot scanning (>GSpots/s) on the output facet of a multi-mode endoscopic probe, could be achieved. This level of spectral-spatial field synthesis, enabled by full-field input control, allows to generate waveforms traditionally only available to receiver side digital signal processing (DSP), where the phase shifts in the receiver arms are controlled in the digital domain[3].

To enable transmitter-side beamforming, the complex fields spanning amplitude, phase and polarization on each spatial mode have to be precisely controlled and coherently superimposed (i.e., phase stabilized). Independent inputs can be controlled in amplitude, phase and polarization using regular Mach-Zehnder modulators, and injected onto each mode using a mode multiplexer. The output field will only be coherently combined correctly if the relative optical phase between all signals is known. Coherent combining in conjunction with amplitude and polarization control can shape the spatial content of a beam at a single frequency and is often accomplished using reconfigurable phase holograms generated using spatial light modulators followed by a Fourier lens[4]. Broadband compensation of a frequency-dependent scattering medium, such as a multi-mode fiber, requires a "time-reverser" that produces independent waveform shaping at each frequency or full control over all degrees of freedom of the optical field[2].

In this work we demonstrate 10-mode beamforming over 45 spatial mode multi-mode fiber using a time-interleaving scheme to produce 45 uniquely shaped waveforms. We combine the output of a dual-polarization IQ-modulator, a 45 arm phase-stabilized delay tree and a 45-mode multi-plane light conversion (MPLC)-based mode-multiplexer to achieve full control over the multi-mode fiber input. By pre-distorting the transmitted waveform with the inverse channel response, an arbitrary waveform can be generated at the output of a 4.5 km multi-mode fiber. The inverse transfer matrix is directly estimated from the output of a 90×90 MIMO equalizer and the resulting filter coefficients are used to shape the transmitted waveform. We demonstrate successful reception of quadrature phase shift keying (QPSK) waveforms generated by coherently superimpose up to 10 modes, (4 Hermite-Gaussian mode groups) using a standard dual-polarization coherent receiver, showing that the pre-distortion successfully cancels the strong mode mixing induced by the multi-mode fiber. The capability to accurately estimate the frequency-dependent inverse channel matrix provides a through path for achieving large-scale full-field control of multi-mode signals, enabling new applications in areas such as communication, fiber imaging and fiber lasers.

Experimental Setup

The experimental setup used is shown in Fig. 1(a). A 1550 nm fiber laser (NKT Koheras Basik) was separated into two paths. One path was modulated using a dual-polarization Mach-Zehnder modulator driven by 4 60 GS/s, 6 bit resolution, digital-to-analog converters (DACs) with >100µs of offline memory for generating long waveforms. The modulator output was amplified and connected to a 1×45-splitter and then to the inputs of a fiber delay tree. The relative delay between each arm was 10 m (49 ns) and all delay fibers were sandwiched between two blocks of acoustic foam to prevent the fibers from

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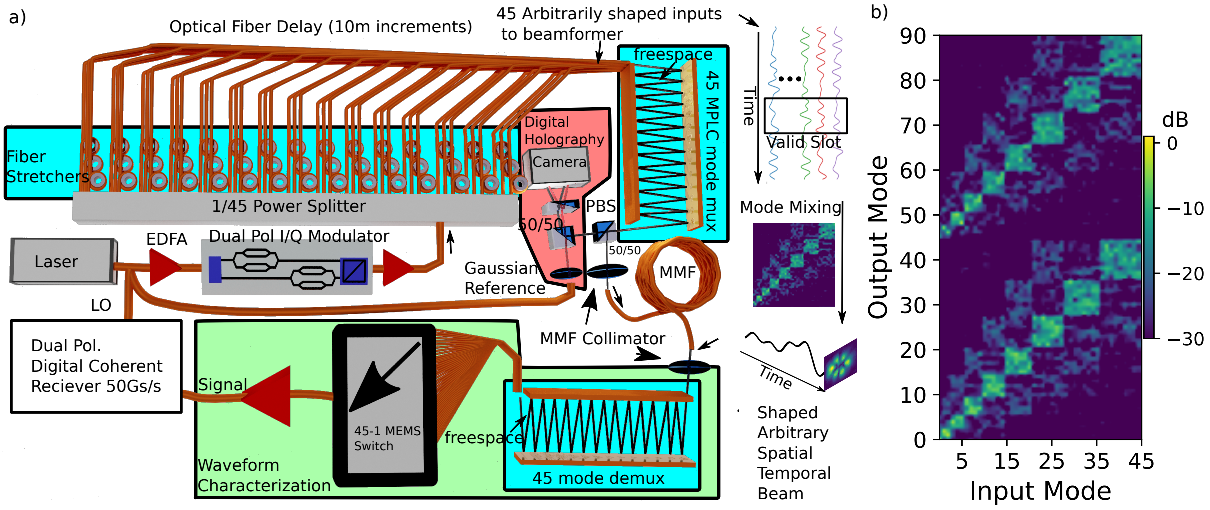

Fig. 1: (a) Experimental setup. A Hz level linewidth laser is modulated and fed to a 1x45 splitter. Each splitter arm is connected via fiber delays with 10 m relative increments to 45 piezo-based stretchers for phase stabilization. The 45 output fibers are then connected to the inputs of a 45-mode multi-plane light conversion mode-multiplexer. A beamsplitter is inserted at the MUX output, prior to collimation, to tap of a part of the output bean. This signal is combined with a flat-phase reference beam in an off-axis digital holography configuration to extract the relative phase of each mode, which is acting as error signal for updating the piezo stretchers. The output is either spliced directly to the receiver demultiplexer or to a 4.5 km multi-mode fiber span. The outputs of the receiver demultiplexer are connected via an optical switch to a real-time oscilloscope. (b) Transfer matrix (single input pol) of the transmitter multiplexer showing an integrated cross-talk of $<$-9dB and mode-dependent loss of 3.6 dB.

acting like phase modulators. The tree outputs were connected to 45 piezo-based fiber stretchers, as shown in Fig. 1(a). The stretcher outputs were connected to the input fibers of a 45 (9 Hermite-Gaussian mode-groups) MUX based on multi-plane light conversion (MPLC)[5],[6]. The MUX used 14 phase-masks to complete the transformation from an input 127µm-spaced linear spot array ($w_0 \approx 35$µm) to the 45 output modes (90 counting polarization). The masks were fabricated using binary gray-scale lithography with 6 bit resolution covering 2π at 1550 nm. A beam splitter (BS) followed by a small mirror was inserted before the MUX output collimator, as shown in Fig. 1(a), to extract part of the output beam for holographic decomposition. A small ($\approx$10 dB) carrier was created on the modulator pattern by slightly opening one arm in the modulator, enabling holographic extraction and phase error calculation by combining the modulated signal with a reference beam in an off-axis configuration, as shown in Fig. 1. The stretchers supported about 900 Hz update rate but 10 ms delay in the feedback loop limited the overall update rate.

The MUX output was connected via 10 m (B2B) and 4.5 km 50µm graded-index multi-mode fiber supporting 45 spatial modes to a second MUX used as de-multiplexer. This enabled decomposing the received multi-mode beams into 45 single-mode beams. The single-mode outputs were connected to an optical switch (10ms switching time). The switch output was connected via a 27 MHz frequency shift acousto-optic modulator to a dual-polarization receiver and a 50 GS/s real-time oscilloscope. The scope was operated in shared-memory mode to capture all 45 outputs sequentially. In order to perform beamforming, the inverse transfer matrix must be estimated. In this work we used a traditional least-mean-squared (LMS)-based 90×90 multiple input multiple output (MIMO) to estimate the inverse transfer matrix directly. By first applying a long pattern ($>$the longest fiber delay), the 45 delays from the delay tree were identified. The inverse channel matrix was then estimated by running the equalizer in data-aided mode. The equalizer used 50 T/2-spaced complex tap per polarization/mode, well within the about 350 symbol periods separating each delay in the delay tree. The inverse signal, corresponding to a given spatial mode/polarization, was then generated by filtering the target signal with equalizer output taps.

Results and Discussion

We first measured the transfer matrix of the mode-multiplexers, as shown in Fig. 1(b). The mode-dependent loss (MDL) was measured to 3.6 dB with a cross-talk $<$-9dB. The cross-talk is defined as the power ratio between the diagonal and all other matrix elements after summing the modes within each mode-group. As can be seen in Fig. 1(b), the strong coupling between modes within the same mode-group results in a complete scrambling even with only 5 m output MMF. The receiver MUX has very similar MDL and about 2dB lower XT, compared to the transmitter-side

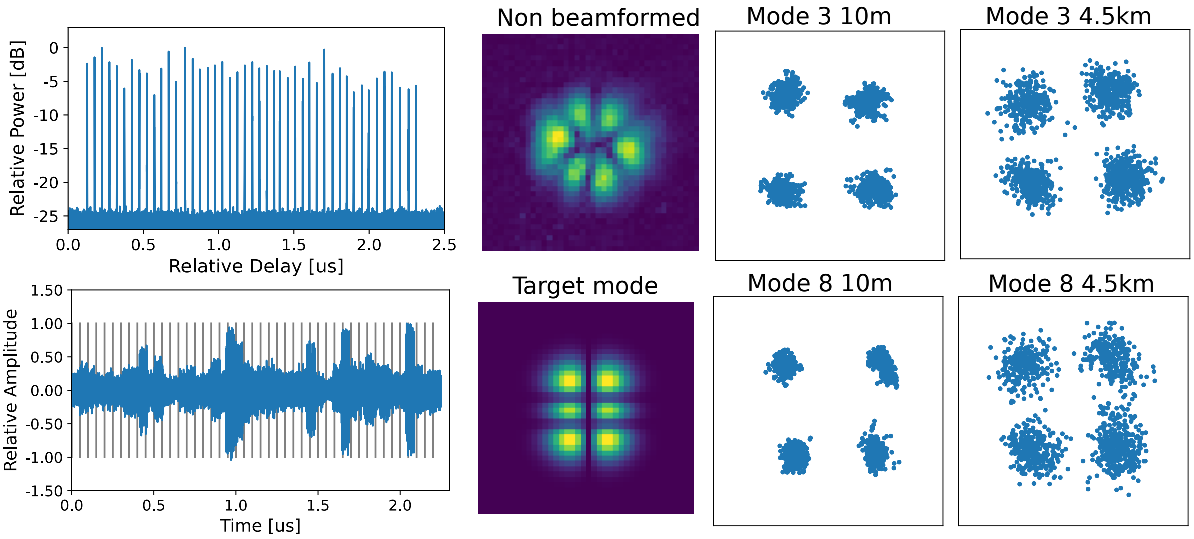

Fig. 2: (a) Sum of powers from cross-correlation-based measurements of all the 45 fiber delays. (b) Example of pre-distorted input waveform to beamform to mode 8 (X-polarization, real value). Horizontal divisions indicate time slots dedicated to unique modulation for each 45 inputs. (c) and (d) Reference and measured output mode 8 after 5 m of multi-mode fiber. The strong mode coupling quickly scatters the light into all modes within each mode group. (e) and (f) Received QPSK constellations after beam forming to mode 3 and 8, respectively, in back-to-back configuration. (g) and (h) Received constellations after beam forming over 4.5 km of multi-mode fiber.

device. The result from the fiber delay estimation described in Section is shown in Fig. 2(a). The visualized power is the sum for all 45 modes, showing a total power variation of $<$10 dB. The average relative delay was 49.5 ns. While we in principle could modulate all the 45 modes, large environmental distortions (acoustic noise and temperature fluctuations), originating from a malfunctioning AC unit, caused phase distortions between the fiber delays outside the feedback loop bandwidth. The phase error estimation accuracy was furthermore decreased due to the trade-off between the amount of DC carrier needed for locking and resulting signal quality. Given these limitations, we restricted the beam forming to 10 spatial modes (20 counting polarization). Further improvements in the environmental isolation and the locking feedback speed are expected to enable the use of the full 45-mode capability.

As a proof-of-principle demonstration, we generated standard dual-polarization QPSK waveforms. We used mode 3 and 8 in group 2 and 4, respectively, as our goals to beamform. An example of generated waveform for mode 8, real value of transmitted X-polarization), is shown in Fig. 2(b). As previously measured in[7], while the MPLC-based MUX/De-MUX are capable of very high modal selectivity, adding a couple of km of multi-mode fiber significantly increase the mode coupling. This illustrated in Fig. 2(c) and (d) showing mode 8's ideal launched shape and how it was received. As can be seen in Fig. 2(d), already after 5 m of MMF, the strongly coupled modes have scrambled and a superposition of multiple spatial modes is needed to undo the mode mixing. Figure 2(e) and (f) shows the received constellation in B2B configuration. In both cases, the received waveform is outputted on a single spatial mode, with no multi-mode DSP required to recover the signal. The only receiver-side DSP used is resampling to 2 samples/symbols, a short interpolation filter to correct timing errors between the DACs and the real-time scope and a phase correction to account for the uncertainty in the local oscillator phase. While the constellations are clear, a small skew/imbalance can be observed. This is attributed to system calibration errors not accurately accounting for polarization-dependencies of the transmitter and receiver. Figure 2(g) and (h) show the corresponding received constellation after transmission through 4.5 km MMF. The LMS estimation error was very similar between the B2B and 4.5 km measurements, so the added noise is mainly attributed to a faster varying channel. Higher-order modes are naturally more sensitive to any environmental perturbations, matching with the higher penalty observed for mode 8 compared to mode 3.

In conclusion, we have demonstrated a system for full-field spectro-spatial-temporal control supporting up to 45 spatial modes (90 counting polarization). The inverse transfer matrix was estimated using 90×90 MIMO-DSP and used to generate 90 waveforms that superimpose to a single output mode at the receiver.

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