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Expanded Modal Capacity for OAM with Standard 2×2 MIMO

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Abstract *Standard commercial, electronic 2×2 MIMO can greatly extend modal multiplexing compared to MIMO-free strategies. We experimentally demonstrate the highest bit rates achieved with multiplexing of orbital angular momentum (OAM) modes at 475 Gb/s per wavelength. Our demultiplexing strategies are compatible with commercial solutions. ©2022 The Author(s)*

Introduction

Modal multiplexing can increase fiber capacity linearly with the number of modes supported. Much attention has been focused on modes that can be exploited without multiple-input multiple-output (MIMO)[1]. The MIMO-free variety is especially attractive when more than six data channels (modes) are supported, as MIMO complexity grows with the square of the channel number. In[2], MIMO-free transmission of twelve channels over three orbital angular momentum (OAM) mode groups was demonstrated. Another demonstration with linearly polarized (LP) modes required 12×12 MIMO, i.e., 144 equalizers[3].

Commercial coherent receivers exploit polarization multiplexing using 2×2 MIMO; hence, there is no appreciable added complexity for MIMO-free vs. 2×2 MIMO. We used a commercial 100G line card for quadrature phase-shift keying (QPSK) transmission over OAM modes in[4], with no modification of digital signal processing (DSP) to accommodate multiplexing of four channels. In this paper, we demonstrate experimentally eight data channels. We use a programmable free-space demultiplexer configured to target any two transmitted channels for standard 2×2 MIMO. In our 600 m demonstration, we improve capacity across the entire C-band. At the edges of the band, we go from 425 Gb/s to 475 Gb/s net rate. These are the highest bit rates ever recorded for OAM, compared to 215 Gb/s in[2] (MIMO-free at 1 km) and 384 Gb/s in[5] (4x4 MIMO at 25 km).

Compatibility with Commercial Receivers

There are no commercially available OAM multiplexers; hence, we must rely in our demonstration on free-space, bulk optics as described in the next section. Ideally, we would exploit an integrated device currently under research, such as in[6], with a separate output single-mode fiber (SMF) for each data channel on a single polarization. With such a device, MIMO-free reception would take one SMF output and send it to a coherent receiver, while 2×2 MIMO would combine two fiber outputs on orthogonal polarizations before the coherent receiver. From a complexity point of view, there would be little difference between MIMO-free and 2×2 MIMO.

Fibers supporting OAM modes have been shown to be polarization maintaining. Many data transmission experiments[1][2] manipulate the polarization at each multiplexer lane to minimize the contributed crosstalk at reception. This coordination of transmitter and receiver is a type of optical MIMO within degenerate states[2], allowing detection without electronic MIMO. However, this coordination is impractical in deployed systems.

We adopt and demonstrate multiplexers and transmitters aligned to absolute references of polarization. The only coordination between transmitter and receiver is for better alignment of free-space beams, unnecessary in future systems with integrated multiplexers. We launch circularly polarized light into our OAM fiber and do not minimize crosstalk by adjustment of polarization to launch elliptical polarization[2], as in optical MIMO.

Experimental Setup

The experimental setup is provided in Fig. 1. A bit pattern generator and IQ modulator produce a 32 GBaud QPSK signal from a Cobrite tunable laser with 100 kHz linewidth. The signal is amplified and sent to a polarization multiplexing emulator. The polarization multiplexed signal is split four times. The copies are delayed to decorrelate the data. A variable optical attenuator equalizes the received power, compensating for unequal cou-

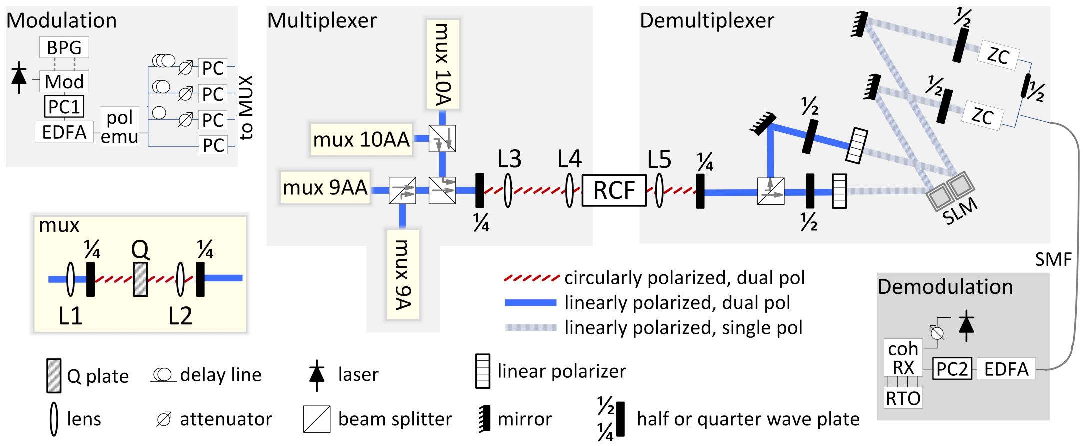

Fig. 1: Experimental setup. BPG: bit pattern generator, Mod: In-phase and quadrature-phase modulator, pol emu: polarization emulator, EDFA: erbium-doped fiber amplifier, PC: polarization controller, ZC: zoom collimating lens, coh RX: coherent receiver, RTO: real time oscilloscope, SLM: spatial light modulator, RCF: ring core fiber

pling efficiency across modes. The polarization controllers (PC) align each signal to the linear polarization of 0° and 90°. We adjust PC1 at each wavelength for 18.4 dBm power at the polarization emulator output.

We generate OAM modes using the assembly labeled “mux”. The first lens, L1, collimates the dual polarization Gaussian beam. The quarter-wave plate (QWP) converts the beam polarization to circular, essential for the following Q-plate. The Q-plate creates an anti-aligned (AA) OAM pair of modes with a fixed order. The OAM beam is divergent, hence the second lens, L2, creates a convergent beam. The next QWP returns to linearly polarization.

The multiplexer uses four copies of the “mux” assembly to generate the desired OAM modes. Free-space beam combiners distort circularly polarized beams to elliptical polarization, hence our prior conversion to linear polarization. The aligned (A) modes are created from the Q-plate AA output by reflection in the beam combiners. The output of the three beam combiners form a single beam focused on the RCF fiber using lenses L3 and L4. The QWP returns the beam to circular polarization for launch into 600 m of the ring core fiber (RCF) described in[7]. We exploit two OAM mode groups, 9 and 10, with low crosstalk[8].

The demultiplexer rotates the fiber output to linear polarization and creates two copies for simultaneous demultiplexing. The spatial light modulator (SLM) is programmed so that the targeted mode is converted to the fundamental mode. The SLM is polarization-sensitive; hence, a polarizer blocks one polarization. The orientation of the half-wave plate (HWP) and the programming of the SLM determine the demultiplexed mode on each path. The two demultiplexed signals are coupled into the fiber, stripping all but the targeted mode now at fundamental. For MIMO-free reception, only one zoom collimator output is used. For 2×2 MIMO, the two signals are combined, with one signal polarization rotated.

The demodulator is coherent receiver (Picometrix, 25 GHz 3 dB bandwidth) and real-time oscilloscope (Keysight, 63 GHz, 80 GSa/s). The erbium-doped fiber amplifier (EDFA) boosts the signal from -20 dBm to -3.5 dBm. Our demodulator is located in a separate room from the free-space setup; hence, the original exact XY polarization will rotate. We adjust PC2 once at each wavelength reception to compensate for the rotation introduced by the SMF at that wavelength. We use a standard constant modulus algorithm (CMA) with 85 taps for 2×2 MIMO.

The alignment of all free-space beams is made iteratively by observing the received signals. As beam misalignment will excite unintended modes, the multiplexer alignment involves the demultiplexer. Once the beams are aligned, no further coordination is made between transmitter and receiver, e.g., no adjustment as we sweep wavelengths.

MIMO-free vs. 2×2 MIMO Performance

We show in Tab. 1 typical received powers when launching one mode (row) and setting the demultiplexer to each mode in turn (columns). Here, one HWP in the demultiplexer is set to receive signals with right circular polarization, the other left circular polarization. The launched power in each mode varies by 1.5 dB (see diagonal entries). The power entries off the diagonals are crosstalk con-

Tab. 1: Received powers on each mode (column) when one mode (row) launched at 1550 nm after 600 m.

dBm	10A		10AA		9A		9AA	
	+10R	-10L	-10R	+10L	+9R	-9L	-9R	+9L
+10R	**-20.0**	-39.5	-32.5	-39.7	-37.5	-47.0	-41.1	-48.5
-10L	-40.5	**-21.0**	-38.5	-32.5	-50.0	-34.5	-49.1	-41.0
-10R	-32.9	-40.8	**-20.0**	-46.8	-40.8	-48.4	-36.0	-49.6
+10L	-42.0	-33.0	-46.9	**-21.2**	-50.0	-41.4	-50.0	-38.0
+9R	-35.7	-49.5	-41.7	-50.5	**-19.8**	-46.0	-32.7	-35.6
-9L	-48.6	-35.5	-49.7	-41.8	-46.5	**-20.3**	-37.0	-32.5
-9R	-41.0	-49.0	-36.0	-49.5	-32.4	-37.0	**-19.7**	-41.5
+9L	-47.9	-41.4	-49.0	-36.4	-39.7	-31.9	-42.6	**-19.6**

tributions. Each 2×2 block on the diagonal originates from a single “mux” in Fig. 1. The modes with the opposite OAM helicity and the same polarization experience the most crosstalk.

In Tab. 2, we summarize the crosstalk contributions to each mode. The first row shows the worst-case contribution from a single data channel to the crosstalk. We will use 2×2 MIMO to eliminate this component. The middle row shows the next-worst crosstalk from a single data channel. The final row summarizes the total crosstalk (sum over crosstalk in each column in Tab. 1) for MIMO-free reception. Assuming that MIMO eliminates the worst-case crosstalk, the next highest contribution to total crosstalk can be seen in the table to be reduced by roughly 3 dB.

We swept the C-band from 1530 nm to 1565 nm in 5 nm increments. At each wavelength, we completed both MIMO-free and 2×2 MIMO reception using the same equalizer filter lengths in CMA. We counted errors over frames of 30,000 symbols and estimated the bit error rate (BER). The results are plotted in Fig. 2. The markers in black are for MIMO-free reception; red markers are for 2×2 MIMO reception. The MIMO pairs are indicated with arrows and correspond to the pairs with worst-case crosstalk in Tab. 1. Two horizontal lines are given for the forward error correction (FEC) thresholds for 7% and 20% overhead.

We see that most MIMO-free transmission fall above the 7% FEC (35 of the 64 measurements), while all 64 of the 2×2 MIMO BER measurements fall below the 7% threshold, often with a significant margin. Variations across wavelengths can be as high as an order of magnitude, as are variations across modes. In Fig. 3, we plot the net bit

Tab. 2: Summary of crosstalk on each mode, including two worst-case contributors and the total crosstalk.

XT (dB)	10A		10AA		9A		9AA	
	+10R	-10L	-10R	+10L	+9R	-9L	-9R	+9L
worst single ch.	-12.9	-12.0	-12.5	-11.3	-12.6	-11.6	-13.0	-12.9
next worst single ch.	-15.7	-14.5	-16.0	-15.2	-17.7	-14.2	-16.3	-16.0
total	-9.8	-8.7	-9.7	-8.8	-10.3	-8.5	-9.7	-9.7

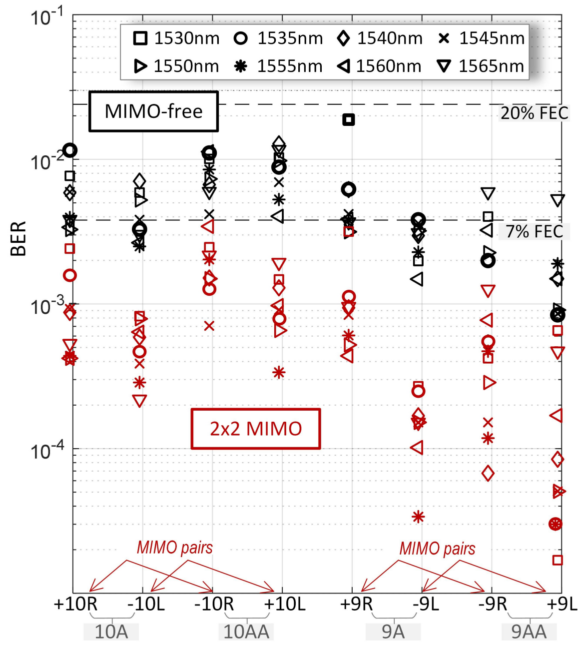

Fig. 2: Bit error rate 32GB QPSK per mode at various wavelengths (see markers); black markers for MIMO-free reception and red markers for standard 2×2 MIMO reception.

rate at each wavelength. The zero-overhead capacity of 512 Gb/s is reduced to 476 Gb/s with 2×2 MIMO. For MIMO-free, the net rate varies with wavelength. In the case of 2×2 MIMO, there remains a significant margin below the 7% threshold for many channels enabling longer distances. The 2×2 MIMO can increase capacity or extend reach vis-à-vis MIMO-free transmission.

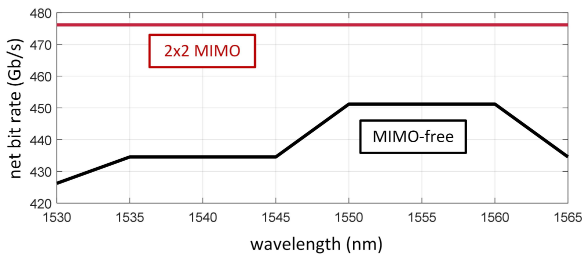

Fig. 3: Net bit rate per wavelength after FEC.

Conclusion

We have demonstrated that two demultiplexed outputs input to 2×2 CMA can greatly reduce crosstalk. The added cost of 2×2 processing is negligible compared to MIMO-free reception, as commercial coherent receivers have long been optimized for this operation. We have demonstrated 475 Gb/s per wavelength, with a margin available to increase reach from the 600 m demonstration.

Acknowledgements

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