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***Abstract*— Mode division multiplexing (MDM) systems using orbital angular momentum (OAM) modes can recover the data in *D* different modes without recourse to full (2*D*×2*D*) multiple input- multiple output (MIMO) processing. One of the biggest challenges in OAM-MDM systems is the mode instability following fiber propagation. Previously, MIMO-free OAM-MDM data transmission with two modes over 1.1 km of vortex fiber was demonstrated where optical polarization demultiplexing was employed in the setup. We demonstrate MDM data transmission using two OAM modes over 1.4 km of a specially designed ring core fiber (RCF) without using full MIMO processing or optical polarization demultiplexing. We demonstrate reception with electrical polarization demultiplexing, i.e., minimal 2×2 MIMO, showing the compatibility of OAM-MDM with current polarization demultiplexing receivers.**

***Index Terms*— Orbital Angular Momentum (OAM), Mode Division Multiplexing, Coherent communications.**

I. INTRODUCTION

Mode division multiplexing (MDM) in multimode fibers has attracted much interest in recent years [1], [2] due to its ability to bypass single mode fiber (SMF) capacity limits imposed by the combination of Shannon's information capacity limit and nonlinear fiber effects [3]. Most of the demonstrated MDM systems using linear polarization (LP) modes over few mode fibers (FMF) [4] require intensive multiple input multiple output (MIMO) processing in receiver digital signal processing (DSP) [5]-[7]. In systems using D modes and two polarizations per mode, it includes simultaneous reception of D modes and MIMO processing with $2D\times 2D$ equalizer blocks ($4D^2$ equalizers). This is called full MIMO processing. The task of each equalizer block is to undo the coupling between the channels that occurs during propagation in fiber and mode (de)multiplexer.

Reducing receiver complexity in MDM systems is crucial for feasible real time operation, i.e., for reasonable processing speed and power consumption. Recently, a MIMO-free data transmission was reported over a 100 m graded-index ring core fiber [8]. Only mode groups were multiplexed (not individual modes) and there was no polarization division multiplexing (PDM), greatly reducing capacity. As coupling was negligible between mode groups, and there was no PDM, no MIMO was required. PDM combined with MDM offers highest capacity, but requires a 2×2 equalizer block for polarization demultiplexing for each mode. This is called dual polarization (DP)-MIMO.

Orbital angular momentum modes (OAM) [9] are an alternative modal basis for MDM systems. In this paper, we focus on OAM-MDM data transmission systems. OAM-MDM systems offer the advantage of minimal mode coupling during propagation and thus reduced DSP complexity by eliminating the need for simultaneous detection of all modes and full MIMO processing. However, OAM modes cannot propagate in few mode fibers (FMF) designed for LP modes, but require specially designed fibers. One of the main challenges in OAM-MDM systems is mode instability at the optical fiber output after propagation.

OAM mode propagation was first demonstrated for 20 m and 900 m fibers [10], [11]. Successful MIMO-free OAM-MDM communications over 1.1 km of OAM fiber (called vortex fiber [12]), with simultaneous transmission of 4 channels over two OAM modes (order zero and one), was reported in [13], [14]. While MIMO-free, the transmission scheme used optical polarization demultiplexing to undo the coupling between the two polarizations in each mode order.

In another experiment [15], successful data recovery without using MIMO processing was reported for OAM MDM data transmission system over 2 and 8 km conventional graded index multimode fiber. As in [8] for LP modes, neither PDM nor individual mode multiplexing was used, rather OAM mode groups (order zero to two) were exploited. Two data channels were constructed by choosing one mode out of degenerate modes inside mode groups of order zero to two (one channel from order zero, the other from order one or two) without polarization diversity.

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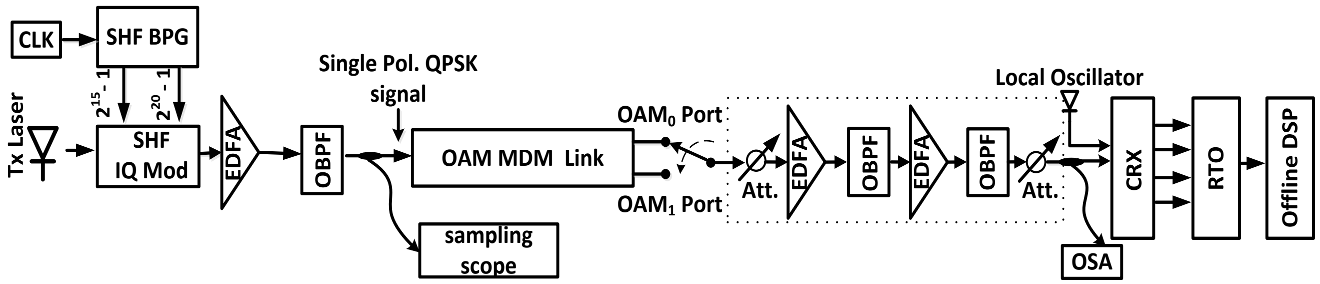


Fig. 1. OAM-MDM data transmission setup

In [16], we demonstrated successful data transmission over 1.4 km of ring core fiber (RCF) in four data channels of two OAM modes in two polarizations. For the first time, to the best of our knowledge, we used a polarization diverse demultiplexing scheme and successful data transmission was achieved without using full MIMO or manual optical polarization demultiplexing. We used electrical polarization demultiplexing in DSP, i.e., 2×2 equalizers for each mode group.

In this paper, we discuss in greater detail the data transmission system, and we investigate the BER performance versus OSNR. We examine the case of four channels data transmission and evaluate the OSNR penalty due to increasing the number of channels compared to single channel systems. Furthermore, we discuss the impact of crosstalk in mode demultiplexer and the resulting OSNR penalty.

The remaining sections of this paper are organized as follows. In section II, we discuss the principal of operation in OAM-MDM systems. In section III, we describe the experimental setup used for data transmission and the details of our free-space, polarization-diverse OAM mux-demultiplexer stages. In section IV, we present results for crosstalk measurements in our OAM-MDM link. In section V, we discuss the transmission experiment evaluating our OAM-MDM system performance. In section VI, we conclude the paper.

II. Principals Of Operation in OAM-MDM Systems

The motivation for using the OAM modal basis is to reduce the complexity of DSP in MDM systems. Complexity can be quantified via the number of equalizers required in MDM reception. We consider only systems with full capacity where PDM is being combined with MDM, and all modes supported by the transmission system are used as distinct data channels. Therefore, this discussion will not include systems such as [8],[15],[17], where PDM is not used and only mode groups are used for data transmission. In general, for a LP-MDM system with D modes, we need full MIMO with a $2D\times 2D$ equalizer. The number of equalizers required in these LP-MDM systems with full MIMO processing scales with the square of the number of modes. Examples of this increase in complexity include LP-MDM systems (with two polarizations per mode) supporting 3 modes [5] and 15 modes [6], where equalizer blocks of 6×6 and 30×30 were used, respectively.

By using OAM modes, the complexity of DSP can be reduced as the coupling between different modes can be low enough for separate mode detection. In OAM-MDM systems, the number of equalizers required scales linearly with the number of modes being exploited. As an example, and in our demonstration for a system using two OAM modes of OAM$_0$ and OAM$_1$ in two polarizations, supporting 4 data channels, two blocks of 2×2 equalizers (for polarization demultiplexing) are required instead of a 4×4 equalizer block.

We transmit simultaneously four data channels over two OAM modes. The order zero mode, the fundamental mode, is denoted by OAM$_{0R}$ and OAM$_{0L}$ where R and L denote right and left circular polarization, respectively. The order one OAM modes are denoted by OAM$_{+1}$ and OAM$_{-1}$. The interactions between the two mode groups of order zero and one are reduced to a minimum level by using specialty designed fibers for OAM modes propagation. The two polarizations of each of the two modes (zero and one) are degenerate leading to intra-mode coupling during propagation, i.e., OAM$_{0L}$ couples with OAM$_{0R}$, and OAM$_{+1}$ couples with OAM$_{-1}$. Hence, while MIMO processing of 4×4 equalizer can be avoided, polarization demultiplexing on each mode group is required for successful data recovery in such systems.

Demultiplexing in [13], [14] used optical polarization demultiplexing using polarization controllers to separate the two polarizations of each mode rather than electronic separation. The demultiplexer setup was thus sequentially optimized for detection of each channel as they were captured; one polarization of one mode could be detected at a time at the demultiplexer output. We use a demultiplexing scheme allowing simultaneous detection of two polarizations in each mode group. It enables us to employ electrical polarization demultiplexing in DSP instead of optical polarization demultiplexing (i.e., manipulation of a polarization controller). This is the technique used in all commercial polarization multiplexing systems.

We present results for the transmission of dual polarization quadrature phase shift keying (QPSK) data up to 32 Gbaud on each of 4 channels, for a total rate of 256 Gbps. Without recourse to full MIMO processing, and using conventional DSP for dual polarization single mode coherent detection systems (standard 2×2 MIMO used in single mode fiber systems), we report bit error rate (BER) values below the forward error correction (FEC) threshold for each of the four OAM channels.

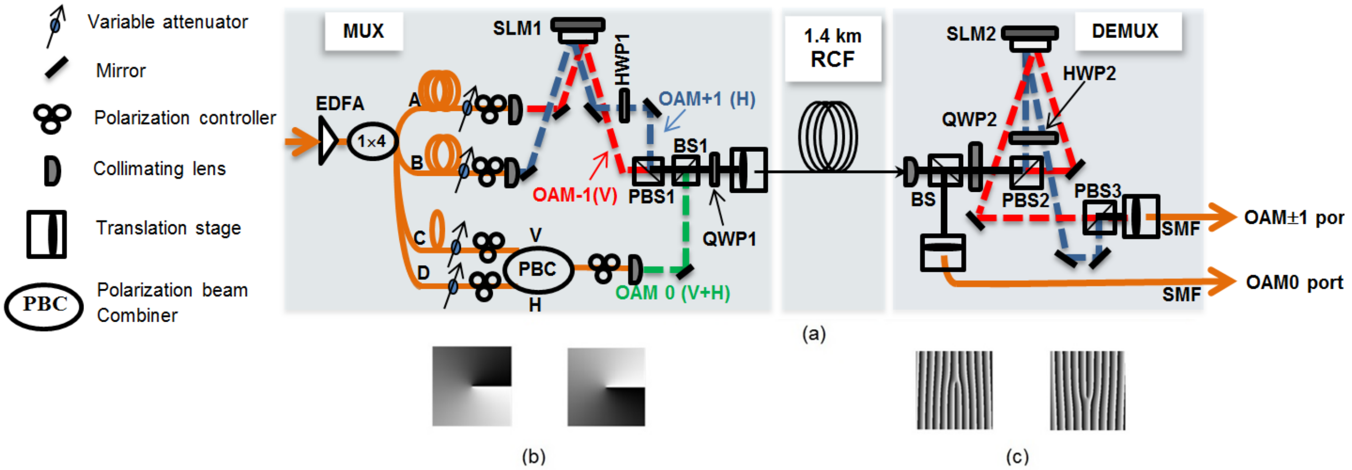


Fig.2. (a) Setup for free-space OAM mux and demultiplexer stages, (b) spiral phase patterns for $OAM_{\pm1}$ at SLM of mux stage, (c) blazed forked gratings for $OAM_{\pm1}$ at SLM of demultiplexer stage

III. EXPERIMENTAL SETUP

Our OAM-MDM link is comprised of three building blocks for mode generation, propagation and reception: a mode multiplexer (mux), a mode demultiplexer (demultiplexer) and specially designed ring core fiber (RCF) for OAM transmission. We first describe test equipment used for signal generation and data capture, followed by a description of the mux, demultiplexer and fiber.

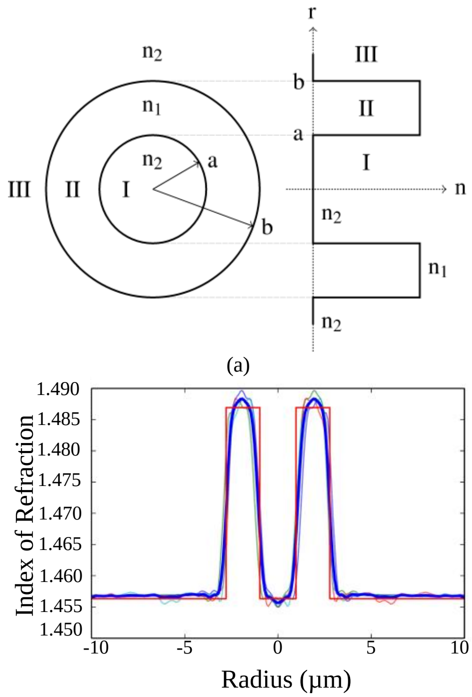
A. Signal Generation and Reception

We used an SHF 12103A bit pattern generator (BPG) with two pseudo random binary sequences (PRBS) of length 2^{15}-1 and 2^{20}-1 to generate a single polarization non-return-to-zero (NRZ) QPSK signal with an SHF46213D IQ modulator. The transmitter laser has a linewidth of 100 kHz and is set to 1550 nm with output power of 16 dBm. After the modulator, the signal is amplified and then sent to the OAM MDM link. At the receiver side, a single coherent receiver is used. The coherent receiver is connected to the appropriate output port of the OAM-MDM link for the OAM mode to be detected. The OSNR is varied by the use of an attenuator after the Demultiplexer. The polarization diverse signal in the selected mode is directed to a Picometrix coherent receiver with bandwidth of 22 GHz. The power input to the coherent receiver is fixed at -5 dBm. The local oscillator has a linewidth of 10 kHz and has output power of 13 dBm. The output electrical signals from the coherent receiver are captured by a Keysight real-time oscilloscope (RTO) with 30 GHz analog bandwidth capturing data at 80 Gsample/s. We use offline processing to apply conventional DSP for dual polarization single mode coherent detection systems to recover the signals in two polarizations of the mode being detected. No 4×4 MIMO processing is used in our four channel system.

B. Free space MUX – DEMULTIPLEXER stages

The setup for our free space mux-demultiplexer stages is shown in Fig. 2(a). In the mode multiplexer stage, the incoming, modulated single polarization signal is first amplified using a high power EDFA with output power of ~23 dBm. The modulated signal is then split into four branches with different delays; the decorrelated replicas of the main data stream are labeled A, B, C and D. The signals in paths A and B are projected on a polarization sensitive spatial light modulator (SLM1) with maximum permitted power of incident light less than 13dBm. SLM1 is programmed with two separate spiral phase patterns, illustrated in Fig. 2(b), to generate OAM_{+1} for path A and OAM_{-1} for path B. A half wave plate (HWP1) rotates the polarization of OAM_{+1} by 90º, i.e., orthogonal to that of OAM_{-1}. The two $OAM_{\pm1}$ modes are then combined using a polarizing beam splitter (PBS1). Paths C and D of OAM_0 (fundamental mode) are combined using a polarization beam combiner (PBC) and finally multiplexed with $OAM_{\pm1}$ at beam splitter BS1. Before coupling into the fiber, the multiplexed signal passes through a quarter-wave plate (QWP1) to change the polarization of signals from linear to circular. The multiplexed signal is then coupled into the RCF, described in the next section, using a six-axis translation stage for fiber alignment.

In our polarization diverse mode demultiplexer, we convert a PDM OAM mode to a PDM fundamental mode; all other modes are simultaneously mapped to other OAM modes. Subsequently, the light is coupled to single mode fiber that strips off all but the fundamental mode. The idea of mapping from spatial modes to single mode fibers at the demultiplexer stage was already exploited in MDM systems [15], [17], where pure mode division multiplexing without polarization division multiplexing was used. The mode demultiplexer stage of Fig. 2(a) splits the fiber output via BS2 into two different paths, one for OAM_0 mode detection and one for $OAM_{\pm1}$ mode detection. In the OAM_0 path, we couple the signal from free space into a single mode fiber (SMF), using the SMF as a mode stripper for OAM±1; as SMF only supports propagation of OAM_0, $OAM_{\pm1}$ will not couple or propagate in SMF. The output of this port, i.e., the SMF output, nominally only includes data transmitted on the OAM_0 mode group in two



(a)

(b)

Fig. 3. (a) Cross section of RCF fiber, (b) Designed (red) and measured index profile (blue: averaged, others: x- and y-scan on both directions)

polarizations. In reality, the non-zero demultiplexer crosstalk leads to small residual OAM$_{\pm1}$ signals.

For the OAM$_{\pm1}$ path, we must use a polarization sensitive SLM (vertical polarization required) for mode conversion. QWP2 converts the polarization of the received signal from circular to linear. Vertical and horizontal polarizations are separated using PBS2. The vertical polarization is routed to one section of the SLM. In the horizontal polarization path, a half wave plate (HWP2) assures that a second section of the polarization sensitive SLM2 again receives a vertical polarization. We program SLM2 with two separate blazed forked gratings, illustrated in Fig. 2(c), to select OAM$_{+1}$ in one path, and OAM$_{-1}$ in the alternate path. The blazed grating leads the OAM$_{\pm1}$ modes being converted to OAM$_0$, each with vertical polarization. The alternate path coming through HWP2, passes a second time through that component to be rotated back to horizontal polarization. The idea of using a HWP to rotate the polarization of a beam directed to and reflected from an SLM was also shown in [17]; however, polarization diversity was not used there. The two OAM$_{\pm1}$ modes, newly converted by SLM2 to the fundamental mode, are combined using PBS3. This forms the polarization diverse receiver for OAM$_{\pm1}$.

Finally, the polarization multiplexed signal is coupled into SMF to strip off any residual unwanted OAM$_0$ signals present. The SMF output at the OAM$_1$ port is nominally only data from the OAM$_{\pm1}$ modes, now on two polarization states of SMF. After initial free-space mode multiplexer and demultiplexer setup alignment, no further manual intervention (e.g., tuning of polarization) is required in our setup, demonstrating the robustness of OAM-MDM data transmissions.

TABLE I

Crosstalk Measurement for Each Mode Group

Crosstalk on OAM$_1$: -10.5 dB	***Crosstalk on OAM$_0$: -10.6 dB***
OAM$_{0L}$→ OAM$_1$: -13.5 dB	OAM$_{-1}$→ OAM$_0$: -13.6 dB
OAM$_{0R}$→ OAM$_1$: -13.5 dB	OAM$_{+1}$→OAM0: -13.6 dB

This demultiplexer scheme can be also used for higher order OAM modes with some modification. For OAM modes of order |N|≥2, there are four data channels in the OAM mode group (an OAM order). A polarization diverse demultiplexer is required for right (R) and left (L) polarizations of each OAM mode (e.g., one for $OAM_{+N}^{R,\,L}$ and $OAM_{-N}^{R,\,L}$ modes). We would place a beam splitter after QWP2 and duplicate the paths to SLM. Four surfaces would be programmed on the SLM, two for order +*N* and -*N*. One SLM surface would be used for one polarization of each of ±*N* modes.

C. Ring Core Fiber

Our OAM fiber is a step-index ring-core fiber supporting OAM$_0$ and OAM$_{\pm1}$ modes at 1550 nm. The cross section of the fiber is shown in Fig. 3a. The inner radius (*a*) of the ring-core is 0.97 µm, and the outer radius (*b*) is 2.78 µm, for a ratio *a*/*b* of 0.35. The cladding has a standard 125 µm diameter. Designed and measured index profiles of fiber are shown in Fig. 3b. The cladding and the center part of the fiber are made of SiO$_2$, while the ring-core is doped to achieve a refractive index contrast of 0.03 at 1550 nm. This refractive index contrast is sufficiently low to avoid spin-orbit coupling effects that are inherent to thin high-contrast ring-core fibers [18], whereas keeping the fiber fabrication process manageable. These characteristics allow a good effective index separation between the supported modes, preventing the OAM modes to easily couple to LP modes.

In coupling the free-space, multiplexed OAM$_{\pm1}$ beam into the RCF fiber, the beam intensity ring should perfectly match with the 1.81 µm ring of the RCF fiber core. Misalignment leads to the fundamental mode being excited with OAM$_{\pm1}$ mode, creating crosstalk at the multiplexer stage. The translation stages used to couple the OAM beam into fiber can have their positions vary by as much as a micrometer due to slight (one or two degree Celsius) temperature changes. This can significantly reduce the purity of the excited OAM$_{\pm1}$ modes. Thermo-insulation of translation stages was found highly effective in minimizing this effect in our experiments.

IV. CROSSTALK MEASUREMENT

We used power measurements to optimize the manual alignment of our free space OAM mux-demultiplexer stages, and to quantify the crosstalk between the modes. The crosstalk can arise from multiplexing, propagation or demultiplexing. It was monitored and minimized by adjusting free-space beam alignment in mux-demultiplexer stages. In an MDM system,

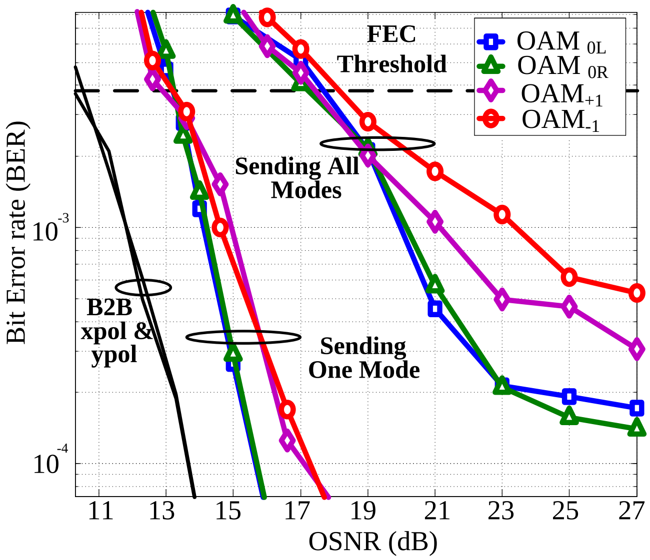


Fig. 4. BER vs. OSNR for all four data channel

low crosstalk is highly desirable, as it results into lower performance penalties.

To calculate the crosstalk, we measured the power of the demultiplexer stage output port for a specific mode when 1) transmitting only that mode, and 2) sending the other mode. The ratio between the measured powers indicates coupling from the other mode due to propagation, multiplexing and demultiplexing:

$$\text{Crosstalk on OAM}_i:\ 10\log\left(\frac{P_{|i-1|}}{P_i}\right),\ i=0,1 \tag{5}$$

where $P_{|i-1|}$ and P_i are the received powers at demultiplexer output port i, for the cases of transmitting OAM modes of order $|i-1|$ and i in the RCF fiber, respectively. For the results reported here, we could reach crosstalk levels reported in Table 1. For RCF fiber supporting two OAM modes, the 1.4 km fiber span was the longest fabricated fiber available for data transmission. The mode coupling will increase with fiber length [2]. Data transmission over longer lengths can be investigated in future as longer RCF fiber becomes available.

V. TRANSMISSION EXPERIMENT

After optimizing the manual alignment of our free space mode multiplexer and demultiplexer stages for minimum crosstalk between modes, we transmitted data and evaluated the performance of our OAM-MDM system. The bit error rate (BER) values are evaluated over 10^6 bits of transmitted data in each data channel.

In Fig. 4, BER versus optical signal to noise ratio (OSNR) at baud rate of 16 Gbaud is depicted. As can be observed, for the case of four channels data transmission, we have BER below the forward error correction (FEC) threshold of 3.8×10^{-3} down to an OSNR of 18 dB. By comparing the cases where a single channel was launched as opposed to all channels being transmitted, we observe an OSNR penalty of 5 dB at the FEC threshold for switching from single mode to two modes in our OAM-MDM system. This penalty is mostly due to the crosstalk between modes.

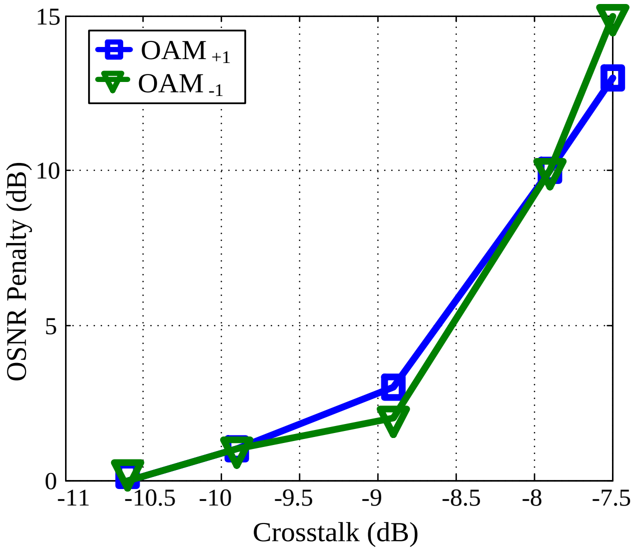


Fig. 5. OSNR penalty vs. crosstalk from OAM_0 on OAM_1 mode group

In Fig. 5, we examine the effect of misalignment in the free-space setup on system performance. We intentionally misalign the SLM in the demultiplexer stage resulting in imperfect mode conversion. Depending on the level of misalignment, we can have different levels of crosstalk from OAM_0 on OAM_1 mode. In Fig. 5, we have plotted the OSNR penalty to reach BER of 3.8×10^{-3} as a function of measured crosstalk levels due to the misalignment. The curves are plotted for the case of sending all channels and detecting $OAM_{\pm1}$ modes. As can be observed, small misalignments resulting in low crosstalk increasement will be tolerated, whereas an imperfect mode conversion leading to crosstalk values greater than -9 dB will result into dramatic OSNR penalty increase. This is helpful for study and development of future integrated OAM mux-demultiplexer stages. In particular, the results of this figure highlight the importance and sensitivity of system performance to imperfect mode conversion in demultiplexing.

In Fig. 6, we swept the baud rate from 16 to 32 Gbaud at OSNR of ~ 28 dB and reported BER versus baud rate results. An inset shows typical constellations of the recovered signals at 32 Gbaud. We could reach BER values below the FEC threshold for all four channels for baud rates up to 32Gbaud. It establishes the viability and robustness of OAM mode division multiplexing with reduced DSP (only DP-MIMO) after propagation in 1.4 km of RCF fiber. Baud rate per channel was limited by equipment availability (the coherent receiver has bandwidth of ~22 GHz).

VI. CONCLUSIONS

We have demonstrated for the first time, OAM-MDM with electrical polarization demultiplexing using minimal 2×2 MIMO. We recovered four channels OAM-MDM over 1.4 km of RCF fiber. Taking advantage of our OAM fiber and our polarization diverse OAM mux-demultiplexer scheme, we simultaneously transmitted four channels on two polarizations

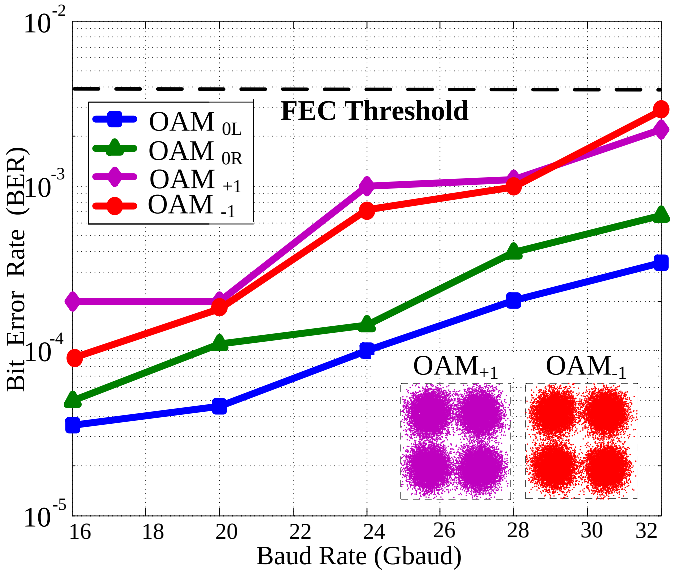


Fig. 6. BER vs. baud rate for all four data channels

of two OAM modes, and recovered each mode separately. This was possible due to crosstalk of less than -10.5 dB per mode in our OAM-MDM system. Switching from single mode to two modes data transmission imposes 5 dB OSNR penalty on our system. Data transmission with bit rates up to 4×64 Gbps QPSK was achieved with BER values below the FEC threshold. No optical control of polarization was used; reception used electrical polarization demultiplexing, showing OAM-MDM is compatible with current polarization demultiplexing receivers.

ACKNOWLEDGMENT

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