Joint WDM and OAM Mode Group Multiplexed Transmission Over Conventional Multimode Fiber

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***Abstract*—To exploit the advantages of multimode fiber (MMF)-based transmission and to improve the overall capacity, transmission of OAM modes over a single wavelength needs to be replaced by multichannel transmission with the proper experimental demonstration in terms of achievable bit error rates (BER), cross-talk(x-talk), etc. over the entire transmission band. In this paper, we have experimentally shown the successful transmission of two OAM mode groups multiplexed signals jointly with three channels using wavelength division multiplexing (WDM) over a 1 km conventional MMF, namely OM3. In this experimental study, each OAM mode over each WDM channel uses 10 Gbps of on-off keying (OOK) modulation format. At the receiver end, the achieved bit error rate (BER) is found well below the required pre-FEC BER of 3.8×10^{-3} without using any MIMO-DSP. To establish the efficacy of the signal transmission, the time evolutions of OAM mode x-talk and BER over wavelengths spanning the entire C-band have been experimentally measured. Under the influence of different x-talks, the BER performances of all three 50 GHz-spaced WDM channels for both OAM modes are measured. With proper adjustment of polarization at the receiver end, a BER value below the pre-FEC threshold is achieved over 900 seconds. The experimental results also revealed that the power penalty contribution of WDM x-talk is negligible compared to OAM mode x-talk.**

***Index Terms*—OAM mode group multiplexing, wavelength division multiplexing, multi-mode fiber.**

I. Introduction

TODAY'S most widely used Internet applications, including search, online interactive maps, social networking, video streaming, and the Internet of Things (IoT), are all powered by data centers (DCs) infrastructure [1], [2]. The quantity of computation and traffic on the data center interconnection network is growing due to the introduction of new machine learning (ML) applications, new web services, and search engines [1], [3]. As a result, maintaining bandwidth scalability is a prime task that research and technology development community are investigating realizing low-cost, short-reach optical connectivity for intra-data center links [4], [5]. Multimode fibers (MMFs) are frequently used in short-reach intra-and inter-data center (IDC) interconnects for distances up to a few km because of their cost-effective transceivers [6]. However, the maximum capacity of the existing technology is limited by the multi-modal dispersion, even for the advanced OM4 and OM5 fibers [7]. Using Intensity Modulation and Direct Detection (IM-DD) based systems with on-off keying (OOK) modulation adopting Ethernet 100 GBASE-SR4 and Fiber Channel (FC) 32G-FC standards transmission speeds up to 28 Gbps per lane over 70 m and 100 m using OM3 and OM4 fibers has been achieved [6]. 100 Gbps transmission over 250 m of advanced OM4 and OM5 fibers using short wavelength division multiplexing (SWDM) at 850 nm, 880 nm, 910 nm, and 940 nm wavelengths are demonstrated [8]. Using C-band wavelengths also data transmission over MMF has been shown to increase the overall link capacity [9], [10], [11]. It is also required to increase the capacity of the short-reach links made of older MMFs (OM2 and OM3), which are still widely used for Intra Data centers(IDC) interconnects without increasing the complexity and cost of the transceivers. Mode division multiplexing (MDM) is a viable technology for enhancing capacity in MMF that uses spatial modes of light as information carriers [12], [13], [14], [15], [16], [17]. A structured light called orbital angular momentum (OAM) mode has been used extensively to enhance the capacity of optical fiber links utilizing the spatial orthogonality of different OAM modes [14], [18], [19]. In recent years, the 1120-channel OAM-MDM-wavelength division multiplexing (WDM) and 224 OAM+WDM transmission through ring core, fiber have been reported using MIMO based receiver and without MIMO-based receiver, respectively [20], [21]. Moreover, OAM MDM transmission through few-mode fiber (FMF) with and without MIMO-DSP receivers also has been reported [22], [23]. Unfortunately, specially designed fiber and MIMO DSP-based receivers both increase the cost and complexity of the transmission system. So it is desirable to have cost-effective conventional MMF-based systems, which use OAM modes, combating the mode cross-talks (x-talks) [24]. Chen et al. show that conventional MMFs such as OM3 and OM4 fibers can also support the OAM modes over C-band wavelengths [13], [25], [26], [27]. Experimental works on OAM mode-assisted MDM systems over MMF using single C-band wavelength shows that the mode x-talk can be minimized to realize MIMO-DSP free receiver if OAM modes of different mode groups are multiplexed [13], [21]. Recently, Y. Liu et al. have reported the performance of the silicon photonic mode multiplexer chip that enables the simultaneous multiplexing of WDM and OAM modes using 800 m OAM ring core fiber using 10 G OOK signals [28]. Thus it becomes necessary to explore the OAM mode-based MDM along with WDM in conventional

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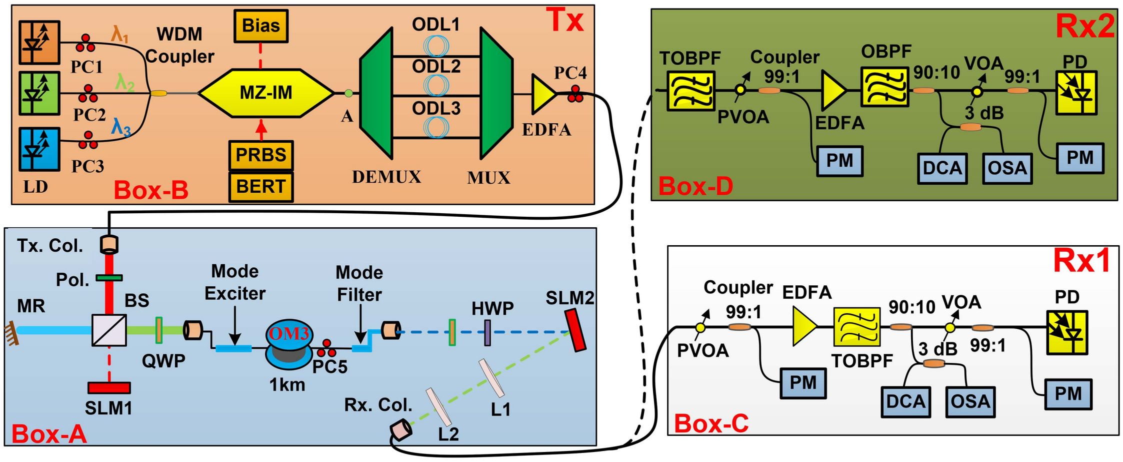


Fig. 1. The schematic diagram of the experimental setup. Box-A: System for OAM mode (single & WDM channel) multiplexing, transmission, and demultiplexing. Box-B: WDM transmitter with 10 Gbps OOK signal/channel. Box-C: Single channel receiver. Box-D: WDM receiver. BERT: Bit error rate tester. ODL: Optical delay line. MZ-IM: Mach-Zehnder Intensity Modulator; SLM: Spatial light modulator. VOA: Variable optical attenuator. PVOA: Programmable variable optical attenuator. PM: Power meter. OBPF: Optical band pass filter. TOBPF: Tunable optical bandpass filter. DCA: Digital Communication Analyzer; PC: Polarization Controller; PD: Photo Detector; OSA: Optical Spectrum Analyzer;; MR: Mirror; BS: Beam splitter; Pol.: Linear Polarizer; HWP: Half Wave Plate; QWP: Quarter Wave Plate. Col.: Collimator; L1: Lens, L2: Lens.

MMF-based links to enhance the capacity. Moreover, experimental investigations of such systems in terms of OAM mode x-talk, WDM x-talk, stability, and bit error rate (BER) also needs to be performed. Based on the authors' best knowledge, no work has been reported on the joint WDM and OAM mode-based signal transmission over conventional MMF fiber using C-band wavelengths. Therefore, in this paper, we report the experimental study of the joint WDM and OAM mode multiplexed transmission over the C band through 1 km OM3 fiber without using the MIMO-DSP receiver. For easy excitation of desired multiplexed OAM mode groups with minimum crosstalk, a homemade OAM mode exciter and filter are used in this experimental study [14]. Moreover, in this study, we also show the time evolution of the OAM mode crosstalk as well as BER values over a time interval of 900 seconds for the wavelengths spanning the C band. Successful transmission of three WDM channels with separation 50 GHz and having two OAM modes on each channel has been shown here with BER values well below the 7% FEC limit. Two lower-order OAM modes from two different mode groups with topological charges $l = 0$ and $+1$ are used in this experimental study. The experimental results indicate that the OAM mode x-talk is the primary source of power penalty, whereas WDM x-talk plays a negligible role. This indeed establishes that one can increase the capacity of MMF links by including more WDM channels without degrading the BER performance. The remaining paper is structured as follows: Section II briefly discusses the experimental setup. In Section III, experimental results and discussions are presented. Concluding remarks are addressed in Section IV.

II. Experimental Setup

Fig. 1 shows the schematic diagram of the experimental setup. The blue-shaded box, Box-A, is the common setup utilized in all the experiments for generating, multiplexing, and de-multiplexing of the OAM mode groups. The WDM signal is generated at the transmitter end by combining the three DFB laser sources using a WDM coupler. To de-correlate the channels, extra SMFs with different lengths are added as delay lines, as shown in Box-B of Fig. 1. Then this optical signal is divided by a 3 dB beam splitter (BS), as shown in the blue shaded box. One part of the BS output is used to generate an OAM beam using a spatial light modulator (SLM), and the other part is not modulated to obtain an optical beam with topological charge = 0; i.e the Gaussian beam. Optical beams are de-correlated by using a mirror to create the path difference between generated OAM beam and the Gaussian beam. A Quarter Wave Plate (QWP) is used to convert the linear polarized light into circular polarization for launching into the MMF fiber. In our experimental work, we have used graded-index multimode fiber, namely OM3 fiber. The make of this fiber is YOFC, core diameter 50 µm, and the measured loss of the fiber is ~0.5 dB/km at 1550 nm with Gaussian mode. To minimize the inter-mode group crosstalk and easy excitation of a few desired lower order modes inside the OM3 fiber a short section of large core fiber fusion spliced to MMF supporting only 15 spatial modes with low attenuations (<0.22 dB/km), low differential mode group delay (<155 ps/km), large effective area ($\geq 95\,\mu\text{m}^2$), and low bend losses at 1550 nm [29]. After 1-km MMF transmission of the multiplex mode group, a second homemade filtering is used to block undesirable higher-order modes using the same few-mode fiber with a length of 20 cm. A three-paddle polarization controller (PC5) over the OM3 fiber is also made to adjust the polarization to minimize the x-talks. It is seen that proper adjustment of PC5 provides stability over several hundreds of seconds. Indeed for long-term stability, one has to use adaptive polarization control methods. It is to be mentioned that in this experimental study, we have used a bare OM3 fiber spool, which is kept in the lab environment without any temperature, and vibration control.

The received optical signal is converted into linear polarization before sending it to the second SLM, as shown in the blue-shaded Box-A. The de-multiplexing of the desired mode is performed by using a reverse phase pattern on SLM and a 4f system ($L1 = 20$ cm and $L2 = 10$ cm). For characterization of the single channel OAM mode group multiplexed transmission system over C-band, Rx1, as shown in Box-C of Fig. 1, is used. The detected Gaussian beam is captured using SMF, which works as a spatial filter. The output of the signal is directly sent to the power meter to measure the crosstalk power. For characterization of joint WDM and OAM mode group multiplexed system Rx2, as shown in the Box-D of Fig. 1, is used.

A. Single Channel OAM Mode Group Multiplexed System

The OAM mode multiplexed system Rx1 (Box-C) of Fig. 1 is used to characterize a single channel. At the transmitter end, a 10 Gbps On-Off Keying (OOK) electrical signal is generated by using a bit error tester (BERT) system having a PRBS length of $2^{31} - 1$. A C-band tunable laser source (not shown in Fig. 1) and MZ-IM are used to modulate a 10 Gbps electrical OOK signal. The following Erbium-doped fiber amplifier (EDFA) provides sufficient optical power up to 13.5 dBm. After fiber transmission, the desired mode is de-multiplexed, and the detected mode is sent to the Rx1. In this experimental study, we have used OAM modes with topological charges $l = 0$ and $+1$ as they are easy to excite, detect, and have low inter-OAM mode x-talk ($< 4\%$) enabling MIMO-DSP free receiver [13]. The output optical signal is directly given to the power meter to measure the crosstalk power for C-band wavelengths through a $99 : 1$ coupler. The other part is given to the preamplifier via a variable optical attenuator (VOA) to alter the input power. After that, the amplified signal is filtered by a tunable optical bandpass filter (TOBPF) having a bandwidth (BW) of 0.9 nm. Then the optical signal is given to the photodiode (PD) through a second VOA to guarantee a constant input power to the PD. Digital Communication Analyzer (DCA) and Optical spectrum Analyzer (OSA) is added after TOBPF using a $90 : 10$ coupler for viewing the eye diagram and measuring the optical signal-to-noise power ratio (OSNR) values, respectively. The BERs are measured using an error detector.

B. Joint WDM and OAM Mode Multiplexed System

For the characterization of joint WDM and OAM mode transmission system using OM3 fiber, the WDM transmitter block is shown in the shaded in the orange box (Box-B) in Fig. 1 (Box-B). The receiver setup is shown in the green shaded Box-D of Fig. 1. The WDM signal is generated by combining the three DFB laser sources, each having 10 dBm power, with 50 GHz spacing (wavelengths 1548.515 nm, 1548.915 nm, and 1549.315 nm) using a WDM coupler. WDM channels are then modulated simultaneously by using a 10 Gbps NRZ-OOK electrical signal and an MZ-IM. Modulated signals over WDM channels are de-correlated using MUX/DEMUX and variable-length SMFs combinations. Then the multiplexed signal is amplified by the EDFA to provide a sufficient total power of up to 13.5 dBm. After fiber transmission, the detected desired mode power is directly given to Rx2, where the TOBPF ($BW = 0.32$ nm) is used to select the particular WDM channel. Then the power meter is connected to the selected channel to measure the crosstalk via a $99 : 1$ coupler. 99% power is further given to the first VOA to alter the input power to the preamplifier. After filtering out the amplified spontaneous emission (ASE) noise, a second VOA is used to fix the power launching on the PD. DCA and OSA are added after the second OBPF using a $90 : 10$ coupler for viewing the eye diagrams and measuring the optical signal-to-noise power ratio (OSNR) values, respectively. The BERs are measured using an error detector for a given OAM mode and wavelength combination.

III. Experimental Results and Discussion

In this section, the experimental results and discussion on the transmission of single-channel OAM mode group multiplexed signal and joint WDM and OAM mode multiplexed signals over 1 km long conventional multimode fiber (OM3) are presented. Moreover, we also reported here the time variation of the crosstalk power and BER values single and WDM channels over the C-band. The proposed system's stability in terms of OAM mode x-talk and BER value is highly dependent on the external perturbation to the MMF, such as stress, squeezing, bending, temperature variation. Unfortunately, all of these can be random over time and their variation can be slow or fast depending on the situation. These perturbations affect the OAM mode profile and purity of transmitted OAM modes. This induces OAM mode coupling and eventually mode crosstalk. Therefore, in our study, we have evaluated the stability in terms of bit error rate (BER) and power fluctuations in the desired OAM modes in presence of the undesired OAM mode for a time duration of fifteen minutes (900 seconds). In the case of day-long measurement, we have to implement an adaptive polarization control mechanism to change SOP continuously in achieving BER values below a targeted value as discussed in [30].

A. OAM Mode X-Talk Measurement Over Time

OAM mode crosstalk, which is the measure of the undesired OAM mode(s)'s power into desired OAM mode, is observed at the receiver when a desired OAM mode is detected. We have seen that due to random fluctuations of environmental parameters, the OAM mode x-talk also changes randomly. This OAM mode x-talk can be controlled and can be brought below a target level by properly adjusting the polarization. This is done by using PC5 in our experimental setup. It is worth mentioning that for a given setting of PC5, the OAM mode x-talk remains low for a while only. After some time due to the changes in environmental conditions, the transfer function of MMF, state of polarization (SOP), and the OAM mode x-talk inside the fiber get altered. This needs adjustment of polarization (using PC5 in our setup) again. In this section, we intend to measure a typical time window over which the OAM mode x-talk remains low (~ 10 dB). The total power of OAM modes, which propagates through the fiber, remains constant and power transfer happens within modes. So it becomes necessary to measure the desired OAM mode's power over time at multiple time instances in the presence and absence of all other OAM modes. Moreover, the measurements should be done randomly to avoid any over/under-estimation of OAM mode x-talk due to periodic perturbation on the fiber, if it exists. Thus in this study, the OAM mode x-talk is measured randomly over a time duration of 900 seconds with a time interval of 10–20 seconds between two measurements. To measure the OAM mode x-talk of the system using either a single channel or WDM channels, we measure the power leakage of the undesired OAM mode into a desired OAM mode after the 1 km long OM3 fiber over time. For this measurement, first, the receiver SLM is set to detect the desired OAM mode for a single-channel OAM mode multiplexed signal at the output of the OM3. For the WDM system first, the desired OAM mode is detected and then intended wavelength is filtered out. The detected power is measured using a power meter, which measures the total power of both desired and undesired OAM modes. Over a time duration of 900 seconds, the desired OAM mode is randomly sent and blocked from the transmitter, while the undesired mode is always present. Thus the power meter measures the undesired mode's power when the desired mode is blocked. From the power difference of the total (desired + undesired) and the undesired modes power, x-talks are measured multiple times over the entire time window of 900 seconds, and the maximum x-talk value (= minimum power difference) is reported.

For the single channel case, to see the wavelength dependency on the time evolution of OAM mode x-talk, the measurements are done at three wavelengths 1535 nm, 1550 nm, and 1560 nm, spanning the C-band. The time variation of x-talk shown in Fig. 2(a) are for the OAM mode multiplexing with $l = 0$ and $+1$ and the desired mode is $l = 0$. Fig. 2(b) depicts the time variation of x-talk when $l = 0$ and $+1$ are multiplexed at the transmitter and $l = +1$ is detected. Results in Fig. 2(a) show that the maximum measured x-talk in detecting $l = 0$ mode at wavelengths 1535 nm, 1550 nm, and 1560 nm are 11.9 dB, 13.1 dB, and 12.2 dB, respectively. For detecting $l = +1$ mode, the maximum x-talks at wavelengths 1535 nm, 1550 nm, and 1560 nm are found to be 9.2 dB, 15.2 dB, and 11.3 dB, respectively, from Fig. 2(b). The x-talk measurement for joint WDM and OAM mode group multiplexed transmission is done by using three 50 GHz spaced WDM channels (wavelengths 1548.515 nm, 1548.915 nm, and 1549.315 nm) and measuring the x-talk for the middle channel using Rx2 configuration as shown in Fig. 1. Fig. 3(a) and (b) show the variations of measured power of the middle WDM channel when $l = 0$ and $+1$ modes are transmitted and $l = 0$ and $l = +1$ modes are detected, respectively. From the results, it is seen that the worst x-talks for detecting OAM mode with $l = 0$, and $+1$ are 13.7 dB and 10.6 dB, respectively. From the x-talk measurements, it is evident that by proper adjustment of only PC5 an x-talk below 10 dB is achievable over a time duration of 900 seconds for both $l = 0$ and $+1$ OAM modes while the single channel and WDM transmission. Also, the results confirm that WDM channels play a negligible role in offering an x-talk compared to OAM modes.

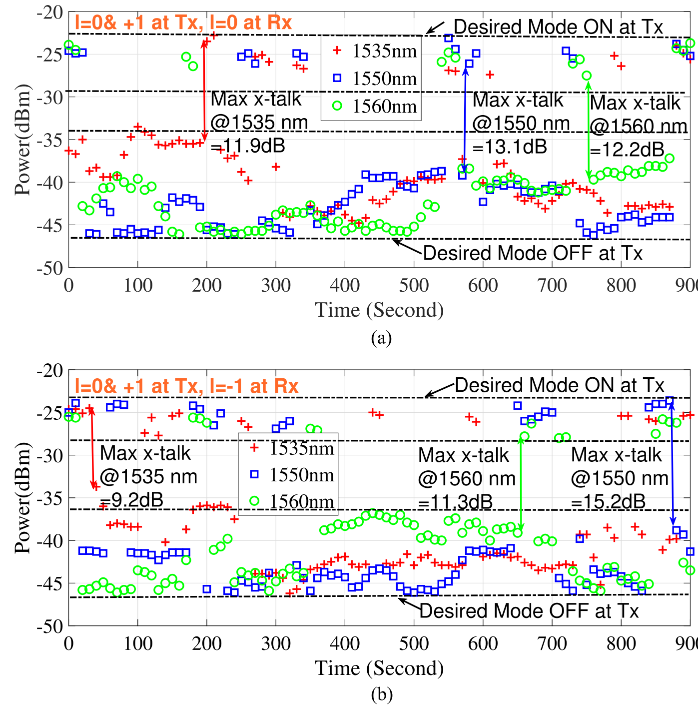
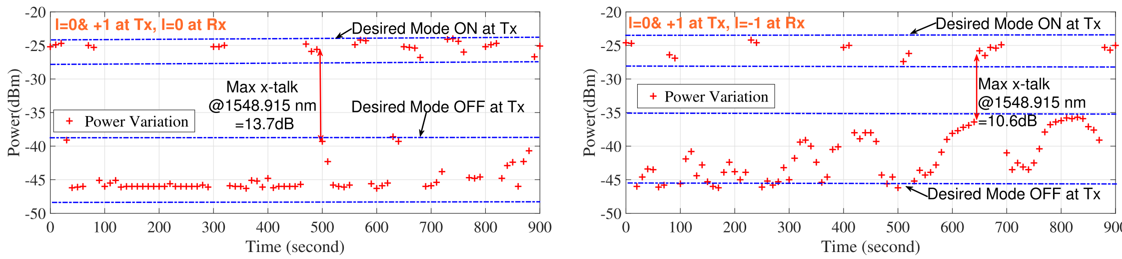


Fig. 2. Time variations of OAM mode x-talk for single channel condition at three different wavelength values (1535 nm, 1550 nm, and 1560 nm). Measured x-talk = total power (desired + undesired) of OAM modes ' power of the desired OAM mode. (a) Transmission of OAM modes with $l = 0$, and $+1$ over a single wavelength and detection of $l = 0$ at Rx1. (b) Transmission of OAM modes with $l = 0$, and $+1$ over a single channel and detection of $l = +1$ at Rx1.

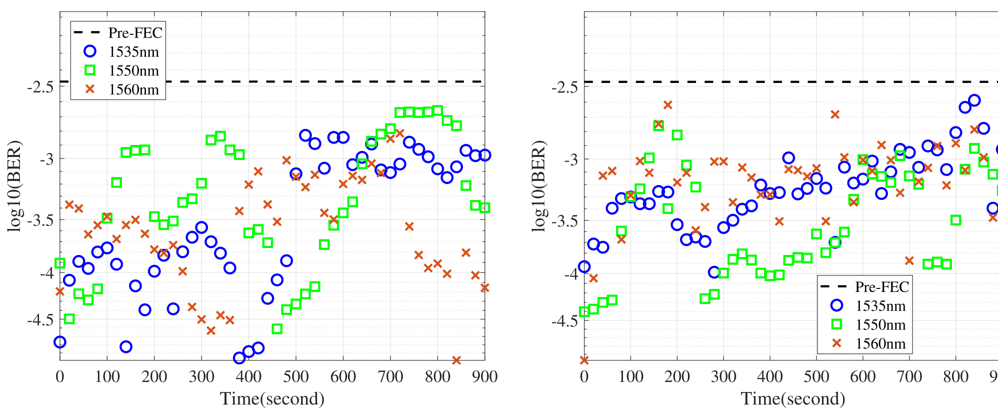
B. BER Measurement Over Time

As mentioned in the previous section, the random OAM mode x-talk occurs due to environment-induced random perturbation on the MMF. To measure the effect of this random fluctuation of OAM mode x-talk on the BER performance in single channel and WDM transmission, we have measured the BER values randomly for a desired OAM mode for 900 seconds, in presence of another undesired OAM mode. The launched power on the PD is kept fixed to obtain a BER around 10^{-3}. It is to be noted that this BER varies randomly for both single-channel and WDM transmission. Thus the BER measurements are done randomly using BERT with a time interval of 10–20 seconds between two successive measurements. The time interval is taken large enough to measure the BER faithfully, i.e. the number of bits in errors becomes large (> 100) and the BER display on the BERT becomes stable. For a single channel (i.e two OAM modes over a single wavelength channel) the BER fluctuation is due to OAM mode x-talk only. In WDM transmission the BER degradation is due to WDM channel x-talk, which is deterministic and much smaller compared to OAM mode x-talk, and the OAM mode-talk. Thus in the WDM transmission, the random fluctuations in BER values is predominantly due to x-talk between the OAM modes, which ride over the same wavelength. The variation in the BER of the OAM mode group multiplex transmission system in the lab environment is investigated by measuring the BER values of the desired OAM mode over a time interval of



(a) (b)

Fig. 3. Power variation of undesired and desired+undesired OAM modes for the middle WDM channel (wavelength 1548.915 nm) over time. (a) WDM transmission of OAM modes with $l = 0$ and $+1$ and detection of $l = 0$ at Rx2. (b) WDM transmission of OAM modes with $l = 0$ and $+1$ and detection of $l = +1$ at Rx2.



(a) (b)

Fig. 4. BER variation of detected OAM modes with time at wavelengths 1535 nm, 1550 nm, and 1560 nm for single channel OAM mode multiplexed system. (a) Transmission of OAM modes with $l = 0$ and $+1$ and detection of $l = 0$ at Rx1. (b) Transmission of OAM modes with $l = 0$ and $+1$ and detection of $l = +1$ at Rx1.

900 seconds under both single channel and WDM transmission conditions. Fig. 4 shows the BER stability of the single-channel system using OAM modes with $l = 0$, and $+1$ at the transmitter. The BER measurements are done for wavelengths 1535 nm, 1550 nm, and 1560 nm covering the C-band. Fig. 4(a) shows the time variation of BER values when $l = 0$ mode is detected. Fig. 4(b) shows the similar time evolution of BER values when OAM mode with $l = +1$ is detected. The results show that the BER values of the system for single channel OAM mode group multiplexing always remain below 7% overhead forward error correction coding (OH-FEC) for the entire 900-seconds time window. For these measurements, the received power of the RX1 (input to the EDFA) and the launched power to the PD are fixed at -25 dBm, and -6.5 dBm, respectively.

Further, we have reported the variation in the BER values of the OAM mode group multiplexed system in the presence of WDM channel. This study is particularly helpful for the practical implementation of the joint WDM and OAM mode group multiplex transmission system over OM3 fiber. This study shows the combined effect of WDM crosstalk and OAM mode crosstalk on the BER performance of the transmission system. The results are shown in Fig. 5(a) and (b when the detected OAM modes are $l = 0$ and $l = +1$, respectively, and the BER values are measured for the middle WDM channel (1548.915 nm) by using RX2 configuration (refer Fig. 1). For these measurements, the received power of the RX2 (input to the EDFA) and the launched power to the PD are fixed at -25 dBm and -6.5 dBm, respectively. The results show that the BER values always remain below the required pre-FEC BER value of 3.8×10^{-3}. It also becomes clear that the significant BER degrading factor is the OAM mode x-talk and not the WDM channel x-talk.

C. BER Performance Over C-Band: Single Channel OAM Mode Group Multiplexed Transmission

To establish that OAM mode group multiplexed signal can be effectively transmitted over OM3 fiber having any wavelengths within C-band, we have multiplexed OAM beams with $l = 0$, and $+1$. These multiplexed OAM modes are then sent using six different wavelengths individually spanning the C-band. We have categorically chosen wavelengths between 1535 nm to 1560 nm with a separation of 5 nm. Fig. 1 shows only three 50 GHz spaced WDM channels used for our proposed setup. For generating Fig. 6 we also used a single channel but tuned the wavelengths at six different values, so that we can span the entire C-band. At the output of the 1 km of OM3 fiber, BER vs. received power (input of EDFA of RX1) plots are obtained for single wavelength transmission. For spanning the entire C-band, the wavelength is tuned at six different values from 1535 nm to 1560 nm. For each wavelength setting, BER measurements

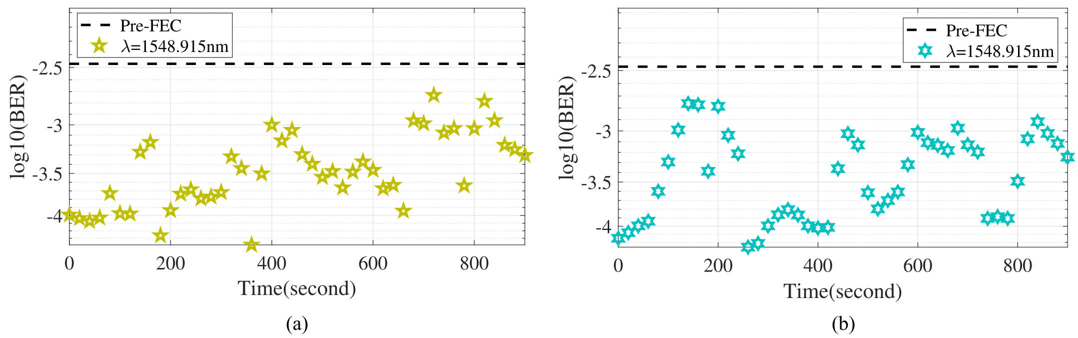


Fig. 5. BER variation over time for middle WDM channel (wavelength 1548.915 nm) in WDM+OAM mode multiplexed transmission system. (a) WDM transmission of OAM modes with $l = 0$ and $+1$ and detection of $l = 0$ at Rx2. (b) WDM transmission of OAM modes with $l = 0$ and $+1$ and detection of $l = +1$ at Rx2.

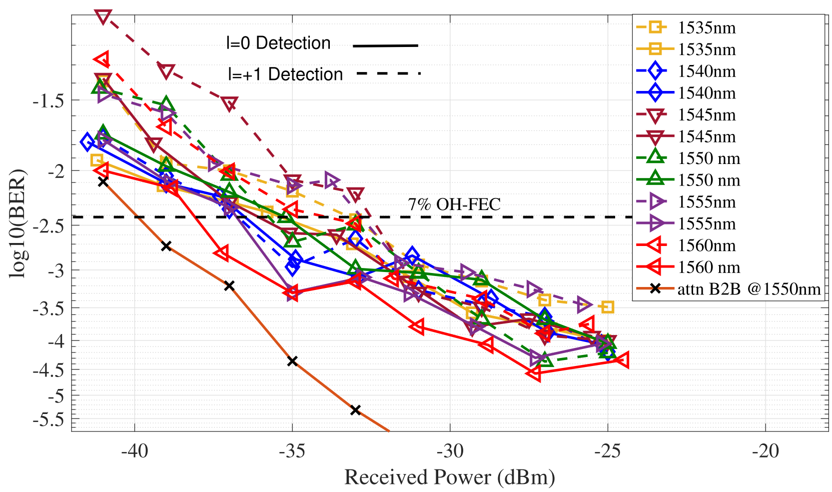
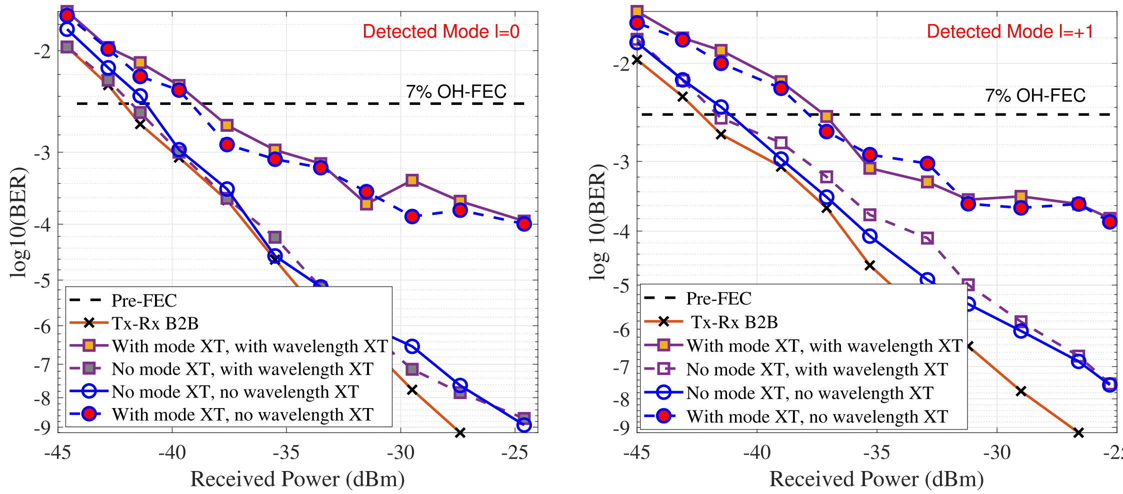


Fig. 6. BER vs. received power variation at different C-band wavelengths for the single channel OAM mode group multiplexed signal transmission over OM3 fiber. Solid and dashed lines are for the detection of OAM modes with $l = 0$ and $l = +1$, respectively.

are done for both the OAM beams with $l = 0$, and $+1$. Fig. 6 shows the BER performance of the multiplexed OAM modes $l = 0$, and $l = +1$ over the C-band wavelengths for the varying received power. For BER versus received power measurement, we have measured the power at the input of the receiver EDFA. The received power at the photo-detector is kept constant at -6.5 dBm. Thus changing input power at the receiver EDFA essentially changes the OSNR value at the photo-detector. The receiver module, which is used in the system, has a receiver sensitivity of -19 dBm for 10 Gbps signal at BER $= 10^{-9}$. The received power is varied over a range of -42 dBm to -25 dBm corresponding to OSNR variation from 13 dB to 27 dB, respectively. The results indicate that all channels achieve BER below the FEC limit after transmitting over 1 km OM3 fiber. The Back to back (B2B) curve is measured at 1550 nm, where the optical signal after the Tx EDFA is directly given to the receiver (Rx1). The Black dashed line in Fig 6 indicates the 7% FEC limit, i.e., BER of 3.8×10^{-3}. In fig.6, the dotted lines are used when the OAM mode of $l = +1$ is detected and the solid line is used for $l = 0$ mode detection. This result shows that MDM transmission over conventional OM3 fiber is indeed possible over the entire C-band. Moreover, it can be seen that depending on the wavelength, the power penalty (referenced to the B2B condition) measured at 7% Pre-FEC BER varies from ~ 2.3 dB to ~ 6.7 dB. BER curves also show floors at higher received power (or OSNR) indicating the presence of OAM mode group x-talk. We strongly believe that the results can be further improved with a more optimized receiver configuration. The proposed setup can also support the transmission of other OAM modes with different groups in multiplexed form. Although due to the unavailability of the required hardware, we could realize a 10 Gbps OOK signal over each mode/channel only, the data rate can be further increased, especially by using higher-order complex modulation formats.

D. BER Performance: Joint WDM and OAM Mode Group Multiplexed Transmission

In this section, we show the BER performances of the WDM and OAM Mode group multiplexed system, which uses three 50 GHz spaced WDM channels (wavelengths 1548.515 nm, 1548.915 nm, and 1549.315 nm). Each wavelength carries two OAM modes ($l = 0$, and $+1$), and each wavelength-OAM mode combination carries a 10 Gbps NRZ-OOK signal. Before establishing the successful transmission of joint WDM and OAM mode group multiplexed signal over OM3 fiber, measurements



(a) (b)

Fig. 7. BER performance as a function of received power under the influence of different x-talks for a channel having wavelength = 1548.915 nm. (a) Detected OAM mode, $l = 0$ (b) Detected OAM mode, $l = +1$.

are done to find the contributions of different x-talks toward the power penalty. We have realized that the two sources of x-talks in joint WDM and OAM mode multiplexed systems are OAM mode x-talk and WDM channel x-talk. Thus BER performances of the middle WDM channel (1548.915 nm) for both OAM modes are measured under four different scenarios. The BER plots are provided in Fig. 7. The four scenarios are; (i) single channel and single OAM mode transmission that is denoted as no mode XT, no wavelength XT, (ii) single channel and OAM mode multiplexed transmission that is denoted as with mode XT, no wavelength XT, (iii) WDM channel and single OAM mode transmission that is denoted as no mode XT, with wavelength XT, and (iv) WDM channel and OAM mode multiplexed transmission that is denoted as mode XT, with wavelength XT. Fig. 7(a) and (b) are generated when both OAM modes ($l = 0$, and $+1$) are multiplexed. Fig. 7(a) is for the detection of OAM mode with $l = 0$ and the OAM mode x-talk is coming from $l = +1$. For Fig. 7(b), OAM mode with $l = +1$ is detected and OAM mode with $l = 0$ is producing the OAM mode x-talk. The plots also include the B2B BER performance for calculating the power penalty at pre-FEC BER of 3.8×10^{-3}. We have measured the WDM cross-talk from Fig. 7 for OAM modes having $l = 0$ and $l = +1$. We have measured the excess power penalty at the targeted BER of 3.8×10^{-3}, when a single channel (1548.915 nm) in the transmission system is replaced by three 50 GHz spaced WDM channels. The middle channel, which is expected to have the most WDM crosstalk, is also having a wavelength of 1548.915 nm. The measurement is done for the middle channel only and the WDM crosstalk for $l = 0$ and $l = +1$ is ~ 0.7 dB for both OAM mode.

From the results, it can be confirmed that in the absence of OAM mode x-talk, the power penalty is negligible for both single channel and WDM transmission. Also, in the presence of OAM mode x-talk, it is observed that the number of wavelengths does not change the power penalty significantly. On the other hand, only OAM mode x-talk can result power penalty of 3 dB (or 4.5

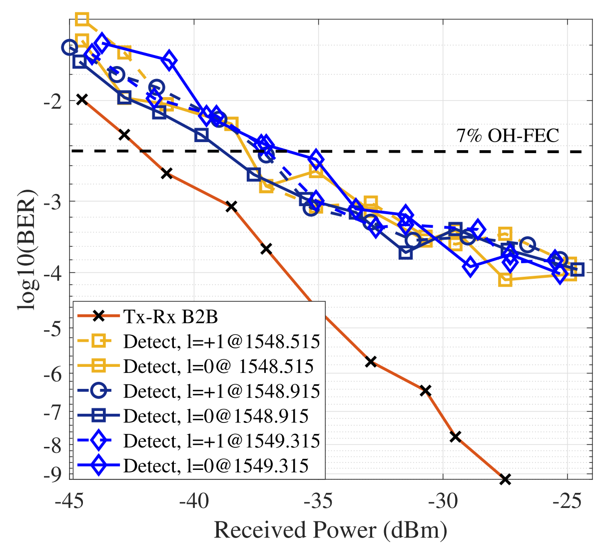


Fig. 8. BER vs. received power variation at different C-band wavelengths for the single channel OAM mode group multiplexed signal transmission over OM3 fiber. Solid and dashed lines are for the detection of OAM modes with $l = 0$ and $l = +1$, respectively.

dB) when OAM mode with $l = 0 (or + 1)$ is detected. OSNR penalty estimations also provide the same conclusions. These results are significant as they indicate that for OAM mode transmission through conventional MMF, one has to tackle only the mode x-talk. The overall capacity of the link can be substantially increased by accommodating more WDM channels. Thus in this study, although the number of WDM channels is limited to three, it can be increased further to accommodate all other ITU standard WDM channels. To show the successful transmission of all WDM channels and to carry both the OAM modes, we measure the BER vs received power for all three 50 GHz spaced WDM channels in the presence of both WDM and OAM mode x-talks. The BER performance results are depicted in Fig. 8. For these measurements the received power is varied between -45 dBm to -25 dBm, and the OSNR varies between 16 dB to 36 dB accordingly. The power at the input of the PD is kept at -6.5 dBm. The results show that all WDM channels achieved BER values below the pre-FEC limit, i.e. 3.8×10^{-3} for both OAM modes.The power penalty varies between $\sim$ 3dB to ~ 6 dB. The reason for the penalty of the OM3 fiber for OAM modes transmission is dependent upon the many parameters such as intrinsic defects and external perturbation (e.g. stress/strain, squeezing, twisting, bending, heating/temperature) during the fabrication process and the deployment can cause distortion on the mode profile and purity of synthesized OAM modes. Due to these OAM mode coupling loss and crosstalk take place that cause the penalty in the OAM mode transmission through the OM3 fiber. Another source of power penalty is the imperfect excitation of OAM modes in conventional MMF. It is simpler to excite desired OAM modes and suppress undesirable modes with the specially designed fiber-based mode exciter because it has a smaller core than the MMF. In MMF, a launched OAM mode, which is launched using a mode exciter, excites other OAM modes as well, especially those which are in the same mode group. This unwanted excitation of modes causes a power penalty. Moreover, at the receiver the mode filter is used to separate the desired mode from undesired modes. These mode-exciter/filter, which are implemented by splicing pieces of specialty fiber (as FMF used in this paper) with the MMF, also cause a power penalty.

IV. Conclusion

This paper experimentally demonstrates the successful transmission of joint WDM and OAM mode group multiplexed signal over 1 km of conventional MMF (OM3). The characterization of the link is done for three 50 GHz spaced WDM channels. Each WDM channel carries two OAM modes ($l = 0$ and $+1$). 10 Gbps OOK modulated signal is sent through each WDM+OAM mode combination resulting 60 Gbps total capacity. The experimental results also revealed that the OAM mode x-talk is the main reason for the power penalty, whereas WDM x-talk has a penalty of ~ 0.7 dB. This opens up the possibility of including more WDM channels to further increase the link capacity. For efficient OAM mode excitation and filtering, we have used two sections of large core fibers at the input and output of the MMF. Single-channel OAM mode multiplexed signal transmission over six different wavelengths spanning the C-band is also demonstrated in this study. Moreover, the results show that the successful data transmission over 1 km of OM3 fiber is indeed possible with a BER value well below the required 7% OH-FEC BER of 3.8×10^{-3} in the presence of both OAM mode and WDM x-talks. Here we also report that with proper adjustment of the polarization controller, the system can provide an x-talk below 10 dB and BER below the required Pre-FEC threshold for a time interval of 900 seconds. Most importantly, this study reveals that due to the selection of optical modes from two different OAM mode groups successful detection becomes possible without using a MIMO-DSP receiver. This experimental investigation indicates that a conventional MMF-based link in the future can support many OAM modes, WDM channels, and higher-order modulation formats for increasing the link capacity.

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