Optical Multi Input Multi Output signal processing with linearly polarized mode groups to enhance mode division multiplexing

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This paper investigated the effect of different LP_{lm} mode index grouping combinations (Even, Odd, Random Even+Odd and Symmetric Even+Odd with mode gap) on performance of different OMIMO-Mode division multiplexed configurations (5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9 MIMO). It is reported that mode index grouping combination (Symmetric Even+Odd with mode gap) provide best results for all optical MIMO MDM configurations covering 120km of transmission distance over MMF with acceptable Quality-factor (>8.3 dB) to enhance the system performance. The optimization of system is done by utilizing LMS (least mean square) adaptive MIMO filter algorithm to minimize the mean-squared error at the output signal in order to avoid mode group coupling in MDM based system. Featuring distinctive simplicity with reduced interference, the proposed design is ideal to cope up with the reliable and error free transmission with minimum use of bandwidth for upcoming optical communication. The proposed transmission system can be used for access related optical and super computer interconnects. This analysis can further be used for mode group division multiplexing to increase the capacity of high speed transmission over multimode fiber link.

(Received January 24, 2019; accepted April 9, 2020)

Keywords: Optical fiber communication, LP (linearly polarized) modes, MDM (Mode Division Multiplexing), MMF (multi-mode fiber), MM EDFA (Multi-mode Erbium Doped Fiber Amplifier) and OMIMO (Optical Multi-input multi-output)

1. Introduction

Optical Multi-input multi-output Mode Division Multiplexing (OMIMO-MDM) is an attractive multiplexing technology as it potentially offers flexible, reliable and robust communication to fulfill the increasing demand for higher internet capacity. MDM utilizing MMFs (multi-mode fibers) has recently been of immense interest from last 3 to 4 years to large extent for its capability to support multiple modes, boost capacity of optical communication systems and compensate for power losses [1-2].

In literature, several multiplexing techniques has been reported that utilize phase, amplitude and wavelength of light like WDM, DWDM (Dense WDM), 3-D OCDMA, 3-D coherent spatial-phase-time coding etc. that support SMF [3-6]. But still research field is exploring spatial multiplexing with multi-moded domain to fulfill the demand of higher quality and forthcoming capacity as required by end-user applications [7]. Different numerical analysis and experiments have been made for investigation of LP modes in MDM system with MMF [8-10]. The demonstrations done firstly on MDM system with MMF presents coverage of 10 km distance using 3 spatial modes modulated at 14GBaud PDM-QPSK [11]. Koebele et al. [12] utilized 5 modes (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a} and LP_{21b}) for MIMO MDM system covering a distance of 40km over FMF with low mode coupling. Bai et al. [13] demonstrated a mode division multiplexing based WDM system covering distance of 50-km over FMF (Few-mode fiber) and utilizing two modes: LP_{01} and LP_{11} (degenerate modes). Schmidt et al. [14] investigated different modes and nonlinear interaction in strongly coupled multimode fibers. They numerically calculated the field distributions of LP and exact-vectored modes with finite difference mode solver. They compared and verified the analytical results with simulation results.

Different numerical analysis and experiments have been made in the field of mode division multiplexing over MMF to increase internet capacity [15]. But, research in this area does not included investigation of mode index grouping combinations of linearly polarized modes. So, here we explored best suited mode combination for long and reliable transmission of data in OMIMO-MDM system. This paper deals with different LP mode grouping combinations for four cases (Even, Odd, Random Even+Odd and Symmetric Even+Odd with mode gap) to investigate the performance of 3 × 3, 4 × 4, 5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9 OMIMO MDM configurations to enhance the transmission quality of the system.

After the introduction, section 2 explains the system setup. Section 3 presents results and discussion and finally, section 4 summarizes the conclusions.

2. Concept of LP mode grouping

Modes are a set of guided electromagnetic waves that corresponds to the propagation of energy in form of light in fiber. Mostly for communication fibers where index difference between the core and cladding is moderately small, different modes can be grouped collectively into a single series of modes referred to as LP (Linearly

Polarized) modes [16]. The LP_{lm} modes can be represented as [17]:

$$E_t(r,\phi) = \Psi_{l,m}(r)\begin{Bmatrix}\cos l\phi \\ \sin l\phi\end{Bmatrix} \tag{1}$$

where, index $l \geq 0$corresponds to light intensity variation in azimuthal plane with respect to ϕ and index $m \geq 1$ refers to the radial (r) dependence in the light intensity pattern, $\Psi_{l,m}$ contains radial dependence and E_t depicts transverse field. In optical fibers with Δ<<1 (low index contrast between core and cladding), linearly polarized modes are dictated as weakly guided. It is clear from equation (1), for LP_{lm} modes with $l \geq 1$: two spatial modes depicting sine: LP_{lma} or cosine: LP_{lmb} configuration and further each having 2 polarization states. Thus, in total of four degenerate (same propagation constant β) modes are formed. For LP_{0m} modes with $l = 0$: one spatial mode with only two polarization states forming two degenerate modes. The linearly polarized LP_{0m} modes are the two-fold degenerate hybrid HE_{1m} modes. The LP_{1m} modes are produced by addition of exact modes: HE_{2m} + TE_{0m} or HE_{2m} + TM_{0m} forming four-fold degenerate as shown in Table 1. Similarly, LP_{lm} modes for l >1 are formed with the addition of hybrid modes: $HE_{l+1,m}$+ $EH_{l-1,m}$.

Four different groups of mode combinations are considered step by step in the setup (Table 2) to observe effect of mode coupling on performance of MIMO MGDM system.

Group G-I: Mode index (M) even
Group G-II: Mode index (M) odd
Group G-III: Random mix Even + Odd mode index
Group G-IV: Symmetric Even + Odd with mode index gap unity.

Table 1. Formation of LP_{lm} Modes

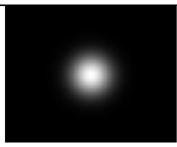
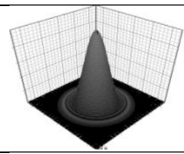
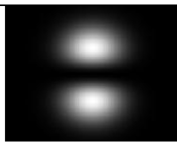
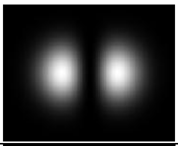
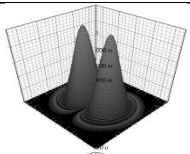
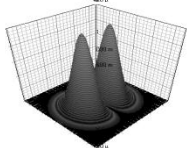
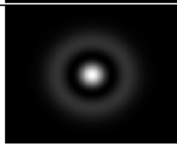
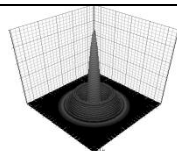
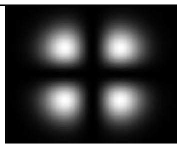
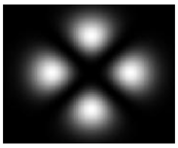
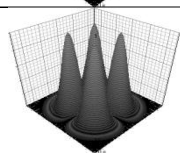
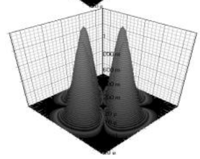
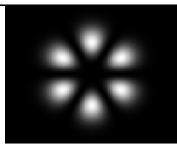
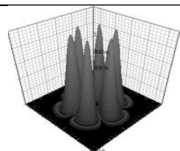
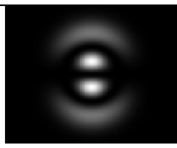
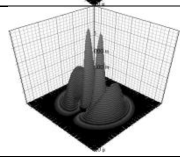
Hybrid or Exact modes	**LP_{lm} modes**	**Spatial intensity distribution**	**3D profile**
HE_{11}	LP_{01}		
HE_{21} + TE_{01} + TM_{01}	LP_{11a} LP_{11b}	 	 
HE_{12}	LP_{02}		
HE_{31}+ EH_{11}	LP_{21a} LP_{21b}	 	 
HE_{41}+ EH_{21}	LP_{31}		
HE_{22} + TE_{02} + TM_{02}	LP_{12}		

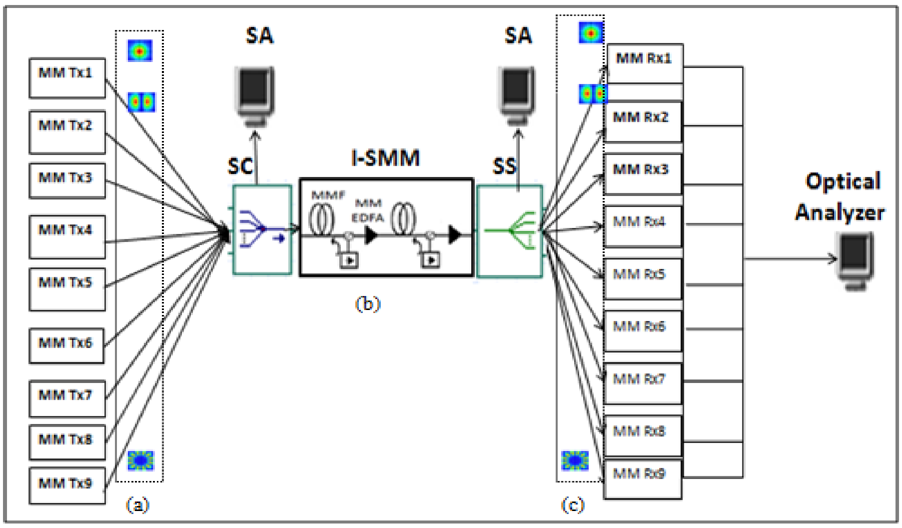
Table 2. Grouping of Modes

Groups	**Mode index M**	**LP_{lm} Modes**
Group G-I	M is even 4, 6, 8, 10, 12	LP_{11}, LP_{12}, LP_{13}, LP_{14}, LP_{15} LP_{31}, LP_{32}, LP_{33}, LP_{34} LP_{51}, LP_{52}, LP_{53} LP_{71}, LP_{72} LP_{91}
Group G-II	M is odd 3, 5, 7, 9, 11	LP_{01}, LP_{02}, LP_{03}, LP_{04}, LP_{05} LP_{21}, LP_{22}, LP_{23}, LP_{24} LP_{41}, LP_{42}, LP_{43} LP_{61}, LP_{62} LP_{81}
Group G-III	Random mix Even + Odd	LP_{01}, LP_{02}, LP_{11}, LP_{04}, LP_{13} LP_{01}, LP_{21}, LP_{02}, LP_{03}, LP_{13} LP_{01}, LP_{02}, LP_{12}, LP_{32}, LP_{13}, LP_{21}
Group G-IV	Symmetric mix with mode index gap unity (M=1)	LP_{01}, LP_{11}, LP_{02}, LP_{12}, LP_{03} LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41}, LP_{51} LP_{11}, LP_{02}, LP_{31}, LP_{03}, LP_{51}, LP_{61}

Group G-I includes combination of modes having even mode index with (a) same azimuthal index (*l*) like LP_{11}, LP_{12}, LP_{13}, LP_{14}, LP_{15}; LP_{31}, LP_{32}, LP_{33}, LP_{34}; LP_{51}, LP_{52}, LP_{53}; and (b) same radial index (m) like LP_{11}, LP_{31}, LP_{51}, LP_{71}, LP_{91}; LP_{12}, LP_{32}, LP_{52}, LP_{72}; LP_{13}, LP_{33}, LP_{53}, LP_{73} as shown in Table 2. Group G-II includes combination of modes having odd mode index with (a) same azimuthal index (l) like LP_{01}, LP_{02}, LP_{03}, LP_{04}, LP_{05}; LP_{21}, LP_{22}, LP_{23}, LP_{24}; LP_{41}, LP_{42}, LP_{43}; and (b) same radial index (m) like LP_{01}, LP_{21}, LP_{41}, LP_{61}, LP_{81}; LP_{02}, LP_{22}, LP_{42}, LP_{62}; LP_{03}, LP_{23}, LP_{43}, LP_{63}. Group G-III contains mixed groups of modes with odd and even mode index chosen randomly like LP_{01}, LP_{02}, LP_{11}, LP_{04}, LP_{13}; LP_{01}, LP_{21}, LP_{02}, LP_{03}, LP_{13}; LP_{01}, LP_{02}, LP_{12}, LP_{32}, LP_{13}, LP_{21}. In Group G-IV a gap of one mode index between two adjacent mode index is considered and further modes include combinations of mixed modes with odd and even mode index in sequence like LP_{01}, LP_{11}, LP_{02}, LP_{12}, LP_{03}; LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41}, LP_{51}; LP_{11}, LP_{02}, LP_{31}, LP_{03}, LP_{51}, LP_{61}.

3. System setup

To investigate the effect of mode index grouping combinations on performance of different MIMO-MDM configurations, the simulation layout is shown in Fig. 1. Each MM transmitter includes laser source and MZ modulator for each information source and the information source is in NRZ format with 10 Gb/s bit rate. The electrical driver creates the suitable data format for transmission, converts the input binary logical signal into electrical one and MZ modulator modulates the laser beam.



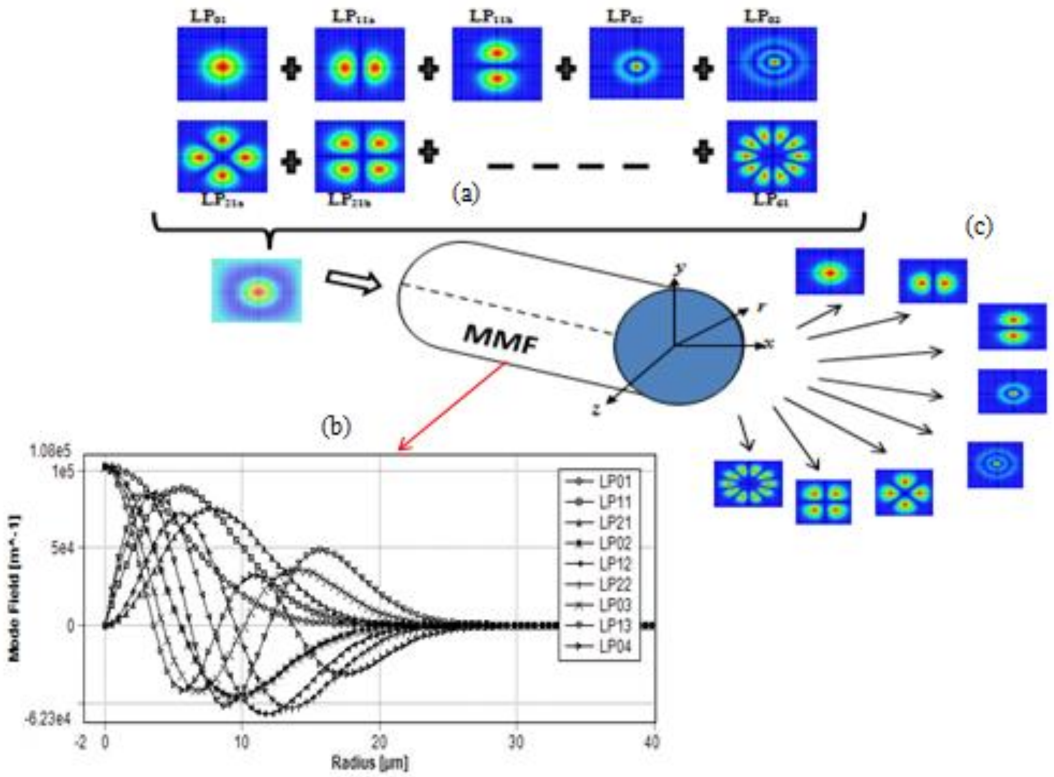


Fig. 1. System setup of 9 channel OMIMO-MDM communication system; SC: spatial combiner, SS: spatial selector + splitter, SA: spatial analyzer, I-SMM: inline-MM EDFA amplifier configuration, MMF: multimode fiber, MM EDFA: multimode EDFA amplifier (a) Intensity profile of LP modes at MM Transmitter (b) Normalized mode field distribution of modes propagating through MM fiber and (c) Intensity profile of LP modes at MM Receiver

Signals over N (= 3, 4, 5, 6, 7, 8 and 9) different LP_{lm} (linearly polarized) modes from N corresponding transmitters are fed to mode converter for mode conversion and then to spatial mode combiner (indicated as SC) for multiplexing of all the LP_{lm} modes. Inline-spatial multimode (I-SMM) EDFA is designed to amplify multiple spatial modes having multi-mode information signals at 1550 nm through graded index MMF with parabolic index.

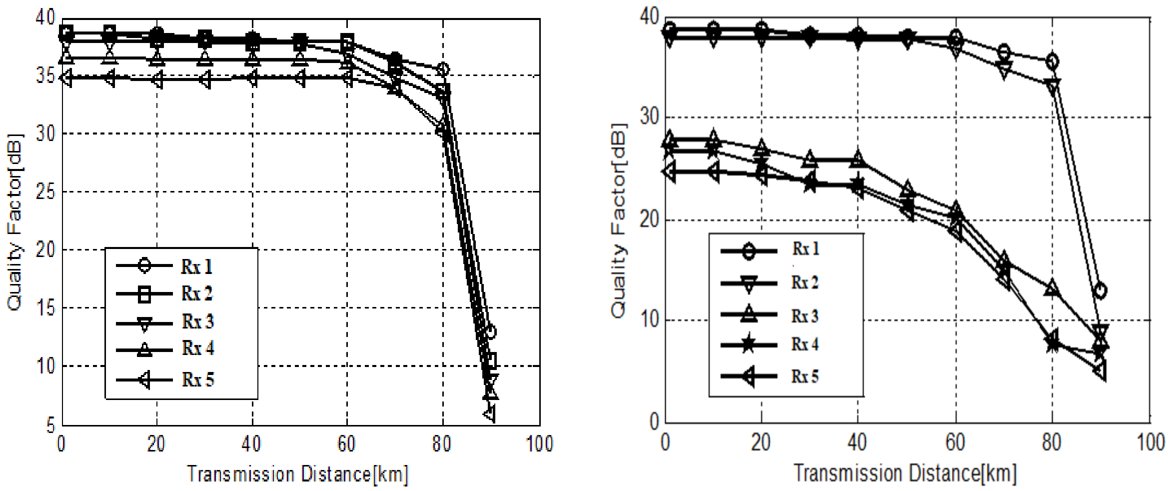
Table 3. System parameters

Name of parameter	Value
Power	0 dBm
Linewidth	10 MHz
Signal wavelength	1550 nm
EDFA Pump type	Counter-propagate
EDFA Pump wavelength	980 nm
EDFA Noise Figure	4 dB
EDFA Gain	Flat
Amplifier configuration	Inline-MMEDFA configuration
Dispersion	-100 ps/nm/km
Responsivity	1 A/W
Dark current	10 nA
Length	120 km

In receiver section, signals having different modes are demultiplexed by spatial mode selectors (indicated as SS). Different independent signals over N modes are recovered by N MM (multi-mode) receivers. The various simulation parameters of MIMO MDM transmission system are described in Table 3. Each MM receiver contain PIN photo detector which is used to convert the optical signal into electrical followed by a LPF; optical analyzer for monitoring the BER, eye diagram and Quality-factor of transmission link and SA (spatial analyzer) to observe intensity profiles of LP_{lm} modes in the entire schematic.

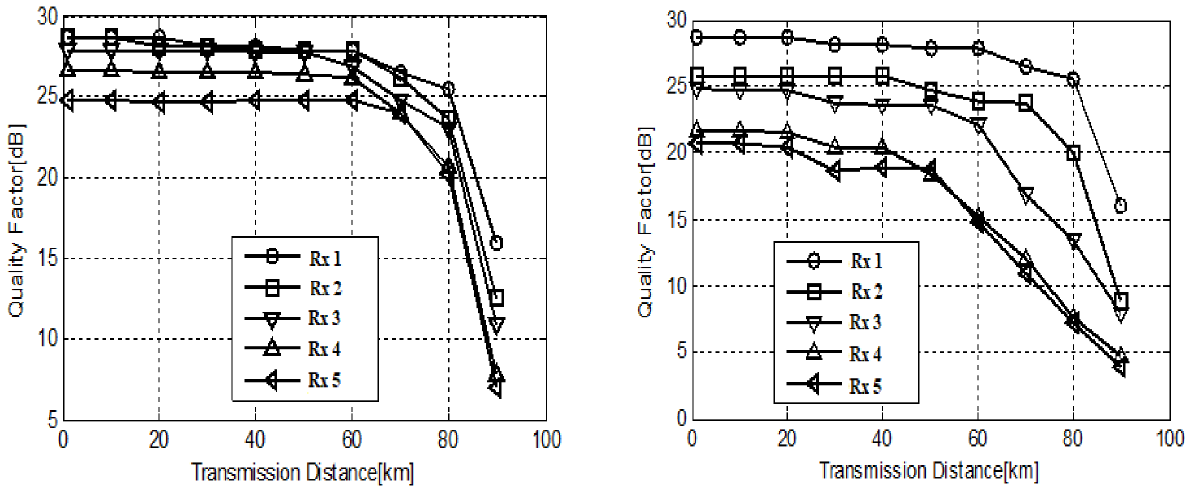
4. Result and discussions

Different groups of linearly polarized modes are taken into account to observe the transmission performance of OMIMO-MGDM system. The transmission distance for four different combinations of LP modes with mode index M (Even, Odd, Random Even+Odd and Symmetric with mode index gap unity) has been varied to observe the transmission performance for different configurations of OMIMO MGDM over MMF link.



(a) (b)

Fig. 2. Transmission quality of 5 × 5 MIMO-MGDM system using group G-I with same (a) azimuthal index l and (b) radial index m



(a) (b)

Fig. 3. Transmission quality of 5 × 5 MIMO-MDM system using Group G-II with same (a) azimuthal index l and (b) radial index m

Different possible mode groups are considered to observe the performance quality of MIMO-MGDM system for longest possible transmission. The transmission length has been varied to investigate the quality of signal as received by different MM receivers in MIMO MGDM system considering four different mode groups. Fig. 2 illustrates the effect of G-I modes on transmission quality of 5 × 5 MIMO-MDM system. In Fig. 2(a), G-I LP_{lm} modes (LP_{11}, LP_{12}, LP_{13}, LP_{14} and LP_{15}) with same azimuthal index (say l=1) are considered. It is observed that signal received by MM receivers (Rx 1, Rx 2, Rx 3 and Rx 4, Rx 5) provides good quality above 8.8 dB with long transmission distance of (90km and 88km) respectively.

For same radial index (say m=1) G-I LP_{lm} modes: LP_{11}, LP_{31}, LP_{51}, $LP_{71}$and LP_{91} are considered in Fig. 2(b). For G-I with same m, the quality of signal received by MM receivers (Rx 1, Rx 2) is same as in case of same l but received by MM receivers (Rx 3, Rx 4 and Rx 5) is poor after 82 km of transmission. The effect of odd mode index grouping of LP modes (G-II) on transmission performance of 5 × 5 MIMO-MDM system is shown in Fig. 3. Figs. 3(a) and 3(b) depicts the quality of signal received by different MM receivers for G-II modes with same azimuthal index (say l=0; LP_{01}, LP_{02}, LP_{03}, LP_{04}, LP_{05}) and same radial index (LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41}). It is examined in this case that quality of signal decreases up to acceptable level (> 8dB) with rise in the length (82km) of MMF transmission link for different MIMO-MDM (3 × 3, 4 × 4, 5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9) configurations.

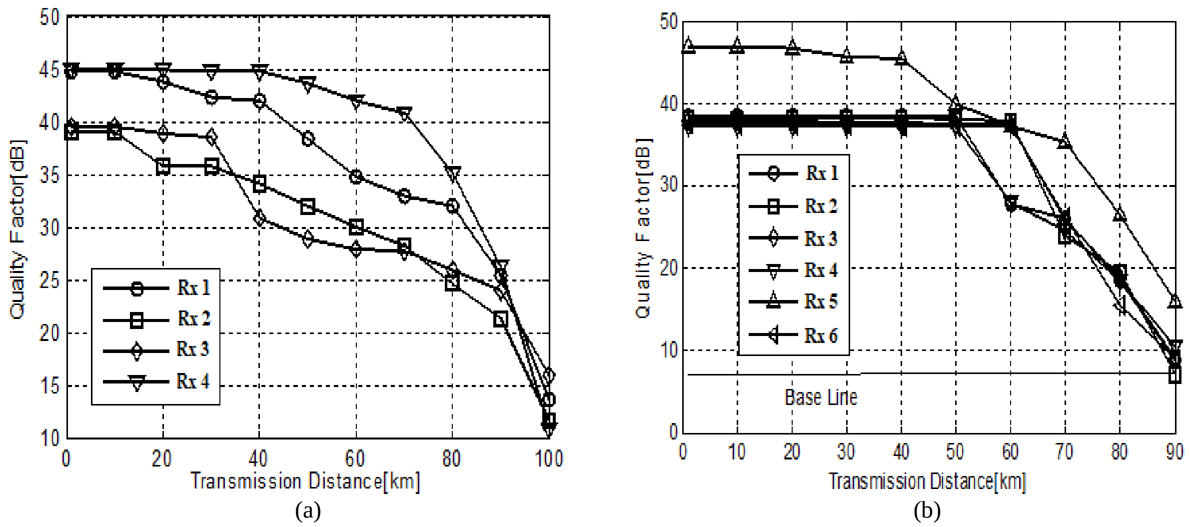


Fig. 4. Effect of Group G-III on transmission quality of (a) 4 × 4 and (b) 6× 6 MIMO-MDM system configurations

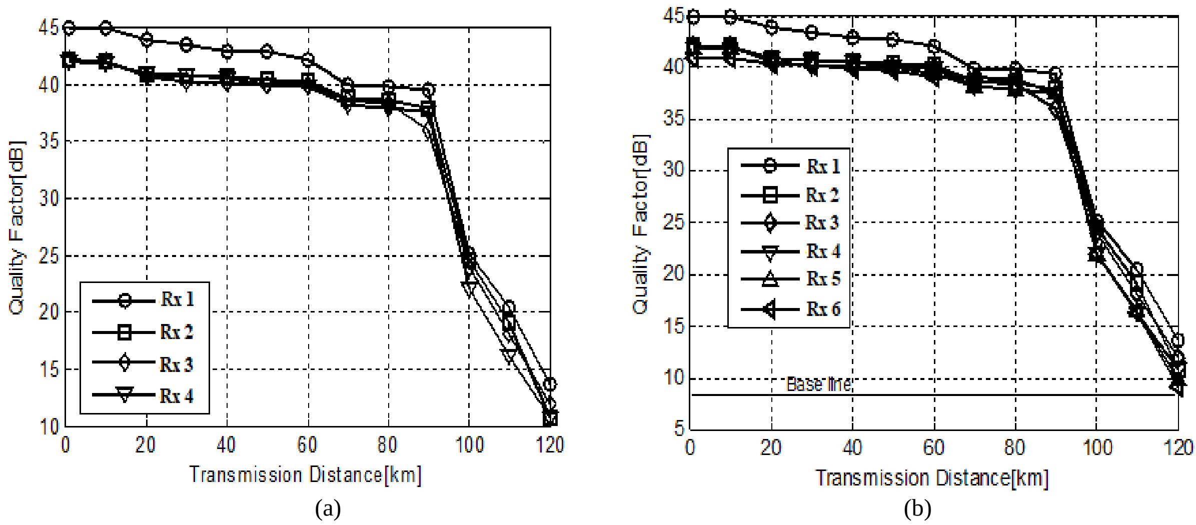


Fig. 5. Effect of Group G-IV on transmission quality of (a) 4 × 4 and (b) 6 × 6 MIMO-MDM system configurations

Fig. 4 presents the effect of modes with mixed random odd and even mode index on quality of MIMO-MDM system. Here, different combinations of random O+E mode groups (G-III) are considered in setup to check the performance of 3 × 3, 4 × 4, 5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9 MIMO-MDM configurations. It is observed from Fig. 4(a) that all MM receivers received signal with good quality up to 100km for 3 × 3 and 4 × 4 MIMO-MDM configurations but all receivers except Rx 1 in MIMO-MDM configurations (5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9) provides good performance only upto 80 km of transmission link due to modal interference as shown in Fig. 4(b).

Fig. 5 represents G-IV that includes mixed odd and even modes in sequence with gap of one mode group to avoid modal interference of higher modes. It is seen from Fig. 5(a) that by considering G-IV modes (LP_{01}, LP_{11}, LP_{21} and LP_{31}) all receivers provide high-quality above threshold (> 10dB) with transmission distance up to 120 km for 3 × 3 and 4 × 4 MIMO-MDM configurations. The same trends are examined for 5 × 5, 6 × 6 and 7 × 7 MIMO-MDM systems and results are shown in Fig. 5(b) for 6 × 6 MIMO configuration. It is observed from Figs. 2, 3, 4 and 5, maximum distance for acceptable Q-factor using mode index grouping combinations (G-I, G-II, G-III and G-IV) is approximately 85 km, 83 km, 90 km and 120 km respectively. On comparing all considered mode groups (G-I, G-II, G-III and G-IV) for all the MIMO-MDM configurations (3 × 3, 4 × 4, 5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9) it is concluded that the latter (G-IV) is superior to the former. Fig. 6 provides information about the power of modes (LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41} and LP_{51} considered in case IV) as received by 6 MM receivers after propagating through the core of MMF. The graph represents a substantial decrease in intensities with lower order modes to higher order modes within a particular range of frequency relative to 193.1 THz.

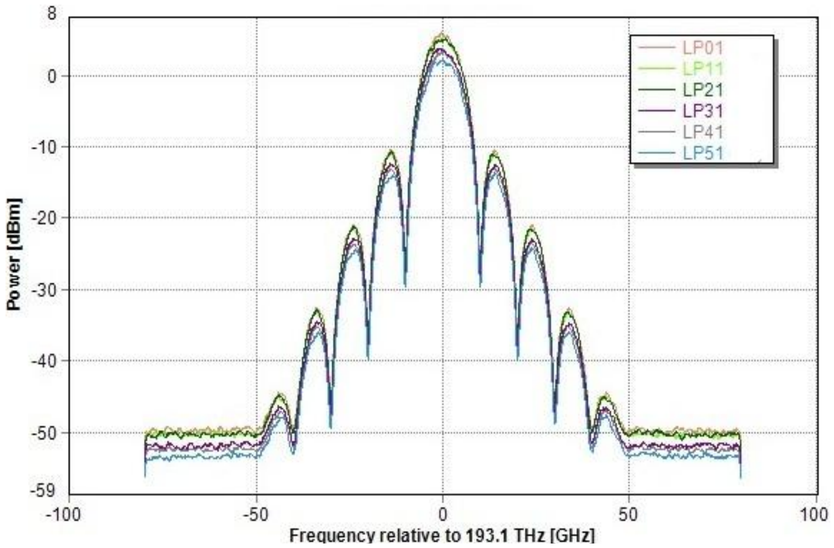


Fig. 6. Received power of 6 considered modes (G-IV) in 6 × 6 MIMO-MDM system configuration (color online)

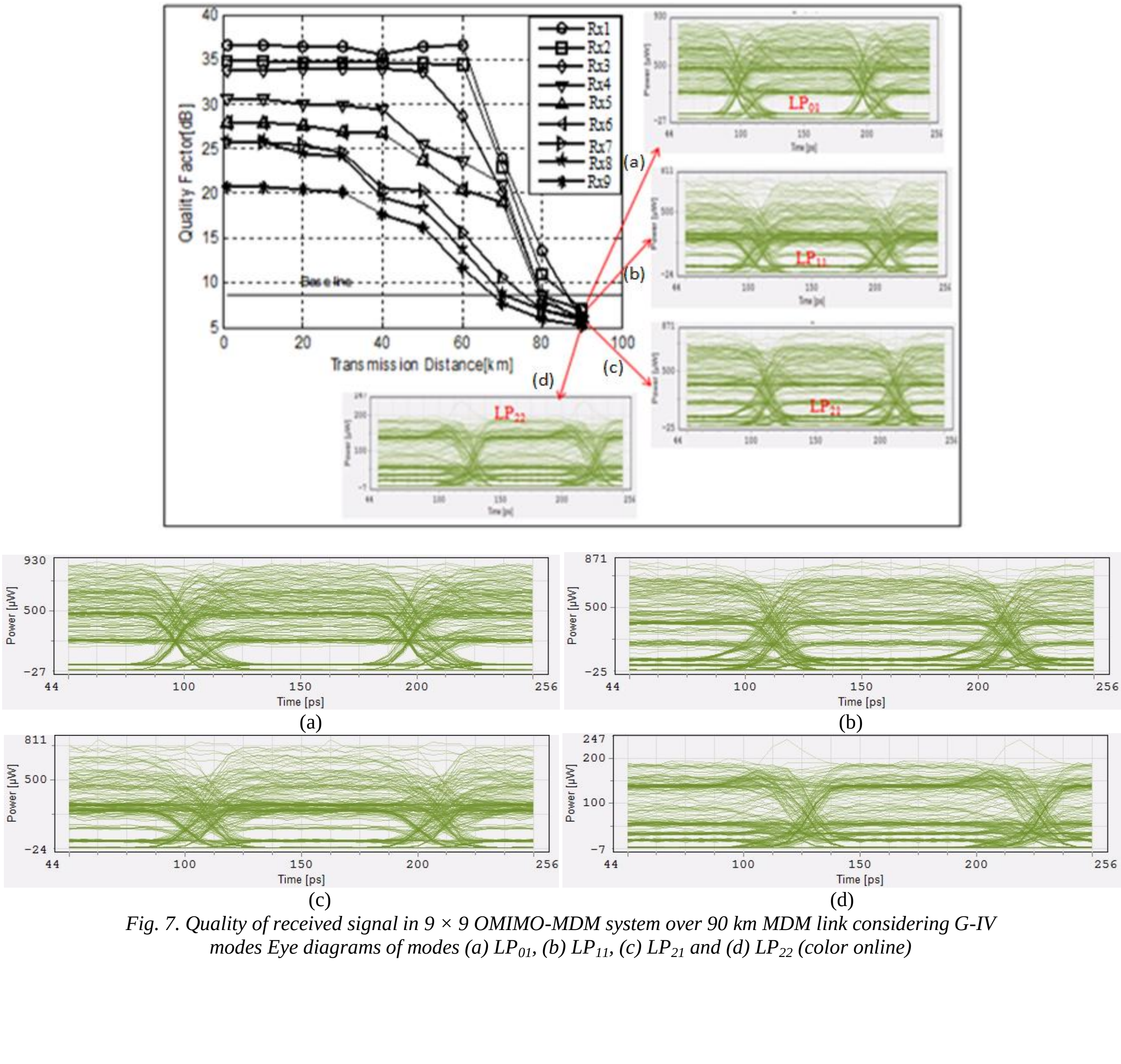
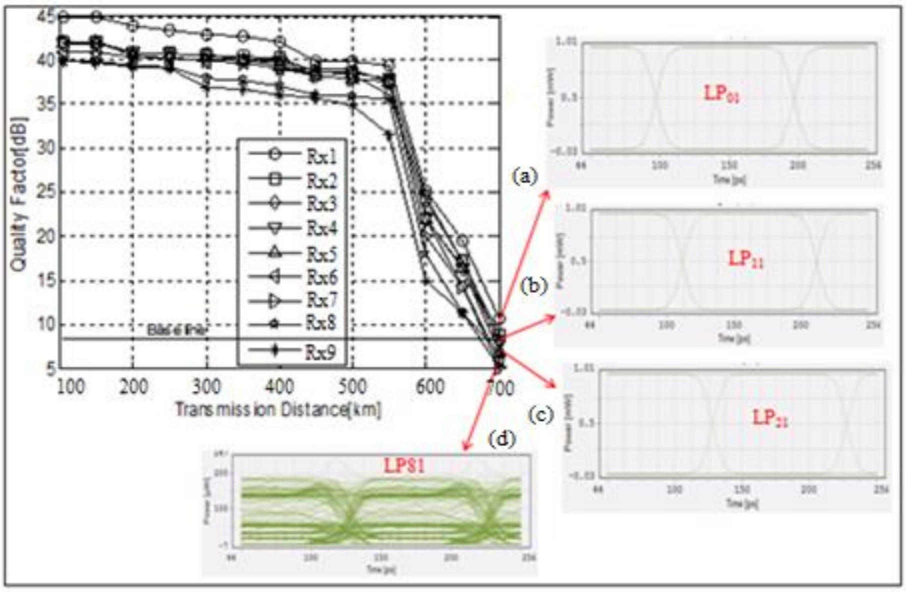
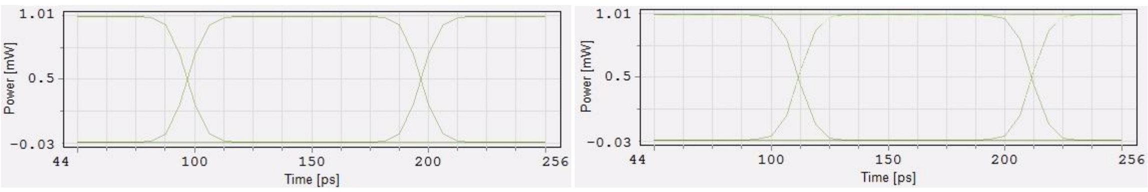


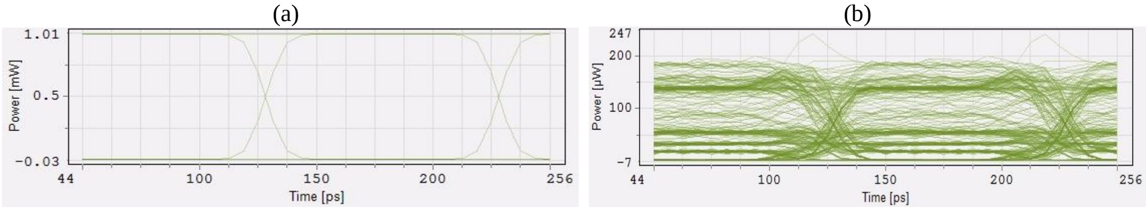
Fig. 7. Quality of received signal in 9 × 9 OMIMO-MDM system over 90 km MDM link considering G-IV modes Eye diagrams of modes (a) LP_{01}, (b) LP_{11}, (c) LP_{21} and (d) LP_{22} (color online)

It is seen from Fig. 7 that the quality of the received signal is impacted by mode coupling and modal crosstalk in MDM link at receiver. The quality of signals received by all 9 MM receivers (Rx 1, Rx 2, Rx 3, Rx 4, Rx 5, Rx 6, Rx 7, Rx 8 and Rx 9) is very poor above 82 km of transmission. The performance is restricted due to intermodal crosstalk and only a maximum distance of 82 km is achieved with acceptable BER ($<10^{-9}$). The transmission performance is then optimized by demultiplexing the modes using DSP filter to lower the intermodal crosstalk. During propagation of the signal mode coupling takes place as the modes travels at different velocities in MMF. The time dispersion and mode coupling caused by channels can be compensated by Equalization technique which is performed in the frequency domain. The optimization of taps (filter coefficient) is done by utilizing LMS (least mean square) adaptive MIMO filter algorithm to minimize the mean-squared error at the output signal in order to avoid mode group coupling in MDM based system.





(a) (b)



(c) (d)

Fig. 8. Quality of received signal in 9 × 9 OMIMO-MGDM system over 700 km MDM link with Adaptive MIMO LMS equalization and Eye diagrams of received modes (a) LP_{01}, (b) LP_{11}, (c) LP_{21} and (d) LP_{81} (color online)

The input-output relation of mode division multiplexed system having M (M1 to M9) spatial modes can be represented as:

$$y(t) = H(t) * x(t)$$

where $x(t)$ denotes transmitted signal, $H(t)$ is channel or coupling matrix having M×M matrix (here in proposed: 9×9)of tap delay line filters and $y(t)$ is received signal respectively. To recover signals from different mode channels and to completely compensate the signal distortion at the receiver, an adaptive equalizer implements matrix $C(t)$ that should be the inverse of channel matrix $H(t)$. At the coherent receiver signals from different mode channels are demodulated and then digitalized. The digital sequence $x_1(n)$, $x_2(n)$………….. $x_M(n)$ is fed to equalizer block for adaptive compensation. The equalization of k^{th} sample on i^{th} mode is calculated as given by equation 2:

$$y_i(k) = \sum_{j=1}^{M} \sum_{i=0}^{Ntaps} h_{ij}(i) X_j(k-i) \qquad (2)$$

where, *Ntaps* is the number of filter taps and *i;j* are values of mode index ranging from 1 to *M*. In frequency Equalization LMS, filter coefficient values are taken in frequency domain and computed using following equation 3:

$$\overline{\overline{C^{(j)}}} = \overline{\overline{C^{(j-1)}}} + \mu \begin{bmatrix} \overline{E_{1,j}(k)} \otimes \overline{Y^{*}_{1,j}(k)} & \overline{E_{1,j}(k)} \otimes \overline{Y^{*}_{2,j}(k)} \\ \overline{E_{2,j}(k)} \otimes \overline{Y^{*}_{1,j}(k)} & \overline{E_{2,j}(k)} \otimes \overline{Y^{*}_{2,j}(k)} \end{bmatrix} \tag{3}$$

where, $\overline{\overline{C^{(j)}}}$ represents inverse channel equalizer filters, μ is convergence step size, $\overline{E_{i,j}(k)}$ depicts j^{th} error block fori^{th} mode, $\overline{Y^{*}_{i,j}(k)}$ is conjugate of the received signal block in frequency domain for i^{th} mode and symbol $\otimes$ denotes element to element multiplication. The error signal (obtained by subtracting received signal from desired signal, $e_i(k) = d_i(k) - y_i(k)$) and the received signal are taken in time-domain. For adaptive Equalization method, to adjust the equalizer coefficients error block is calculated in time domain first and then FFT is taken. After the computation of equalization, comparison of each output sample is done with the desired output and the resultant error is then fed back to Gradient estimation block. The gradient estimation processes the error signal and then updates the value of equalizer filter tap coefficients to minimize the coupling error in the system. After equalization, performance of modes in system is optimized by taps thus minimizing the mean square error.

Fig. 8 depicts that high-quality signals (quality factor above 8 dB) are received by all MM receivers covering distance of 700 km for received modes (LP_{01}, LP_{11}, LP_{21}, $LP_{31,}$ LP_{41}, LP_{51}, LP_{61} and LP_{71}) with Adaptive MIMO LMS equalization. Insets in Figs. 7 and 8 consist of the received eye diagrams for all modes received in MDM link with same scale. It can be examined that how the received eye diagrams of received modes for MDM link without DSP equalization (Fig. 7) are always smaller than with Adaptive MIMO LMS equalization (Fig. 8) in 9 × 9 OMIMO-MDM system. In support to our previous results [2] proposed OMIMO-MDM setup provides enhanced performance in the terms of Q-factor (> 10dB) covering transmission distance of 700 km over MMF.

5. Conclusions

This paper deals with the effect of different LP mode index grouping combinations (Even, Odd, Random Even+Odd and Symmetric Even+Odd with mode gap) on transmission performance of 3 × 3, 4 × 4, 5 × 5, 6 × 6, 7 × 7, 8 × 8 and 9 × 9 OMIMO-Mode division multiplexed systems. The maximum distance covered with Quality-factor (>8.3dB) using mode index grouping combinations (Even, Odd, random Even+Odd and symmetric Even+Odd with mode gap) is approximately 82 km, 79 km, 80 km and 114 km respectively for even 9 × 9 OMIMO-MDM system. Further, system performance is optimized by LMS (least mean square) adaptive MIMO filter algorithm to avoid mode group coupling and transmission is thus enhanced covering 700 km in MDM based system. It is concluded that higher Q-factor and received power with longest transmission is achieved with group G-IV but moderate with rest cases for all considered OMIMO-MDM configurations. This analysis can be used for MGDM (mode group division multiplexing) to increase the capacity of high speed transmission over MMF link.

Acknowledgment

This work was supported by a grant from the Department of Electronics and Information Technology (DeitY) under Ministry of Communication and Information Technology, Government of India with Unique Awardee number: VISPHD-MEITY-1639. The authors would also like to thank the Department of Electronics and Communication Engineering of Thapar Institute of Engineering and Technology, Patiala, Punjab, India for providing the moral support and excellent laboratory facilities (Optical Fiber Communication Research Laboratory) in developing the system.

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