Performance investigation of LP modes over MMF link to boost MIMO mode division multiplexing

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In this paper, we have proposed a MIMO (Multi input multi output) MDM (Mode division multiplexed) system for transmission of 9 independent signals over 9 different modes through MMF (multimode fiber) link. The performance of 4×4, 6×6 and 9×9 MDM systems has been investigated for different LP_{lm} (linearly polarized) modes such as LP_{01}, LP_{02}, LP_{11}, LP_{12}, LP_{03}, LP_{04}, LP_{13}, LP_{21} and LP_{22}. The obtained results reported that LP_{01}, LP_{02}, LP_{11} and LP_{12} modes provide better results for all MIMO configurations and covers 90 km of transmission distance with acceptable Q^2 factor (>8 dB) and bit error rate ($<10^{-9}$) over MMF link.

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1. Introduction

The hasty increase in internet traffic is raising the demand for higher data capacity in existing communication networks. Therefore, to cope up with the internet capacity a variety of optical networks are being explored gradually [1]. According to Global Internet Report 2014, increase in internet traffic is expected to reach a growth rate of 35% by 2018 due to the significant increase in global average traffic per connection per month by 9.5GB [2]. Optical networks traffic has been progressively increasing every decade with a factor value of 100 and capacity of SMF rising 10,000 times from previous three decades [3].

However, current Wavelength Division Multiplexing system has already utilize all degrees of freedom (amplitude, frequency, phase and polarization) of light wave in SMF still research area is exploring new dof (degree of freedom) that is not covered by SMFs. Therefore, space is a new paradigm that is ahead of WDM [4]. SDM (Spatial Division Multiplexing) is the latest research hotspot in the area of optical fiber communication technologies [5]. The transmission of data through fiber modes simultaneously is an efficient and reliable system of communication but its development poses challenges [6]. MDM (mode-division multiplexing) utilizing MMFs (multimode fibers) or FMFs (few-mode fibers) has caught immense attention from last few years to enhance capacity of optical communication [7–8].

The research in field of MDM was started in 1982 [8] but until 30 years researchers never took interest to this novel technique. The first experiment in this field was performed and provided coverage of 10 km utilizing 3 spatial modes modulated at 14GBaud PDM-QPSK [10]. After that, numerous improvements came into picture. Koebele et al. [11] used phase plates free space optics for MDM transmission experiments. They considered 5 modes (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a} and LP_{21b}) and receiver modulated to 28 Gbaud QPSK along with 4×4 MIMO covering a distance of 40km over FMF with low mode coupling. Bai et al. [12] demonstrated a 6×6 MIMO mode division multiplexing (MDM) based WDM system over 50-km of FMF utilized modes: LP_{01} and LP_{11} (two degenerate modes).

Franz et al. [13] experimentally investigated 8 principal mode groups required for spatially separated channels operating at 1550 nm wavelength for data transmission of 10-Gb/s over a 5-km long GI-MMF. The distance of data transmission has been increased to 96 km with 3 modes [14] and successfully transmitted 5 spatial modes over 40 km [11].In previous studies, several novel multiplexing techniques was supported by SMF [15-20] but still research field is exploring spatial (modes) multiplexing to enhance the transmission reliability and capacity.

This paper deals with spatial domain to propose OMIMO MDM system for data transmission of 9 independent channels over MMF (multimode fiber) link. Even though, various experimental, simulation and numerical analysis has been presented in this field. But MDM system need improvement in fibers that support multiple spatial modes, optical amplifiers with less number of optical components can operate on several modes, mode MUX and DEMUX compatible with MDM. In this paper, modified MIMO MDM system was proposed for transmission of 9 independent channels through multimode fiber (MMF) link. Here, 4×4, 6×6 and 9×9 optical MIMO MDM systems were compared to investigate the performance of spatial linearly polarized modes to improve the reliability of transmitted bits.

After the introduction, section 2 explains the setup of the system, in section 3 of the manuscript results and discussion are described and finally, section 4 summarizes the conclusions.

2. Concept of LP modes

Modes are a set of guided electromagnetic waves that represent the propagation of light energy in fiber. Each mode denotes a light beam travelling within the fiber core at different angles in case of multimode fibers. 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 [21]. Any two independent orthogonal plane waves in phase can be combined into a linearly polarized wave. The LP_{lm} modes can be represented by following equation as [21]:

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

where, index $l \geq 0$ corresponds to variation of light intensity in azimuthal plane with respect to ϕ and index $m \geq 1$ refers to the radial (r) dependence or number of zero crossings (one less than the index) in the light intensity pattern, $\Psi_{l,m}$ contains radial dependence and E_t depicts transverse field. All LP_{lm} modes with mode index, $M = l+2m+l$ (as represented by Table 1) must fulfill the equation with same phase constant β and group delay τ_g.

Table 1. LP_{lm} Modes

Mode index / number $M=l+2m+1$ [22]	**LP_{lm} Modes** l and m indices as light intensity patterns in azimuthal (ϕ) and radial direction
3	LP_{01}
4	LP_{11}
5	LP_{02} LP_{21}
6	LP_{12} LP_{31}
7	LP_{03} LP_{22} LP_{41}
8	LP_{13} LP_{32} LP_{51}
9	LP_{04} LP_{23} LP_{42} LP_{61}
10	LP_{14} LP_{33} LP_{52} LP_{71}
11	LP_{05} LP_{24} LP_{43} LP_{62} LP_{81}
12	LP_{15} LP_{34} LP_{53} LP_{72} LP_{91}

3. System setup

The simulation setup of proposed optical MIMO MDM system is presented in Fig. 1. Each multimode transmitter (MM Tx) includes spatial laser source tuned at 1550 nm and MZ modulator for each information source. 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. The independent data signals over N different LP_{lm} (linearly polarized) modes from N corresponding transmitters are fed to mode converter for mode conversion and then to mode combiner for multiplexing of all LP_{lm} modes.

Inline Multimode EDFA is designed as MM amplifier using phasor plates to amplify multiple spatial modes having multi-mode information signals at 1550 nm through graded index MMF with parabolic index. The index gradient causes rays propagating at steeper angles (high order modes) to catch up with rays propagating at shallow angles in the fiber. Due to this feature of graded-index fiber, it provides less pulse dispersion than step-index fibers and therefore, superior bandwidth performance. In Inline-MM amplifier configuration, optical communication system is symmetrically amplified to compensate for transmission losses.

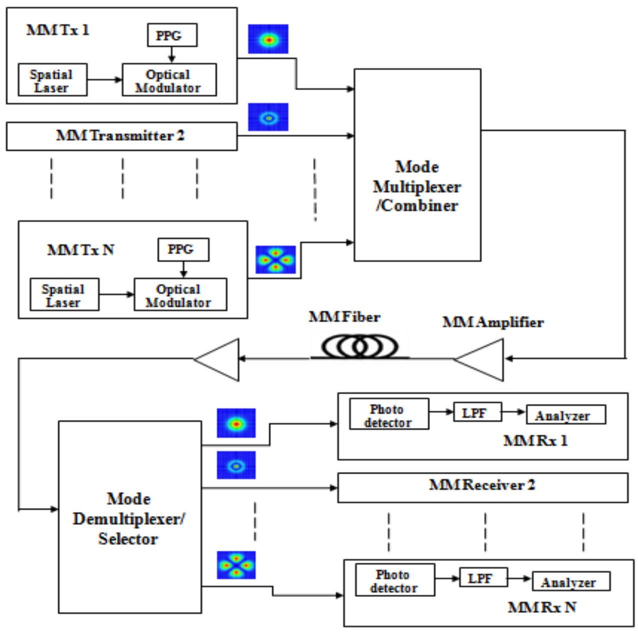


Fig. 1. Schematic of MIMO MDM transmission system

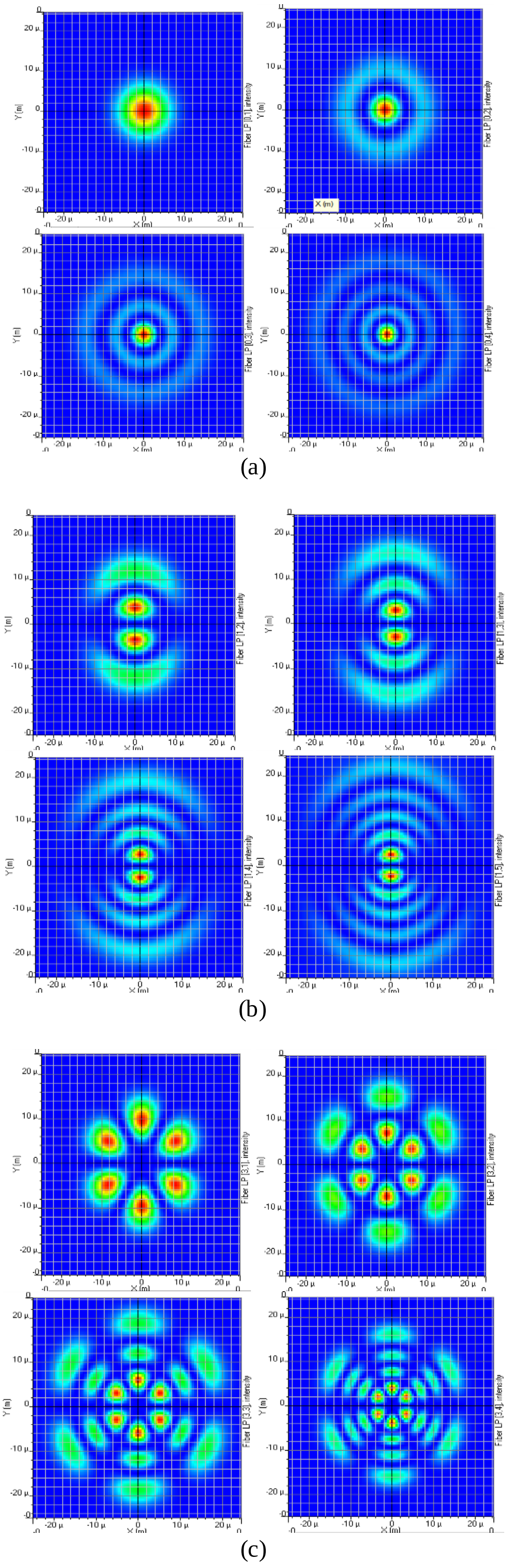


Fig. 2. Spatial intensity field patterns of LP modes for different values of l and m indices as observed by spatial analyzer (a) for l=0, m varies from 1 to 4, (b) for l=1, m varies from 2 to 5 and (c) for l=3, m varies from 1 to 4

Table 2. System parameters

Sr. no.	Parameters	Value
1	Wavelength	1550 nm
2	Power	0 dBm
3	Linewidth	10 MHz
4	Attenuation	2.61 dB/km
5	Noise Figure	4 dB
6	Dispersion	-100 ps/nm/km
7	Responsivity	1 A/W
8	Dark current	10 nA

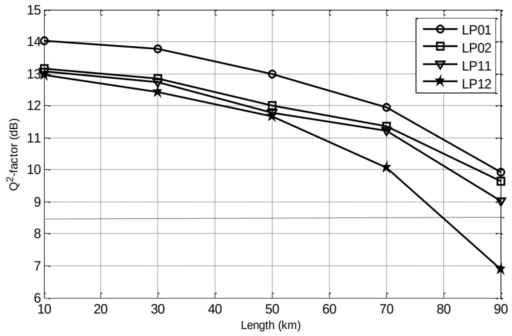
Here, 9 LP modes are multiplexed, transmitted and received using MMF link. In receiver section, signals having different modes are demultiplexed by spatial mode selectors. The independent signals from N MM (multi-mode) receivers are recovered by MIMO processing technique. The various simulation parameters of MIMO MDM transmission system are described in Table 2. 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. Results and discussion

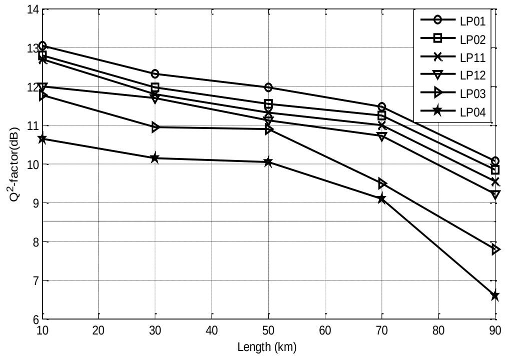
The transmission length from 10 to 90 km for different LP modes has been varied to investigate the performance of 3 different (4×4, 6×6 and 9×9) MIMO MDM configurations. Fig. 3 illustrates the graphical representation of Q^2 factor as a function of transmission length. It is seen that, system provided best results even for 9 different LP modes over MMF link travelling a long distance of 75 km with Q^2 factor above 8 dB.

It is observed from Fig. 3(a) that 4×4 MIMO MDM system containing LP_{01}, LP_{02} and LP_{11} modes provide Q^2 factor above 8.6 dB covering long distance of 90 km but LP_{12} mode covering 80 km. For 6×6 MIMO system; modes LP_{01}, LP_{02}, LP_{11} and LP_{12} travel over 90 km MMF link, LP_{03} over 82 km whereas LP_{04} over 75 km with quality of signal more than minimum acceptable level.

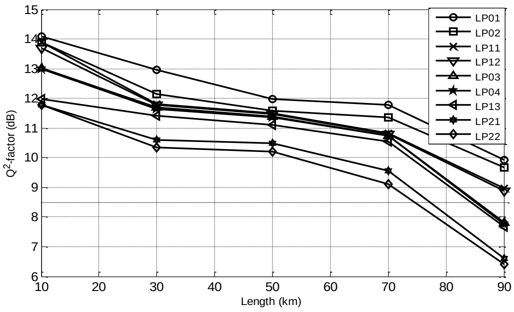
It is shown in Fig. 3(c) that modes (LP_{01}, LP_{02}, LP_{11} LP_{03}, LP_{12}; LP_{04}, LP_{13} and LP_{11}, LP_{22}) propagate with good quality of signal (> 8 dB) covering transmission distance of 90, 85 and 75 km over MMF link. These results indicate that LP_{01}, LP_{02} and LP_{11} modes provide quality more than the power margin i.e. 10 dB over 90km for all considered MDM configurations, this shows an improvement over [14].



(a)



(b)



(c)

Fig. 3. Quality of LP modes as a function of transmission distance for (a) 4×4 (b) 6×6 and (c) 9×9 MIMO MDM systems

Fig. 4 represents the comparison of light intensity patterns at input: - MM Transmitter and output: - MM Receiver of 4×4 MIMO MDM system. The intensity patterns of 4 LP modes (LP_{01}, LP_{02} and LP_{11} and LP_{12}) as generated at MM transmitter section are shown in the left side of curve. The field of these modes was normalized by mode combiner and then the normalized mode fields with respect to radius as propagating through MM fiber is represented by curve. After propagation through MM fiber the intensity distribution of modes as detected by MM Receiver is shown by right side of curve. It is observed from intensity patterns at Transmitter and Receiver that in 4×4 MIMO MDM system light carrying modes (LP_{01}, LP_{02} and LP_{11}) are successfully received at receiver with Q^2 factor above 8.6 dB covering long distance of 90 km but light pattern of higher order LP_{12} mode is distorted to some extent (due to coupling of light to cladding) covering 80 km.

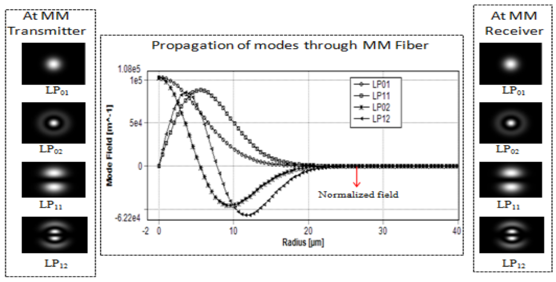
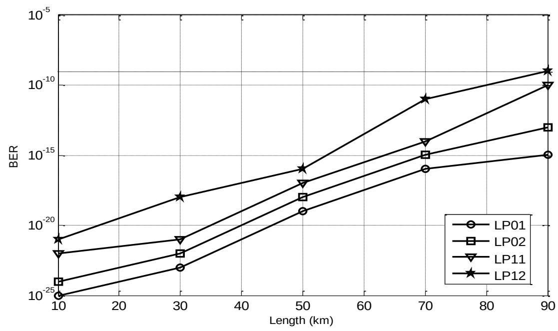
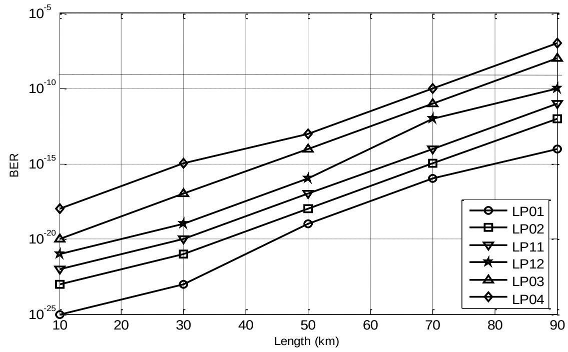


Fig. 4. Intensity distribution of LP modes at MM Transmitter, MM fiber and MM Receiver for 4 × 4 MIMO MDM system

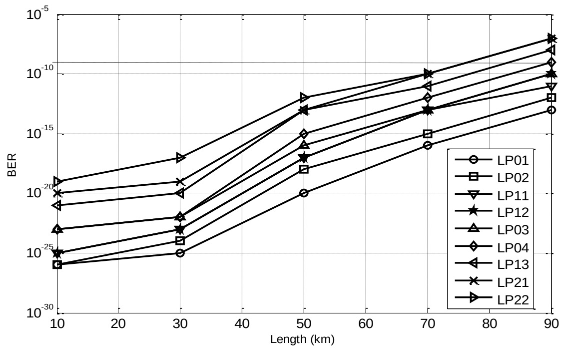
Fig. 5 shows the graphical representation of BER as a function of transmission length for different LP modes propagating in 4×4, 6×6 and 9×9 MIMO MDM systems. It is obligatory to observe the performance of MIMO MDM transmission system with respect to bit error rate to determine the longest possible transmission distance.



(a)



(b)



(c)

Fig. 5. BER across LP modes as a function of distance for (a) 4×4 (b) 6×6 and (c) 9×9 MIMO MDM systems

The bit error rate is measured for different MIMO formats over different modes with different transmission distances as shown in Fig. 5. It is observed that maximum transmission distance (i.e. 90 km) is allowed by modes LP_{01}, LP_{02}, LP_{11} and LP_{12} which provide acceptable bit error rate of 2.6×10^{-9} for 4×4, 6×6 and 9×9 MIMO MDM system. On the other hand LP modes (LP_{03}, LP_{13} and LP_{04}, LP_{21}, LP_{22}) show poor performance above transmission distance (i.e. 82 km and 75 km) respectively as shown in Fig. 5(b, c).

5. Conclusion

We have demonstrated MIMO based MDM system for transmission of 9 signals over 9 different LP modes at 1550 nm wavelength with low input power travelling long distance of 90 km over MMF link. In this paper it is found that LP_{01}, LP_{02}, LP_{11} and LP_{12} modes provide better results for 4×4, 6×6 and 9×9 MIMO configurations. It can be observed that even for 9×9 MIMO MDM system maximum Q^2 factor of 14 dB wih minimum BER of 10^{-9} was achieved.

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