Performance investigation of high capacity 10 Tb/s LP-MDM-WDM over multimode fiber link for short reach applications

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In this paper, the performance of 10 Tb/s LP-MDM-WDM (Linearly Polarized-Mode Division Multiplexed-Wavelength Division Multiplexing) multimode fiber link has been investigated. The effect of channel index spacing is observed in terms of bit error rate at different lengths of multimode fiber. The parameters like different data rates, input power, length of MMF and number of users are varied to examine the system in form of Q-factor. It is reported that moderate channel index spacing (where x-index=2; varying y-index=1,2,3,4 and 5) of LP modes provide best results for 10 Tb/s LP-MDM-WDM system with 15 km transmission distance over MMF with acceptable BER ($<10^{-8}$) and Quality-factor (>9.8 dB) to enhance the system performance. The designed hybrid LP-WDM-MDM transmission link can be used in optical network interconnects at data centers to fulfill the demand of higher internet capacity for short reach applications.

(Received October 27, 2017; accepted August 9, 2018)

Keywords: LP modes, MMF, MDM and WDM

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]. In literature, numerous multiplexing techniques utilizing phase, amplitude and wavelength of light; optical networks like WDM ring topology, DWDM (Dense WDM) ring topology etc. has been reported that enhance system capacity and support SMF [2-5]. But still research field is exploring spatial multiplexing to further enhance the capacity of transmission system.

SDM (Spatial Division Multiplexing) fulfill the demand of higher quality and forthcoming capacity as required by end-user applications [6]. MDM utilizing MMFs (multi-mode fibers) has caught curiosity from last 3 to 4 years to large extent to boost capacity of communication networks and compensate for power losses [7]. The present growth in Linearly Polarized MDM systems for reliable transmission requires the advancement of multiple modes domain with wavelength division multiplexing eliminating the necessity of costly conversions in optic domain.

The research in field of MDM was started in 1982 [8] but until 30 years researchers never took interest to this novel technique. The demonstrations done firstly on MDM system with MMF presents coverage of 10 km distance using 3 spatial modes modulated at 14GBaud PDM-QPSK [9]. Bai et al. [10] 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). Recently, Amphawan et al. [11] investigated HG-MDM (Hermite-Gaussian Mode Division Multiplexing) system with MMF to increase capacity and achieved good BER for channel spacing with HG modes *x*-index (*x*=2, 3) over 800 m distance of MMF. This testing was restricted by the transmission distance and number of modes.

Different numerical analysis and experiments have been made for LP modes transmission in MDM system with MMF. But these need advancement in fibers supporting various spatial modes, amplifiers with multimode domain, mode MUX and DEMUX compatible with MDM to enhance capacity of system. This paper deals with multi-modal domain to propose hybrid 10 Tb/s LP-WDM-MDM system for transmission of 25 independent channels over multimode fiber link and thus, contributes in providing high capacity with minimum use of bandwidth for upcoming optical communication at reduced channel spacing.

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 division multiplexing

The basic concept behind MDM is utilization of an optical fiber that permits propagation of different spatial modes through core. Modes are guided electromagnetic waves in optical fiber refers to a stable propagation state of light within the fiber. The value of refractive-index, $\Delta \ll 1$ as n_1 is very close to n_2 or n_1-n_2 having very small value and this assumption of Δ is dictated as the weakly guiding approximation due to the fact that light energy would not be guided within any medium but uniformly distributed in whole medium. This weakly guided approximation leads to linear combinations of the $HE_{l+1,\ m}$ and $EH_{l-1,\ m}$ modes resulting in LP modes [12].

In LP-MDM technique, several independent data signals are modulated over N different spatial modes over multimode fiber to increase the capacity by N folds. MDM permits several orthogonal spatial modes to be guided and transmitted simultaneously through a single or multiple cores of an optical fiber. Thus, total capacity is the product of capacity per fiber multiplied by number of modes. Thus, by adding spatial degree of freedom, fibre capacity of MMF (multimode fiber) can be increased in the form of MIMO (multi-input multi-output) transmission. MDM permits transmission of a number of channels upon different modes generated by different mechanisms like by few-mode fiber or multimode fiber [12], signal processing [13], photonic crystal fiber [14] etc.

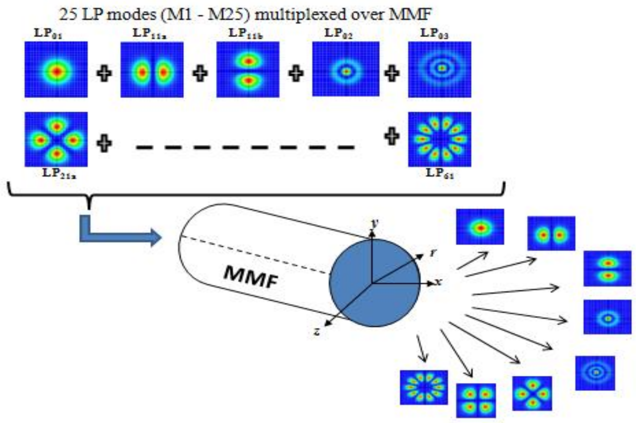

Fig. 1. Concept of LP mode division multiplexing scheme

3. System setup

The schematic of proposed hybrid 10 Tb/s LP-WDM-MDM system is provided by Fig. 2. The software 'VPItransmission Maker/ VPIcomponent Maker 9.7' was utilized to simulate the results. The transmitter section of proposed system consists of five MM Tx (multi-mode transmitter) arrays tuned at wavelengths from 1550 nm to 1550.2 nm with channel spacing of 0.05 nm. Each MM Tx array includes laser source and MZ modulator for each information source (D1 to D25). The information source is in NRZ format with 10 Gb/s bit rate for each wavelength per LP mode producing system data rate of 10 Tb/s. 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. Signals from 5 different transmitter arrays over 25 channels are fed to mode converters for mode conversion and then to 5 mode combiners (indicated as MC) for grouping of modes each with 5 LP modes.

Here, 5 mode groups at 5 different wavelengths as individual data signals with *x*-index and *y*-index separations are multiplexed using WDM multiplexer. Inline-multimode (I-MM) EDFA is designed to amplify multiple modes and support modes (wavelength and mode division multiplexed) through MMF having parabolic index.

The mode calculation algorithm is used to calculate modes in LP-WDM-MDM system. For GI-MMF modes can be computed by utilizing Helmholtz radial equation with different index profile in particular defined computational window Δ_{tot}. Thus, the equation defining transversal field is following [13]:

$$\hat{D}E = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) - \frac{l^2}{r^2}E + \varepsilon(r)k_0^2 E\right] = n_{eff}^2 k_0^2 E \qquad (1)$$

where, *D*: differential operator, *E* depicts mode field distribution, *l* corresponds to variation of light intensity in azimuthal plane, n_{eff} is effective propagation index and k_0 represents wave vector of incident light.

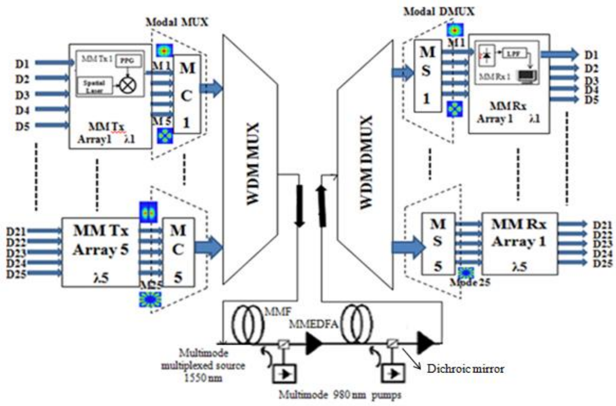

Fig. 2. Simulation setup for 25 channel LP-WDM-MDM optical communication system; MM Tx: multimode transmitter, MC: mode combiner, MMEDFA: multimode EDFA amplifier configuration, MS: mode selector and splitter, MM Rx: multimode receiver

In this algorithm a scalar approach is followed where terms related to polarization mode coupling are neglected. An adaptive solution grid is utilized where the total number of grid points or radial points can be defined by G_{tot}. It is considered here that the spacing between the grid points is not constant. The grid is chosen such that: Δ_1 grid is made dense for the areas where major part of mode power is focused and Δ_2 grid is made rough within areas having lower refractive index. Thus, the ratio of Δ_2 grid to Δ_1 grid can be defined as grid discrete factor (G_f). If it is unity then a grid with constant mesh is utilized. The index of discretized point (G_I) provides the index profile for which the spacing of grid is varied is given as:

$$G_I = \frac{\frac{1}{2}(1-G_p)+(G_{tot}-1)}{G_p+G_f-1} \qquad (2)$$

where, $G_p = G_{tot} / \Delta_M$ presents the proportion of fiber core within the whole computational window. Here, term Δ_M is dependent on the method of attaining the refractive index profile. As graded index profile is used in block diagram thus, Δ_M is considered to be $2a$, where a: diameter of core. The computational window is to be made large enough for mode power to attenuate significantly at the boundaries. The grid discretization intervals can be calculated by putting value of G_I from equation (2) in (3) as:

$$\Delta_1 = \frac{\Delta_M}{G_I + 1/2}, \Delta_2 = \Delta_1 . X \tag{3}$$

The coordinate r_i can be defined by equation (4) as below:

$$r_i = \begin{cases} (i + 1/2)\Delta_1, i \le G_I \\ (G_I + 1/2)\Delta_1 + (i - G_I)\Delta_2, G_I < i \le G_{tot} - 1 \end{cases} \tag{4}$$

By solving all these equations a computational grid is set with profile then finally mode intensity profiles of LP modes can be computed in polar coordinates as [12]:

$$i^{(u,k)}(r,\phi) = i^{(u,k)}(r) \begin{Bmatrix} (\cos l\phi)^2 \\ (\sin l\phi)^2 \end{Bmatrix} \tag{5}$$

where, $i^{(u,k)}$ (r) represents the radial dependence of mode intensity and terms of cosine and sin depicts two spatial configurations of mode u. Different parameters of source MM transmitter array, MMF fiber and MDM system are described in Table 1.

Table 1. System parameters

Name of parameter	Value
Signal wavelengths	1550 to 1550.2 nm
Channel spacing	0.05 nm
No. of data signals	25
Data rate	10 Tb/s
Linewidth	10 MHz
Attenuation	1.81 dB/km
EDFA Pump type	Counter-propagate
EDFA pump wavelength	980 nm
EDFA gain	Flat
EDFA noise figure	4 dB
MMF refractive index peak	1.80
Dispersion	-99 ps/nm/km
Dark current	10 nA
Length	15 km

In receiver section, signals having different modes at different wavelengths are demultiplexed first by WDM demultiplexer and then by 5 optical mode selectors (indicated as MS). Different independent signals over 25 modes are recovered by 5 MM (multi-mode) receivers. Each MM receiver contain PIN photo detector which is used to convert the optical signal into electrical followed by a LPF and optical analyzer for monitoring the BER, eye diagram and Quality-factor of transmission link.

4. Result and discussion

The propagation constant of linearly polarized modes is dependent on modal intensity patterns. Each mode carries part of light energy during propagation along the fiber. The equation mentioned below represents modal fields inside optical MMF fiber.

$$b_{norm} = 1 - \sum_{i=1}^{n} \frac{Y_c^2}{Y_i^2 + Z_i^2} \exp\left[\frac{2}{\sqrt{Y_c^2 - x^2 - 1}} \sin^{-1}\left(\frac{\sqrt{Y_c^2 - x^2 - 1}}{Y_c} \right) - \sin^{-1}\left(\frac{\sqrt{Y_c^2 - x^2 - 1}}{V} \right) \right] \tag{6}$$

where, b_{norm} is normalized propagation constant; V is normalized frequency that characterizes fibers and their ability to carry modes; x represents channel index light intensity variation of LP modes in the azimuthal plane; Y_i and Z_i are modal parameters for core and cladding with refractive index η_1 and η_2 respectively; Y_c depicts value of modified modal parameter Y at cut off frequency and i is total number of LP modes.

The relationship between parameters b_{norm} (normalized propagation constant) and V (normalized frequency) is used to determine the interference properties of LP_{lm} modes inside MMF fiber. Fig. 3 represents the normalized mode field of different linearly polarized modes (Mode 1 to Mode 25) considered in the system at 1550 nm as calculated by considering adaptive solution grid approach in mode calculation algorithm. These 25 LP modes were generated at 5 different MM transmitters (MM Tx Array1 to 5) using mode calculation algorithm and then normalized by 5 different mode combiners (MC1 to MC5).

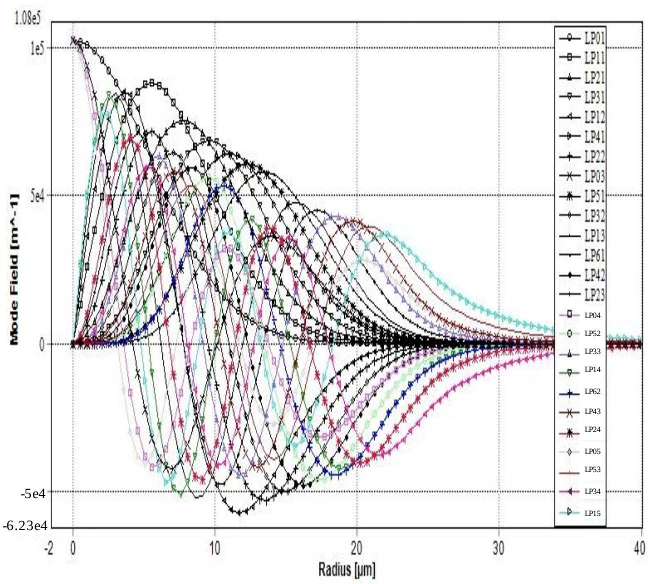

Fig. 3. The mode field intensity distribution of 25 LP modes in 10 Tb/s LP-WDM-MDM system

The performance of transmission system is generally measured by parameters like BER (bit error rate) and Q-factor. BER is measure of probability of erroneous bits with respect to total bits received during transmission and Q-factor is the measure of quality of transmitted signals in form of SNR. As, the eye opening value becomes larger then, mean value difference between signal levels become larger and higher the value of Q-factor with lower the percentage of erroneous bits.

Fig. 4 illustrates the variation of bit error rate with MMF length for different channel indices of LP modes for each mode group. Three cases are considered to observe the result of channel spacing of LP modes on performance of system:- case1: when x-index spacing is narrow (i.e x=1, x=2 for y-index= 1 to 5) represented by Fig. 4(a, b); case 2: when x-index spacing is moderate (x=3 for y-index= 1 to 5) represented by Fig. 4(c) and case 3: when x-index spacing is too large (x=4, x=5 for y-index= 1 to 5) represented by Fig. 4(d, e).

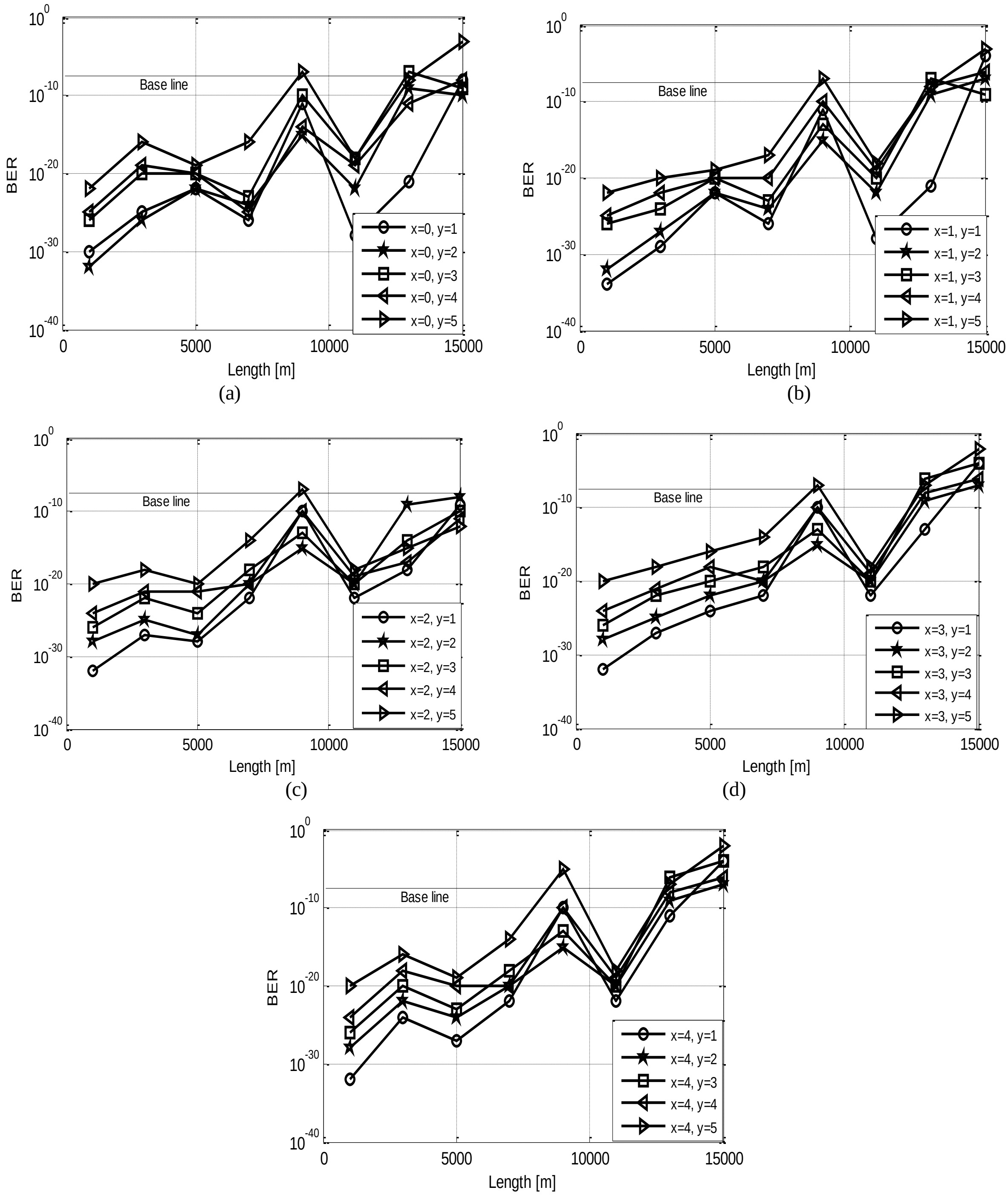

Fig. 4. BER of 25 channel LP- WDM-MDM system as a function of distance for index separations (a) x=0, y= 1 to 5, (b) x=1, y= 1 to 5, (c) x=2, y= 1 to 5, (d) x=3, y= 1 to 5 and (e) x=4, y= 1 to 5

The length of MMF has been varied from 1 km to 15 km to investigate the outcome of channel spacing on performance of hybrid LP-WDM-MDM system. The y-index of LP mode is varied from $\Delta y = 1$ to 5 whereas keeping constant the value of x-index of the LP mode for each group in first simulation run. Again, in next run value 1of x-index is varied from $\Delta x = 1$ to 5 keeping the value of y-index to be constant for each mode group. Thus, channel spacing with varied *x* and *y*-index of LP modes is observed in terms of bit error rate to evaluate the performance of MDM WDM system.

From Fig. 4(a, b) for case1, it is observed that from length 1000 m to 5000 m, power coupling between LP modes increases and then decreases but modal delay difference is moderate resulting in low interference. From 5000 m to 9000 m, power coupling still prevails but modal delay difference becomes large giving rise to interference but after 13000 m interference goes on increasing.

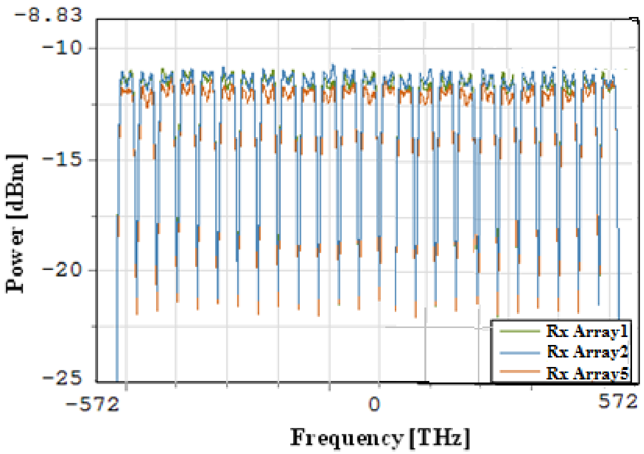

Fig. 5. Optical spectrum of received WDM-MDM signal in LP-WDM-MDM system

Same trends are seen in Fig. 4(d, e) when x-index separation is too large, modal delay is large and higher interference. When x-index separation of modes is moderate (x=2 in Fig. 4(c)) then good BER is attained for all y-index configurations, therefore low propagation delay and improved interference. It is concluded that maximum transmission distance (i.e. 15 km over MMF) is achieved with low interference and acceptable BER ($<10^{-9}$) for moderate x-index channel spacing (x=2, y=1 to 5) between LP modes. Fig. 5 represents the optical spectrum of WDM-MDM signal as received at receiver arrays of LP-WDM-MDM link.

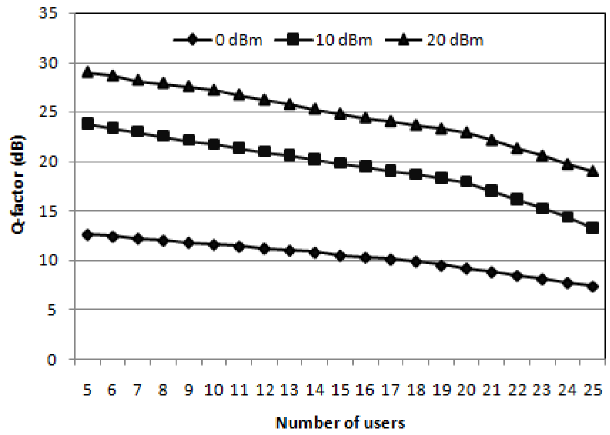

Fig. 6. Quality performance of MIMO WDM-MDM system with number of users with the variation in input power

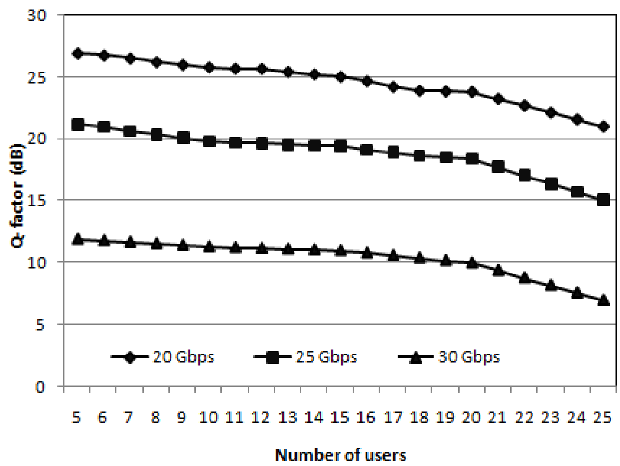

Fig. 7. Quality performance of MIMO WDM-MDM system with number of users at different data rates

The performance of system has also been investigated with the variation in power of input signal at each terminal unit. The quality of system is observed for different input powers (0 dBm, 10 dBm and 20 dBm) at each terminal unit with different number of users as shown in Fig.6. With the increase in input power, performance quality of system improves. Fig. 7 depicts the effect of number of channels on the performance of MIMO WDM-MDM system in terms of quality factor for different data rates (20 Gbps, 25 Gbps and 30 Gbps). Generally, with the increase in number of channels and data rate, quality of system starts degrading due to interference. But by controlling channel spacing in the system interference can be reduced. Thus, it is clearly examined that as the number of users increases from 5 to 25 in system along with increase in data rate, quality of signal starts distorting but not below acceptable level. These results prove better performance over [9] in which authors achieve good BER for channel spacing (x=2, 3) of HG modes over distance of 800 m MMF.

5. Conclusion

This paper investigated the effect of channel index spacing of LP modes in hybrid LP-Wavelength Division Multiplexed Mode Division Multiplexing system to improve modal interference and enhance performance capacity. The effect of parameters (channel index spacing of LP modes, different input power and different data rates for different number of users) is observed in terms of BER and quality-factor at different lengths of multimode fiber. It is concluded that moderate channel index spacing (x-index=2 and varying y-index) provide best results for 25 channel 10Tb/s hybrid LP-MDM-WDM system at input power of 20 dBm covering transmission distance of 15 km with acceptable BER ($<10^{-8}$) and Quality-factor (>9.8 dB) over MMF link. Featuring distinctive simplicity with reduced interference and low power consumption, the proposed design is ideal to cope up with the higher data capacity and short reach applications.

Acknowledgments

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 grant number: PhD-MLA-5(1)/2014. The authors would also like to thank the Department of Electronics and Communication Engineering of Thapar University, Patiala, Punjab, for providing the moral support and excellent laboratory facilities (Optical Fiber Communication Research Laboratory) in developing the system.

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