Augmenting Data Rate Performance for Higher order Modulation in Triangular Index Profile Multicore Fiber Interconnect

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Abstract

A triangular profile multicore fiber (MCF) optical interconnect (OI) is investigated to augment performance that typically degrades at high data rates for higher order modulation in a short reach transmission system. Firstly, probability density functions (PDFs) variation with inter–core crosstalk is calculated for 8–core MCF OI with different index profile in the core and it was observed that the triangular profile MCF OI is the most crosstalk tolerant. Next, symbol error probability (SEP) for higher order quadrature phase shift keying (QPSK) modulated signal due to inter–core crosstalk is analytically obtained and their dependence on typical characteristic parameters are examined. Further, numerical simulations are carried out to compare the error performance of QPSK for step index and triangular index MCF OI by generating eye diagram at 40 Gbps per channel. Finally, it is shown that MCF OI with triangular index profile supporting QPSK has double spectral efficiency with tolerable trade off in SEP as compared with those of binary phase shift keying (BPSK) at high data rates which is scalable up to 5 Tbps.

Keywords: Optical interconnects; symbol error probability; multicore fibers; crosstalk.

1. Introduction

To keep pace with tremendous increase in data volume requirement and to overcome bandwidth density drives, optical interconnect (OI) is fast becoming a viable solution to support futuristic data centers, high performance computers, and emerging on–chip integrated photonic systems [1]. Fiber ribbon or individual standard single mode fiber based interconnection technology is on the verge of fundamental limit and is struggling to cope with steadily growing demand for bandwidth in next generation rack-to-rack, board-to-board, box-to-box and chip-to-chip interconnect applications [2]. Space division multiplexing (SDM) has recently attracted attention as a potential means to overcome the imminent capacity crunch of short reach optical transmission system [3]. The key issues for design of the forthcoming heterogeneous and bandwidth intensive OI are high fiber count and high density cable with minimum escalation in link cost and power budget [4, 5]. The SDM technology based on multicore fibers (MCFs) has potential to thrust the data traffic capacity up to an unprecedented level [6]. Recently, with short-range MCF OIs an aggregate data transmission capacity of 240 Gbps has experimentally been achieved in a multichannel transmission using low-cost vertical cavity surface emitting lasers [7]. Furthermore, it has been recently reported that, although hexagonal configurations of cores in MCF are more closely packed but are not well suited to number of parallel lanes in data buses required in computers as well as in integrated silicon photonic transceivers [8]. For such specific applications, rectangular array of 8–core MCF has been recently proposed for future exaflop (10^{18}) high performance computing systems [8, 9].

MCF with SDM, not only increases system capacity but is also less vulnerable to limits imposed by fiber non-linearity as it guides less power per core [6]. However, one of the most critical issues impending efficient usage of MCF as OI, is inter-core crosstalk [10-13]. The inter-core crosstalk inevitably occurs due to the mode coupling between the adjacent cores, and as a consequence limits the transmission performance of ultra-short and short-reach optical interconnects. In this context, effect of inter-core crosstalk on the symbol-error probability (SEP) performance of multi-level modulation formats has assumed great importance as it is being speculated that multi-level modulation along with SDM in MCF can overcome bandwidth density drives of big-data era [14]. Recently, an experimental work has been reported that demonstrates the impact of quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) for long distance transmission using hexagonal 7-core MCF [15]. In short reach OI system, MCF combined with spectral efficient higher order modulation format is considered as an alternate efficient method to increase the transmission capacity provided crosstalk tolerance is decreased concurrently [16]. On-off keying (OOK) is the only modulation and main source of interest for short reach commercial links today, since they are sufficiently low cost with low power consumption [17]. However, to realize spectrally efficient short reach optical transmission, various modulation formats, such as quadrature amplitude modulation in combination with sub-carrier modulation [18], carrier-less amplitude/phase modulation [19], pulse amplitude modulation [20], poly-binary modulation and discrete multi-tone modulation [20] have been recently reported. However, all modulation formats invariably use standard single mode fiber (SSMF) that cannot cope with future bandwidth hungry services required in data centers, core routers, terabit switches, high performance computers and digital cross connect systems. On the other hand, MCF based short reach OI communication system using binary phase shift keying (BPSK) modulation format has been recently reported as an effective solution, but may not be enough to exploit huge optoelectronic bandwidth disparity existing between requirement and availability in forthcoming era of big data and high speed internet traffic [21].

In this paper, transmission of higher order QPSK modulation in index profiled MCF based short reach OI system is investigated. First, probability density function is statistically obtained for crosstalk variance in MCF having different index parameter α. Based on the distribution, MCF OI with α = 1 is selected for further study. Next, mathematical expressions for symbol error probability in QPSK modulated SDM system using MCF is derived with a view to apply in short reach OI communication systems. The effect of the inter-core crosstalk on SEP performance is investigated for rectangular arrayed 8-core MCF with triangular (α =1) refractive index profile [9] for various parameters. Next, a simulation experiment is carried out in Rsoft OptSim that compares performances of binary phase shift keying (BPSK) and QPSK in step index MCF OI through eye diagram. Lastly, the same experiment is repeated for QPSK in triangular index profile MCF OI. Throughout the paper, conventional definition of index profiled refractive index $n(r) = n_c\sqrt{\left\{1-2\Delta\left(r/a\right)^{\alpha}\right\}}$ in individual cores of MCF is followed. Here $n(r)$ is refractive index at a radial distance r from center of the core, a is the core radius, n_c is the refractive index of the core at r=0, n_{cl} is homogeneous (i.e. $n(r) = n_{cl}$ for $r \geq a$) refractive index of the cladding, Δ represents relative refractive index difference between core and cladding and α defines the shape of the profile.

2. Theoretical Expression for Symbol Error Probability

Stochastic variation of crosstalk (X_T) in a MCF is identified as major impeding factor which fluctuates predominantly at phase matching points by scant random perturbations of various internal and external factors, such as bends and twists [11]. The probability density function of the crosstalk distribution is represented as [11]

$$f(X_T) = \frac{X_T}{4\sigma^4}\exp\left(-\frac{X_T}{2\sigma^2}\right) \tag{1}$$

here, σ^2 represents variance of normally distributed in-phase and quadrature components of polarization modes of the coupled power. The individual cores are of diameter 7.8, 7.0, 6.6 and 5.0 μm for different index profile, $\alpha = 1$, 2, 3 and ∞ respectively. The relative refractive index difference Δ for different index profile $\alpha = 1$, 2, 3 and ∞ in 8-core MCF OI are 1.04, 0.88, 0.85 and 0.80 % respectively with a mode field diameter of 6.76 μm. The core separation within a row is 50 μm and the two rows are separated by 100 μm which is twice the core-to-core spacing within a row. Other parameters, such as, fiber length and cladding refractive index is assumed to be, 100 *m* and 1.45 respectively, at the operating wavelength of 1.55 μm [9]. The crosstalk between adjacent cores is calculated by using the coupled power theory [12]. Analytical approach based on exponential autocorrelation function is used to realize accurate estimation of inter-core crosstalk in the non-phase-matching region of MCF [12]. The power coupling coefficient for exponential autocorrelation is written as [12]

$$h_{mn} = \frac{2K_{mn}^2 d_c}{1+(\Delta\beta_{mn} d_c)^2} \tag{2}$$

where m, n represent the core m and n, K_{mn} is the average mode coupling coefficient between these two cores, d_c is the correlation length and $\Delta\beta_{mn}$ is the propagation constant difference between the cores m and n.

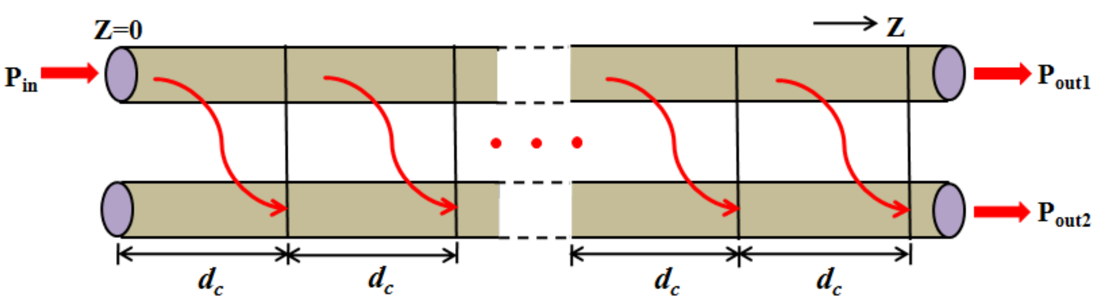


Fig. 1. The schematic of distributed optical power coupling in a MCF with correlation length d_c.

In order to consider the distributed crosstalk in bend-induced randomly perturbed MCF, it is divided into finite segment of correlation length d_c, as shown in Fig. 1. The average value of inter-core crosstalk with d_c= 0.05 m agree well with the measurement results [13] and therefore, it is thought to be the preferred value in present calculation. By using the average power coupling coefficient $\bar{h}_{mn}$ and coupled power theory, the crosstalk between two α index profile cores of MCF over a length L is expressed as [12]

$$X_T = \tanh(\bar{h}_{mn} L) \tag{3}$$

Probability density functions (PDFs) for statistical crosstalk distribution in 8-core MCF OI for different index profiles are calculated from Eq. (1) and depicted in Fig. 2. The distribution of PDF shows that inter-core crosstalk can be considered as virtual additive white Gaussian noise (VAWGN).

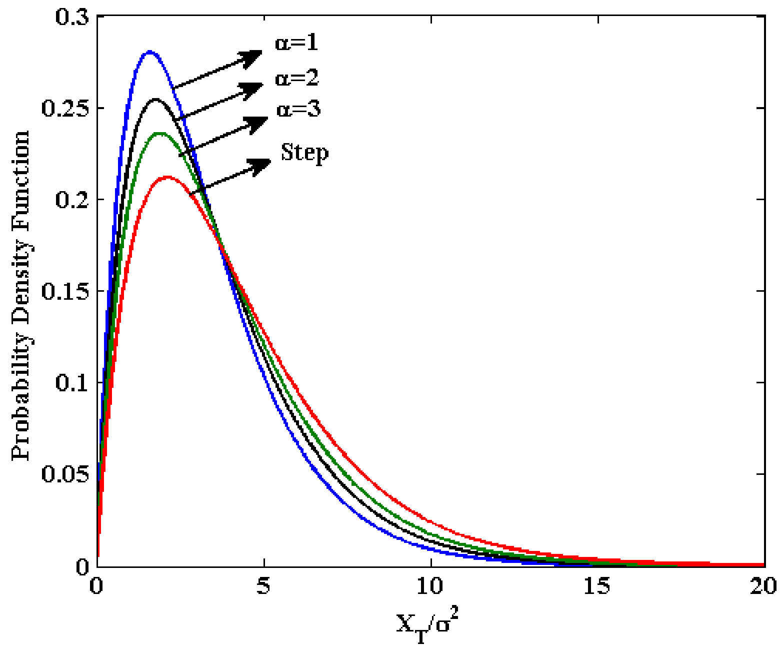


Fig. 2. Crosstalk distributions for different index profile α in 8-core MCF.

In BPSK system, the coordinates of the transmitted signal pair can be written as $-\sqrt{E}$ and $+\sqrt{E}$ to represent bits '0' and '1', respectively, where, E = E_b represents the transmitted signal energy per bit. To focus only on impact of inter-core crosstalk in MCF OI short reach communication system, the signal received at the receiver when bit '0' is transmitted can be written as [22, 23],

$$y = -\sqrt{E_b} + X_T \tag{4}$$

where, X_T is the crosstalk between the adjacent cores and considered as VAWGN. From (1), conditional error probability at the receiver is given as [21-23]

$$P(1/0)=\int_{X_{T\mu}}^{\infty}\frac{y+\sqrt{E_b}}{4\sigma^4}\exp\left[-\left(\frac{y+\sqrt{E_b}}{2\sigma^2}\right)\right]dy \qquad (5)$$

where, $X_{T\mu}$ is the mean value of the crosstalk distribution. After solving the integral of Eq. (5), the conditional error probability at the receiver is obtained as [21]

$$P(1/0)=\left(3+\frac{\sqrt{E_b}}{2\sigma^2}\right)\exp\left[-\left(2+\frac{\sqrt{E_b}}{2\sigma^2}\right)\right] \qquad (6)$$

Similarly, due to symmetry of BPSK signal constellation, the conditional error probability when bit '1' is transmitted can be expressed as P(0/1) = P(1/0) [22, 23]. Since, '0' and '1' are equally probable to occur at the input of MCF interconnects transmission system, the bit error probability (BEP) or equivalently SEP for coherent BPSK system is expressed as [21]

$$\begin{aligned}P_{eb}&=\frac{1}{2}P\left(1/0\right)+\frac{1}{2}P\left(0/1\right)\\&=\left(3+\sqrt{\frac{E_b}{4\sigma^4}}\right)\exp\left[-\left(2+\sqrt{\frac{E_b}{4\sigma^4}}\right)\right]\end{aligned} \qquad (7)$$

Furthermore, the probability of symbol error for the coherent QPSK system is [22, 23]

$$P_{eq}=1-P_c \qquad (8)$$

where, P_c is probability that the symbol is received correctly. The coherent QPSK system can be consider as two coherent BPSK systems in parallel with phase quadrature carriers. Therefore, for coherent QPSK system the signal energy per bit is $E = E_b/2$.

Thus, P_c can be given as

$$P_c=\left(1-P_{eb}\right)^2=\left[1-\left(3+\sqrt{\frac{E_b}{8\sigma^4}}\right)\exp\left\{-\left(2+\sqrt{\frac{E_b}{8\sigma^4}}\right)\right\}\right]^2 \qquad (9)$$

Substituting (9) in (8), P_{eq} is obtained as

$$P_{eq}=\left(6+2\sqrt{\frac{E_b}{8\sigma^4}}\right)\exp\left[-\left(2+\sqrt{\frac{E_b}{8\sigma^4}}\right)\right]-\left(9+\frac{E_b}{8\sigma^4}+6\sqrt{\frac{E_b}{8\sigma^4}}\right)\exp\left[-2\left(2+\sqrt{\frac{E_b}{8\sigma^4}}\right)\right] \qquad (10)$$

Equations (7) and (10) are used to estimate SEP for BPSK and higher order QPSK by evaluating variance that depends on crosstalk in different configurations.

3. Simulation setup of MCF interconnects transmission

Simulation setup on Rsoft OptSim platform for QPSK modulated SDM MCF interconnects transmission system is shown in Fig. 3(a) [21]. Each polarization multiplexed transmitter block consists of individual transmitters configured using two nested Mach-Zehnder modulators. Blocks are used that can generate non return-to-zero (NRZ) modulation and parameters set for eight channels of 10 Gbaud QPSK signals with channel spacing of 50 GHz. Further, each channel is shaped by a fourth order super Gaussian optical filter having 3 dB bandwidth of 45GHz (i.e. 90% of channel spacing) to suppress spectral side lobes and minimize influence of the inter-channel crosstalk. Continuous wave optical source at 1550 nm is tuned to give 100 kHz linewidth optical carrier which is fed into an integrated modulator. In modulator pseudo-random bit sequence (PRBS) of period $2^{15}-1$ is selected to modulate the phase of the optical carrier [21].

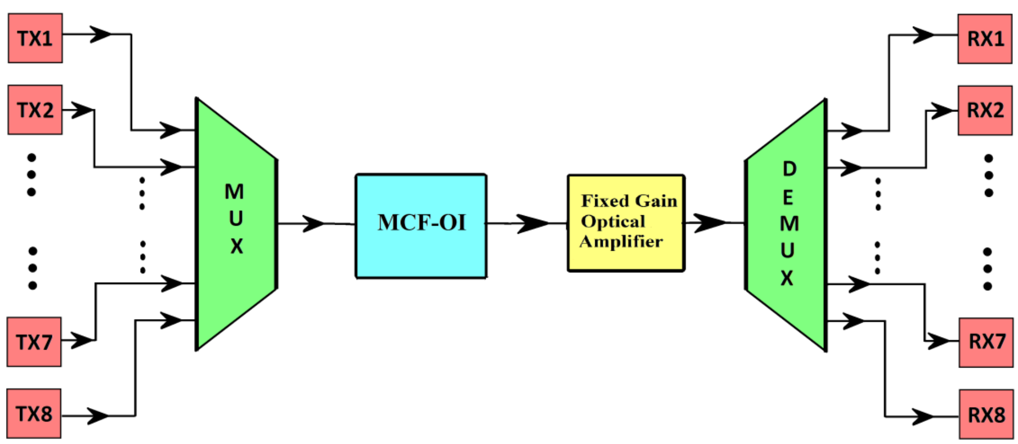


Fig. 3(a) Simulation setup for QPSK modulated short reach transmission system using 8-core MCF. TX: transmitter, RX: receiver, MUX: multiplexer, DEMUX: demultiplexer.

The transmission block is connected to 8:1 wavelength division multiplexer (WDM) through which combined NRZ QPSK optical signal can be launched into MCF OI module that consists of rectangular arrayed with eight α index profile identical cores and is shown in inset of Fig. 3(b). The MCF has two linear rows with each row having of 4 cores. The parameters for step index profile ($\alpha = \infty$) and triangular index profile ($\alpha = 1$) MCF are same as that in Fig. 2, at the operating wavelength of 1.55 μm. The equivalent functional module that replicates the rectangular arrayed 8–core MCF and can be integrated with communication system of Fig. 3(a) is shown in Fig. 3(b) [21]. In the equivalent module, the modulated QPSK signal is splitted into eight channels representing 8 cores of MCF having optical transmission of 100 m of SSMF [21].

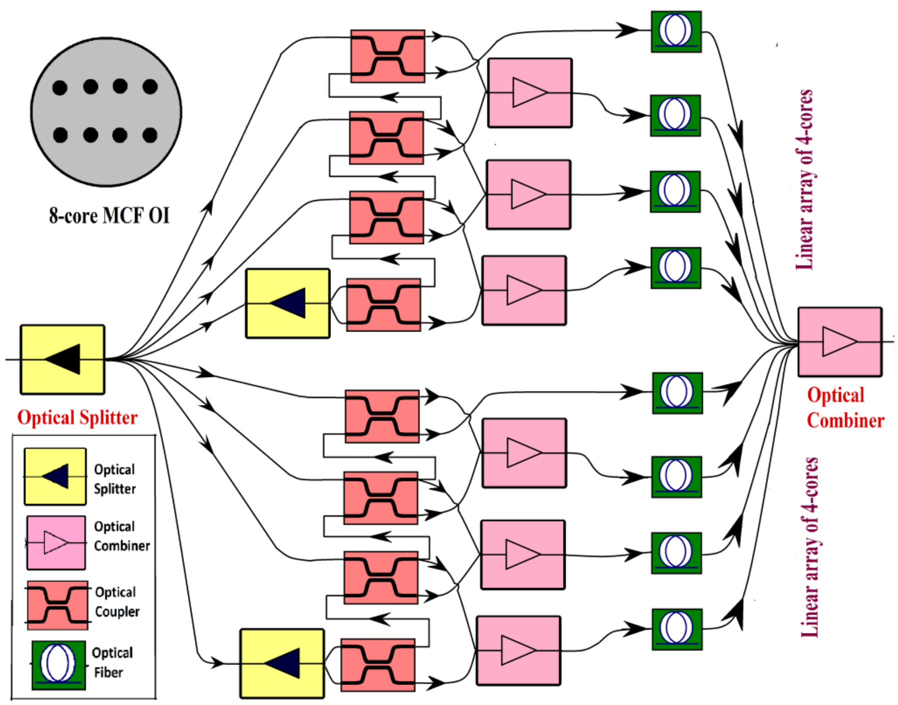


Fig. 3(b). Equivalent simulation model of 8-core MCF OI. The schematic of rectangular array 8-core MCF with triangular index profile is shown in inset [8, 9].

In order to obtain mode coupling coefficient between adjacent cores, firstly electric field distribution of MCF is calculated using commercial finite element analysis software FemSIM [9]. Key issue of inter-core crosstalk in MCF interconnects transmission system is evaluated in absence of nonlinear noise as MCF is less sensitive to fiber nonlinearities [6]. Crosstalk in any core 'A' is defined as the ratio of crosstalk power leaking into 'A' from adjacent core to the signal power guided in core 'A'. Crosstalk among cores that are in different rows are minimal due to larger separation and are ignored [9]. The distributed crosstalk powers between neighboring cores (see Fig. 1) over a length 100 m is calculated by coupled power theory [12]. First, the power coupling coefficient is obtained for correlation length d_c and then integrated over total length L. Next, an exact coupling ratio is estimated between two α index profile cores of MCF, which is equivalent to cumulative crosstalk over a length L (100 m). In the equivalent module, eight cores vulnerable to crosstalk are represented by eight SSMF with couplers. In order to specify the optical power coupling between two cores of MCF OI cumulative coupled power ratio is assigned to optical coupler in the module of Fig. 3(b) and all are ultimately combined though optical combiner to give a single output [21].

The WDM output of MCF OI is amplified by 25 dB fixed gain optical amplifier with a Noise Figure of 4.5 dB and then demultiplexed [21]. In the receiver block, optical filter identical to the one in transmitter is used to remove noise power outside the signal bandwidth. The photodetector inside the receiver block converts the received optical QPSK signal into electrical equivalent QPSK signal, which is further subjected to a 4^{th} order Bessel low pass filter. The filtered signals are sampled at two samples per symbol by a finite impulse response (FIR) filter. The pre-convergence is processed by an equalizer containing 15 tap FIR filters driven by constant modulus algorithm (CMA) [24], having coefficients adjusted through decision directed least mean squares (DD-LMS) method that finally provides the required numerical value of symbol error probability.

4. Results and Discussion

Figure 2, apart from establishing VAWGN properties of inter–core crosstalk for cores with different index profiles α, also reveals that probability density function has higher peak and narrower distribution as value of α is decreased. It is inferred from the figure that for triangular index profile (α = 1), samples of probability distribution are close to mean value of crosstalk, which promises better and crosstalk tolerant response of digital receivers in short reach signal transmission system using MCF OI.

To further investigate the crosstalk tolerance of triangular index profile MCF, different configurations are considered that can occur while fabrication of MCFs or during their usage as interconnects. While fabrication separation between cores can alter and during application as interconnects it may have to undergo bends. In both the cases crosstalk between cores of MCF will change resulting in variation in SEP. Here, considering the practical situation, different configurations are considered that depend on bending radii varying from 15 – 65 cm in steps of 5 cm. Table I lists crosstalk and SEP calculated for QPSK modulated short reach OI transmission system for step index and triangular index cores of MCF with bending radius. It can be inferred from the table that for alike configuration which corresponds to equivalent bending radius, triangular index profile MCF is more tolerant to crosstalk than that of step index MCF resulting in lower SEP.

Table I. Crosstalk and SEP comparison for triangular and step index profile MCF OI

Bending Radius (in cm)	Crosstalk (dB)		Symbol error probability = $\log_{10}$ SEP	
	Step index ($\alpha=\infty$)	Triangular index ($\alpha=1$)	Step index ($\alpha=\infty$)	Triangular index ($\alpha=1$)
15	-52.00	-71.00	-4.28	-7.14
20	-47.35	-65.43	-3.79	-5.60
25	-42.61	-59.87	-2.97	-4.39
30	-37.94	-54.21	-2.33	-3.44
35	-33.22	-48.64	-1.83	-2.70
40	-28.53	-43.20	-1.45	-2.12
45	-23.79	-37.41	-1.02	-1.67
50	-19.13	-31.83	-0.72	-1.32
55	-14.38	-26.19	-0.53	-1.05
60	-09.79	-20.63	-0.47	-0.84
65	-05.13	-15.08	-0.29	-0.68

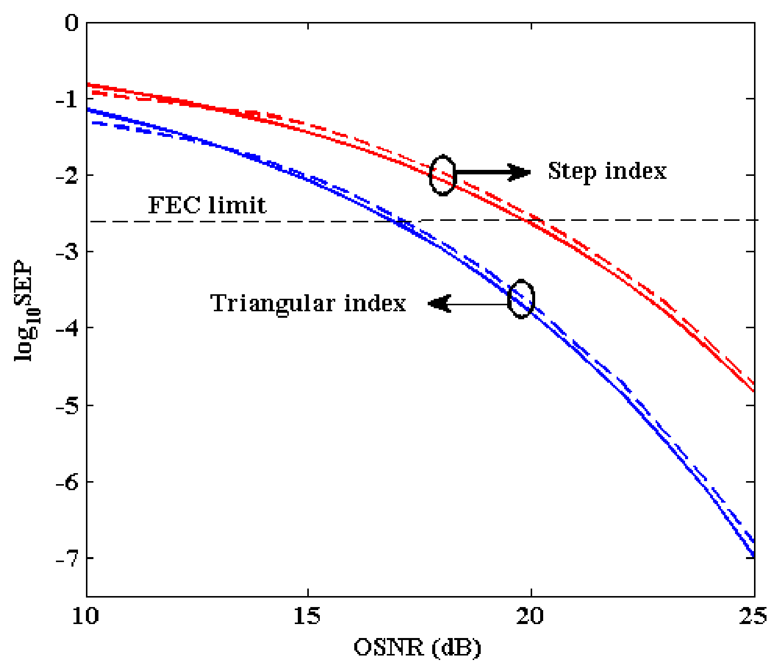


Fig. 4. SEP as a function of OSNR for QPSK system in step index and triangular index MCF OI. Solid curves are obtained from theory of Section 2 and dashed curves from simulation experiment of Section 3.

A triangular index profile MCF can be suitable in a short reach communication system supporting higher order QPSK, if symbol error probability performance shows remarkable improvement. In this regard, SEP is calculated for different OSNR and input launched power for 40 Gbps per channel. Figure 4 shows that for a given OSNR, SEP decreases for triangular profile as compared to that of step index. Forward error correction (FEC) limit [25] defining threshold sensitivity level of a QPSK receiver reduces by about 3 dB when triangular profile MCF is used establishing better receiver performance. Further, SEP predicted by theory of Section 2 and simulation experiment of Section 3 agree well for both step index and triangular index MCF. It is worth noting that for a given error probability, maximum discrepancy between theory and simulation is about 0.3 dB in OSNR for both step index and triangular index MCF OI.

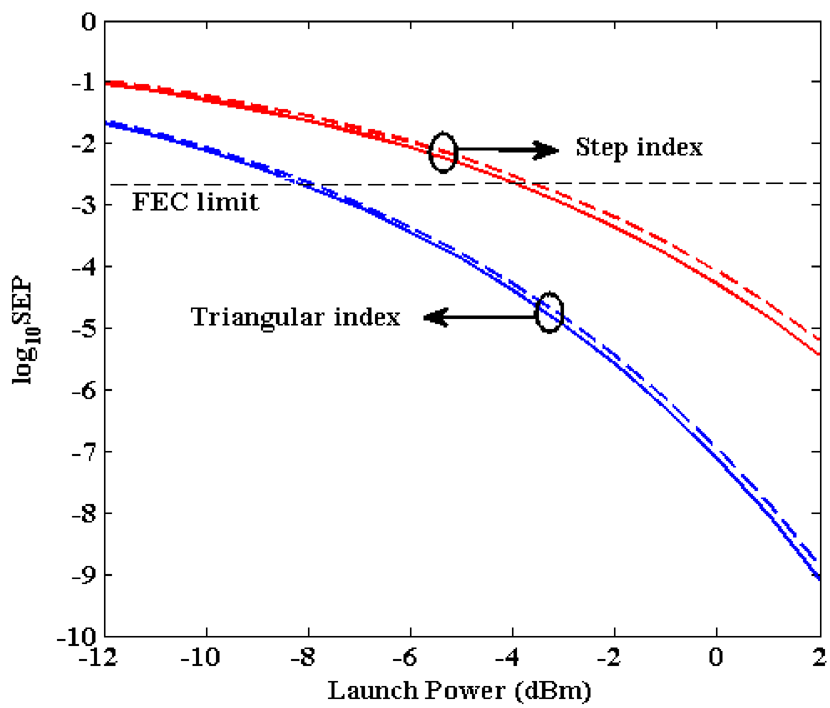


Fig. 5. SEP as a function of launch power for QPSK modulated system in step index and triangular index MCF OI. Solid curves are obtained from theory of Section 2 and dashed curves from simulation experiment of Section 3.

Figure 5 illustrates the error probability performance of 100 m long 8-core QPSK modulated OI transmission system as a function of launch power at 40 Gbps per channel. It can be seen from intersection point of FEC limit and SEP that sensitivity of a digital receiver reduces from –4 dBm (398.1μW) for a step profile to –8 dBm (158.5 μW) for a triangular profile. Theory and simulation experiment results for both the cases are in good agreement as well. For step index MCF an error less than 3.5% is observed and agrees within 1% for triangular index MCF OI at 40 Gbps. The discrepancy between the error probability values is sufficiently small, which proves the feasibility of simulation module for MCF OI transmission system.

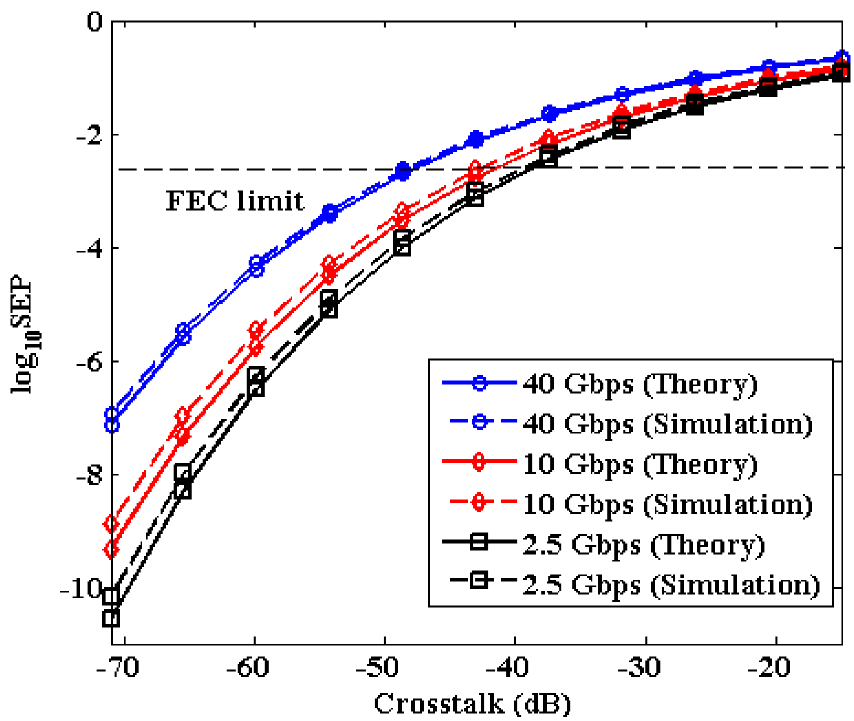
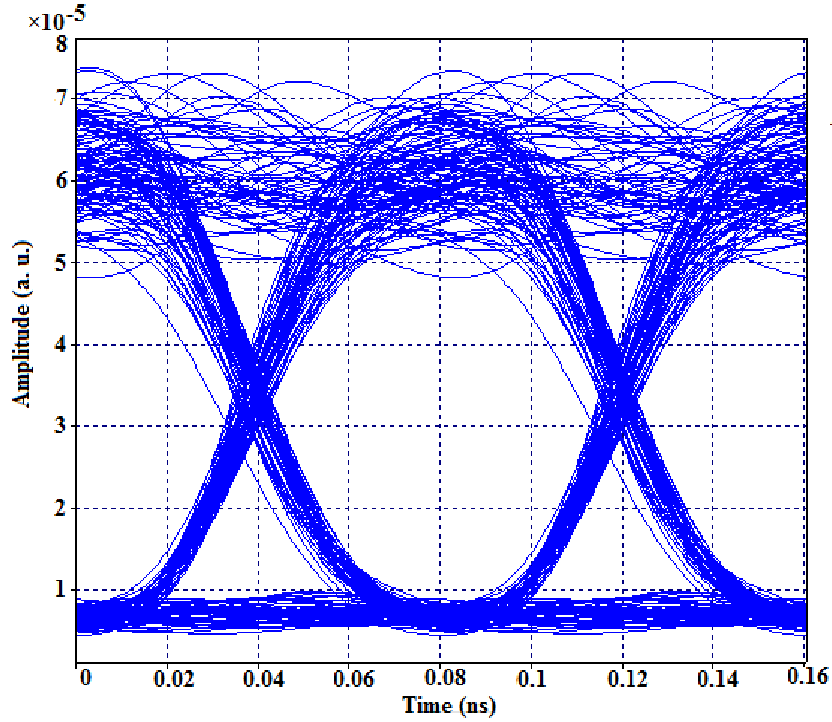


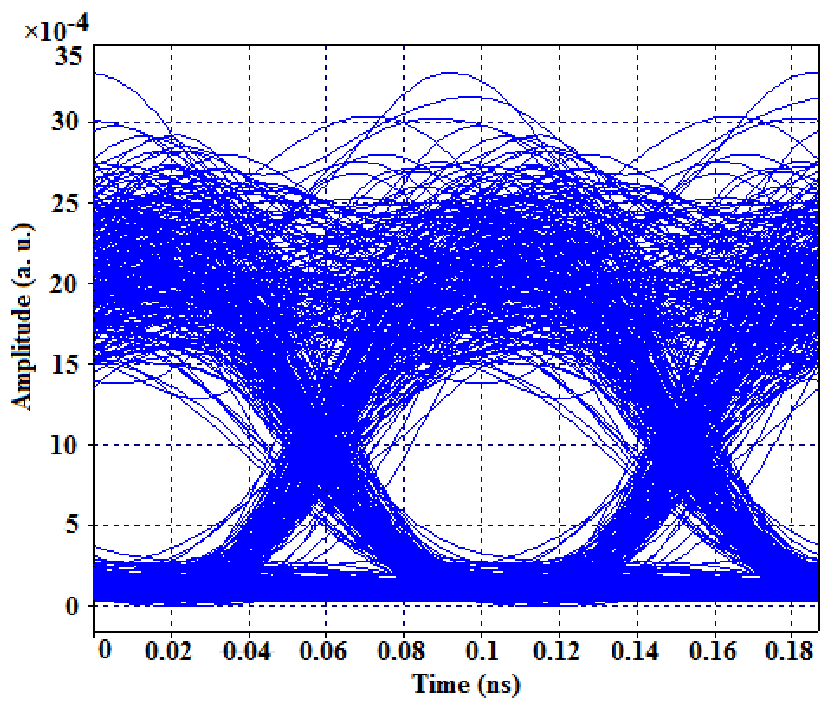
Fig. 6. SEP as a function of inter-core crosstalk for various QPSK modulated Signal.

For triangular profile MCF and various data rates used in optical communication, error probability performances for different configurations both calculated and simulated at 0 dBm launch power are given in Table I. It can be seen from Fig. 6, inter-core crosstalk degrades the error performance by increasing the value of SEP at all data rates. Moreover, for a given crosstalk, the maximum degradation is for 40 Gbps per channel. It suggests that high data rate short reach transmission has relatively low tolerance to crosstalk. From Fig. 6, it can be inferred that for 40 Gbps per channel, sensitivity is −48.27 dB at the FEC threshold of SEP while it increases to −43.21 dB at 10 Gbps per channel and −39.13 dB at 2.5 Gbps per channel. Hence, to achieve high speed and lower cost per bit in practical short reach interconnects transmission and high performance computing applications data rate of 40 Gbps per channel is viable if crosstalk can be reduced below −48.27 dB. Theoretical and simulated results for SEP at 40 Gbps [see Fig.

6] are almost identical. However, at data rates of 2.5 Gbps and 10 Gbps, for a given error probability, discrepancy between theory and simulation is less than −0.8 dB which is small enough to be of any practical significance.



(a)



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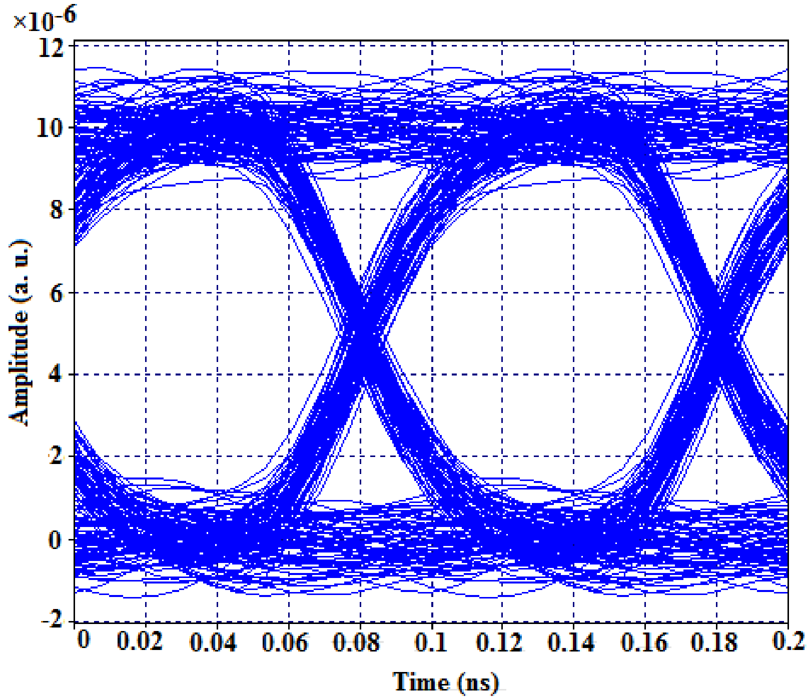

Figs. 7. Eye diagrams of (a) BPSK and (b) QPSK signal for step index MCF and (c) Eye diagram of QPSK signal for triangular index MCF.

Experiment is carried on using Rsoft OptSim simulator to measure eye patterns for short reach transmission system consisting of step index and triangular index MCF. First, for step index MCF transmission, eye pattern is measured for BPSK and higher order QPSK modulated signals. Next, experiment is repeated for QPSK after replacing the step index MCF with a triangular index one. The measured eye patterns and related parameters are shown in Fig. 7 and Table II respectively.

Table II. Performance parameters measured from eye diagrams of Fig. 7.

Parameters	**BPSK($\alpha = \infty$)**	**QPSK($\alpha = \infty$)**	**QPSK($\alpha = 1$)**
Eye width (in ns)	0.074	0.060	0.085
Distortion	2.6×10^{-5}	20×10^{-4}	2.4×10^{-6}
Zero crossing time jitter (in ns)	0.008	0.022	0.01
Timing error sensitivity (in ns)	0.037	0.030	0.043
Slope of timing error sensitivity	1.68	2.30	2.01

From Fig. 7 and Table II, it can be observed that for MCF with $\alpha = \infty$, higher order QPSK has smaller eye width and higher distortion with respect to BPSK. In particular, it can be seen from Fig. 7, there is strong inter-core crosstalk effects at the wave transition points and sampling points for QPSK signal with step index profile ($\alpha = \infty$). Thus for step index MCF, QPSK is not an appropriate modulation format for transmission. However, from above Fig. 7 and Table II, it can be observed that for QPSK communication system having triangular index core has widest open area of eye pattern. A more open eye pattern corresponds to minimal inter-core crosstalk distortion and better OSNR performance of QPSK modulated MCF OI short reach communication. Although slope for sensitivity to timing error and zero crossing jitter are low for BPSK signal at $\alpha = \infty$, inter-core crosstalk distortion for QPSK signal at $\alpha = 1$ is 2.4×10^{-6} which is one order lower to that of BPSK (2.6×10^{-5}) with step index profile core.

Finally, aggregate spectral efficiency which is product of number of cores and spectral efficiency per core is calculated. Its variation with respect to OSNR for BPSK and QPSK short reach MCF OI communication system having step index core ($\alpha = \infty$) and triangular index core ($\alpha = 1$) MCF OI respectively is plotted in Fig. 8. It is observed that aggregate spectral efficiency of QPSK short reach MCF OI system having triangular index core is twice at all values of OSNR

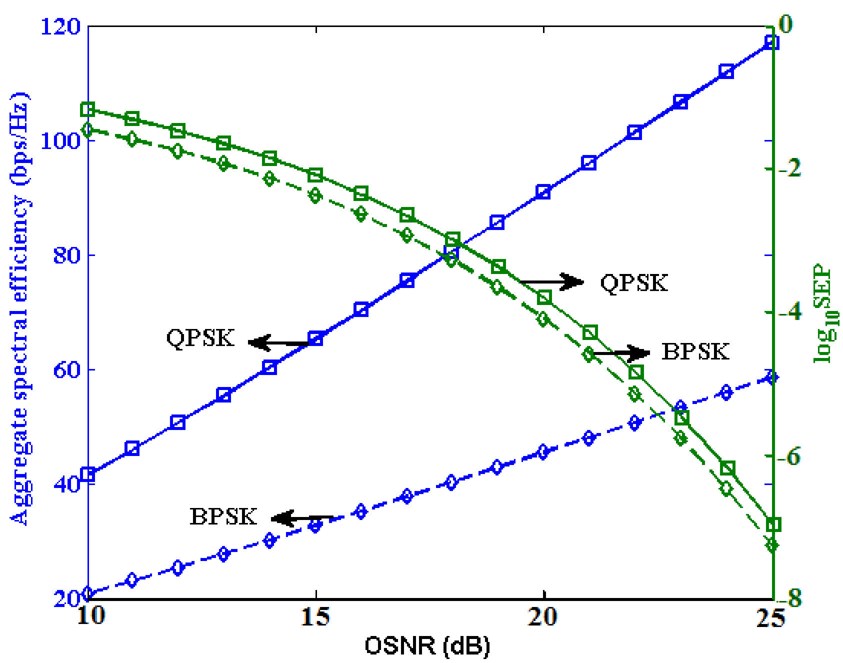

Fig. 8. Aggregate spectral efficiency and SEP as a function of OSNR for BPSK ($\alpha = \infty$) and QPSK ($\alpha = 1$) modulated MCF OI transmission.

as compared to BPSK modulated system having step index MCF. In Fig. 8, SEP as a function of OSNR for the two cases is also plotted. It shows that error probability of QPSK short reach communication system even with triangular index core ($\alpha = 1$) MCF is slightly (0.3 dB) higher than BPSK transmission system with step index core. This marginal increase in symbol error probability can be traded off with two-fold gain in aggregate spectral efficiency. Figure 8 also reveals that the capacity of a MCF based short reach OI system can be increased eight fold with SEP~10^{-7} for 40 Gbps per channel at inter–core crosstalk of −71 dB. Overall capacity of QPSK modulated 8-core MCF transmission can increase upto 5 Tbps (8 cores × 8 λ × 2×40 Gbps) which is much higher than data rates reported till now [7, 19-21].

5. Conclusion

Although BPSK systems has advantage of minimum escalation in link cost and power budget, higher order QPSK modulation scheme for OI application is explored to meet ever increasing bandwidth requirement. QPSK requires half bandwidth compared to BPSK modulation, which can be subsequently exploited to meet high capacity transmission demands of next generation short reach MCF interconnects. However, higher order modulation is more susceptible to inter-core crosstalk, and inevitably degrades the error probability performance of MCF interconnects transmission. To overcome this issue, firstly, statistical crosstalk distribution of inter-core crosstalk for 8-core MCF OI having different index profiles is investigated. It is observed that triangular profile MCF OI may be most suitable for crosstalk tolerant communication. Next, a closed-form error probability expression for QPSK modulated signal applicable to MCF interconnects with inter-core crosstalk is analytically derived. The dependence of SEP on various parameters such as OSNR, launch power, and inter-core crosstalk is investigated for both step index and triangular index MCF OI supporting QPSK modulated data rate of 40 Gbps per channel. An extensive numerical simulations have been carried out to verify the theoretical predictions and are found to be in good agreement. Further, performances of BPSK and QPSK in a short reach MCF OI based communication are investigated by simulating eye diagrams. It is shown that crosstalk degradation in QPSK modulated step index MCF OI system can be drastically improved by using a triangular index MCF OI. Present results clearly substantiate that inter-core crosstalk distortion for QPSK signal at $\alpha = 1$ is 2.4×10^{-6} which is one order lower than that of BPSK with step index profile core. Moreover, minimal penalty of 0.3 dB in terms of error probability performance for QPSK modulated triangular index MCF interconnects transmission is traded off with two-fold gain in aggregate spectral efficiency. These results offer a framework to augment the transmission capacity up to 5 Tbps for MCF based practical short reach communication system and silicon photonic transceivers.

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