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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.

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

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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 $\alpha=1$ 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 ($\alpha=1$) 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 $n(r) = n_c\sqrt{\{1 - 2\Delta(r/a)^{\alpha}\}}$ 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, α=1, 2, 3 and ∞ respectively. The relative refractive index difference Δ for different index profile α=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.

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).

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]

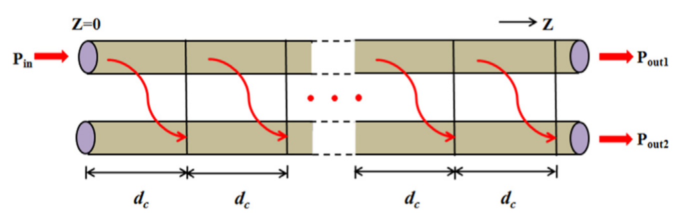

Fig. 1. The schematic of distributed optical power coupling in a MCF with correlation length d_c.

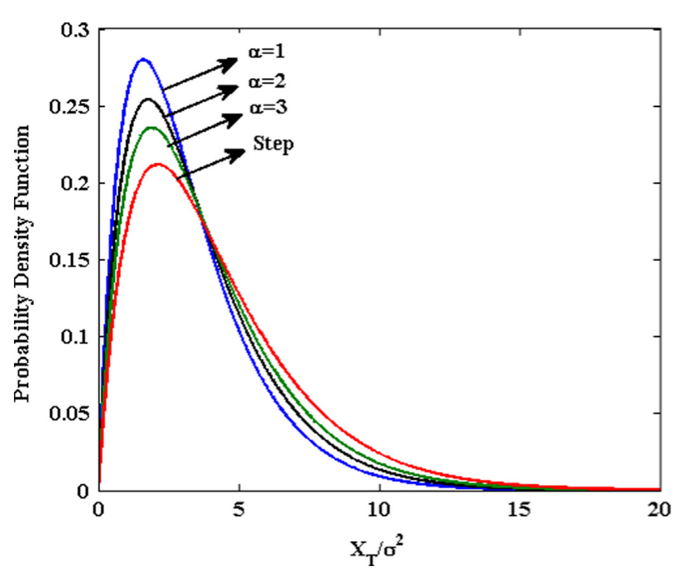

Fig. 2. Crosstalk distributions for different index profile α in 8-core MCF.