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Frequency-interleaved SDM transmission over multicore fiber for next generation short-reach optical interconnect systems

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ABSTRACT

Space division multiplexing (SDM) technique is proposed to overcome the bandwidth density drives of short-reach optical transmission systems by utilizing 8-core multicore fiber (MCF). Intercore crosstalk (XT) and higher order modulation format are the most challenging impairments of SDM based optical interconnect (OI) systems. To satisfy the exponential growth of the Internet traffic a frequency interleaving scheme is applied to short-reach MCF OI transmission systems. The negative effects of spectral overlap and intercore XT is reduced by shifting channel frequencies between adjacent cores. To exploit the full potential of SDM power efficient binary phase shift keying (BPSK) modulation format and digital signal processing such as multiple input multiple output (MIMO) equalization are used.

Keywords: Multicore fiber, optical interconnects, space division multiplexing, crosstalk, fiber optics communications

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1. INTRODUCTION

Owing to the continuous growth of cloud services, proliferation of smart devices, baseband centralization in radio access networks and high speed broadband penetration, data centers have experienced explosive increases in capacity demand [1]. It is a challenge to meet these requirements with conventional copper interconnects because of the inevitable increase in energy consumption and number of interconnections that follow. To cope with these ever-growing bandwidth requirement, optical interconnect (OI) is fast becoming a viable solution for bandwidth intensive short-reach communications because of its low propagation loss and high data transfer density [1]. Although, parallel spatial paths in the form of fiber ribbons or individual fibers have been widely used, they are costly, bulky, unmanageable and may not be enough to combat the rapidly growing capacity demand of future high performance short-reach OI system [2]. In order to relax the stress of data starvation of futuristic data centers, core routers, digital cross connect systems, and on-chip integrated photonic systems, OI configuration based on multicore fiber (MCF) has sparked tremendous interest among researchers as a potential and effective solution [3]. MCF is a single strand of glass fiber contains a multitude of single mode cores at different positions in the aggregated fiber cross-section, which effectively reduces the fiber volume and cable complexity in short-reach OI applications [3]. Space division multiplexing (SDM) technology using MCF is a powerful candidate to overcome the capacity crunch foreseen for the near future in short-reach OI communication systems [4].

However, intercore crosstalk (XT) is a primary concern in interconnection technology, which plays an important role for determining the overall system performance [5]. Moreover, escalating the data rate incurs high link cost and power requirement due to XT. Intercore XT can be reduce by suppressing the power coupling and phase matching between the cores during propagation. Recently, several kinds of MCFs such as homogeneous MCFs [6], heterogeneous MCFs [5], hole-assisted MCFs [7], and trench-assisted MCFs (TA-MCFs) [8] have been reported in order to reduce the XT between the neighboring cores. Recently, it has also been established that 8-core MCF arranged in a rectangular array can be more compatible with high performance computers and silicon photonic transceiver chips comparing to MCF with popular hexagonal or ring structure [9-10].

On the other hand, with a view to increase transmission capacity, higher order modulation formats has assumed great importance. Moreover, it is being speculated that higher order modulation along with SDM in MCF OI can overcome the exponentially growing traffic driven by greater demand coming from outside and changes to network architectures and usage patterns from within data centers [11]. To realize spectrally efficient optical transmission, various modulation formats, such as quadrature phase shift keying (QPSK) [12], polarization division multiplexed (PDM) QPSK [13] and quadrature amplitude modulation (QAM) [14] have been recently reported using hexagonal or ring configuration of MCF. It has also been reported that SDM with higher order modulation formats increase the transmission capacity provided crosstalk tolerance is decreased concurrently [14]. Furthermore, power efficient binary phase shift keying (BPSK) modulation format has been recently reported as an effective solution for forthcoming era of big data and high speed internet traffic [4]. Currently most studies focus on the design of low XT MCF and hybrid modulation formats. A better approach to mitigate the harmful effect of inercore XT is frequency-interleaved (FI) scheme in which channel wavelengths in one core are interleaved from those in adjacent ones.

In this paper, a FI scheme is proposed to mitigate the deleterious effects of intercore XT on tomorrow's high capacity MCF OI systems. Intercore XT due to bend is a primary concern in interconnection technology and it is evaluated using coupled power theory [5] and the modal solution approach based on the numerically efficient finite element method (FEM) [15]. The effectiveness of the FI scheme is investigated for BPSK modulation format using digital signal processing such as multiple input multiple output (MIMO) equalization.

2. THEORY

2.1 Calculation of XT between MCF OI cores

In order to obtain the XT between two adjacent cores in MCF, coupled power theory [5] is employed. But before that the value of mode coupling coefficient C_{mn} between two neighboring cores of MCF OI is investigated at first. The expression of coupling coefficient between two cores is given as [16]

$$C_{mn} = \frac{\omega\varepsilon_0 \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\left(N^2 - N_n^2\right)E_m^{*}.E_n dxdy}{2\sqrt{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\left(E_{mx}H_{my}^{*} - E_{my}H_{mx}^{*}\right)dxdy}.\sqrt{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\left(E_{nx}H_{ny}^{*} - E_{ny}H_{nx}^{*}\right)dxdy}}, \qquad (1)$$

where ω is an angular frequency of sinusoidally varying electromagnetic fields, and ε_0 is the permittivity of free-space. The pair m and n is either (1, 2) or (2, 1). E and H represent the electric and magnetic fields respectively. A full-vectorial FEM [15] is used in this work to calculate the mode coupling coefficient C_{mn}. The mode coupling coefficients between the cores are used to evaluate the power coupling coefficient [5]. The XT between two cores of MCF OI over a length L is estimated by the coupled power theory as [5]

$$XT = \tanh(\bar{h}_{mn}L), \qquad (2)$$

where $\bar{h}_{mn}$ represents the average power coupling coefficient. The full-vectorial field obtained by using the FEM is utilized to calculate C_{mn} and $\bar{h}_{mn}$ and finally the XT.

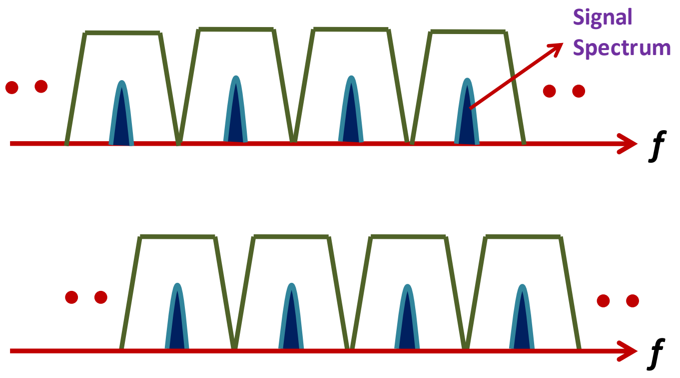

Fig. 1. Schematic of frequency-interleave transmission scheme.

2.2 Frequency interleaved (FI) scheme

Figure 1, illustrates the FI transmission scheme for short-reach MCF interconnect transmission system. The standard wavelength division multiplexed (WDM) grids are adopted in all spatial channels, where channel frequencies in one core are shifted from those in adjacent cores by half WDM channel spacing. The power coupling between adjacent cores is suppressed in FI scheme to improve the performance of MCF OI transmission system.

2.3 Simulation setup of MCF OI transmission system

The simulation setup of the BPSK modulated 8-core MCF OI transmission system is shown in Fig. 2. In the equivalent MCF OI module [4], the relative refractive-index difference between core and cladding is taken as 0.8%, and the radii of the cores are 5 μm. The spacing between adjacent cores is assumed to be 50 μm. The intercore XT due to bend is calculated using the coupled power theory and FEM [15] over a length 100 m at operating wavelength of 1.55 μm [4].

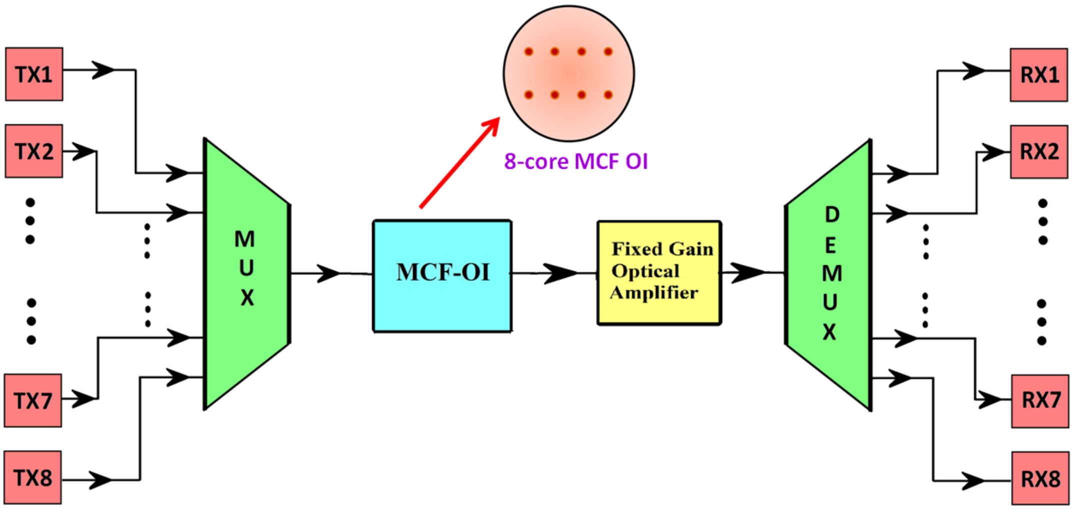

Fig. 2. Simulation setup for BPSK modulated 8-core MCF transmission system using FI scheme. TX: transmitter, RX: receiver, MUX: multiplexer, DEMUX: demultiplexer.

At the transmitter, eight channels of 10 Gbaud nonreturn-to-zero BPSK signals with channel spacing of 50 GHz are generated with pseudo random bit sequence (PRBS) of period $2^{15}-1$, which is then frequency shifted by half the WDM channel separation such that data bits are uncorrelated during transmission [4]. An individual transmitter comprises of continuous wave laser diode of linewidth 100 kHz and 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 [4]. Thus, the power coupling between adjacent cores is suppressed in FI scheme, and the performance of MCF OI transmission system can be significantly improved. Propagation loss and chromatic dispersion is compensated by 25 dB fixed gain optical amplifier with a Noise Figure of 4.5 dB and then demultiplexed. At the receiver, an electrical low pass filtering is applied and signals are then sampled by two samples per symbol by a finite impulse response (FIR) filter. The bit error probability (BEP) is finally obtained by an equalizer containing 15 tap FIR filters driven by constant modulus algorithm followed with a decision-directed least-mean squares method [4].

3. RESULTS AND DISCUSSION

Variation of BEP with and without FI for a 40 Gbps BPSK system is shown in Fig. 3. It can be observed from Fig. 3 that for a given OSNR, BEP decreases for FI scheme as compared to that of without interleaving the channel frequencies between adjacent cores. Forward error correction (FEC) limit having typical value 2.1×10^{-3} defining threshold sensitivity level of a BPSK receiver reduces by about 1.8 dB when FI scheme is used establishing improved error probability performance.

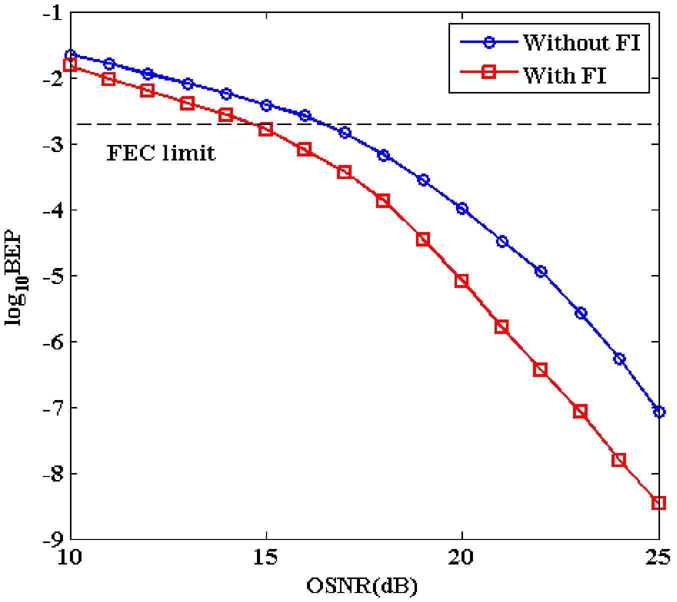

Fig. 3. BEP versus OSNR for BPSK modulated signals.

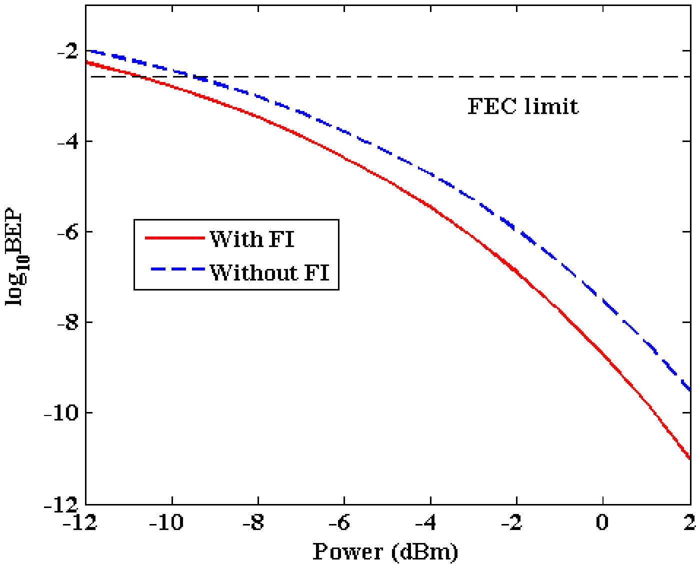

Fig. 4. BEP as a function of power for BPSK modulated signals.

The error probability performance of 8-core BPSK modulated OI transmission system as a function of power at 40 Gbps per channel is illustrated in Fig. 4. It can be seen from Fig. 4 that for a given power, BEP decreases for FI scheme as compared to that of without interleaving the channel frequencies between adjacent cores. Moreover, it can be observed from intersection point of FEC limit and BEP that sensitivity of a digital receiver reduces from –9.5 dBm without FI to –10.6 dBm with FI. Thus performance of MCF OI transmission system can be notably improved by suppressing the effect of intercore XT.

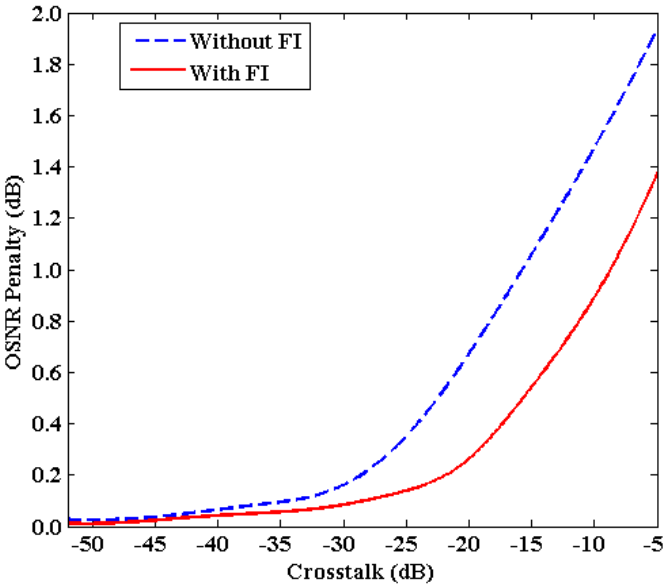

Fig. 5. OSNR penalty as a function of crosstalk for BPSK modulated signals.

The optical signal-to-noise ratio (OSNR) penalty due to XT for BPSK modulation format at the launch power of 0 dBm is plotted in Fig. 5. The OSNR penalty is compared to the case no FI at BEP threshold of 2.1×10^{-3}. It can be observed from Fig. 5 that for 40 Gbps per channel, sensitivity is -30.8 dB without FI at the FEC threshold of BEP while it increases to -24.6 dB in case of FI. It is worth noting that the FI scheme improves the allowable XT by 6.2 dB for BPSK signals.

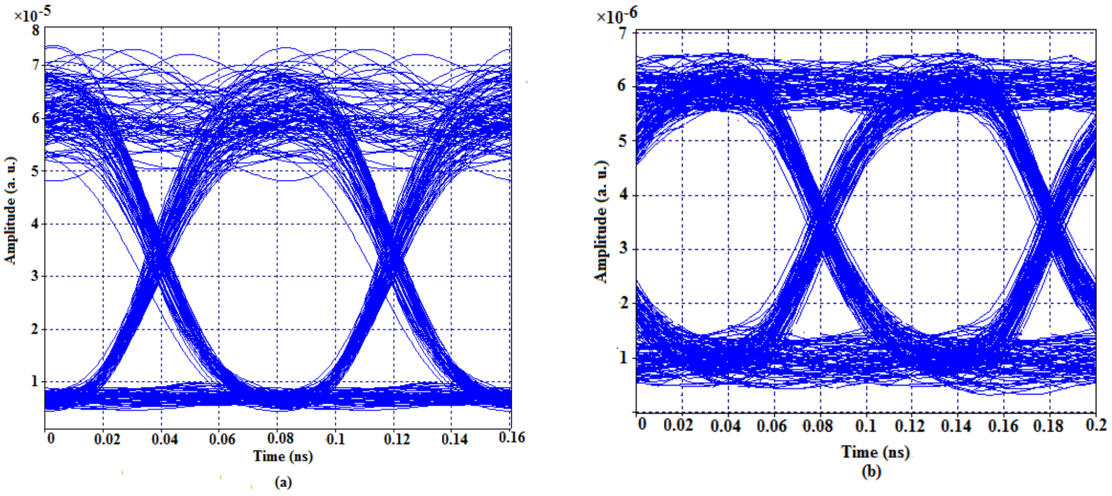

Fig. 6. Eye diagram of BPSK modulated MCF OI transmission system at 40 Gbps (a) without FI (b) with FI

The electrical eye diagrams with and without FI for BPSK modulated MCF OI transmission system are shown in Fig. 6. It can be observed from Fig. 6 that for BPSK communication system having FI scheme has widest open area of eye pattern. A better eye diagram opening degree corresponds to minimal intercore XT distortion and better OSNR performance of BPSK modulated MCF OI transmission system.

4. CONCLUSION

FI scheme is proposed to mitigate the negative effects of intercore XT in BPSK modulated MCF OI system. The 8-core MCF OI can provide higher spatial channel density compared with the standard single mode single core fibers and can also improve the power tolerance characteristics and suppressed nonlinear optical effects to realize high capacity transmission. Further, performances of BPSK with and without FI in a short reach MCF OI based communication are investigated by simulating eye diagrams. It is shown that crosstalk degradation in BPSK modulated MCF OI system can be drastically improved by using FI scheme. The present results demonstrate the strong applicability of the FI scheme to the future short-reach MCF interconnects transmission system.

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