Performance Investigation of Multicore Optical Interconnects for Data Centers

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Performance Investigation of Multicore Optical Interconnects for Data Centers

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Abstract— **Recently, there is increasing interest in the design of high-capacity data center optical interconnects (OICs) for data centers using space-division multiplexing (SDM) technique. This paper presents design concepts and performance evaluation of multicore fiber (MCF)-based OIC suitable for 50 THz data transmission. The OIC is designed with 7 cores, 24 wave length-division multiplexed (WDM) channels, and 320 Gbps dual-polarization (DP) 16 quadrature amplitude modulation (QAM) signaling per channel. Simulation results reveal that the OIC can support 10 km transmission when the intercore crosstalk level is less than -18.5 dB. The simulation results are obtained using VPIphotonics software and can be used as a guideline to design higher data rate SDM-OICs.**

Keywords—Space division multiplexing; Multicore fiber; Intercore crosstalk.

I. INTRODUCTION

Over the last few years, the exponential increase of the Internet traffic, essentially driven from emerging applications (e.g., social networking, streaming video, and cloud computing) has formed the requirement for more robust warehouse data centers. To deal with increasing traffic requirement, advanced optical networks are generally operating with hybrid multiplexing techniques based on a combination of wavelength-division multiplexing (WDM) and dual-polarization (DP) transmission (i.e., polarization multiplexing) and supported by space-division multiplexing (SDM) [1-3]. In fact, SDM technique opens a new direction to enhance the capacity of the optical transmission link by multiplexing the data in the modes of a multimode fiber, cores of multi single-mode core fiber, or a hybrid of both multiplexing schemes [4,5]. The performance of optical networks incorporating SDM technique may be degraded due to the presence of intermodal or/and intercore crosstalk and this subject has been investigated by different research groups [6,7]. The results reveal that crosstalk management and compensation are essential issues in high-capacity long-haul MCF transmission.

Using SDM-based optical interconnects (OICs) to transfer huge data between data centers has attracted increasing interest in recent years. In 2012, Sakaguchi et al. [8] achieved a 109 Tbps transmission over 16.8 km using 7-core SDM OIC operating with 97-WDM-PMD-QPSK (2×86 Gbps) signaling per core. Yuan et al. [9] derived a wavelength–dependent crosstalk formula for bi-directional MCF with unequal core pitches. Their simulation on SDM-WDM data center networks (DCNs) reveals that MCF core density and layout play an important role of optimizing various scales of DCNs. The same research group addressed the challenges facing the use of MCF-based SDM in data centers and proposed solution for crosstalk–suppressed resource allocation [10]. They proposed a bi-directional DCNs solution using single MCF for crosstalk reduction between adjacent cores. The transmission performance of the MCF link was investigated for different core arrangement and different number of cores (7, 19, 37, and 61) over transmission distance extending from few meters to 10 km. In 2019, Sakaguchi et al. [6] demonstrated the feasibility of bi-directional transmission over 13 km 39-core 3-mode fiber with a total of 228 spatial channels. These references do not address in details the effect of intercore crosstalk in MCF-based data center OICs and suggests this issue for further investigation as a future work. This paper addresses this issue for (7-core, 24-channel, 320 Gbps per channel) interconnect.

II. THE INVESTIGATED SDM-BASED OIC

A simplified schematic diagram of the SDM-WDM-DP OIC under investigation is shown in Fig.1. The system is composed of three main parts, namely transmitter unit, transmission link, and receiver unit.

A. SDM-WDM Transmitter

At the transmitter side, a bank of continuous wave (CW) semiconductor lasers is used and these lasers act as a source of unmodulated optical carriers for each of the WDM system. The number of these lasers equals the number of WDM channels per core and their frequencies are separated by a channel spacing Δf. The outputs of these CW lasers are combined using a WDM multiplexer to produce an optical waveform containing N_{ch} of equally-spaced unmodulated optical carriers. The resultant waveform is split equally into number of components by using $1{:}\,N_c$ optical splitter. Each component acts as unmodulated WDM carriers source for a specific core. This optical component is then modulated by the data to be transmitted by that core using "core WDM transmitter". The input and output ports of this unit are connected to SMFs. The outputs of the N_C WDM transmitters are coupled to the corresponding N_C cores of the MCF using SMF-MCF coupler.

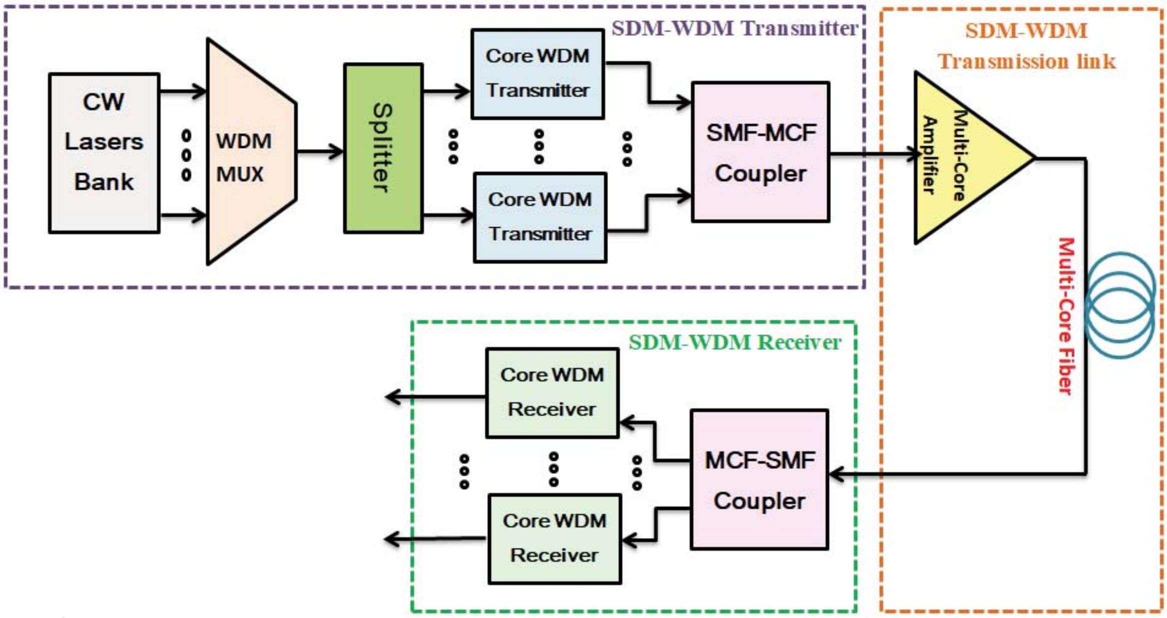


Fig. 1. Block diagram of SDM-WDM optical interconnect (OIC).

B. SDM Transmission Link

The generated optical SDM-WDM signal is amplified by the MCFA before launching it to the MCF. A MCF amplifier (MCFA) is inserted after the optical SDM-WDM transmitter unit to compensate the transmitter insertion loss and to boost the power of the optical signal launched to the MCF link. For short-length interconnect, no additional optical amplifier is used to compensate the MCF loss. The fiber end is connected to the SDM-WDM receiver.

C. SDM-WDM Receiver

The first stage of this receiver is a MCF-SMF coupler which acts as an interface between the input MCF and N_C output SMFs. Each out port of this coupler is connected to a single-core WDM receiver which uses an $1{:}N_{ch}$ optical demultiplexer to split the WDM signal received from the coupler output port in to N_{ch} components using frequency-domain filtering. The data is recovered from each demultiplexed channel using digital signal processing (DSP)-based coherent DP-QAM demodulator. DSP unit is used to perform DSP steps required in coherent single-carrier communication systems utilizing single-polarization or dual-polarization modulation formats. The unit is provided with a range of DSP algorithms to perform different procedures. Among these procedures, which are used in this works are

i. Compensation of chromatic dispersion (CD) and polarization-mode dispersion (PMD) of the fiber.

ii. Carrier frequency recovery (CFR) and carrier phase recovery (CPF).

iii. Matched-filter equalization.

iv. An adaptive multi-input multi-output (MIMO) time-domain equalizer (TDE).

III. Simulation Results

This section presents simulation results related to 7-core OIC. Each core supports a single–mode operation and carries 24-channel C-band WDM subsystem. Each WDM channel operates with 320 Gbps DP 16-QAM signaling. The main parameters values used in the simulation are listed in Table I. The SDM-OIC under investigation is simulated using VPIphotonics 9.8 software.

A. Design Concepts

i. The symbol rate for each WDM channel is $R_s = 40S$ (= 320 Gbps/ (2×4)). Therefore, WDM channel spacing Δf of 50 GHz is used. The thirteenth channel (Ch13) is taken as the central channel where the corresponding unmodulated laser operates at 193.1 THz frequency. The frequencies of other transmitter WDM laser span from 192.5–193.65 THz with 50 GHz channel spacing.

ii. The total bit rate R_{bT} carries by the SDM interconnect equals $N_C N_{ch} R_b = 7{\times}24{\times}320$ Gbps = 53.76 Tbps. Here N_C, N_{ch} and R_b stand for number of cores, number of WDM channels per core, and bit rate of each WDM channel, respectively.

iii. The spectral efficiency SE of the interconnect is given by $N_C N_{ch} R_b / N_{ch}\Delta f = N_C R_b/\Delta f = 44.8$ b/Hz. Note that the total optical transmission bandwidth ($= N_C\Delta f$) = 1.2 THz.

The primary simulation results revel that when the power of each unmodulated transmitter laser P_{LT} is set to 5 mW (=7 dBm), the SDM transmitter offers a total output power of 3.5 dBm. Thus the insertion loss of this transmitter equal $10\log(24 \times 5) - 3.5 = 17.3$ dB. Therefore, an optical amplifier may be inserted after the SDM transmitter to act as a booster amplifier to enhance

TABLE I. PARAMETERS VALUES USED IN THE SIMULATION

Subsystem	Component	Parameter	Value	Remark
SDM-WDM Transmitter	Lasers Bank	Laser power	5mW	
		Central frequency	193.1 THz	
		Channel spacing	50 GHz	
		Linewidth	100 kHz	
	Optical Modulation	Modulation format	DP 16-QAM	Optical IQ modulation based on Mach-Zehnder configuration.
		VΠ	5 V	
		Insertion loss	6 dB	
		Extinction ratio	35 dB	
	Optical Multiplexed /Demultiplexed	Insertion loss	5 dB (each)	Based on arrayed waveguide grating
	SMF-Multicore Coupler	Insertion loss	0	Ideal
		Coupling efficiency	100%	
Transmission Link	Multicore Fiber Amplifier	Gain	17.2 dB	Gain controlled mode of operation
		Noise figure	4 dB	
		Number of cores	7	
		Polarization dependenced	Neglected	
	Multicore Fiber	Number of cores	7	
		Length	10 km	
		Mode operator	Single mode	
		Loss	0.2 dB/km	
		Group velocity dispersion at 193.1 THz	17 ps/(nm.km)	
		Dispersion slope at 193.1 THz	0.075 ps/(nm^2.km)	
		Nonlinear index	2.6×10^{-20} m^2/W	
		Core effective area	80 μm^2	
	Multicore-SMF Coupler	Insertion loss	0	Ideal
		Coupler efficiency	100%	
SDM-WDM Receiver	Local Lasers Bank	Laser power	5 mW	
		Central frequency	193.1 THz	
		Channel spacing	50GHz	
		Linewidth	100 kHz	
	90° Hybrid	Insertion loss	0 dB	Ideal
	Photodiode	Responsivity	1 A/W	
		Dark current	0	
	Lowpass Filter	Order	4	
		Bandwidth	Baud Rate	

the power launched to the MCF. When a 17.3 dB-booster amplifier is used, the insertion loss of the SDM transmitter is completely compensated. The performance of the OIC under investigation is estimated under the assumption that the maximum acceptable bit error rate (BER), i.e. threshold BER "BERth" is 4.5×10^{-3}. This corresponds to 7% hard decision (HD) forward error correcting (FEC) code.

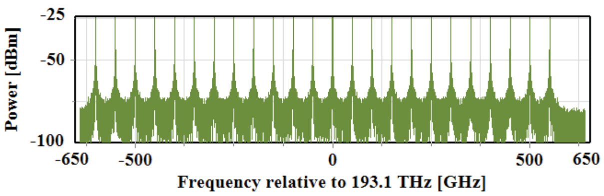
B. Performance Evaluation

The first point of investigation is related to an interconnect of length L= 10 km and uses 5 mw-lasers (i.e., P_{LT} = 7 dBm) with a booster optical amplifier of gain Gb = 17.3 dB. The central channel Ch13 is kept under observation during the investigation. The results reveal that almost errorless transmission is achieved when the crosstalk level CT is below -25 dB.

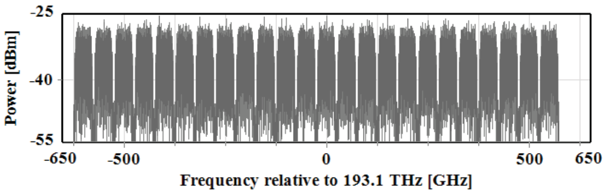
Figure 2 illustrates the optical spectra of the signals at different points of the system when the interconnect operates with -20 dB crosstalk. The figure also contains the constellation diagrams corresponding to Ch13 received in three different cores (core1, core5, and core7) which show an average BER of 1.0×10^{-3}.

The variation of BER with crosstalk level is displayed in Figs. 3a and 3b for 10 km- and 20 km-OIC, respectively. Investigating the results reveals that a BER less than the threshold (BER_{th} = 4.5×10^{-3}) is achieved when CT is less than -18.5 dB for both OICs.

Table II lists the dependence of BER on transmitter laser power PLT when the 10 km link operates with either -20 dB crosstalk or without crosstalk. Note the threshold BER can be achieved with P_{LT} = 2 mW when -20 dB crosstalk exists. This is to be compared with P_{LT} = 1 mW in the absence of crosstalk.



(a)



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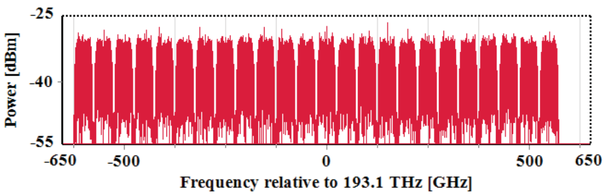

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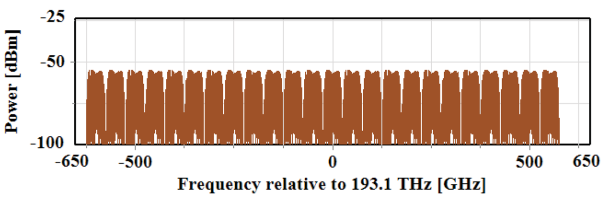

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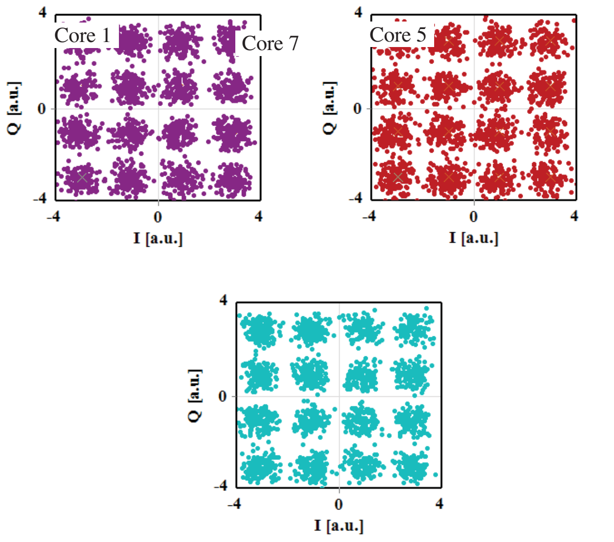
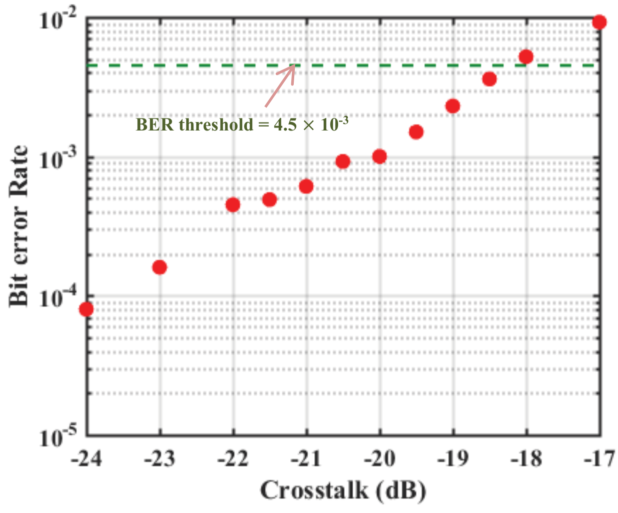
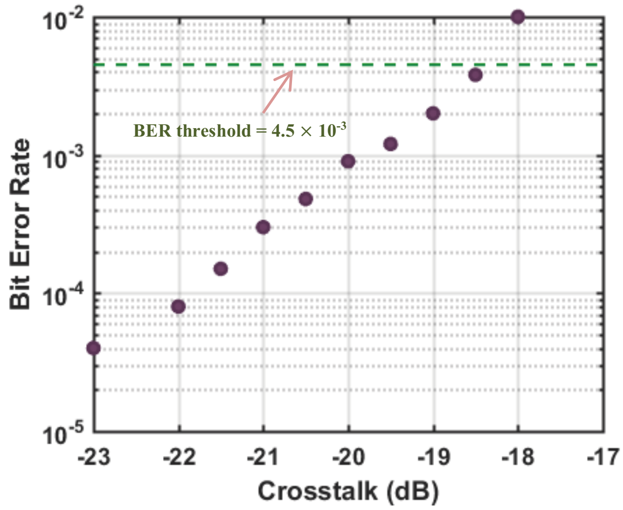


(e)

Fig. 2. Optical spectra and constellation diagrams related to (7-core, 24-channel, and 320 Gbps) OIC operating with -20 dB crosstalk (a) Unmodulated WDM optical carriers (b) Amplified SDM-WDM transmitter signal (c) Optical signal after 10-km transmission (d) Intercore crosstalk signal (e) Constellation diagrams corresponding to Ch13 received in three different cores (core1, core5, and core7).



(a)



(b)

Fig. 3. Variation of BER with crosstak level after transmission length of (a) 10 km (b) 20 km.

TABLE II. EFFECT OF TRANSMITTER LASER POWER ON BER OF 10 KM OIC

Transmitter Laser Power (mW)	Bit Error Rate	
	Without Crosstalk	With -20 dB Crosstalk
1	7.3×10^{-4}	6.5×10^{-3}
2	8.0×10^{-5}	4.0×10^{-3}
3	3.0×10^{-5}	2.0×10^{-3}
4	0	1.3×10^{-3}
5	0	1.0×10^{-3}
6	0	7.5×10^{-4}

The next step is to assess the effect of laser linewidth on interconnect performance. In this investigation it is assumed that all the semiconductor lasers used in the transmitter side and receiver side have an identical linewidth δf. For 10 km-OIC and negligible crosstalk, the receiver BER is 0, 1.9×10^{-3}, and 9.1×10^{-3} when δf = 0, 100, and 200 kHz, respectively, and assuming that (CFR+CPR) unit in the channel receiver is turned OFF. These values are to be compared with 1.0×10^{-3}, 8.6×10^{-3}, and 1.8×10^{-2}, respectively, when the interconnect operates with -20 dB crosstalk. Turning ON the (CFR+CPR) unit has strong impact on reducing the effect of finite laser linewidth. This is illustrated in Fig. 4 where the BER is plotted versus δf when the OIC operates in the presence of -20 dB crosstalk. The results reveal that the (CFR+CPR) unit is able to tolerate the effect of linewidth when δf is below 5 MHz. Note that lossless transmission is achieved when CT is negligible in this regime. The threshold BER is achieved when CT = -20 dB, at δf= 3 MHz.

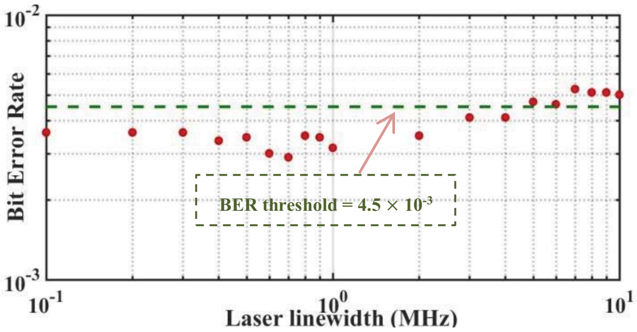


Fig. 4. Dependence of BER on laser linewidth after turning ON (CFR+CPR) unit for 10-km OIC operating with -20 dB crosstalk.

The gain of boost optical amplifier G_b affects the maximum transmission distance L_{max} offered by the interconnect while keeping the receiver BER less than the threshold level (= 4.5×10^{-3}). Many simulation tests are performed to determine the dependence of L_{max} on G_b. In each test, the value of G_b is fixed while the interconnect length L is increased and the associated BER, BER (L), is recorded. The maximum reach L_{max} corresponds to the value of L which makes BER (L) = BERth. Summary of the simulation results are depicted graphically in Fig. 5 where the values L_{max} are given for different levels of amplifier gain. The results are reported for both absence and presence of -20 dB crosstalk. Note that L_{max} increases almost linearly with G_b for both cases with a slope ≈ 5 km/dB This value corresponds to 1/α where α = 0.2 dB/km which is the value of the loss of the MCF used in the simulation. Thus 1 dB increase in the amplifier gain will support 5 km extra interconnect length. When $G_b = 15$ dB, $L_{max} = 110$ and 125 km in the presence and absence of crosstalk, respectively.

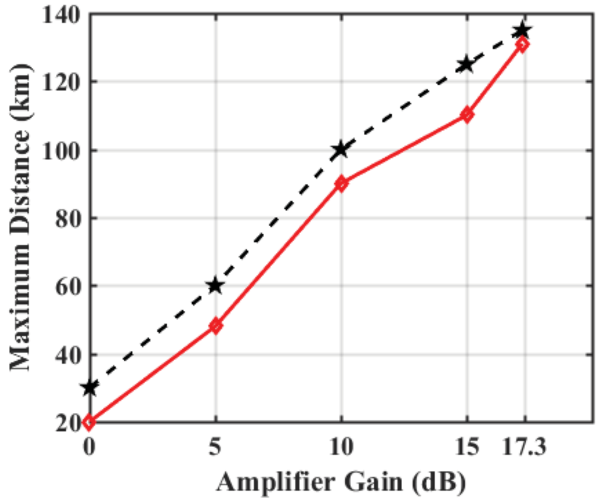


Fig. 5. Effect of amplifier gain on maximum transmission distance for OIC operating without and with -20 dB crosstalk.

IV. Conclutions

The performance of 50 Tbps (7 cores, 24 WDM channels, 320 Gbps DP-16 QAM per channel) OIC has been reported in the presence of intercore crosstalk. The main conclusions drawn from this simulation are

i) A 10 km-OIC can support the 50 Tbps transmission when the intercore crosstalk level is below -18.5 dB.
ii) Using 15 dB-booster amplifier will enhance the maximum reach to 110 km when CT= -20 dB.
iii) Turning ON the receiver (CFR+CPR) unit enables the designed SDM-OIC to support transmission of 50 Tbps data over 10-km distance when the laser linewidth is below 5 MHz.

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