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Performance of Reconfigurable Free-Space Card-to-Card Optical Interconnects under Atmospheric Turbulence

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Abstract—**Free-space based card-to-card optical interconnects are promising candidates for the provision of parallel high-speed and reconfigurable interconnectivity in data-centers and high-performance computing clusters. However, the atmospheric turbulence may degrade the interconnect performance due to the beam wander, signal scintillation, and beam broadening effects. In this paper, the experimental investigation of the impact of both moderate and comparatively strong atmospheric turbulence on the bit-error-rate (BER) performance of our proposed reconfigurable free-space card-to-card optical interconnects is presented. Experimental results show that the BER performance does suffer power penalties of ~0.5 dB and ~1.6 dB at BER of 10^{-9} under moderate and strong levels of turbulence respectively.**

Keywords-free-space optical interconnects, atmospheric trubulence, reconfigurable optcail interconnects.

I. INTRODUCTION

The transistors have scaled down to the deep sub-micrometer region and millions of transistors can now be densely integrated in the state-of-art CMOS processes [1]. Therefore, the computing capability supported by a single chip has increased considerably. In addition, the multi-core architecture has been widely deployed for high-performance computing and in data-centers [2]. Consequently, ultra high-speed interconnects between chips, cards, as well as racks are highly demanded. Sustained improvement in multi-channel on-chip and on-board interconnection has been demonstrated using the Si photonics technology [3, 4]. However, the capacity of interconnections between cards and racks has not kept to the pace. Conventionally, copper based cables are being used for data transmission between cards and racks. However, electrical technologies are impractical for future high-throughput interconnects due to the fundamental limitations, including the electric power consumption, heat dissipation, transmission latency and electromagnetic interference [5].

To overcome the electrical bottleneck, the use of parallel short optical links has been proposed and intensely studied, including the polymer waveguide based [6], the multi-mode fiber (MMF) ribbons based [7], and the free-space based schemes [8]. However, the MMF ribbons and polymer waveguide based point-to-point architecture is inherently non-reconfigurable, and the flexibility in dynamically interconnecting electronic cards is very limited.

On the other hand, the free-space based card-to-card optical interconnects have the capability of switching the signal beams along different directions via a link selection block, thus adding significant flexibility to the communications between various cards [8]. In previous studies, we have proposed and experimentally demonstrated a reconfigurable optical interconnect employing the MEMS-based steering mirror as a link selection block with high efficiency, wide tuning range, and with a simple tuning mechanism [9]. A proof-of-concept 3 × 3 10 Gb/s PCB-based interconnect demonstrator has been developed, demonstrating both port-to-port and board-to-board reconfigurability with a bit-error-rate (BER) of ~10^{-6} over up to 30 cm card-to-card distances [9].

However, the performance of free-space based optical interconnects is normally degraded by the turbulence caused by heat airflows existing in typical interconnection environments [10]. The turbulence may lead to refractive index fluctuations along the optical path and effects such as scintillation of the received signal, beam wander, and beam broadening. These may then result in the increase of system BER and degradation in the receiver sensitivity. In this paper, the impact of turbulence on our proposed high-speed reconfigurable free-space card-to-card optical interconnect architecture is experimentally investigated. Results show that compared with the scenario without turbulence, with moderate turbulence, the BER performance of the proposed interconnect is slightly worse for the same horizontal distance between the transmitter and receiver cards, and the receiver sensitivity at BER < 10^{-9} is degraded by ~0.5 dB. When the turbulence intensity is comparatively strong, the power penalty is found to be ~1.6 dB.

II. PROPOSED RECONFIGURABLE FREE-SPACE CARD-TO-CARD OPTICAL INTERCONNECT ARCHITECTURE AND THE IMPACT OF TURBULENCE

A. Architecture of Proposed Reconfigurable Free-space Card-to-Card Optical Interconnect

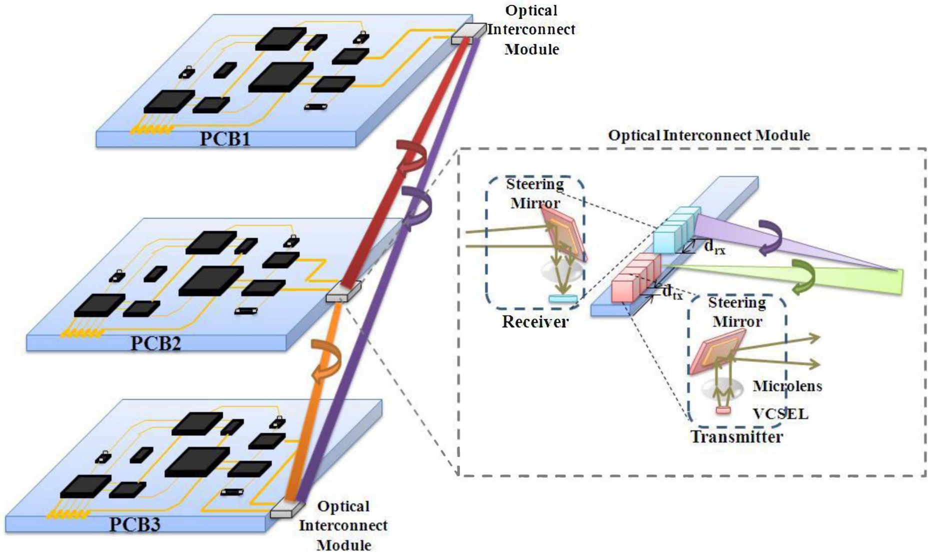

Fig. 1 Proposed reconfigurable free-space card-to-card optical interconnect architecture.

The proposed reconfigurable free-space card-to-card optical interconnect architecture is shown in Fig. 1, where a dedicated optical interconnect module is integrated onto each electrical card (typically a printed-circuit-board (PCB)) [9]. This optical interconnect module mainly consists of a VCSEL array, a photodiode (PD) array, two micro-lens arrays, and two MEMS-based steering mirror arrays. At the transmitter side, the electrical signal from the attached card first modulates the VCSEL optical beam, and then the modulated optical beam is collimated by the associated micro-lens. To minimize the VCSEL beam divergence, the distance between the VCSEL and micro-lens is made equal to the focal length of the micro-lens. Subsequently, the optical signal is steered towards the corresponding receiver with a steering MEMS mirror element. At the receiver side, the modulated optical signal is appropriately steered with another MEMS mirror element and focused onto the corresponding PD element. With analog steering mirrors being used, the transmitted optical beam can dynamically be steered along arbitrary directions, realising adaptive optical interconnection with receivers at arbitrary locations within a communication range. In addition, inside a typical rack, the electrical cards are placed in parallel and the free-space link may be blocked if the optical interconnect modules are placed at the same position with respect to the adjacent cards. Since the proposed optical interconnect module is small in size, this possible blockage problem can be avoided by installing the module at different positions of the cards, as shown in Fig. 1.

It has been found that the major limiting factor of proposed optical interconnect scheme is the Gaussian beam divergence while propagating in the free-space [9]. Due to the beam expanding with transmission distance, less signal power can be collected at the receiver side and severe inter-channel crosstalk is induced, leading to a degraded BER performance. In previous studies [9], this crosstalk issue has been suppressed by using a receiver MEMS steering mirror array with a large spacing between the elements. This is because (i) the intensity of a Gaussian beam drops rapidly with the radial distance from the centre of the beam and (ii) the crosstalk signal induced by a Gaussian beam illuminating a MEMS element does not strike the other MEMS elements at their optimum incidence angles that maximize the optical coupling efficiency and signal detection by their associated PD elements.

B. Impact of Turbulence on Free-space Optical Interconnects

In free-space card-to-card optical interconnects, modulated optical signal radiated from the transmitter card directly propagates through the air to the destination card [8]. As shown in Fig. 2, air turbulence normally exists due to the high temperature of the chips or due to the heat dissipation fans, which mixes hot air with cold air [10]. Hot air turbulence may lead to refractive index fluctuations along the optical path and result in effects such as scintillation in the received signal, beam broadening, as well as beam wander [11]. Therefore, the received signal power of free-space optical interconnect may fluctuate rapidly, the beam center may be displaced from the corresponding receiver element, and the system performance may be degraded.

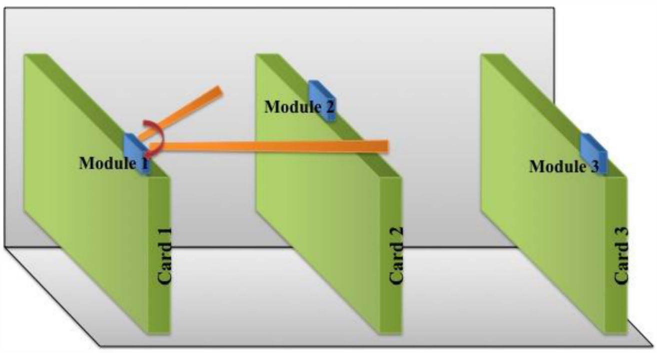

Fig. 2 Typical free-space optical interconnect environments with air turbulence.

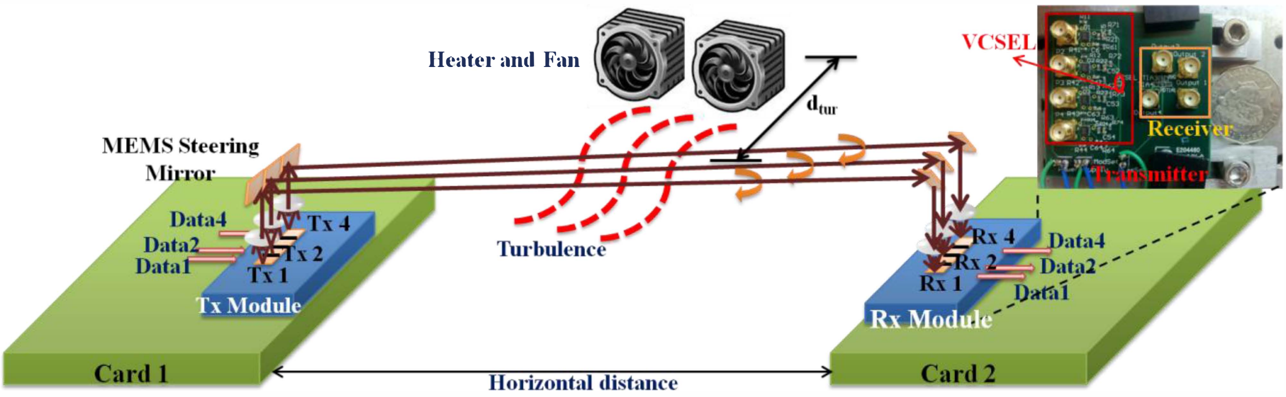

Fig. 3 Experimental setup to investigate the impact of turbulence on the proposed optical interconnect architecture.

In free-space optical communications, the irradiance fluctuation (log-intensity fluctuation) due to scintillation effect caused by turbulence is normally described by the Rytov variance. For a plane wave, it can be expressed by [12]

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (1)$$

where k is the wave number, C_n^2 is the refractive index structure parameter, and L is the propagation distance in free-space. In a practical system, the scintillation can be seen as a noise source at the receiver side and the noise variance can be described as [13]

$$\left\langle \sigma^2 \right\rangle = 0.31 C_n^2 k^{7/6} L^{11/6} \quad (2)$$

III. EXPERIMENTS AND DISCUSSIONS

Experiments have been carried out to study the impact of air turbulence on the proposed free-space reconfigurable optical interconnect architecture and the setup is shown in Fig. 3. For data transmission, the setup is similar to that described in [9]. An optical interconnect module was designed, fabricated and integrated onto a PCB, as displayed in the inset of Fig. 3. Specifically, a 1 × 4 VCSEL array, the corresponding VCSEL driver circuits (4 packaged drivers), a 1 × 4 PD array and 4 trans-impedance amplifier (TIA) chips were integrated onto a single small-size PCB. A micro-lens array was then aligned and mounted on top of the VCSEL array and the PD array to collimate the VCSEL beams and focus received optical beams onto the active windows of the PD elements. Each of the micro-lens arrays was attached to an XYZ translational stage, and the distance between the VCSEL/PD plane and the lens was equal to the focal length. Furthermore, separate MEMS steering mirror chips with < 5 ms large angle point-to-point switching time were used to switch the optical beams to various cards. The MEMS mirror chips were attached to XYZ translational stages and dynamically steered by changing the voltage applied to their activators.

Atmospheric turbulence was intentionally introduced into the interconnect architecture with a heater and two electrical fans in the experiments. The temperature of the hot air flow from the heater was ~60 °C. The heater and fans were placed at almost the same height as the interconnect link and the horizontal distance between the link and the turbulence source was ~50 cm to emulate moderate impairment.

In the experiment, an 850 nm VCSEL array with a 250 µm pitch was used and wire-bonded onto the PCB. The average divergence angle of the VCSEL beams was ~17° and varied slightly among the 4 elements. The maximum bit rate of the VCSEL driver chips was 11.3 Gbps. The VCSEL and PD micro-lens arrays had a pitch of 250 µm, a clear aperture of ~ 236 µm and a focal length of ~ 656.5 µm. The PD array had also a pitch of 250 µm. Each PD element had an active aperture diameter of 60 µm and a responsivity of ~0.61 A/W at 850 nm, and was wire-bonded onto a TIA chip. The 3-dB bandwidth of the TIA was ~12.6 GHz and its differential trans-impedance was ~5 kΩ.

The bit rate of each channel was set to 10 Gb/s with on-off-keying (OOK) modulation and the output power from each VCSEL was set to 2 mW. At the receiver side, same as previous experiments and mentioned in Section 2, 2.5 mm spacing between the MEMS steering mirrors was chosen to suppress the crosstalk. In addition, the size of the MEMS mirror was larger than the pitch of VCSEL and PD arrays, so only three out of the four available channels were used (the third VCSEL and PD elements were not used).

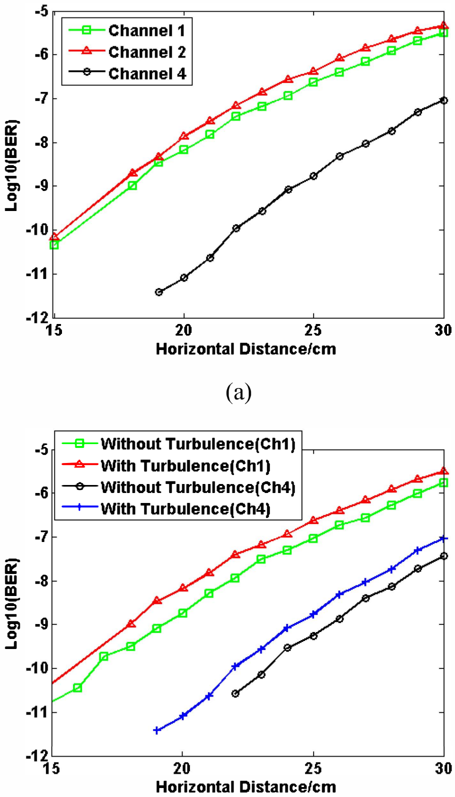

Fig.4 Experimental results on BER with respect to the distance between the transmitter and receiver PCBs. Bit rate = 10 Gb/s and transmission power from each VCSEL = 2 mW. (a) performance with moderate turbulence; and (b) performances with and without turbulence.

In the first measurement, VCSEL element n in the array was interconnected to PD element n. With the purposed introduced atmospheric turbulence along the free-space optical interconnect signal propagation path, the measured BER with respect to the horizontal distance between the transmitter and receiver optical modules is shown in Fig. 4(a). Here, it should be noted that the horizontal distance is smaller than the total optical transmission distance from the VCSEL element to the corresponding PD element. It is clear from Fig. 4(a) that the BER of all channels increases with the increasing horizontal distance between the VCSEL and PD PCBs. This is because the diameter of the Gaussian beam increases with the propagation distance, resulting in a smaller collected signal power (the transmission power from VCSELs was fixed) and more inter-channel crosstalk power being coupled, thus degrading the BER performance. It can also be seen that channel 4 performs the best while channel 2 has the worst performance. This can be explained by the fact that channel 4 is further away from the other 2 channels and it is less vulnerable to inter-channel crosstalk.

In Fig. 4(b), the BER performance of the proposed optical interconnect architecture (channels 1 and 4) with and without the impact of turbulence is compared. It is clear from the figure

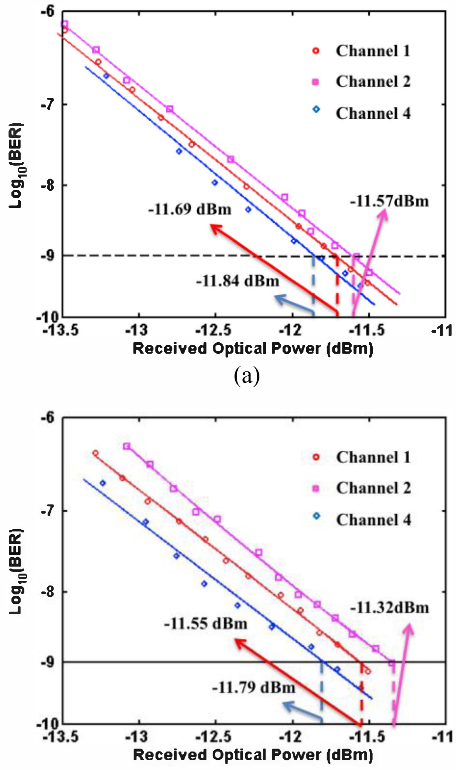

Fig. 5 BER versus received optical power for the three optical interconnects. Horizontal distance between the transmitter and receiver modules is (a) 20 cm; and (b) 25 cm.

that the turbulence slightly degrades the interconnect BER performance of both channels.

Fig. 5 shows the measured BER versus the received power when the horizontal distance between the transmitter and receiver PCBs was 20 cm and 25 cm, respectively. The

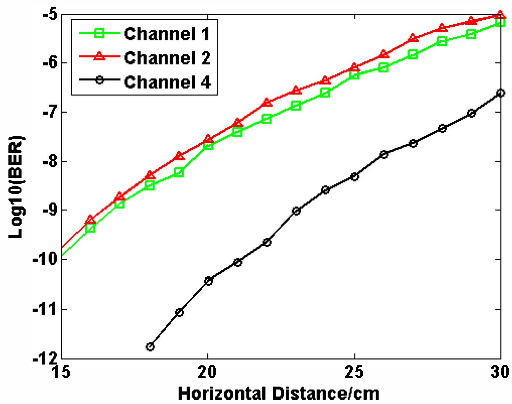

Fig.6 Experimental results on BER with respect to the distance between the transmitter and receiver PCBs (comparatively strong turbulence). Bit rate = 10 Gb/s and transmission power from each VCSEL = 2 mW.

received power was varied in the experiments by changing the VCSEL elements transmission power. It can be seen that channel 4 always has the best receiver sensitivity (defined as BER < 10^{-9}), consistent with the results shown in Fig. 4. In addition, it is noticed that the receiver sensitivity degrades when the horizontal distance between the transmitter and receiver PCBs increases. This is because that Gaussian beam expands while propagating in the free-space, leading to stronger inter-channel crosstalk. Compared with results of the optical interconnect system without turbulence [9], Fig. 5 indicates that the receiver sensitivity is degraded by ~0.5 dB.

In some practical racks, the temperature can be as high as 75 °C. The electronic components on the cards even have a higher temperature and the speed of airflow can be as high as 6 m/s [14]. Therefore, the air turbulence resulted in might be comparatively strong. To further investigate this impact, the distance between the heater and the optical interconnect channel in the experiments was reduced to ~30 cm to purposely introduce stronger turbulence. The bit rate was still set to 10 Gb/s for each channel with 2 mW transmission power. The measured BER with respect to the horizontal distance between the transmitter and receiver PCBs is shown in Fig. 6. Compared with the results shown in Fig. 4(a), it is clear that the BER performance is worse for all working channels when the turbulence is stronger. When the horizontal distance between the transmitter and receiver PCBs was 25 cm, the receiver sensitivity at BER < 10^{-9} was also measured. For Channels 1, 2, and 4, the sensitivity was ~-10.55 dBm, ~-10.25 dBm, and ~-10.64 dBm, respectively. Compared with the results without turbulence [9], the degradation in sensitivity is ~1.6 dB.

IV. Conclusions

In this paper, the impact of atmospheric turbulence on our proposed reconfigurable free-space card-to-card optical interconnect architecture has been experimentally investigated. It was shown that the turbulence may lead to the received signal power fluctuation, beam broadening, and beam wander. Experimental results have shown that the interconnect BER performance suffers a power-penalty of ~0.5 dB under moderate intensities of turbulence and this increases to ~1.6 dB when the link is subjected to strong levels of turbulence.

Acknowledgment

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