

Free-space Reconfigurable Optical Interconnects for the Next Generation Datacenters

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Abstract—Micromirror-based free-space optical interconnects are proposed with operation principles, including vertical input/output, reconfigurability, and alignment, being demonstrated. The proposed system enables reconfigurable, dense channels for next-generation datacenters based on many slow channels, potentially achieving >1 Tbps/mm bandwidth density with a total bandwidth of >10 Tbps.

Keywords—optical interconnects, micromirror arrays, alignment

I. INTRODUCTION

By 2028, datacenters are expected to consume 6.7-12 % of the United States electricity [1]. This energy crisis has driven optical interconnects innovation, but they are yet to cross the threshold to replace electrical wires, which marks simultaneous achievement of <1 pJ/bit, >100 Tbps/socket, and <\$0.10/Gbps [2]. Today's commercial optical interconnects all use optical fibers as optical channels, and the maximum number of channels demonstrated with optical fibers is smaller than 500, which introduces the trade-off between energy consumption and total bandwidth — In order to achieve 100 Tbps/socket, 800 Gbps/channel is the minimal requirement, increasing the energy consumption. On the other hand, using slow channels (i.e., <10 Gbps/channel) is limited by the total achievable bandwidth of 1-5 Tbps due to the channel number limits [3], [4], [5].

We propose a free-space optical interconnect system, without optical fibers, formed by a pair of micromirror arrays as reconfigurable photonic channels. The free-space architecture enables massive parallelism and reconfigurability, expected to realize optical interconnects targeting >10,000 channels.

II. SYSTEM DESCRIPTION

We propose the concept illustrated in Fig. 1 (a), based on the commercialized fiber optic switch concept [6], [7], [8] but with free-space optics. As free-space beams can cross without interference, a large number of dense channels are possible in contrast to fiber-based interconnects. A similar concept has been provided earlier with a smaller number of channels and large components [9]. In our proposed system, the input and output beam is perpendicular to the chip, which is made possible with

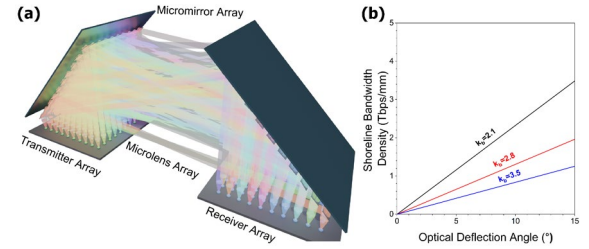


Fig. 1. (a) Proposed chip-to-chip optical communication, and (b) achievable shoreline bandwidth density, assuming 10 Gbps/channel.

a two-micromirror-array configuration. The proposed system is synergetic with micro-LED-based optical interconnects [3], [5], as it removes fiber coupling and enables massive parallelism not limited by the number of fibers within a fiber bundle.

To ensure all pixels can be connected to any pixel within the chip, the minimum size of the chip, s , obeys the following [6]:

$$s \approx \frac{Nk_b^2\lambda}{\pi\alpha\sqrt{\cos\beta}} \quad (1)$$

, where N is the number of channels, k_b is the tunable parameter indicating maximum acceptable crosstalk, λ is the wavelength, α is the maximum optical deflection angle, and β is the incidence angle of the beam. The k_b values can be $k_b=3.5$ for -40 dB (e.g., for long-reach), $k_b=2.8$ for -30 dB (e.g., for pulse amplitude modulation 4-level short-reach), and $k_b=2.1$ for -20 dB (e.g., for on-off keying short-reach) maximum acceptable crosstalk. Thanks to the free-space optics, $\lambda=450$ nm or shorter wavelength can be used. The calculation shows that the MEMS deflection angle of $\pm 11.5^\circ$ (i.e., $\alpha \approx 0.4$) is sufficient to fit ~3,000 channels into 1cm shoreline, which leads to 30 Tbps bandwidth and 3 Tbps/mm bandwidth density even if each channel is operating at 10 Gbps.

Fig. 1(b) shows the bandwidth density derived from Eq. (1) by calculating $N/s \times (\text{Bandwidth per Channel})$. The results reveal that the system can theoretically achieve >1 Tbps/mm shoreline bandwidth density with a modest MEMS deflection angle of $\pm 5^\circ$, and 10 Gbps/channel bandwidth.

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III. EXPERIMENTAL RESULTS

A. Vertical Input/Output and Reconfigurability

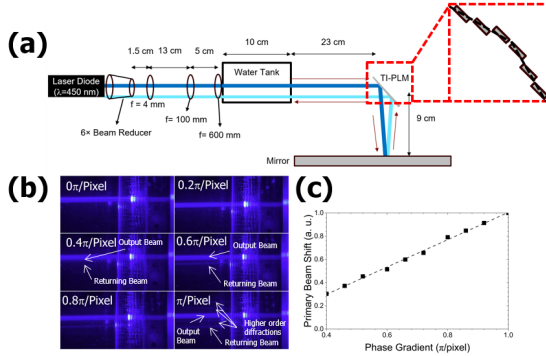


Fig. 2. Reconfigurable vertical input/output of the micromirror system.

Fig. 2 (a) shows the demonstration setup. A 450 nm solid-state laser diode was used as a light source, which is incident to Texas Instruments phase-light modulator (TI-PLM) [10] at 45° incidence angle. The piston-motion mirrors are configured with two opposite-steering blazed grating patterns that converge at the center. The light is reflected twice by TI-PLM, effectively emulating the two-micromirror-array configuration in Fig. 1 (a). To visualize the vertical beam path, a water tank is used as a scattering material. Fig. 2 (b) visualizes that the returning beam is parallel to the original beam, as the two-micromirror-array configuration cancels the beam-steering angle introduced by the first mirror. This vertical input and output enables the size of the receiver to be minimized, reducing the energy consumption [11].

B. One-to-Many Mapping and Reconfigurable Alignment

Fig. 1 (b) shows that the optical deflection angle is crucial for a large shoreline bandwidth density. Although tip-tilt mirrors can achieve large deflection angles, analog tip-tilt mirrors are yet to be commercially available. On the other hand, piston mirrors are becoming readily available (e.g., Texas Instruments or Silicon Light Machines), but the maximum deflection angle is limited. For TI-PLM with 45° angle of incidence in x-direction, $\theta_x \approx \pm 1.71^\circ$, $\theta_y \approx \pm 1.19^\circ$ at $\lambda=450$ nm, which translates to ~ 240 Gbps/mm with -40 dB maximum acceptable crosstalk. We suggest leveraging the additional advantage of piston mirrors (i.e., enabling complex beam patterns such as one-to-many mapping) to enhance the capabilities of the system.

Fig. 3 demonstrates the mapping of one input channel to five output channels. Fig. 3 (a) shows the setup, where only the beam with net diffraction orders of 0 (i.e., parallel to the original beam after the 2nd reflection at TI-PLM) appears on the camera. Binary phase grating patterns are utilized to demonstrate one-to-many mapping, utilizing $+1$ and -1 diffraction orders in both X and Y directions. Fig. 3 (b) and (c) show the peak intensities and the camera images of each diffraction order, enabled by the variations of the binary phase grating with 10-pixel periods, pattern 0 indicating the symmetric pattern. It can be seen that arbitrary intensities can be achieved with fine-tuning. It is worth noting that comparing pattern 0 and pattern 12 clearly shows the alignment capabilities of the system. Due to system imperfections, the symmetric binary phase grating pattern at pattern 0 shows low intensity at $+1, -1$ diffraction order (i.e., right bottom side of the camera image). In pattern 12, the

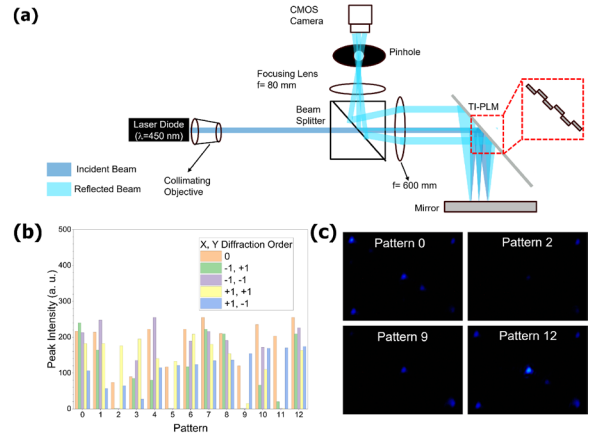


Fig. 3. One channel-to-five channel mapping and fine-tuning of intensities.

patterns are reconfigured so that the $+1, -1$ diffraction order intensity increases, and the four diffraction orders have a more uniform distribution. This reconfigurability will significantly reduce the alignment challenges.

IV. CONCLUSION

A fiber-free optical interconnect system is proposed and its basic principles are demonstrated with a single light source. The results show the micromirrors' potential to replace optical fibers and achieve unmatched parallelism of optical interconnects.

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