Co-Packaged Optics With Multimode Fiber Interface Employing 2-D VCSEL Matrix

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Abstract—We propose and demonstrate a mode-division-multiplexed transmitter by employing a VCSEL-based 2-D matrix and a multi-plane light converter (MPLC). The triangular matrix light spots from VCSELs are designed with a 250-µm pitch in both x- and y-directions for scalable and low-loss mode multiplexing. The VCSELs are directly modulated by co-packaged BiCMOS drivers on a silicon interposer, fabricated on a wafer level. The MPLC is utilized to form seven phase masks to convert the individual Gaussian beams to multiplex Hermite-Gaussian modes, which can be coupled into a multi-mode fiber. In the demonstration, we packaged ten 10-G class VCSELs with the drivers, and the form factor of the co-packaged optics is 10-mm × 10-mm. With the fan-out evaluation board, the sub-module is characterized for short and long transmissions by multiplexing the ten directly modulated outputs from VCSELs. The testing results indicate 200-Gb/s capacity over 100-m MMF with direct detection and 28-km few-mode fiber with coherent detection.

Index Terms—Optical interconnections, mode division multiplexing, silicon interposer, VCSEL, co-packaged optics.

I. INTRODUCTION

EXPOENTIAL growth in cloud services drives the need for high bandwidth density optical interconnects supporting a variety of length scales from a few meters to tens of km for the intra- and inter-data center applications [1]. By increasing optical interconnecting channels, the capacity of the link meets the growth trend. In short-reach interconnects, parallel optical interconnects usually employ fiber ribbons, with multiple fiber channels, to increase the interconnecting bandwidth [2]. While multiple parallel fibers, either single-mode or multi-mode, are widely applied within buildings, wavelength-division multiplexed (WDM) systems aggregate single fiber capacity for longhaul transmission by utilizing different wavelength carriers. However, in both scenarios, the number of channels is approaching their limits. The fiber connector of parallel optics becomes bulky and needs to be carefully designed [3]. In the WDM system, the usable wavelength channels, ranging from 1300 nm to 1700 nm, are limited by the amplification technologies [4].

In addition to the WDM system, the use of multiple spatial channels by space-division multiplexing (SDM), supported by a single fiber, is another physical dimension [5]. The multiple spatial modes, supported by multi-mode fiber (MMF) [6] and few-mode fiber (FMF) [7], [8], allow for orders of magnitude increase in capacity. These fibers maintain a standard fiber footprint with a 125-µm cladding diameter, which would enable very high data rate densities. Compared to multi-core fiber (MCF), MMF has a much higher space utilization efficiency and can increase the mode count by simply enlarging the fiber core size. Utilizing the spatial channels to transmit parallel data signals in MMF, SDM becomes a promising candidate to support the increased capacity of optical networks.

To date, almost all SDM transmission demonstrations use sophisticated transmitters, consisting of externally-modulated lasers (EMLs), optical IQ modulators, and electrical amplifiers [9], [10]. Due to these discrete devices, the total power consumption and hardware cost become high, making it far from practical usage. Besides, the 1-D fiber array used in the system limits the scalability of spatial channels. Vertical-cavity surface-emitting laser (VCSEL) is a preferable light source in optical interconnects due to its low power consumption, low cost, and direct modulation capabilities. Moreover, in contrast to edge-emitting lasers, VCSELs have significant advantages for 2-D matrix integration. Multi-mode VCSELs have been designed corresponding to the seven-core MCF, but no mode channel has been utilized [11]. Single-mode and long-wavelength VCSELs are developed [12], operating with high bandwidth, which can be
employed as the light source for the mode-division-multiplexed transmitter (MDM-Tx). A Multi-plane light converter (MPLC) has been proposed as the mode multiplexer, and 14 masks are used to convert 45 collimated beams on a linear array [13]. In the conversion, an arrangement in form of a triangular matrix is preferred for higher-order mode multiplexing, as half of the masks can be saved to reduce the reflection losses [14]. However, it is challenging to package the VCSELs with two-dimensional (2D) configuration with standard wire bonding technology.

There has been increased interest in co-packaged optics (CPO) technology, where optical components are integrated with their electronic parts in ever-smaller form factors, highly improving the performances and power efficiency [15]. Among different packaging platforms, silicon proves to be a good candidate for the high bandwidth density transceivers [16], since the lithographic patterning and wafer-level process can be employed, which allow for precise definition and low cost in the mass production. In addition, the silicon, having a high thermal conductivity, enables flexible and excellent thermal dissipation [16]. A triangular 2D matrix of VCSELs can be packaged with their drivers with the particular electrical traces design on the silicon interposer.

In this paper, we present a MDM-Tx prototype to equip CPO with MMF/FMF interface for high spatial density optical interconnect, extended from our previous ECOC paper [17]. Ten single-mode C-band VCSELs and three 4-channel BiCMOS drivers are flip-chip bonded on a silicon interposer and assembled with a fan-out high-speed printed circuits board (PCB). The MDM-Tx supports ten spatial modes by directly interfacing a 2-D 10G-class VCSEL matrix arranged in a triangular spot layout with an MPLC. The output power from the Tx varies from $-5$ dBm to $-9$ dBm for different modes. With on-off keying (OOK) modulation, all signals in mode channels are modulated at 20 Gb/s. By employing the 10-mode MDM, we demonstrate a line rate of 200-Gb/s transmission over 100-m graded-index (GI) OM3 MMF using direct detection and 28-km 10-mode GI-FMF using coherent detection.

This paper is organized as follows. Firstly, the concept of employing MDM to enhance optical interconnect density for high throughput CPO is illustrated. Using silicon interposer and VCSELs-based 2D triangular spots, CPO with MMF interface is demonstrated. Secondly, detailed fabrication and packaging procedure is present including lithographic and flip-chipping steps. Finally, the MDM-Tx is evaluated with 200-Gb/s transmission over 100-m MMF for intra-data center interconnect and 28-km FMF for inter-data center interconnect.

II. SCHEMATICS OF MDM-TX

An MPLC can convert between two sets of orthogonal optical beams through a series of phase planes separated by free space propagation [18], [19], which is used as the spatial mode multiplexer (SMUX). Low-loss mode (de)multiplexing can be achieved with sufficient phase planes to secure broadband and adiabatic transitions from Gaussian beams to spatial modes, which is essential to achieve low insertion loss and low mode-dependent loss. Similarly, the MPLC is implemented to convert the outputs of single-mode VCSELs in the MDM-Tx. Fig. 1(a) shows a design example of a 10-mode SMUX converting a linear array of 10 equally spaced Gaussian beams into 10 Hermite-Gaussian (HG) modes. The device has two mappings: (1) from the linear array into a triangular matrix spots layout and (2) from the triangular matrix spots layout to the HG modes. During the conversion, the sum of intensities of all modes is given according to each step in the Fig. 1(b). It is found that conversion from the triangular matrix spots layout to the HG modes requires the least number of planes due to the symmetries of the modes and the 2D spot arrangement and can scale to 200–1000 modes [14], [20]. Conversion from other matrix layout requires more phase planes. Employing more phase planes helps to smoothen the masks therefore avoid phase wraps at the cost of a larger footprint. Seven phase planes are designed and implemented as a compromise between performance and available pixels from the liquid crystal on silicon (LCoS).

Since each reflection will introduce excess loss, the triangular spot layout saves seven masks for the first mapping, in Fig. 1(a). Therefore, ten VCSELs are arranged in the triangular spots layout, collimated by an array of micro-lenses and directly interface with the MPLC using only seven phase planes. In Fig. 1(c), all the VCSEL beams pass through seven phase planes at the same
Fig. 2. Schematic drawing of the CPO assembly. VCSELs are co-packaged with the BiCMOS drivers on silicon interposer with flip-chip bonding technology. PCB is used to fan-out RF and DC inputs for the module evaluation. Microlens array and TEC are attached from the backside of the silicon interposer.

time. Fig. 1(d) shows the simulation results of conversion from ten Gaussian spots at the input to ten HG modes at the output of MPLC. The HG modes can be coupled into GI fiber with no losses since they are the solutions to the wave equation for GI-MMF.

To achieve triangular matrix spots layout and reduce the footprint, we propose to package the ten single-mode VCSELs and BiCMOS IC drivers with 2.5-D integration technology, as illustrated in Fig. 2. Further, it is possible to scale up to 15 or 21 modes by using multiple metal layers for the matrix fan-out electronic connections. In this silicon interposer design, impedance-matched traces electrically connect the BiCMOS driver ICs to the 2D VCSELs matrix. Based on standard semiconductor technology, silicon interposers are fabricated on a wafer level, which provides a robust and low-cost matrix configuration [21]. From the bottom side, the silicon interposer also optically connects the VCSELs and the micro-lens array through wet-etched optical through silicon vias and thermally connected to the thermal electric cooler (TEC) for thermal dissipation. The heat generated by the driver ICs can be dissipated rapidly through silicon due to its high thermal conductivity. The fan-out pads of driver ICs are wire-bonded with specially designed evaluation PCB for the DC and RF I/Os.

III. FABRICATION PROCESS

We design and fabricate the wet-etched silicon interposers, for the first time, on a 3-inch silicon wafer, and the process flow is demonstrated according to four lithographic steps in Fig. 3. Silicon nitride layers (SiNx), as the hard mask of wet etching, are firstly deposited on both top and bottom surfaces of a 200-µm thick silicon wafer (a). After that, a plating base is sputtered for the following steps of traces and pads forming (b). Then, lithographically defined metal traces are plated for the high-speed differential inputs, high-speed single-ended outputs, and power supplies. The traces design can support higher than 40-GHz bandwidth [21]. Top and bottom sides alignments are used to pattern the opening on both sides. The optical through silicon vias are then etched from both sides of the silicon wafer simultaneously (c). Because of different openings size on the two sides of the wafer, funnel shape vias are formed. Comparing with dry etching technology, wet etching can efficiently fabricate different shaped vias, which can be tailored to the apertures of the opto-electronics and the thickness of the wafer. A photo of 3-inch silicon wafer processing is shown in Fig. 3(d).

After the fabrication process, the silicon interposer is cleaved out from the wafer for the module assembly. The sample size is 10-mm × 10-mm, and the design area is 7-mm × 7-mm. We select the identical single-mode VCSELs, produced by Vertilas, with an aperture size of 5 µm, which are working at 1545.7 nm ± 0.2 nm. The C-band VCSEL has a stable polarization output, so the silicon interposer has been designed to keep the same polarization for all the VCSELs by placing them along one direction. The TE polarization is shown in the Fig. 4(c). The VCSELs are firstly bonded by aligning the aperture with the optical through silicon via (200 °C). The micro-photos in Fig. 4 show the triangular VCSELs from the top side (a) and bottom side (b) of the silicon interposer. Fig. 4(b) shows the funnel-shape vias, and the micro-photo (c) shows the VCSEL apertures on a 250-µm pitch in both lateral and longitudinal directions after flip-chip bonding. After that, three 4-channel BiCMOS IC drivers (MTTV28042C2N) are flip-chip bonded by standard soldering reflow process (235 °C). The short impedance matched connections and small form factor are achieved in this packaging.
technology. The micro-photo of co-packaged module is shown in Fig. 4(d) with a form factor of 10 mm $\times$ 10 mm. On the other side of silicon interposer, micro lens array is attached for the free-space experiments.

IV. CHARACTERIZATION

In order to characterize the packaged module, the silicon interposer is further attached to the bottom of the fan-out evaluation PCB, in Fig. 5(b). The bottom side of the interposer is mounted on a TEC, which has a circular opening to allow the emission of light from the VCSELs and placing a micro-lens array for collimation. The PCB and TEC are mounted on a machined aluminum plate.

In the experimental setup Fig. 5(a), the PCB is mounted on the left side, and collimated VCSEL outputs beams with waists of 86 $\mu$m are imaged onto the input plane of the MPLC through 1:1 imaging relay optics (4-f). The MPLC comprises a LCoS with a pixel pitch of 8 $\mu$m and resolution of 1920 $\times$ 1080, a dielectric mirror, and an FMF collimator with a 4.5 mm focal length lens. The GI-FMF supports ten spatial modes with effective areas from 117 to 270 $\mu$m$^2$ for different modes [8]. Seven phase planes are calculated using a photonic inverse design technique called wavefront matching method [14], [19]. The LCoS has a dielectric mirror on top of the backplane to reduce the losses below 0.2 dB per bounce.

In the practical MDM-Tx module, the relay optics will be eliminated by building the MPLC directly on the VCSEL matrix assembly. The MPLC, which can be fabricated with the size of a few cm$^2$, together with the silicon interposer (1 cm$^2$) could be packaged with the QSFP-DD form factor. In this work, the output s-polarized beams from VCSELs are the desired state of polarization of the LCoS. However, MPLCs with fabricated phase masks are polarization insensitive which can further relax the output polarization alignment requirement. In addition, MDM-Tx with polarization diversity can be achieved by multiplexing two 2D VCSEL matrix with orthogonal output polarizations before MPLC.

The measured insertion loss (IL) of the MPLC is around 8 dB for the fundamental mode and increases up to 12 dB for the highest-order modes. The IL is mainly caused by the pixel-to-pixel crosstalk of the LCoS and can be reduced to 3-4 dB employing lithography-fabricated phase masks [13]. Fig. 5(c) provides the captured mode profiles at the FMF output for the VCSELs at the corresponding spot locations.

The VCSELs’ small-signal modulation responses were measured with a Vector Network Analyzer (VNA), and the measured bandwidth of VCSEL is 11.5 GHz biasing at 5.38 mA, as shown in Fig. 6(a). By changing the biasing current, the wavelength of the VCSEL can be tuned. Fig. 6(b) shows the wavelength tuning results with 6 mA biasing range; the wavelength varies from 1544.0 nm to 1548.0 nm.

In the high-speed modulation evaluation, ten decorrelated OOK signals with a sequence length of $2^{16}$ are generated after splitting and delaying the outputs of an eight-channel digital-to-analog converter (DAC). Ten broadband baluns are used to convert the single-ended signals into differential outputs connected to the inputs of the BiCMOS drivers. The drivers are
working at 3.3 V, and set to bias the VCSELs at currents above 6.9 mA, which offers a >12 GHz 3 dB bandwidth, see Fig. 6(a) and >3 dBm output power, which gives the launch power into the MMF above −10 dBm for all the spatial modes.

We employ the 10-mode MDM-Tx in two transmission experiments to demonstrate its capability in short- and medium-reach applications.

Fig. 7(a) shows the experimental setup for mode-multiplexed transmission over 100-m OM3 MMF using direct detection at the receiver side. Ten VCSELs of the MDM-Tx are operated with a center wavelength of 1545.7 nm. We applied different bias currents to further separate the VCSEL wavelengths which provides a smallest frequency spacing of 25-GHz. This wavelength fine-tune using bias current can be avoided by choosing VCSELs with a larger wavelength separation. At the receiver, spatial modes are de-multiplexed using a wavelength de-multiplexer and detected by photo diodes. Here, we used a sharp filter to filter the wavelength the lowest-order mode (LP01) mode as a proof-of-concept demonstration. Fig. 7(b) and (c) show the measured eye diagrams for the received 15-Gbaud/s (left) and 20-Gbaud/s (right) OOK signal. Detecting all the spatial modes requires building a free space sharp filter supporting MMF input and a photo detector with a large aperture. Since different spatial modes are separated in wavelength, this scheme is insensitive to mode coupling. The demonstrated VCSEL-based Tx avoids the usage of a shared laser source and external modulators as in conventional MDM transmissions. Since the wavelength of each VCSEL can be easily tuned, it makes the MDM-Tx capable of arranging different modes at different wavelengths and mitigate mode coupling through wavelength filtering at the Rx. This multiple-input and multiple-output free (MIMO-free) MDM transmission scheme could be useful for some applications having a loose requirement for spectrum efficiency. Moreover, mode multiplexing could be more efficient than wavelength multiplexing. Adding one wavelength channel needs one additional thin film filter, which means 1000 filters will be needed to support 1000 wavelength channels for VCSEL based WDM. In contrast, only 14 phase planes were needed to multiplex 1000+ spatial modes due to strong mode overlap [20]. This scaling advantage could be essential for CPO with a limited footprint.

Fig. 8(a) shows the experimental setup for 10-mode MDM 200-Gb/s transmission over 28-km 10-mode FMF. Coherent detection is applied to tackle modal dispersion and mode coupling. The 10-mode FMF has a trench-assisted GI-core profile optimized to get the smallest possible differential mode group delay (DGD) [8]. The measured differential DGD after the 28-km GI-FMF is less than 4 ns, see Fig. 8(a), where four prominent discrete peaks represent the four fiber mode groups. The attenuation of the fundamental mode is measured around 0.22 dB/km at 1550 nm. A photonic lantern (PL)-based SMUX [22], which provides an adiabatic transition between the 10-mode GI-MMF and ten SMFs, is used at the receiver to demultiplex the spatial modes. The PL-SMUX has an IL from 0.5 to 2.5 dB across all the spatial modes. Scrambled signals are detected by ten polarization-diversity coherent receivers and captured by oscilloscopes. The frequency separation between the VCSELs and local oscillator (LO) is kept smaller than the bandwidth of the coherent receiver. Front-end skews are first compensated in off-line MIMO digital signal processing (DSP). Frequency offset compensation is followed by a 20 × 20 frequency domain equalizer with 500 symbol-spaced taps updated using a least-mean-square algorithm. [23], [24] The frequency offset after coherent detection can be easily determined by searching the peak since OOK signal has a strong carrier which is different from complex-valued QAM signal whose carrier is usually suppressed. Phase recovery is not needed due to the intensity modulation. The recovered constellations of 15 Gbaud/s and 20 Gbaud/s examples are shown in Fig. 8(c),(d). Besides, all ten modes are measured at the same time at 15 Gbaud/s, and the constellations of all channels are shown in Fig. 9(a). Measured bit error rates (BER) of all the 10 modes are below the threshold of 20% forward-error-correction overhead (FEC-OH) after 28-km GI-FMF transmission in Fig. 9(b).
Fig. 9. (a) Recovered constellation diagrams of all 10 modes; (b) BER results for all the ten mode channels at 15-Gbaud/s and 20-Gbaud/s.

V. CONCLUSION

We demonstrated 200-Gb/s line-rate transmission over 100-m OM3 MMF and 28-km FMF employing a 2-D VCSEL matrix-based 10-mode MDM-Tx. The total power consumption of the CPO module is <1 W (<5 pJ/bit). Arranging the VCSEL wavelengths provides receiver flexibility to use either direct detection or coherent detection to satisfy different applications’ cost and reach requirements. The results confirm the potential of employing spatial multiplexing to scale transceiver capacity while reducing cost per bit and power consumption through integration and component parallelism [5].

We expect to scale up the line rate to 400 Gb/s employing higher speed VCSELs and PAM4 modulation format. The MDM-Tx will support 1 Tb/s transmission by multiplexing 15 or 21 spatial channels, which is supported by the MPLC. In the future, based on the same platform, a MDM transceiver can be also packaged by adding photo detectors and amplifiers on the same interposer and reversely using the same MPLC.

REFERENCES


