VCSEL to Single-Mode Fiber Coupling Module for C-band Optical Transmitter

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Abstract *In this paper, a VCSEL-based C-band transmitter coupled to single-mode fiber is demonstrated. Using an on-wafer processed lens, low coupling loss (2.5dB) and large alignment tolerance (±3.4µm -1dB drop) are realized, allowing for up to 6km 25Gbps error-free data transmission.*

Introduction

Because of its cheap and compact format, higher reliability, and capability of high-speed direct modulation, vertical-cavity surface-emission laser (VCSEL) is an ideal light source for datacom optical transmitters[1]. Currently, modules based on 850nm multimode VCSELs (MM-VCSEL) and fibers (MMF) are very popular as they offer an attractive cost option. However, due to mode dispersion in MMF, links are limited to short-reach distances (<100m). For long-reach (>100m) optical transmission (for example, intra-campus interconnection in data center network[2]), optical interconnects based on long-wavelength (LW) single-mode VCSEL (SM-VCSEL) and single-mode fiber (SMF) are in demand.

Realizing a long-reach optical interconnect based on LW SM-VCSEL and SMF is challenging. Fundamentally, mode matching between SM-VCSEL and SMF leads to limited coupling efficiency and forces narrow alignment tolerance[3]. The low alignment tolerance needed to support SM-VCSEL to SMF low-loss coupling can be achieved using active alignment, which increases the cost of packaging[4]. Besides, it is also difficult to package the aligned components into a compact module. The coupling between SMF and SM-VCSEL is often realized with lensed fibers[3] or cleaved fibers[5], which in both cases result in hard-to-achieve optimum mode matching and/or a compact structure. Hence, low-cost integrated optical interconnects based on LW SM-VCSEL/SMF transmitters are rarely reported in comparison to 850nm MM-VCSEL/MMF solutions.

This paper presented a 25Gbps C-band (1530nm-1560nm) SM-VCSEL-based transmitter. In this transmitter, SM-VCSEL to SMF coupling is realized with on-wafer processed lenses and a pluggable on-chip photonic light-turn (PLT) module[6]. This coupling system is first designed and simulated using OpticStudio and verified with an experimental setup. Simulation results suggest a coupling efficiency higher than 95% and a -3dB alignment tolerance of $\pm 5.2\mu m$. The measured fabricated prototype yielded a minimum insertion loss of 2.5dB for such a package, with $\pm 3.4\mu m$ -1dB alignment tolerance ($\pm 6.5\mu m$ -3dB tolerance), which is well supported with the standard passive alignment process. The complete silicon interposer is fabricated with wafer-level processes to house not only the SM-VCSEL but also the BiCOMS driver MTTV28nn using flip-chip assembly technique, which allows for high-bandwidth electrical connection[7]. To demonstrate the performance of the fully packaged sub-module, high-speed characterization is performed. 25Gbps error-free performance is verified with the BER test and eye diagram for a distance of up to 6 km with a penalty of 3.43 dB due to fiber dispersion and attenuation.

Design and Simulation

The C-band SM-VCSEL based transmitter has four parts: SM-VCSEL, driver, PLT, and silicon interposer with photoresist lens. The setup of the optical system is shown as Fig. 1.

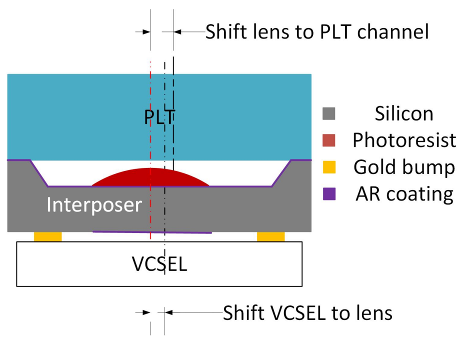

Fig. 1: Setup of optical system.

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Because the PLT is designed for light coupling between a silicon photonics grating coupler and a SMF[6], there is a mismatch between SM-VCSEL output (5μm waist Gaussian beam) and PLT input (tilted 6.5μm waist Gaussian beam). In our solution, a photoresist lens is introduced between those two parts to compensate for this mismatch. The parameters of photoresist lens, 50μm diameter and 48μm radius of curvature, and its position in the optical system are defined based on generalized beam propagation matrices[8]. The surface with cavities is designed to ensure the proper distance between the reflowed lens and PLT entrance surface for designed beam size amplification. And desired beam shifting is achieved by shifting SM-VCSEL for 12μm along the y axis. The coupling efficiency of the designed system is studied on OpticStudio. The simulation results are shown in Fig. 2.

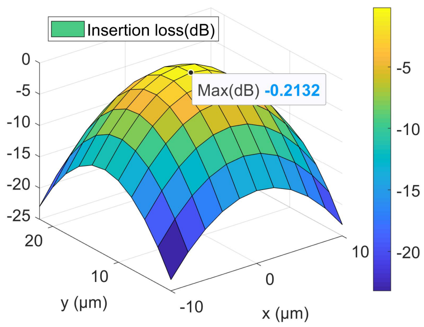

Fig. 2: Insertion loss vs. PLT misalignment.

The simulation results indicate that the theoretical coupling efficiency of the optical system is over 95%. Besides, the -3dB tolerance of the PLT modules is over $\pm 5.2\mu m$, which means that the assembly of the PLT can be realized by camera aided passive alignment.

Fabrication and test of sample

To verify the concept, a prototype interposer is fabricated and tested. The fabrication process is shown as Fig. 3.

To avoid optical reflections that cause power penalty and influence the high-speed performance of SM-VCSEL[9] antireflection coating based on SiN_x and SiO_2 is designed and fabricated on the interface between silicon and air, and the interface between silicon and photoresist, to make sure that the reflections on those interfaces are smaller than 1%.

The lenses are fabricated with a reflow process in which the photoresist cylinders patterned with lithography processes will form a spherical surface. And the thickness and size of the photoresist cylinders define the radius of curvature of the lens[10]. To achieve consistent photoresist thickness with spin coating, thus, to achieve consistent lens profiles for each channel, an array of square cavities are patterned for a multi-channel structure. Besides, to stabilize chemical and physical proprieties of reflowed lens[11], the lens is baked at 300 degrees. Finally, photoresist lenses with sizes of around 53μm diameter and radius of curvatures of 48μm ($\pm 0.4\mu$m) are patterned within the cavity array, the picture and the profile of the lens is shown in Fig. 4.

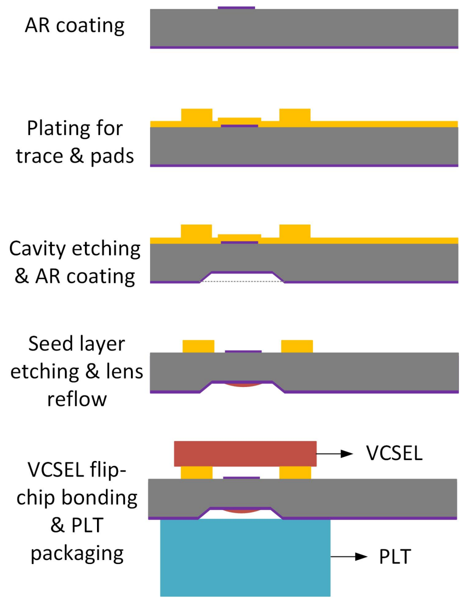

Fig. 3: Fabrication processes of silicon interposer.

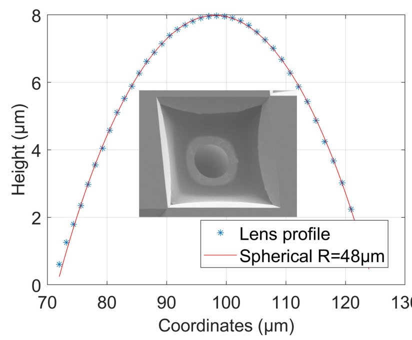

Fig. 4: Profile and SEM picture of photoresist lens.

Based on the silicon interposer with reflowed lens, a one-channel optical module is made to test the optical performance of the system by flip-chip bonding the SM-VCSEL on the silicon interposer and scanning the position of the PLT module on the reflowed lens side with submicron accuracy. The SM-VCSEL with 2dBm output is powered up to test the optical efficiency. Fig. 5(a) shows the experiment results of insertion loss versus PLT position regarding the center of the photoresist lens. Experiment results demonstrate that

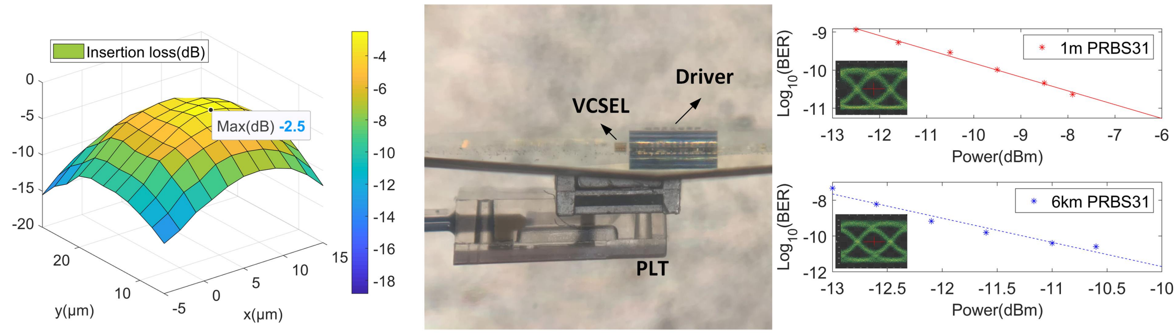

Fig. 5: (a) Insertion loss vs. PLT position; (b) Packaged module; (c) BER and eye diagram of 25Gbps signal.

this module has a lowest insertion loss of 2.5dB, with $\pm3.4\mu$m -1dB tolerance ($\pm6.5\mu$m -3dB tolerance). A 1.9μm assembly error of SM-VCSEL is the main reason for the extra 2.3dB loss than simulation.

After testing the performance of the optical system, a transmitter module is assembled using the silicon interposer, a 1536nm SM-VCSEL, and a BiCMOS driver IC to test the high-speed performance. The packaged device is shown as Fig. 5(b). In the high-speed characterization, the input of the optical transmitter is the 25 Gbps non-return to zero (NRZ) with a 2^{31}-1 pseudo-random bit sequence (PRBS31) signal, generated by high-speed test module ML4004E (multi-Lane) and fed to packaged chip through differential RF probes. Pre-emphasis of SM-VCSEL current is set by I^2C communication between laptop and driver. Pre-emphasis function on MTTV28nn is used (level: 40%). Then, the modulated optical signal from the SM-VCSEL is transmitted through a 1m optical fiber (0.96dB insertion loss) and a 6km TW-SM fiber fabricated by Lucent Technologies (3.37dB insertion loss) to an optical receiver RXM25BF (Thorlabs). Different gains of the amplifier embedded in the receiver are set for the two transmission distances (2300V/W for 1m fiber transmission and 7200V/W for 6km fiber transmission) to ensure identical amplitudes of the electrical signals. The electrical signals are then analyzed with the error detector and oscilloscope in ML4004E to test the bit-error rate (BER) and eye diagrams. Except for the default equalizer, the reflection canceller of the ML4004E BER test module is switched on to achieve error-free detection for 6km transmission. The eye diagram and BER of the test channel are shown in Fig. 5(c). The BER indicates the error-free operation is the obtainable performance for both the short-reach (1m) or long-reach connection (6km) albeit with different slopes and an Rx sensitivity penalty of 0.3dB at BER=10^{-9} (3.43dB after subtracting the extra linear gain from the receiver) after 6km. This penalty is mostly the result of the higher electrical gain of the receiver and the additional dispersion incurred at 6km.

Conclusion and discussion

This paper presents the design, fabrication, and testing results of a C-band optical transmitter. After testing, the optical system of this SM-VCSEL to SMF packaging structure shows an insertion loss of 2.5dB and -1dB tolerance of $\pm3.4\mu$m. And low-cost processes which have sufficient tolerance to support assembly using passive alignment can be used to realize this coupling structure. The high-speed characterization shows the error-free operation on 25Gbps PRBS31 patterns for short-reach connection (1m) and long-reach connection (6km) based on this transmitter. As for the measured performance, the experimental results show an extra 2.2dB loss than the simulation results. The extra insertion loss mainly comes from the flip-chip bonding of SM-VCSELs, which using our available system is limited to a precision of ~2μm. By improving the bonding precision to 1μm, insertion loss of the system will be further reduced below 1dB. This packaging concept can be used to fabricate a multi-channel transmitter by flip-chip bonding an SM-VCSEL array with 250μm pitch.

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