Ultra-Thin Bottom-Emission VCSEL-Based Optoelectronic Flexible Printed Circuit Module for High-Speed Transmission

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Abstract: Innovative integration of back emission VCSEL-based optoelectronic module with optical waveguide achieves remarkable 50Gbps PAM4 optical and 25Gbps NRZ electrical transmission speeds. An ultrathin USB3.2 type C optoelectronic module with 0.2mm thickness has been realized.

I. Introduction

With the increasing demand for high-bandwidth applications in the consumer electronics market, various interfaces such as USB, Thunderbolt, PCIe, HDMI, MIPI, etc. [1 - 4] have continuously introduced new specifications to meet the high data transmission requirements associated with higher-resolution videos, larger-pixel cameras, and increased data streaming between application processors and modules. Furthermore, mobile devices have become smaller, thinner, and lighter than ever before, incorporating diverse antennas and receiving modules such as Bluetooth, wireless LAN (local area network), GPS (global positioning system), NFC (near-field communication), satellite phones, and more. As a result, the signal quality, into which electromagnetic interference (EMI) noises are mixed, must further deteriorate under ultrahigh circuit density. To address this challenge, some researchers have proposed the application of optoelectronic interconnection modules for transmitting high-speed optical signals. This innovative approach not only prevents EMI problems but also allows mobile devices to maintain their usual compactness [5].

Conventional FPCs (Flexible printed circuits), as depicted in Fig. 1(a), are flexible mediums that consist of multiple Cu layers and resin materials such as PI (polyimide), MPI (modified polyimide), and LCP (liquid crystal polymer). These FPCs are widely utilized within mobile devices for signal interconnection due to their advantages, such as flexibility, lightweight, thinness, and reasonable price. Even with the application of LCP material, known for its low dielectric constant, low dissipation factor, and excellent RF (radio frequency) characteristics [6], a multi-layered design and thicker LCP inter-layers are still necessary to minimize signal transmission loss for high-speed and low-noise communication. In addressing the need for strictly high-speed and low-noise communication, we propose AOW (active optical waveguide) embedded FPCs, illustrated in Fig. 1(b). These FPCs not only demonstrate superior performance by transmitting high data rate signals through optical waveguides but also reduce the thickness of multiple FPC layers by more than 65%. This achievement highlights its potential to advance high-speed data communication systems while maintaining an ultrathin form factor. Fig. 1(c) illustrates the simulation of signal transmission loss concerning the thickness of LCP. Using hybrid AOW, we can achieve ultra-low transmission loss compared to conventional FPCs at various trace dimensions.

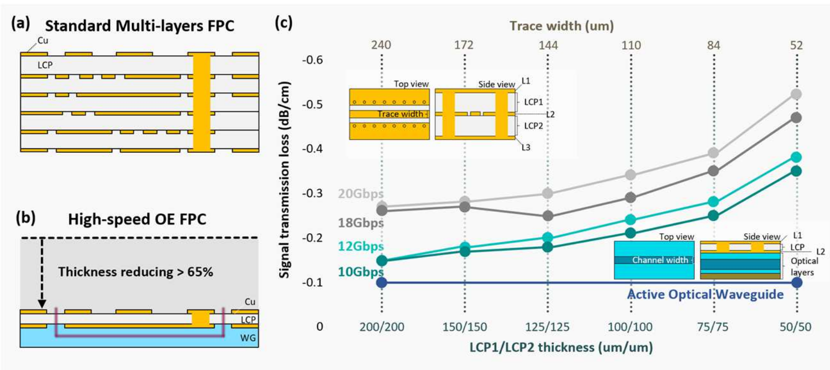

Fig. 1 (a) Schematic of conventional multi-layers FPC, (b) Schematic of novel OE FPC, (c) The signal transmission loss of multi-layers FPCs compared with OE FPC.

In line with the optoelectronic interconnection module developed by previous researchers [5, 7], our initial approach involved the fabrication of a VCSEL-based optoelectronic hybrid module. This module comprised a polymer waveguide embedded LCP-based FPC, a driver IC, TIA (transimpedance amplifier) and high-speed optical chips, including a 850nm VCSEL (vertical-cavity surface-emitting laser) and a GaAs-based PD (photodiode). Subsequently, all these chips were assembled onto the FPC module using a flip-chip process, enabling 25Gbps NRZ error free full-link transmission with a [bit error ratio (BER)< 1x10^{-12}]. However, despite this success, achieving mass production proved challenging due to the non-ideal compatibility of the conventional flip-chip process with FPC materials. Slight misalignments of optical chips on the board or distortion of mirrors and waveguides caused by high temperatures and stress during the flip-chip process resulted in significant light coupling losses, bandwidth penalties and subsequent reliability issues [8].

To address these challenges, we proposed an innovative solution that involved replacing the original flip-chip VCSEL and PD with bottom-emission VCSELs and bottom-illuminated PDs. This modification allowed precise positioning of the optical chips on the board and facilitated wire bonding to ICs, ensuring production feasibility and high yield. Recently, it had been proven that 980nm VCSELs with excellent high-temperature and wear-out characteristics are far more robust than 850nm counterparts, and IEEE802.3cz selected 980nm VCSELs to meet automotive reliability and lifetime standard [9, 10]. Additionally, shifting the operating wavelength from 850nm to 980nm offers advantages in designing high-performance bottom devices, as 850nm is not transparent for GaAs substrate. To address the absorption limit of GaAs PDs, we applied a bottom illuminated InGaAs PD with a novel metamorphic buffer growth on the GaAs substrate, extending the absorption cutoff over 980nm [11]. The overall schematic of the module is presented in Fig. 2(a), while Fig. 2(b) to (f) depict pictures of each components.

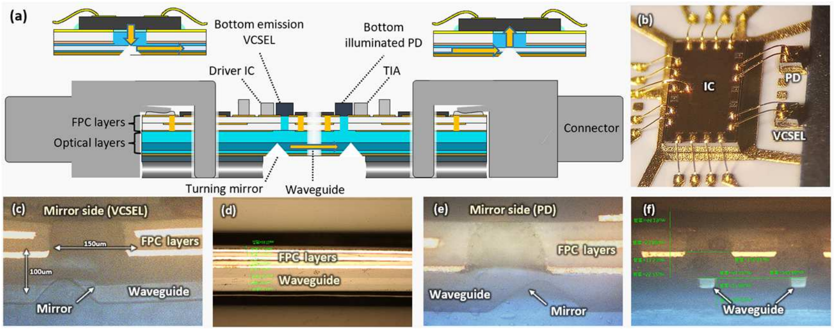

Fig. 2 (a) Schematic of ultra-thin high-speed VCSEL-based OE FPC module, (b) Photo of driver/TIA IC and bottom emission type VCSEL/PD with wire-bond connection, (c) mirror of VCSEL side, (d) cross-section of waveguide and FPC layers, (e) mirror of PD side, and (f) multi-channel waveguides.

II. Measurement Results

To assess the high-speed performance of the embedded waveguide, optical eye diagram measurements were conducted at a baud rate of 26.5625 Gbaud using a SSPRQ (short stress pattern random quaternary). As illustrated in Fig. 3, two MMFs (multi-mode fibers) were positioned at the input and output. The PAM4 modulated light wave emitted from the transceiver via the input MMF was directed onto a 45° turning mirror. Subsequently, the coupled light wave propagated within the polymer waveguide and came out from the output port through another turning mirror into the output MMF. Finally, an oscilloscope was used to detect the optical eye-pattern. A comparison of the eye-patterns and TDECQ (transmitter dispersion and eye closure quaternary) between the transceiver without and with the waveguide revealed that this configuration did not significantly degrade signal transmission or bandwidth.

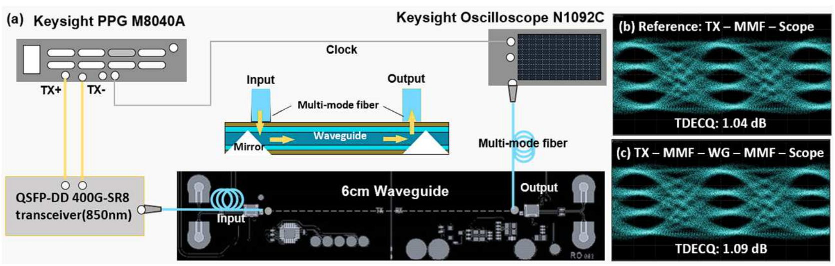

Fig. 3 (a) The optical eye diagram measurement set up and its eye patterns (b) without waveguide and (c) with waveguide.

To further assess the performance of the VCSEL-based OE module, electrical eye diagram measurements were conducted at various NRZ (non-return-to-zero) data rates of 10/14/25 Gbps using a pseudo random-binary sequence of 2^{31} -1 data stream length (PRBS 31). In Fig. 4(a), high-speed NRZ signals with an output voltage of 0.2 V, generated by a PPG (pulse pattern generator) were input into the module. Subsequently, an oscilloscope was used to detect the output signal and perform electrical eye-pattern analysis. Figures 4(b) to 4(d) shows the resulting eye-patterns, illustrating successful full link transmissions at NRZ rates of 10/14/25 Gbps.

In this study, we also successfully developed a compact VCSEL-based OE FPC module integrated with a USB IC, as depicted in Fig. 5. This module effectively carried out data transmission and high-resolution video broadcasting between mobile devices. The slim profile of approximately 0.2mm thickness showcased its tremendous potential when applied to consumer mobile electronics.

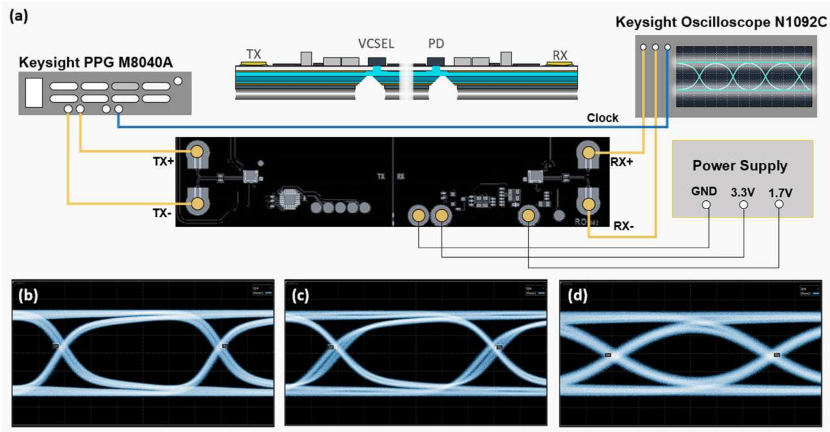

Fig. 4 (a) The electrical eye diagram measurements set up for OE modules, Eye pattern quality at (b)10 Gbps (c) 14 Gbps and (d) 25 Gbps.

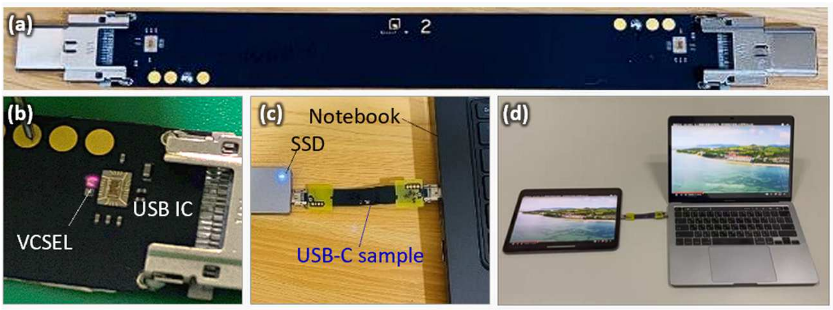

Fig. 5 (a) Picture of USB-C sample based on OE FPC module, (b) VCSEL chips and USB IC, (c) Data transmission between SSD and laptop, and (d) High-resolution video transmission.

III. Summary

In this paper, we have developed and demonstrated VCSEL-based OE FPC modules with an exceptionally slim profile, showcasing their efficiency in optical communication for consumer electronics. These modules incorporate bottom-emission VCSELs, supporting 25G NRZ full-link transmission, and utilize an embedded waveguide capable of PAM4 high-speed signal transmission up to 50 Gbps. Additionally, we have successfully integrated a compact module with USB-C functions, highlighting its strong potential for high-speed applications in consumer electronics.

IV. References

[1] J. Balich, “USB-IF Announces Publication of New USB4,” https://usb.org/sites/default/files/2022-10/USB.

[2] HDMI®, "HDMI® 2.1b Specification," https://www.hdmi.org/spec/hdmi2_1.

[3] M. Zea "PCI-SIG Announces PCI Express 7.0 Specification to Reach 128 GT/s," https://www.businesswire.com/news/home/ 20220621005137/en

[4] T. McKee "MIPI A-PHY specification," https://www.mipi.org/specifications/a-phy

[5] H. Uemura, K. Kobayashi, K. Hiyama, H. Furuyama, Y. Sugizaki and H. Shibata, "Ultralow EMI interconnection module for mobile devices using 3D-flexible hybrid multi-fin optoelectronic FPC," in Proceedings of 62nd Electronic Components and Technology (IEEE, 2012), pp. 1540-1546.

[6] Z. Zhou, et al. "Flexible liquid crystal polymer technologies from microwave to terahertz frequencies." Molecules **27**, 1336 (2022).

[7] T. Shiraishi et al. "Cost-effective low-loss flexible optical engine with microlens-imprinted film for high-speed on-board optical interconnection." in 62nd Electronic Components and Technology Conference (IEEE, 2012), pp. 1505-1510.

[8] T. Yagisawa et al. "FPC-based compact 25-Gb/s optical transceiver module for optical interconnect utilizing novel high-speed FPC connector." in 63rd Electronic Components and Technology Conference (IEEE, 2013), pp. 274-279.

[9] M. Gębski et al. "30 GHz bandwidth temperature stable 980 nm vertical-cavity surface-emitting lasers with AlAs/GaAs bottom distributed Bragg reflectors for optical data communication." Journal of Physics: Photonics **2,** 035008 (2020).

[10] R.P. de Aranda, “KDPOF Celebrates Release of IEEE 802.3cz-2023 Standard,” https://www.kdpof.com/kdpof-celebrates-release-of-ieee-802-3cz-2023-standard/

[11] I.V. Samartsev et al. "1.06 μm wavelength photodetectors with metamorphic buffer layers grown on GaAs substrates." Journal of Physics: Conference Series **1124**, 041037 (2018).