# 100 Gbps PAM4 VCSEL-based Transmission over Meter-scale Flexible Multimode Polymer Waveguides for Board-level Optical Interconnects Application

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**Abstract:** We demonstrate 100 Gbps PAM4 VCSEL-based transmission over 12-channel connectorized meter-scale flexible multimode polymer waveguides with a bandwidth-length product greater than 56 GHz·m at a wavelength of 850 nm for board-level optical interconnects application.

**OCIS codes**: (200.4650) Optical Interconnect; (130.5460) Polymer waveguides;

## 1. Introduction

With the development of high-performance computers (HPC) and hyperscale data centers, especially driven by the rapid progress in artificial intelligence (AI) and AI-generated content (AIGC), there are increasing demands in board-level and chip-to-chip interconnects such as all-to-all GPU communications in order to optimize overall system performance. Board-level optical interconnects have intrinsic advantages in terms of bandwidth, potential in data rate scaleup, and power consumption compared with their electrical counterparts [1]. Electrical and optical 50 Gb/s and 56 Gb/s single-lane interconnect standards are defined by IEEE 802.3bs and OIF CEI-56G-VSR. CEI-112G-VSR to develop a 100 Gbps single lane implementation agreement for chip-to-module interface has also been launched [2,3]. Multimode polymer waveguides have good potential in board-level optical interconnects application due to their low transmission loss, large bandwidth, low cost, and mass-producibility [4]. The propagation loss of multimode polymer waveguides can be as low as 0.05 dB/cm at a wavelength of 850 nm [5,6]. In addition, they can be conveniently coupled to and from multimode fibers (MMF) with a negligible coupling loss and a large alignment tolerance of 20 μm [7]. 40 Gbps non-return-to-zero (NRZ) transmission and 56 Gbps 4-level pulse amplitude modulation (PAM4) transmission in 1 m-long waveguides have been demonstrated [8,9], however, there is no report on multimode polymer waveguides that supports 100 Gbps transmission and beyond.

In this paper, we demonstrated 100 Gbps vertical cavity surface emission laser (VCSEL) based PAM4 transmission over 12-channel connectorized meter-scale flexible multimode waveguides at a wavelength of 850 nm for the first time to the best of our knowledge. The averaged insertion loss of the connectorized waveguides under overfilled launch conditions is about 0.042 dB/cm at 850 nm. The measured bandwidth-length products of the waveguide are greater than 67 GHz·m and 56 GHz·m under underfilled and overfilled launch conditions, respectively. The results imply that the connectorized flexible multimode waveguide has excellent optical properties and is suitable for high-speed board-level optical interconnects application with a single-lane data rate of 100 Gbps and beyond.

## 2. Waveguide fabrication and transmission performance evaluation

The flexible polymer waveguides were fabricated using polynorbornene by a "photo-addressing" technology proposed by Sumitomo Bakelite Co., Ltd [10]. The fabrication process is depicted in Fig. 1. The core layer material is coated

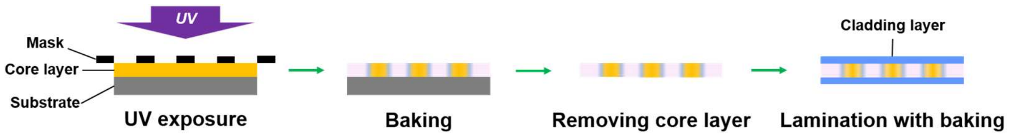


Fig. 1. The fabrication process of Flexible Multimode Polymer Waveguides.

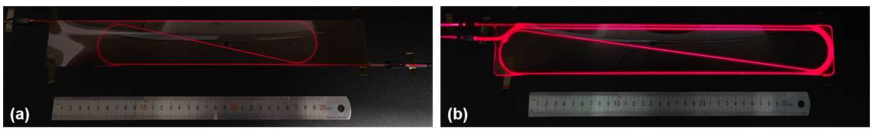


Fig. 2. Images of (a) 1 m-long and (b) 1.7 m-long polymer waveguide illuminated by using a red identification light.

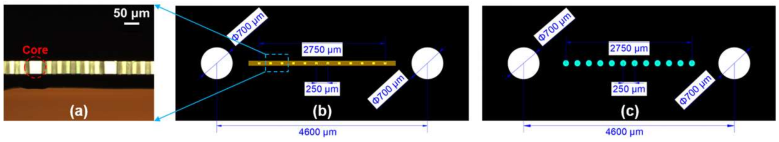


Fig. 3. (a) Microscope image of the fabricated polymer waveguides, (b) 12-core MT connector for polymer waveguides, and (c) 12-core MT connector for OM3 optical fibers.

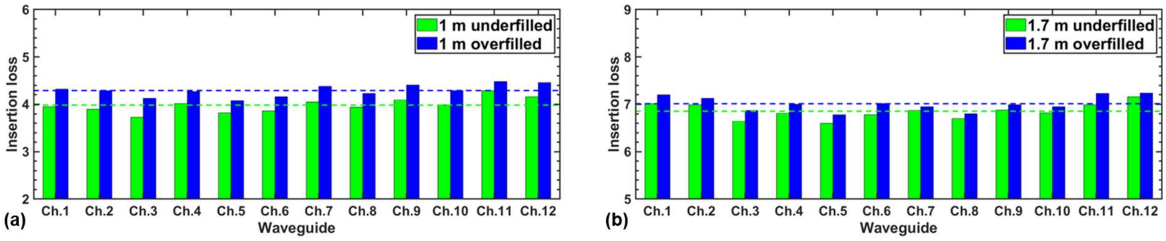


Fig. 4. (a) Insertion loss of 1 m-long waveguide and (b) Insertion loss of 1.7 m-long waveguide.

onto the substrate for UV exposure. Then, the core layer is baked and removed. Finally, the lamination is finished with baking. The refractive index of the core is 1.55, and the refractive index of the horizontal and vertical cladding is 1.53 and 1.52 at a wavelength of 850 nm, respectively [11]. The fabricated waveguides with a length of 1 m and 1.7 m illuminated by using a red identification light are shown in Fig. 2. The minimum bending radius of the 1 m-long and 1.7 m-long waveguides is 24 mm and 21 mm, respectively. As shown in Fig. 3(a), the core size of the waveguide is about 43×44 μm and each waveguide group contains single-row12-channel waveguides with a core pitch of 250 μm, which coincides with that of the VCSELs, photodiode arrays, and multimode fiber ribbons. The waveguides are connectorized in accordance with the recommendation of ICE 92496-4-1 (Fig. 3(b)) which guarantees a low-loss interconnection with a 12-core fiber MT connector in accordance with IEC 61754-5 (Fig. 3(c)). The insertion loss of the connectorized waveguides under overfilled and underfilled launch conditions was measured by use or without the use of a mode scrambler (Newport's FM-1 MS), respectively. As shown in Fig. 4, the 12-channel averaged insertion loss of the 1 m-long waveguides under overfilled and underfilled launch conditions is 0.043 dB/cm and 0.04 dB/cm, respectively, which is 0.042 dB/cm and 0.04 dB/cm for the 12-channel connectorized waveguides with a length of 1.7 meters.

In order to evaluate the bandwidth-length product of the waveguides, we used a vector network analyzer (VNA) to measure their $S_{21}$ response curves, and the results are shown in Fig. 5(a). The distributed Bragg reflection (DBR) laser emits 850 nm light, which passes through a polarization controller (PC) and enters an intensity modulator (IM) to be modulated. The modulated 850 nm light passes through the multimode variable optical attenuator (VOA) and enters the waveguide through the OM3 fiber. By connecting waveguides with a length of 0.2 m, 1 m, and 1.7 m, respectively, we obtained waveguide links with different lengths. The normalized $S_{21}$ response curves measured under

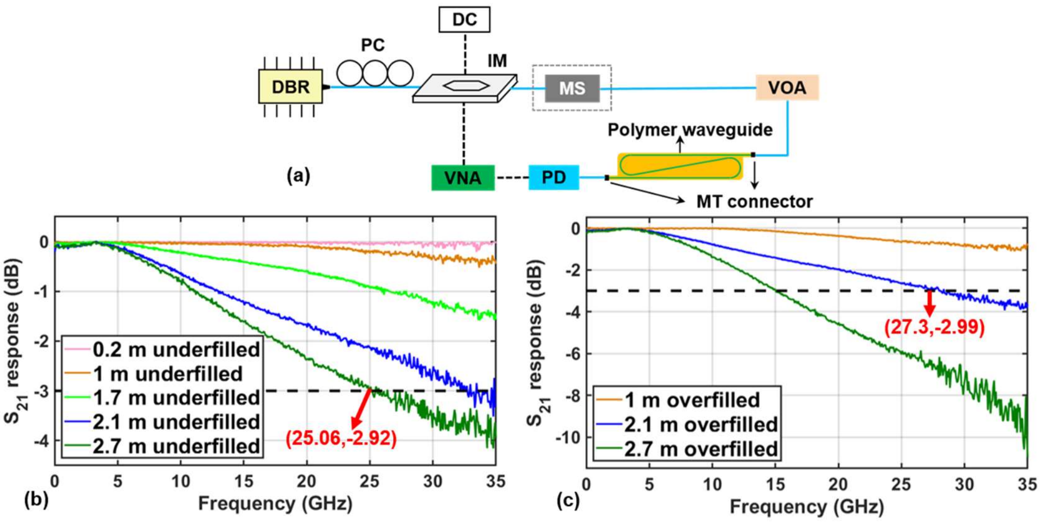


Fig. 5. (a) Experimental setup for the S21 response measurement; (b) Normalized $S_{21}$ response curves under the underfilled launch condition and (c) normalized $S_{21}$ response curves under the overfilled launch condition.

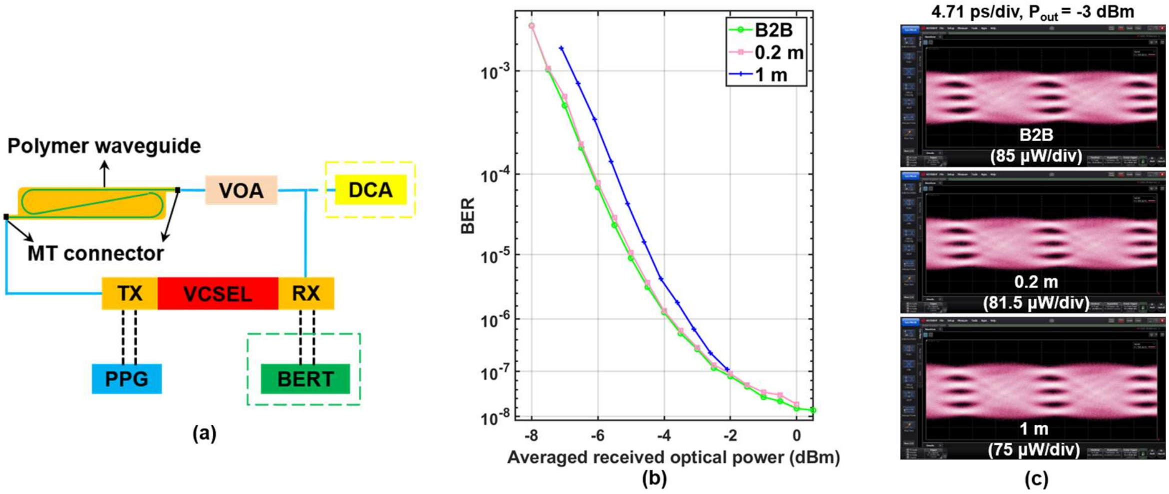


Fig. 6. (a) Experimental setup for 53.125 Gbaud PAM4 transmission, (b) BER curves for the B2B and waveguide links with different lengths, and (c) received eye diagrams for the B2B and waveguide links with different lengths.

underfilled launch conditions are shown in Fig. 5(b). The attenuation of the $S_{21}$ response curve at 25 GHz is less than 3 dB for a waveguide link with a length of 2.7 m. As a result, the bandwidth-length product of the waveguide is greater than 67 GHz·m. The normalized $S_{21}$ response curves measured under the overfilled launch condition are shown in Fig. 5(c). The attenuation of the $S_{21}$ response curve at 27 GHz is less than 3 dB for a waveguide link with a length of 2.1 m. As a result, the bandwidth-length product of the waveguide is greater than 56 GHz·m.

100 Gbps PAM4 VCSEL-based transmission over the fabricated meter-scale polymer waveguides was carried out. A schematic of the experimental setup is shown in Fig. 6(a). The transceiver (TX) of the VCSEL received the radio frequency signal of 53.125 Gbaud PAM4 from the pulse pattern generator (PPG) and output the 850 nm modulated light. A multimode VOA was used for optical power adjustment. The receiver (RX) of the VCSEL received the modulated light and passed the corresponding RF signal into the bit error ratio tester (BERT) to obtain the bit error rate (BER). Eye diagrams were obtained using a digital communications analyzer (DCA). Figure 6(b) shows measured BER curves for 53.125 Gbaud PAM4 versus different received optical powers for B2B, and 0.2 m-long or 1 m-long polymer waveguide links. The measured BERs are well below the forward error correction limitation (BER = $3.8\times10^{-3}$). The waveguide bit error rate curve of the 1.7 m-long waveguide was not measured due to the limited power margin of the measuring system. Figure. 6(c) shows the received eye diagrams for B2B, and 0.2 m-long or 1 m-long links at -3 dBm, respectively. The eye diagram is open after the signal propagated through the 1 m-long waveguides.

## 3. Conclusions

We achieved 100 Gbps PAM4 VCSEL-based transmission over 12-channel connectorized meter-scale flexible multimode polymer waveguides. The average insertion loss of the waveguide under overfilled launch conditions is about 0.042 dB/cm at a wavelength of 850 nm. The measured bandwidth-length products of the waveguide are greater than 56 GHz·m and 67 GHz·m under overfilled and underfilled launch conditions, respectively. The results imply that the connectorized flexible multimode waveguide has excellent optical properties and is suitable for high-speed board-level optical interconnects application with a single-lane data rate of 100 Gbps and beyond.

## 4. Acknowledgments

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