# 56 Gb/s PAM-4 Data Transmission Over a 1 m Long Multimode Polymer Interconnect

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**Abstract:** Advanced modulation formats can enable >40 Gb/s data rates in waveguide-based optical interconnects without the need for high-specification optoelectronic components. Record 56Gb/s PAM-4 data transmission is demonstrated over a 1 m-long multimode polymer waveguide.
**OCIS codes:** (250.5460) Polymer waveguides, (200.4650) Optical interconnects, (250.7260) VCSELs.

## 1. Introduction

Optical interconnects have attracted significant research interest in recent years owing to the clear performance advantages they can offer for high-speed data communication over copper-based interconnects [1]. In particular, multimode (MM) polymer waveguides are an attractive technology for implementing cost-effective board-level optical links owing to their favourable optical and material properties and large dimensions that allow low loss transmission at the datacommunication wavelength range and direct integration onto standard printed circuit boards (PCBs) with relaxed alignment tolerances [1-4]. Vertical-cavity surface-emitting lasers (VCSELs) are the optical sources of choice for such applications as they offer low-power operation, high optical output power (>1 mW) and large bandwidth (>20 GHz), don't require any temperature control, are sufficiently low cost and can be readily produced in large array configurations. A number of system demonstrators have been recently reported achieving large aggregate on-board interconnection capacities by deploying large arrays of high-speed VCSELs and parallel MM polymer waveguides [2, 3]. In order to further increase the interconnection capacity of such systems, a larger number of on-board optical links need to be deployed, or faster data rates per waveguide channel need to be implemented. We have recently demonstrated record 40 Gb/s NRZ data transmission over a 1 m long MM polymer waveguide [5]. However, the implementation of such high data rates on-board imposes strict requirements on the performance of the active devices (VCSELs, photodiodes), driving electronic circuits and transmission quality of the radiofrequency (RF) signals. In this paper, we propose the use of advanced modulation formats in short-reach optical interconnects as an alternative way to achieve high data rate transmission without the need for very high-specification photonic and electronic components and RF system design.

Pulse amplitude modulation (PAM) has attracted considerable interest for use in datacommunication links as it can take full advantage of the available link bandwidth and achieve data rate transmission beyond the conventional on-off keying limits without much increase in system complexity [6]. In this work, we present link studies on the implementation of a PAM-4 optical link over MM polymer waveguides and demonstrate 56 Gb/s PAM-4 data transmission over a 1 m long spiral waveguide. Open eye diagrams are recorded for the link without the use of any equalisation, while the estimated bit-error-rate (BER) performance is ~$10^{-5}$ which is within low-latency forward error correction (FEC) limits. This result constitutes a record data rate transmission over a single MM polymer waveguide channel.

## 2. Link simulation studies

A simple link model is produced to investigate the feasibility of board-level optical links based on the use of MM polymer waveguides, VCSELs and PAM-4. The basic link components are shown in Fig. 1(a) with the major simulation parameters noted. These are chosen to match the values of the actual components employed in the link implementation. The simulated symbol rate is 28 Gbaud which corresponds to a bit rate of 56 Gb/s for PAM-4, while the employed data pattern is a $2^7$-1 pseudo-random bit sequence (PRBS) emulating the short pattern length which is typical in datacommunication standards. The performance of the link is investigated for a 0.5 m, 1 m and 1.5 m long waveguide and the available power margin for achieving the BER threshold for different FEC schemes is calculated. Two FEC limits are considered: $10^{-5}$ and $10^{-3}$. The $10^{-5}$ FEC scheme imposes a more stringent link performance requirement but can provide low-latency correction with small overheads (~3%) [7]. Fig. 1(b) shows the obtained power budget for the links studied with the different power penalties noted and the available power margin in red. The simulation results show that the 56 Gb/s PAM-4 optical link is feasible for both FEC schemes for both the 0.5 m and 1 m long waveguide link. The 0.5 m long link exhibits large power margins (> 6 dB) while the 1 m long waveguide link can be operated with a $10^{-5}$ and a $10^{-3}$ FEC threshold with a power margin of 2.6 dB and 4.9 dB respectively. The longest waveguide link of 1.5 m can only operate using the higher $10^{-3}$ FEC threshold.

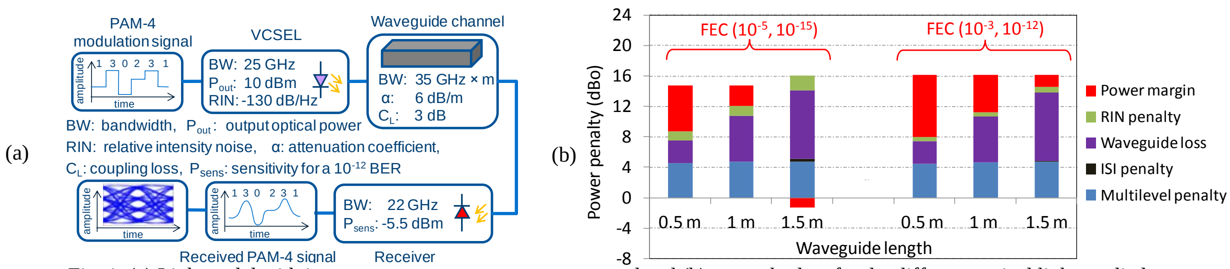

Fig. 1. (a) Link model with important component parameters noted and (b) power budget for the different optical links studied.

## 3. Link setup and data transmission experiments

A 56 Gb/s PAM-4 optical link over a 1 m long MM spiral polymer waveguide is implemented (Fig. 2a). The polymer waveguide has a cross section of ~32×35 $\mu m^2$ and is fabricated on an 8-inch Si substrate with conventional photolithography from siloxane materials [Dow Corning® WG-1020 Optical Waveguide Core and OE-4141 Cured Optical Elastomer (cladding)]. The spiral waveguide has a total length of 105.5 cm and exhibits a 3 dB bandwidth beyond 35 GHz [5]. The employed 850 nm VCSEL has ~25 GHz of bandwidth. The PAM-4 modulation signal is generated using the two data outputs of a pattern generator and discrete RF components (Fig. 2a) and is fed to the VCSEL via a RF probe and a bias tee. The light is coupled into the waveguide with a pair of microscope objectives (16×) and collected at the waveguide output with a cleaved 50/125 µm MMF patchcord. The total insertion loss of the spiral waveguide is measured to be 7 dB. The MM optical module of a digital sampling oscilloscope (DSA8300, Tektronix 80C15) is used as the receiver (Rx). A MM variable optical attenuator (VOA) is inserted in the link to adjust the optical power level at the Rx. The back-to-back link (without the waveguide) is also setup and tested to provide a performance comparison. Open 28 Gbaud PAM-4 eye diagrams are recorded in both the waveguide and back-to-back links (Fig. 2b and 2c). The configuration of Rx module does not allow proper BER measurements but a Q-factor analysis is applied to estimate the BER (Fig. 2d). The waveguide link achieves a BER of ~$10^{-5}$ while a power penalty of ~1 dB is observed due to the insertion of the waveguide in the link.

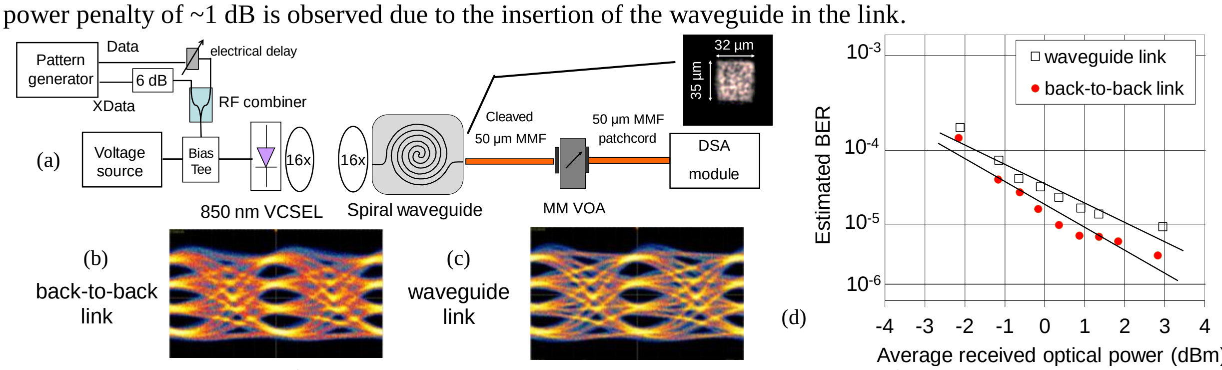

Fig. 2. (a) Experimental setup of the waveguide optical link. Inset image shows the waveguide output facet Recorded 28 Gbaud (56 Gb/s) eye diagrams for the (b) back-to-back and (c) waveguide link. (d) Estimated BER using Q-factor analysis.

## 4. Conclusions

The deployment of large arrays of multimode polymer waveguides and high-bandwidth VCSELs can offer high aggregate capacity board-level optical interconnection. Advanced modulation formats, such as PAM-4, can enable very high data rates (> 40 Gb/s) over a single waveguide channel without the need for very high-specification photonic, electronic and RF components. We indicate the feasibility of such optical links via simulation and demonstrate record 56 Gb/s PAM-4 data transmission over a 1 m long polymer waveguide with a BER of ~$10^{-5}$.

## 5. Acknowledgments

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