28 Gbaud PAM4 Real Time Optical Datacom Link up to 10 km

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ABSTRACT

We present a forward error correction (FEC)-assisted, 10 km long, 28 Gbaud PAM4 optical link having error free performance over a wide dynamic range of -10 dBm to 0 dBm received optical power. The link was formed by driving a 1550 nm externally modulated laser with a commercial PAM4 transceiver chip. The optical signal was transmitted over 10 km long dispersion compensated fiber, fed to a low-noise 28 GHz linear receiver having variable gain, and routed back to the PAM4 transceiver chip. Real time bit error rate measurements demonstrate the advantage of employing linear receivers having automatic gain control (AGC).

Keywords: Datacom, Scalable Platforms, PAM4, Linear InGaAs photoreceiver, Automatic Gain Control.

1. INTRODUCTION

Ubiquitous 25 Gbps Non-Return to Zero Amplitude Shift Keyed (NRZ-ASK) optical links are not sufficient for satisfying the ever-increasing demand of data throughput in datacom severs. Several communication standards, including 100G Ethernet and Infiniband EDR, allow aggregating multiple parallel 25 Gbps lanes and enhance the data throughput. However, the maximum number of lanes that can be coalesced is ultimately restricted by interconnect density and crosstalk considerations. Increasing the NRZ-ASK bit rate to say 50 Gbps significantly increases the cost of the components, the printed circuit board, and connector technology to maintain necessary signal integrity, both in terms of signal to noise ratio (SNR) as well as crosstalk for multilane systems. Four-level Pulse Amplitude Modulation (PAM4) has emerged as an attractive alternative to NRZ-ASK for doubling the data throughput without increasing the analog bandwidth requirements, which will benefit both commercial datacom and net-centric defense platforms. This modulation format has been recognized as the path forward to achieve data rate of up to 400 Gbps by the IEEE 400 GbE standard [1, 2].

We present a forward error correction (FEC)-assisted, 10 km long, 28 Gbaud PAM4 optical link having error free performance over a wide dynamic range of -10 dBm to 0 dBm received optical power. The link was formed by driving a 1550 nm externally modulated laser with a commercial PAM4 transceiver chip. The optical signal was transmitted over 10 km long dispersion compensated fiber, fed to a low-noise 28 GHz linear receiver having variable gain, and routed back to the PAM4 transceiver chip. Real time bit error rate measurements demonstrate the advantage of employing linear receivers having automatic gain control (AGC).

2. SYSTEM CONSIDERATIONS

In a PAM4 link, two electrical binary bit streams are combined to form 4 symbols using an electrical Digital-to-Analog Converter (DAC), as shown in Fig. 1. Such a combination doubles the data throughput while preserving the symbol period, and thus, the nominal bandwidth requirements of all the components of the link. The DAC's output drives an optical transmitter, and the resulting optical PAM4 signal is transported over a fiber span. The optical signal is converted back into the electrical domain by using a linear photoreceiver and fed to a PAM4 electrical receiver. The photoreceiver's linear transfer ensures that the four symbols remain equally spaced, and can be easily distinguished from each other by using three decision thresholds in the PAM4 electrical receiver. The electrical receiver subsequently maps the received signal back to its constituent Most Significant Bit (MSB) and Least Significant Bit (LSB) streams.

The PAM4 electrical receiver is typically implemented using an Analog-to-Digital Converter (ADC) followed by Digital Signal Processor (DSP). As a result, the linear photoreceiver should ideally provide an optimal output voltage level, irrespective of the received optical power level, to maximize the Effective Number of Bits (ENOBs) of the

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electrical receiver. Therefore, the photoreceiver should have variable gain that can be controlled in a feedback loop to provide Automatic Gain Control (AGC).

It should be noted that limiting photoreceivers, which are used in traditional binary links, are inappropriate for PAM4 links. Although a limiting photoreceiver provides fixed electrical output amplitude, its nonlinear transfer function will close the outer eyes and cause unacceptable Bit Error Ratio (BER) for the LSB channel.

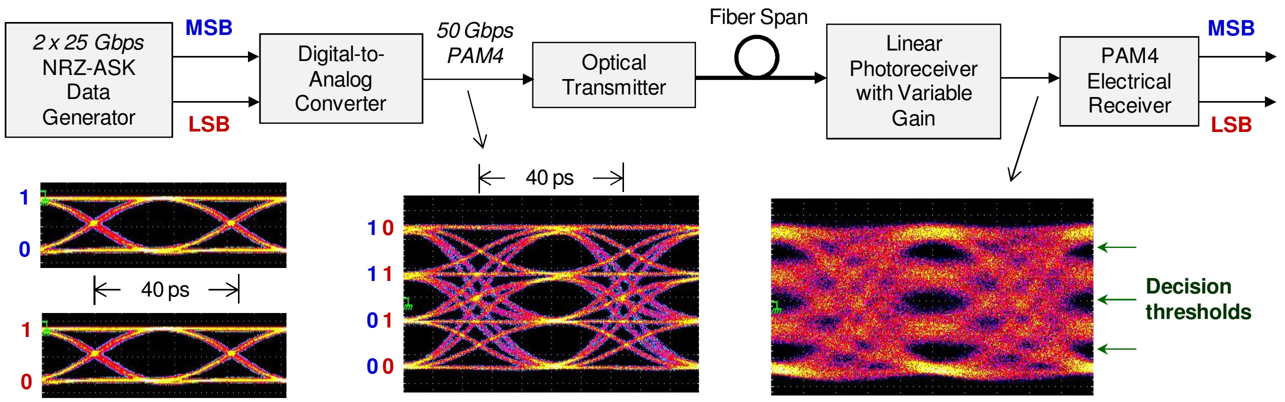

Figure 1. Simplified block diagram of an optical 50 Gbps PAM4 link. The four-level eyes, shown at the optical transmitter's input and the photoreceiver's output, have the same symbol period of 40 ps as that of the two constituent binary bit streams. The mapping of the Most Significant Bit (MSB) and Least Significant Bit (LSB) to the four symbols is shown with Gray coding. The ideal locations for the decision thresholds at the PAM4 electrical receivers are also shown.

Even in such idealized conditions, a PAM4 link suffers additional penalties with respect to a NRZ channel having the same symbol rate for several reasons [3, 4]:

- PAM4 signals demonstrate a fundamental SNR penalty as the separation between the neighboring symbols reduce by a factor of three. Additional sources of noise, such as laser RIN, may also have a larger impact on PAM4 signals. This penalty can be mitigated by a combination of coding techniques, such as Gray coding, line coding, and forward error correction (FEC). In fact, it is customary to use FECs, such as KR4 to achieve error-free performance in PAM4 links.
- PAM4 signals also demonstrate more transitions than NRZ signals, and is therefore more susceptible to inter-symbol interference (ISI) due to group delay ripples, VSWR, etc. Adaptive equalization techniques that include feed-forward equalization (FFE), decision feedback equalization (DFE), and continuous time linear equalization (CTLE), are often required in practical PAM4 links.
- The eye opening in temporal (i.e. horizontal) dimension is also more restricted in PAM4 signals as compared to NRZ signals, thus making PAM4 more susceptible to timing errors such as jitter and clock drifts.

Nevertheless, doubling of data throughput with same analog bandwidth requirements makes it worthwhile to use more complicated PAM4 components, especially in the context of upgrading scalable platforms. Fiber-optic interconnects are being currently investigated for use in avionics platforms to link multiple processors, radars, sensors, and communication terminals owing to their natural advantage in speed, electro-magnetic immunity, scalability, and weight as compared to all-electronic interconnects. Utilization of star network topology further promises to improve scalability and flexibility in these platforms [5]. In these systems, every node is assigned a unique optical wavelength and can be broadcast or routed to other nodes without any concern of packet collisions or blocking. These links are still been designed for NRZ-ASK formats, such as 100G Ethernet.

Upgrading the data throughput of such systems by switching to PAM4 will not change any bandwidth sensitive components such as optical filters and routers. Also, PAM4 format continues to encode information in optical intensity and will not require any modifications to the network topology. Alternatives, such as dual-polarization coherent formats, needs discrimination of optical phase and polarization also, and would require significant changes, such as inclusion of optical hybrids and local oscillator lasers [6].

3. PAM4 LINK DESCRIPTION

The experimental setup, shown in Fig. 2, was used to realize a single-channel PAM4 optical transmission link over 10 km fiber span with a maximum data throughput of 56 Gbps (symbol rate up to 28 Gbaud). The 50G PAM4 transceiver, used to generate and receive the PAM4 electrical data, has several attractive features:

- The transmitter section can be programmed to generate either electrical PAM4 signal or the constituent NRZ data streams. The configuration shown in Fig. 2 utilizes an external DAC for best signal integrity. The PAM4 transceiver was programmed to internally generate PRBS31 signals for both MSB and LSB data.
- The receiver section digitizes the incoming PAM4 signal, deconstructs it into the MSB and LSB bit streams, and compares the received binary signals with the transmitted counterparts. Therefore, the transceiver acts as a real-time PAM4 bit error ratio tester.
- The real-time BER measurements can be performed with and without built-in FEC having a BER threshold of 1E-4.
- The DSP modules of the transceiver include adaptive FFE and DFE equalizers and Gray codecs.
- The transceiver can also be programmed to interface with external network elements and pass MSB and LSB electrical data via a CAUI interface. This “bypass mode” was not used for the results reported here, as we required the internal PRBS generator and checker to be activated and use the transceiver as a BER tester.

The electrical PAM4 signal generated by DAC was amplified and fed to a 1550 nm wavelength, single-mode externally modulated laser (EML) having an extinction ratio of 12 dB. The DAC’s output levels and the EML’s drive current were optimized to ensure equal separation between the four symbols of the optical PAM4 signal.

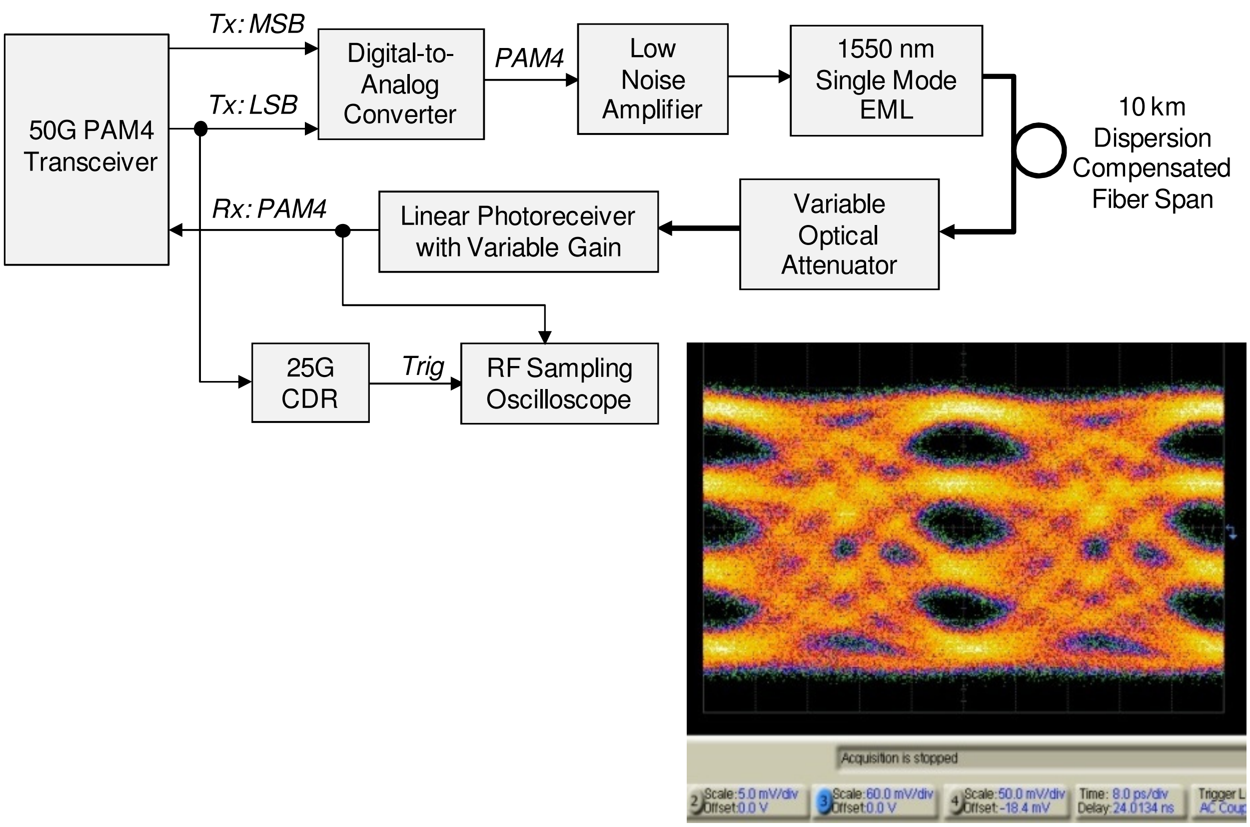

Figure 2. Experimental setup for PAM4 data transmission up to 56 Gbps over 10 km of optical fiber. **(Inset)** Single-ended 52 Gbps PAM4 eye diagram recorded at the photoreceiver’s output for an average received optical power of -4 dBm. The photoreceiver’s gain is controlled to generate 300 mVpp output amplitude for both non-inverting and inverting RF outputs, i.e. differential RF amplitude of 600 mVppd.

The optical PAM4 signal was transmitted through a 10 km long dispersion compensated fiber span. This setup is equivalent to transmitting a 1310 nm wavelength optical PAM4 signal over a 10 km long standard single mode fiber. The 10 km fiber span was bypassed for back-to-back measurements.

The fiber output was passed through a variable optical attenuator and input to a 28 GHz bandwidth, linear PIN-TIA photoreceiver having variable gain. The photoreceiver is optimized for PAM4 operation for several reasons [7]:

- The photoreceiver has a DC responsivity of 0.65 A/W at both 1550 nm and 1310 nm wavelengths. Therefore, the 1550 nm transmission results presented here can be used to estimate the performance of 1310 nm PAM4 link.
- The differential RF output of the photoreceiver is linear up to maximum amplitude of 1.0 Vppd. This is more than sufficient to drive the differential receive inputs of the PAM4 transceiver, which ideally requires 600 mVppd to maximize the ENOBs of its front-end ADC (see Fig. 2 Inset).
- The differential conversion gain of the photoreceiver can be varied up to 3000 V/W, which allows operating the PAM4 link with AGC over a large dynamic range of received input optical power.

The experimental setup also utilizes an external 25G Clock and Data Recovery (CDR) unit to produce a half-rate trigger for the RF sampling oscilloscope.

4. TRANSMISSION RESULTS

The BER was measured for the 10 km PAM4 transmission link in AGC mode for different data rates with and without FEC. The uncorrected BER curves, shown in Fig. 3, intersects the FEC threshold of 1E-4 at an average received optical power of -10 dBm for 52 Gbps and 54 Gbps PAM4 signal. Increasing the data rate to 56 Gbps resulted in 0.5 dB penalty in the link's sensitivity. Turning on the FEC on the PAM4 transmitter demonstrated error-free performance for received optical power exceeding the link's sensitivity, thus resulting in a dynamic range exceeding 10 dB.

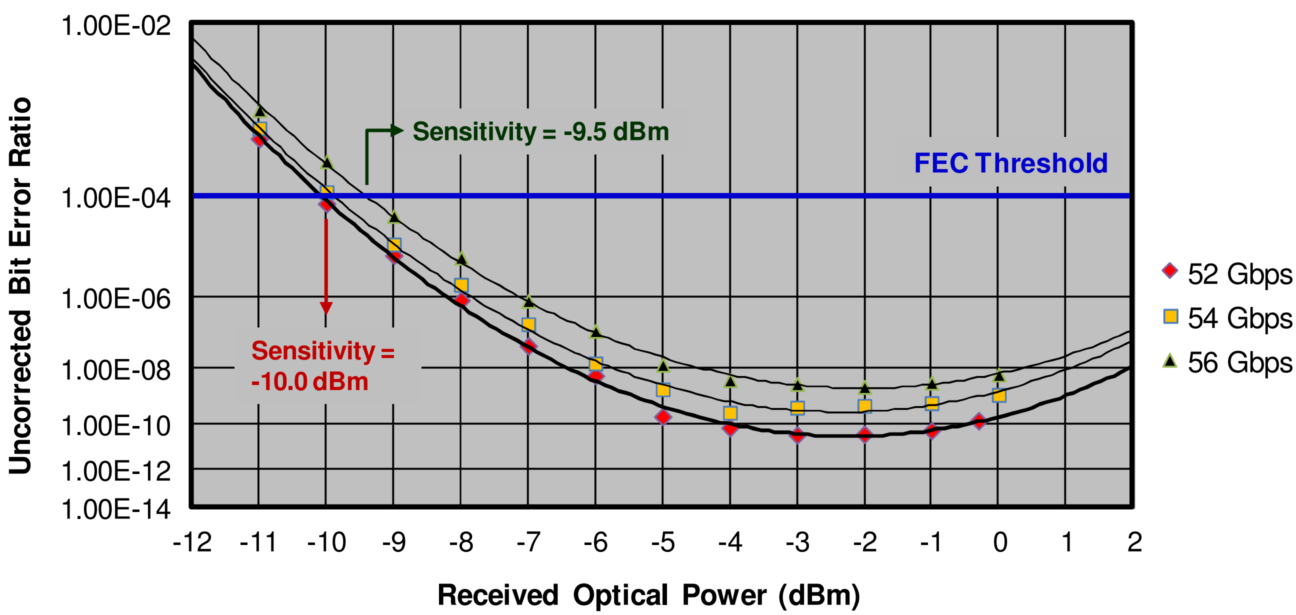

Figure 3. Uncorrected Bit Error Ratio for 10 km PAM4 link in AGC mode as a function of received optical power. The sensitivity is defined as the received optical power above which the FEC's activation results in error-free operation.

The 10 km fiber spool was then bypassed to measure BER in the back-to-back (B2B) link. As shown in Fig. 4, the inclusion of the fiber spool leads to only 0.5 dB penalty in the sensitivity for 56 Gbps transmission. This demonstrates significant flexibility in utilizing such links in scalable platforms having a diversity of optical power levels and transmission distances.

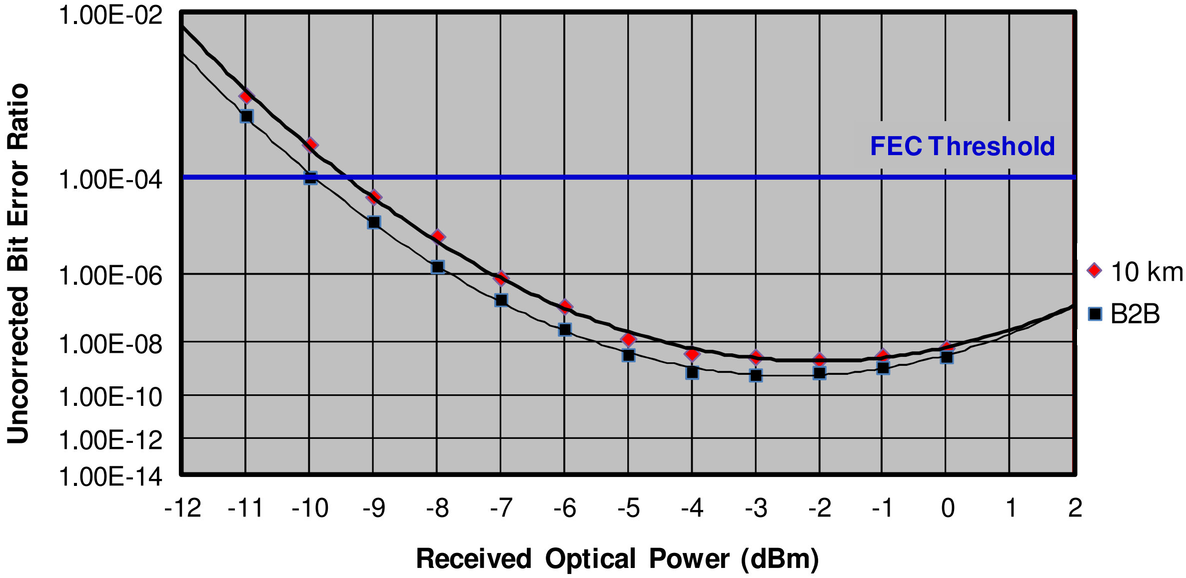

Figure 4. Uncorrected Bit Error Ratio 56 Gbps PAM4 link in AGC mode with and without 10 km fiber span. Fiber pigtails of the optical components resulted in total fiber length of ~10 m in the back-to-back (B2B) setup.

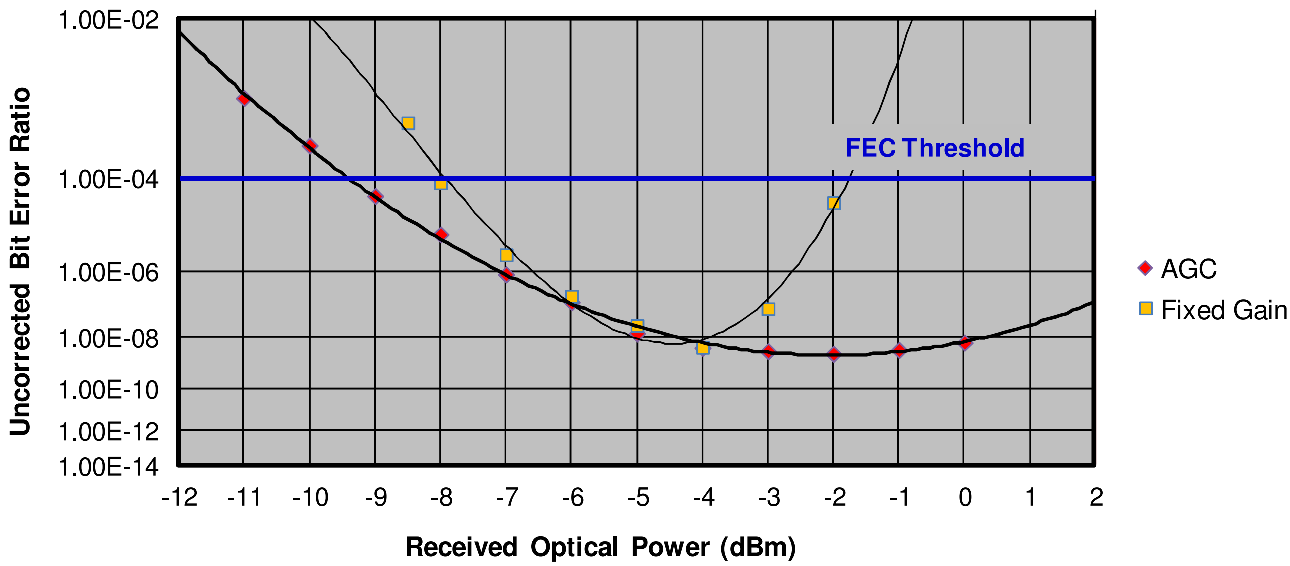

Figure 5. Uncorrected Bit Error Ratio 10 km PAM4 link with and without AGC for 56 Gbps data rate.

To quantify the impact of AGC on the dynamic range of this PAM4 link, the uncorrected BER of the 10 km PAM4 link was measured by operating the linear photoreceiver with fixed gain. These results are shown in Fig. 5 for 56 Gbps data rate. In the fixed gain setting, the dynamic range of the PAM4 link was restricted to an average received optical power ranging from -8 dBm to -1.8 dBm. The fixed gain results match the optimized AGC results over a narrow 2 dB range of received optical power. It can be argued that the 6.2 dB dynamic range of the PAM4 link with fixed gain is primarily due to the FEC. A PAM4 link with an alternative correction code having a BER threshold of say, 1E-6 would be even more impaired by the lack of AGC. This drastic reduction in dynamic range can be explained as follows:

- For optical power less than -6 dBm, the photoreceiver's RF output was insufficient for exploiting the full range of the PAM4 transceiver's input ADC. The consequent degradation in SNR due to the ADC's quantization noise results in a BER penalty.

- Optical power exceeding -4 dBm caused the photoreceiver's RF output to overload the ADC and caused BER penalty due to non-linear compression. This effect is similar to the degradation of LSB BER that a limiting photoreceiver could cause in a PAM4 link.

5. CONCLUSION

In summary, PAM4 modulation format is an attractive alternative to NRZ-ASK to increasing the throughput of data networks. PAM4 continues to use only optical intensity to encode information and has similar bandwidth requirements as NRZ-ASK, which is especially useful in upgrading scalable systems. Being a multilevel format, PAM4 imposes linearity requirements on the digital link. Notably, limiting photoreceivers used in NRZ links need to be replaced by linear photoreceivers. Also, automatic gain control is necessary to combat the inherent non-linearity of ADC-DSP based PAM4 electrical receivers. These features have been experimentally demonstrated in a FEC-assisted, 10 km long, 28 Gbaud (56 Gbps) PAM4 optical link having a dynamic range exceeding 10 dB.

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