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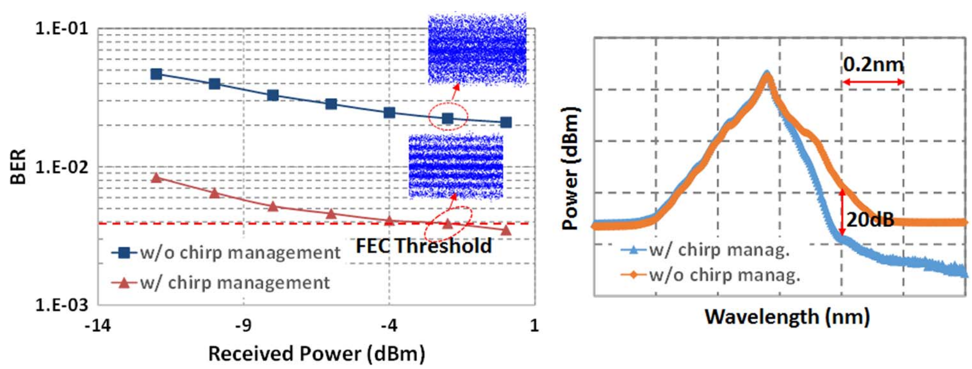

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IM/DD-Based 112-Gb/s/lambda PAM-4 Transmission Using 18-Gbps DML

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Abstract: Single-channel 112-Gb/s PAM-4 transmission based on low-cost intensity modulation and direct detection (IM/DD) optics is experimentally demonstrated over 1-km standard single-mode fiber. By employing a digital precompensation, duobinary encode/decoding with PAM-4 signal and 7-level training-sequence-aided least mean square (TS-LMS) algorithm, we successfully achieve a receiver sensitivity of about −2 dBm with 7% overhead HD-FEC. Chirp management is applied at the transmitter side to extend the reach to 1 km for transmission at 1500 nm. This is the first demonstration, to the best of our knowledge, that 112-Gb/s PAM-4 modulation is achieved using only a 18-GHz (3-dB-bandwidth) commercial directly modulated laser. The method proposed in this paper is both bandwidth and computationally efficient, which is thought to be feasible in the low-cost short-reach optical applications.

Index Terms: Direct detection, PAM-4, directly modulated laser (DML).

1. Introduction

Due to the fast growth of mobile and cloud services, there is strong demand for short reach optics with lower cost and higher capacity. Intensity modulation and direct detection (IM/DD) is well-suited to provide such low cost interfaces. Based on the IM/DD architecture, various advanced modulation formats, such as pulse amplitude modulation (PAM), multi-band carrierless amplitude and phase modulation (Multi-CAP), discrete multi-tone modulation (DMT), have been demonstrated with up to 112-Gb/s per channel line rate for short reach applications, such as data centers and metro networks [1]–[6]. Among the candidates, the PAM-4 and DMT formats have been under active investigation for standardization of 100G and 400G interfaces [7]–[9]. Table 1 has listed state of the art demonstrations employing intensity modulation and direct detection, with DMT or PAM-4 format. For DMT format, each subcarrier can be adapted to the frequency-dependent transmission characteristics of channel, thus being able to make the maximum use of the bandwidth of transmission link. Kai *et al.* reported the transmission of 130-Gb/s DMT signal over 2-km single mode fiber (SMF) using silicon Mach–Zehnder modulator (Si-MZM),

TABLE 1

State of the art demonstrations with DMT or PAM-4 modulation and direct detection for short reach optical applications

Author Affiliation	Line Rate (Gb/s)	Reach (km)	Modulation Format	Modulation Optics
Fujitsu [10]	130	2	DMT	Si-MZM
Alcatel Lucent [11]	115	0.5	DMT	VCSEL
Hitachi [12]	102	40	PAM-4	EML
Hong Kong Poly. Uni. [13]	128	2	PAM-4	EML
Tech. Uni. of Denmark [14]	56	10	PAM-4	DML
This Work	112	1	PAM-4	DML

whose 10-dB bandwidth is around 18 GHz [10]. Xie *et al.* demonstrated single channel 115-Gb/s transmission of DMT signal over 500-m SMF using a 1550-nm single-mode vertical-cavity surface-emitting laser (VCSEL), in which 20% HD-FEC overhead is assumed [11]. Likewise, PAM-4 modulation can also provide beyond 100-Gb/s line rate for a single channel with cost-effective solutions. Kikuchi *et al.* reported the generation of 102-Gb/s Nyquist PAM-4 signal based on commercial 1300-nm 28-Gbps electro-absorptive modulated laser (EML) [12]. Zhong *et al.* demonstrated the highest rate for PAM-4 modulation with single channel 128-Gb/s and four channel 500-Gb/s based on 25 Gbps EML TOSA and 25 Gbps PIN ROSA, in which digital equalizer, post filter and maximum likelihood sequence estimation (MLSE) are employed at the receiver-end digital signal processing (DSP) [13]. Suhr *et al.* reported the transmission of 56-Gb/s duobinary PAM-4 signal over 10-km SMF using 10-Gbps directly modulated laser (DML), in which 56-GSa/s digital to analog convertor (DAC) with digital Bessel filter are applied jointly to effectively obtain the 7-level partial response PAM-4 signal [14].

In this paper, we experimentally demonstrate single channel 112-Gb/s transmission with PAM-4 signal over 1-km standard SMF. To the best of our knowledge, this is the first time that 112-Gb/s PAM-4 transmission is demonstrated with commercial 18-Gbps DML and direct detection. By employing transmitter-side digital duobinary encoding of PAM-4 signal, digital pre-compensation, and receiver-side 7-level training sequence aided least-mean square (TS-LMS) algorithm, duobinary decoding, we successfully achieved a receiver sensitivity of about −2 dBm with 7% overhead HD-FEC. The duobinary encoding process, together with S21 pre-compensation are realized digitally with the 56-GSa/s DAC. No further DSP is needed in the receiver other than TS-LMS and duobinary decoding. Besides, the required number of taps for the proposed TS-LMS algorithm is small, based on the 7-level training sequence. The method proposed in this paper is both bandwidth and computationally efficient, which is thought feasible in the low-cost short reach optical applications.

2. Principal of Operation

In order to achieve 112-Gb/s line rate with only 18-GHz (3-dB bandwidth) DML, digital signal processing (DSP) is essential for both transmitter and receiver. In this paper, 56-GSa/s DAC is used to generate the driving signal of DML. Partial response is first introduced by digital duobinary encoding of PAM-4 signal, which is fulfilled by a two-tap finite impulse response (FIR) filter with equal weights. Because the generation method introduces correlation between adjacent bits, meaning that the current bit is also defined by the values of the k preceding bits, pre-coding at the transmitter side is necessary in order to avoid error propagation at the receiver side. Considering a_k as the original bit sequence, b_k as a pre-coded PAM-4 sequence, and c_k as the

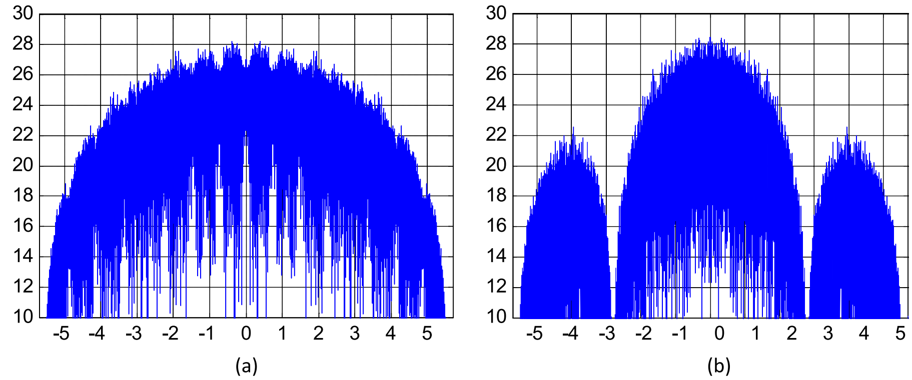

Fig. 1. Spectrum of (a) PAM-4 signal and (b) partial response PAM-4 signal with duobinary encoder, respectively.

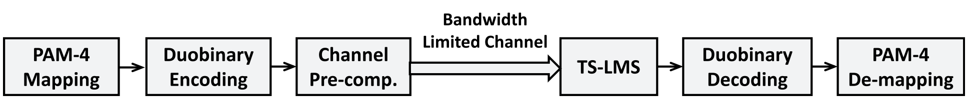

Fig. 2. Block diagram of signal processing for the proposed IM/DD-based PAM-4 transmission system.

7-level generated signal, it is possible to recover the original PAM-4 sequence from independent decisions on c_k, provided the relationship in

$$b_k = a_k - b_{k-1} \bmod 4 \tag{1}$$
$$c_k = b_k + b_{k-1} \tag{2}$$
$$a_k = c_k \bmod 4. \tag{3}$$

is used. The partial response PAM-4 signal can be also achieved with a digital Bessel low pass filter (LPF) [15], however, which requires blind channel equalization with constant multi-level modulus algorithm (CMMA) in the receiver DSP [16]. Fig. 1 shows the spectrum of PAM-4 signal and partial response PAM-4 signal with duobinary encoder, respectively.

Besides, a digital channel (S21 parameters) pre-compensation is required at the transmitter side to overcome the bandwidth limitation from electronics and optics. In the receiver side DSP, 7-level training sequence aided least-mean square (TS-LMS) algorithm is first used to restore the duobinary encoded signal. Although the training sequence introduces overhead, TS-LMS algorithm is easy for implementation and more suitable for real applications due to the fast tracking of channel variations. Then, duobinary decoding is carried out to convert the signal back to 4 levels with simple "modulus-4" operation. PAM-4 signal de-mapping and bit error ratio (BER) calculation comes lastly. Fig. 2 shows the block diagram of signal processing for the proposed IM/DD based PAM-4 transmission system.

However, the 3-dB bandwidth of DML is even smaller than the Nyquist bandwidth for 56-GBaud PAM-4 signal, further spectrum shaping is necessary. In order to get a benchmark, simulation is carried out to investigate the impact of compression ratio on the duobinary encoded PAM-4 signal. The compression ratio (CR) is defined as $(B_{\mathrm{PAM}} - B_{\mathrm{LPF}})/B_{\mathrm{PAM}}$, in which B_{PAM} is the baud rate of PAM-4 signal, and B_{LPF} is the 3-dB bandwidth of a Bessel LPF. Fig. 3 shows the curve of Q-factor penalty versus CR for 112-Gb/s duobinary encoded PAM-4 signal. We found that almost no Q-factor penalty is found for CR less than 52%, since duobinary encoded signal takes only half spectrum of traditional PAM-4 signal. About 1-dB Q-factor penalty is found for CR at ~55% ratio, corresponding to 25-GHz LPF for the 56-GBaud duobinary PAM-4 signal. A 3-dB Q-factor penalty is observed at around 60% CR, corresponding to 22.5-GHz LPF. The spectrum shaping process is

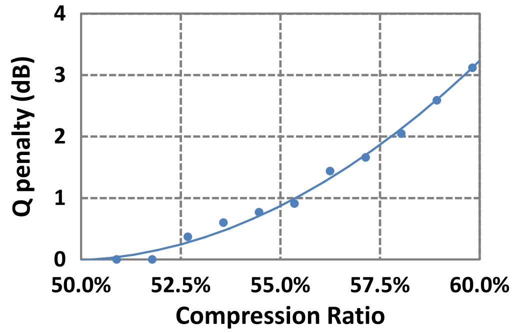

Fig. 3. Q-factor penalty versus CR for 112-Gb/s duobinary-encoded PAM-4 signal.

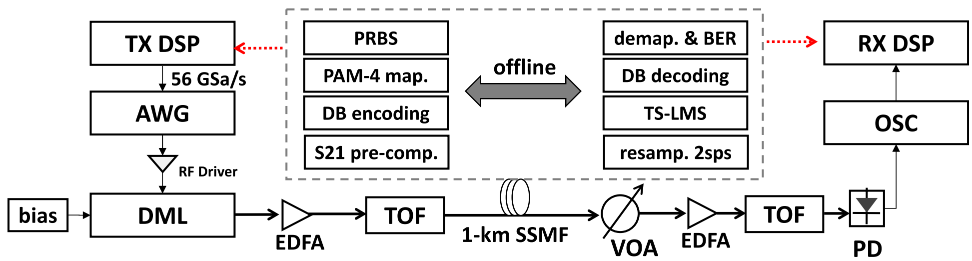

Fig. 4. Experimental setup for the transmission of single-channel 112-Gb/s PAM-4 signal over 1-km standard SMF based on commercial 18-Gbps DML.

achieved digitally by the frequency domain equalization (FDE) [17], which can be carried out at the same time with S21 pre-compensation.

3. Experimental Setup

The experimental setup for the transmission of single channel 112-Gb/s PAM-4 signal over 1-km standard SMF based on commercial 18-Gbps DML is shown in Fig. 4. In the transmitter offline DSP, a PAM-4 sequence (length: 32768 symbols) is first duobinary encoded. Three percent of the generated 7-level signal is used as the training sequence for TS-LMS in the receiver DSP. Then, the encoded signal is digitally pre-compensated in the frequency domain, according to the pre-measured S21 response. A 0.8 amplitude clipping ratio is applied to reduce the peak to average power ratio (PAPR). The output signal is sent to the Keysight arbitrary waveform generator (AWG) running at 56 GSa/s, resulting in single channel 112-Gbit/s line rate. The AWG output is amplified by a linear RF driver with 3-dB bandwidth of 25 GHz and then fed to a commercial DML at 1.53 μm (3-dB bandwidth: 18 GHz). The output power of DML is 6-dBm. A tunable optical filter (TOF) is used after the DML to filter out one sideband of the signal for optical chirp management. Before the TOF, an EDFA is used to compensate the overall insertion loss.

After transmission over 1-km standard SMF, a variable optical attenuator (VOA) is used to adjust the received power. The received signal is detected by a 40-GHz pin-PD without TIA. The detected RF output is then fed to a Tektronix real-time scope, acquired at 100 GSa/s, and processed offline. In the receiver DSP, input data is first re-sampled to 2sps, then a 37-taps TS-LMS is applied to restore the 7-level signal. Finally, PAM-4 signal is recovered by duobinary decoding, which is followed by PAM-4 de-mapping and bit error ratio (BER) calculation.

4. Results and Discussion

Fig. 5(a) and (b) shows the measured amplitude and phase response (S21 parameters) of the system, which includes DAC/ADC, RF driver, DML, and PD. The major performance limiting

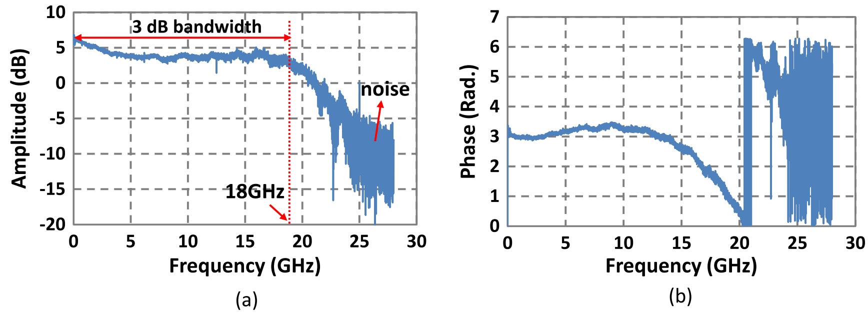

Fig. 5. Measured (a) amplitude and (b) phase response (S21 parameters) of the system, which includes DAC/ADC, RF driver, DML, and PD.

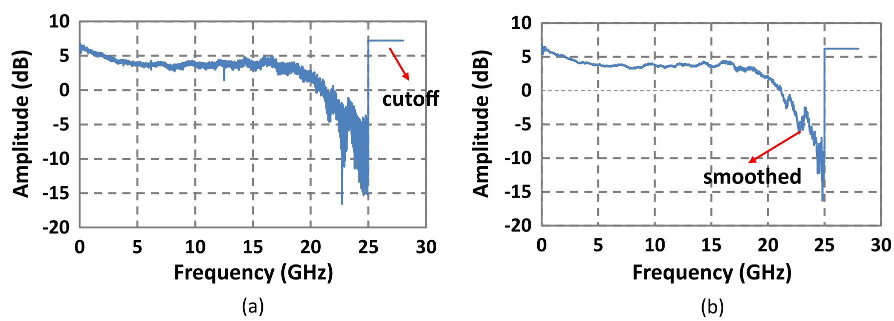

Fig. 6. (a) Amplitude response with 55% CR and (b) the smoothed amplitude response with 55% CR.

factor in the experiment comes from the constrained bandwidth of DML. The overall 3-dB bandwidth is around 18 GHz, while it drops rapidly to beyond 10-dB bandwidth at frequency around 21 GHz. For frequency higher than 25 GHz, the amplitude/phase response is dominated by the noise.

Since 55% compression ratio contributes only 1-dB Q-factor penalty to the performance, a 25-GHz LPF will help improving the overall BER performance. For easy implementation, the final channel response is viewed as the multiplication of pre-measured S21 curve with a LPF response. Thus, the spectrum shaping of LPF can be fulfilled simultaneously with channel pre-compensation using only one frequency domain equalization operation. Zooming into the frequency range from 20 to 25 GHz, significant noise is still observed in the S21 curve, thus, a smoothing window is applied to the S21 curve for noise suppressing. Fig. 6 shows the amplitude response with 55% CR, and the smoothed amplitude response with 55% CR, respectively.

Fig. 7 shows the receiver sensitivity measured at back to back (B2B) for the 112-Gb/s PAM-4 signal, using only S21 pre-compensation without CR, S21 pre-compensation with 55% CR, and pre-compensation by smoothed S21 with 55% CR, respectively. For the 7% overhead HD-FEC, the optimal receiver sensitivity (B2B) is around −2 dBm by employing both 55% CR and a smoothing window. The inset of Fig. 7 also shows the corresponding 7-level signal, which is restored from TS-LMS.

Fig. 8(a) shows the curve of Q-factor penalty versus required number of taps in TS-LMS algorithm for the 112-Gb/s PAM-4 signal based on 18-Gbps DML. In the experiment, 37 taps are used in the TS-LMS algorithm, considering both required DSP resources and performance. Note that smaller number of taps are possible, such as nine taps only contributes less than 1-dB Q-penalty to the overall performance. Fig. 8(b) shows the distribution of error vector in TS-LMS algorithm, using 37 taps and an adapting factor of 0.005. Less than 15-ns is required for the error vector to converge, showing the fast tracking ability of channel variations.

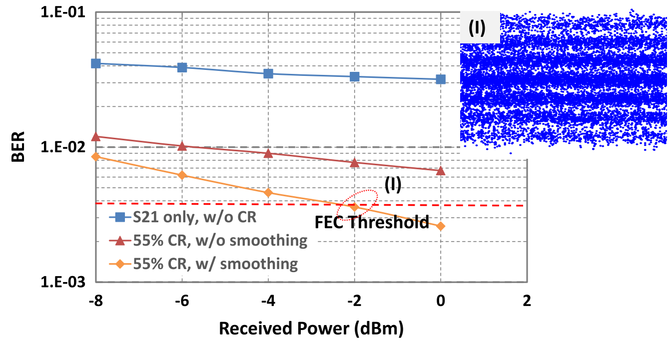

Fig. 7. Receiver sensitivity measured at back to back (B2B) for the 112-Gb/s PAM-4 signal, using only S21 precompensation without CR, S21 precompensation with 55% CR, and precompensation by smoothed S21 with 55% CR, respectively.

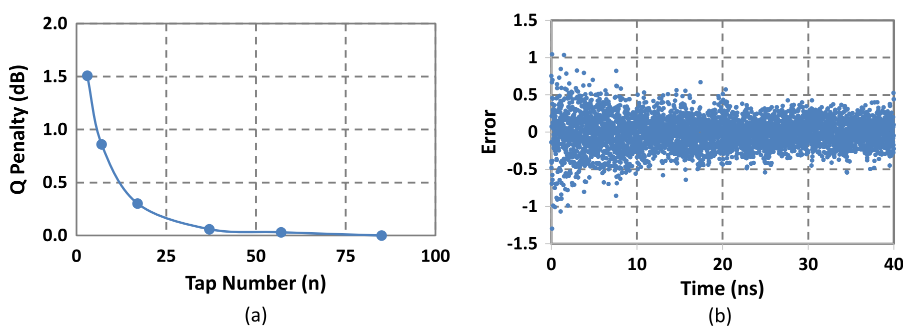

Fig. 8. (a) Q-factor penalty versus required number of taps in TS-LMS algorithm for the 112-Gb/s PAM-4 signal based on 18-Gbps DML. (b) Distribution of error vector in TS-LMS algorithm, using 37 taps and an adapting factor of 0.002.

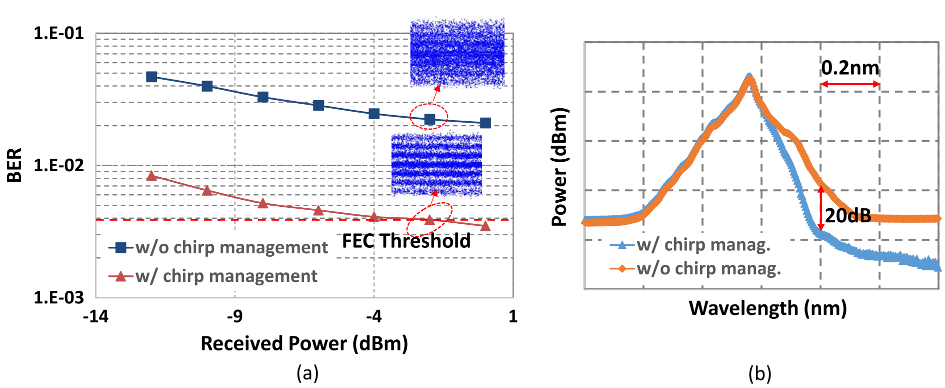

Fig. 9. (a) Receiver sensitivity measured after 1-km SMF, both with and without chirp management at the transmitter side. (b) Corresponding optical spectral with and without chirp management.

Finally, the transmission performance of 112-Gb/s PAM-4 signal is measured over 1-km SMF (G.652). Due to the chirp of DML, significant BER degradation is found compared to the back to back measurement. A TOF is used after DML for chirp management, filtering one sideband of the PAM-4 signal [18]. Fig. 9(a) shows the receiver sensitivity measured after 1-km SMF, both with and without chirp management at the transmitter side. Around -2 dBm receiver sensitivity is found for the 7% overhead HD-FEC, which corresponds to a BER threshold of 3.8×10^{-3}. Fig. 9(b) also shows the optical spectral with and without chirp management, respectively.

5. Conclusion

We have experimentally demonstrated single channel 112-Gb/s transmission with PAM-4 signal over 1-km standard SMF. To the best of our knowledge, it is the first time that 112-Gb/s PAM-4 transmission is demonstrated with commercial 18-Gbps DML and direct detection. The proposed method is both bandwidth and computationally efficient, which is thought to be feasible in future low-cost short reach optical applications.

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