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Complex Modulation and Differential Coherent Detection of Directly Modulated Lasers

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Abstract: We propose and experimentally demonstrate carrier interleaved modulation and differential coherent detection for direct modulation lasers, achieving over 11-dB enhancement in received OSNR at 7% HD-FEC after 74-km SSMF transmission of PAM-4 signals.

1. Introduction

The fast-growing intra-data center traffic drives the demand for high speed short reach optical interconnect beyond 100Gb/s/λ. Compared with intensity modulation and direct detection (IM/DD) systems, coherent technologies capable of recovery of polarization-multiplexed and compelx-modulated signals can provide spectral effecient solutions for next generation Ethernet 800GbE or 1.6TbE. However, expensive narrow-linewidth lasers and power hungry digital signal processing (DSP) required in coherent receivers are two major challenges for its application in short-reach optical interconnects[1]. Various variants and combinations of coherent and IM/DD systems have thus been proposed, including self-homodyne coherent detection (SHD), stokes vector direct detection (SVDD), polarization controller assisted coherent BiDi systems, etc[2-5]. Directly modulated lasers (DMLs) have been extensively used in short reach and metro applications up to 25 Gb/s, due to their low cost and simple implementation. Further increasing the modulation rate of DMLs can be difficult because of intensity modulation and the large modulation chirp. In [5], a complex modulation and coherent detection approach was proposed taking advantage of the modulation chirp of the DML, showing the potential of significant received OSNR improvement. The OSNR improvement comes by turning one-dimensional intensity modulation into a two-dimensional one after coherent detection thanks to the chirp induced phase shift among different coding bits. This approach however, uses an extra narrow-linewidth laser at the receiver end, thus compromises the low cost nature of the DML based applications.

In this work, we propose a new approach to enhance the receiver OSNR using carrier interleaved modulation with differential coherent detection (CIM/DCD). The carriers and signals are modulated in a single DML in a time-division multiplexing (TDM) manner, and a differential optical delay line (ODL) with a one-symbol delay between the two output is utilized at the receiver to generate an aligned signal and carrier pair before they are sent to a 90 degree optical hybrid. The proposed CIM/DCD scheme eliminates the need for local lasers and enables field detection. Furthermore, unlike existing carrier assisted differential detection (CADD) schemes [5], a simple linear equalization is suffice, avoiding complex nonlinear equalization DSP.

2. Principle of the proposed CIM/DCD scheme

Based on DML's diode rate equations, the differential phase of two adjacent signals related to the signal intensity can be expressed as [5]:

$$\Delta\varphi=\frac{\alpha}{2}\left(ln\frac{P(t_2)}{P(t_1)}+\kappa\frac{P(t_1)+P(t_2)}{2}\cdot T\right) \tag{1}$$

where α is the laser linewidth enhancement factor, κ is the adiabatic chirp coefficient, and $P(t)$ is the signal intensity. It can be seen from the Eq. (1) that the differential phase depend on the intensity of the adjacent signals $P(t_1)$ and $P(t_2)$, and therefore the number and distributions of the signal intensity will greatly affect the distribution of the differential phase. For example, there are 4 different levels in PAM-4 modulation so it will have 16 differential phase distributions if it uses direct modulation with conventional coherent detection scheme. The condensed constellation may become an issue in signal detection. It should be noted that the number of constellation points increases dramatically along with the modulation level, making it impossible to increase the data rate using higer order modulation formats in systems with DML and conventional coherent detection schemes. In light of this situation, we

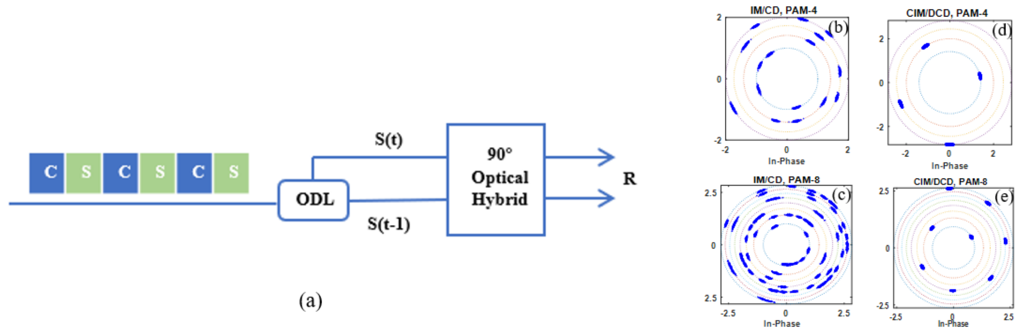

Fig. 1. (a) Structure of CIM/DCD receiver and the corresponding constellation for different schemes:(b) IM/CD, PAM-4; (c) IM/CD, PAM-8; (d) CIM/DCD, PAM-4; (e) CIM/DCD, PAM-8. IM/CD: intensity modulation and coherent detection.

propose a CIM/DCD scheme in this work, as shown in Fig. 1(a). The signal 'C' and 'S' represent carrier and signal field, respectively. The carrier and signal are generated in a TDM manner, so that two consecutive symbols can be expressed as $S(t-1) = C \cdot exp\big(i \cdot \varphi(t-1)\big)$ and $S(t) = A_M \cdot exp\big(i \cdot \varphi(t)\big)$, respectively, where M represents the M^{th} different level in PAM-M modulation. After passing through a differential ODL with a one-symbol delay between the two output, $S(t)$ and $S(t-1)$ are fed into a 90 degree optical hybrid together, and they are detected by balanced photo detectors (BPDs). So the received signal R can be derived as:

$$R = S(t-1)^{*}S(t) = A_M C \cdot exp(i \cdot \Delta\varphi) \tag{2}$$

From Eq. (1) and Eq. (2) one can clearly know that there are only M differential phase distributions in PAM-M modulation after the DCD receiver. One can also find via Figs. 1(d-e) that unlike IM/CD [Figs. 1(b-c)], the DML modulated PAM signals can be directly converted into a two-dimensional constellation with a significantly larger Euclidean distance using the DCD receiver. It is worth noting here that after the DCD receiver, the signals in every two consecutive symbol periods are same in intensity, but different in phase. A maximum ratio combing (MRC) scheme can therefore be used to further enhance the system performance. Also, it should be noted that other TDM schemes, e.g., two symbols followed by one carrier, forming a '…CCSCCS…' structure [7] can also be used in the transmitter to further increase the overall data rate. For simplicity, only '…CSCS…' was experimentally evaluated in the following proof-of-concept experiment.

3. Experimental setup

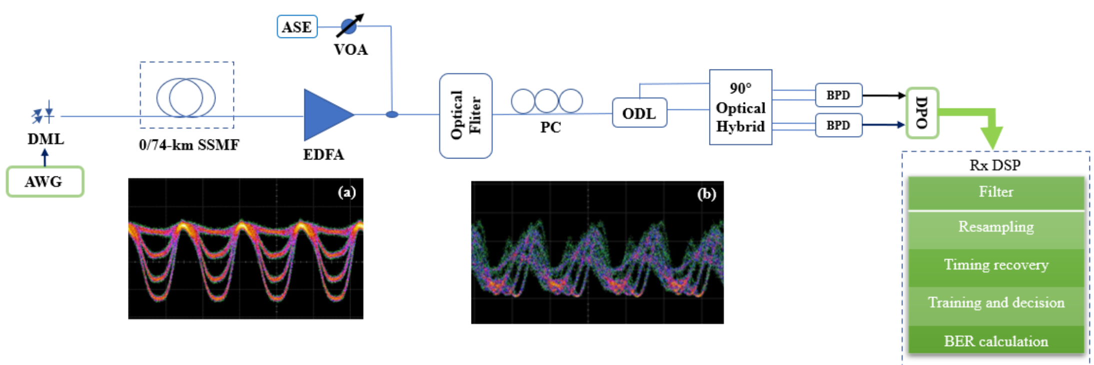

Fig. 2. Experimental setup for CIM/DCD scheme. Inset (a) BtB eyediagram at OSC; inset(b) after 74-km transmission eyediagram at OSC. AWG：arbitrary waveform generator. ASE: amplified spontaneous emission. VOA: variable optical attenuator. EDFA: erbium-doped fiber amplifier. OSC: oscilloscope. DPO: digital phosphor oscilloscope

Fig. 2 depicts the proof-of-concept experimental setup we used to verify our proposed CIM/DCD scheme. A 18-GHz DML with a center wavelength of 1550 nm was modulated by a 100-GSa/s AWG. The 12.5 Gbaud PAM-4 signal and carrier were generated as described in Sec.2. An electrical amplifier (SHF 807s) was used to boost the current of the electrical signal before sending to the DML. The bias of the DML can be adjusted using a separate source. After 74-km SSMF transmission, the received signal was amplified and noise loaded for OSNR scanning. A DCD receiver consisted of a electrical polarization controller with real-time feed-back control, a customized differential ODL, a single polarization 90 degree hybrid and a pair of BPDs was used, followed by a 100G-Sa/s DPO with 33 GHz bandwidth for electrical signal reception and offline digital data processing. Since the two differentially detected signals are of the same origin laser source, the received signal does not require frequency offset estimation and carrier phase recovery, which greatly reduces the complexity of data processing. In order to avoid the calculation error introduced by measuring DML parameters, a small segment of the received signals was used as the training sequence to obtain the distribution of the received constellations. The reamining signals were then detected and demodulated on a symbol-by-symbol basis. There is no need for any complex nonlinear equalization procedures.

4. Results and discussion

In order to make a fair comparison, we also conducted 12.5-Gb/s PAM-4 transmission using IM/DD for both back to back (BtB) and 74-km SSMF fiber link transmission. Fig. 3 shows the measured BER performance of BTB and 74-km transmission using two different schemes. At the BER of 3.8×10^{-3}, which is the threshold of hard forward error correction (HD-FEC) with 7% overhead, the required OSNR is 12.3 dB and 23.8 dB for CIM/DCD and IM/DD at BTB, respectively, resulting in a 11.5 dB OSNR improvement for the CIM/DCD scheme. The required OSNR is 14.1 dB after 74-km transmission, with an OSNR penalty of less than 2 dB compared with BtB. As shown in Fig. 3(a), the proposed CIM/DCD scheme has a significant lower OSNR requirment in Both BtB and 74-km transmission cases.

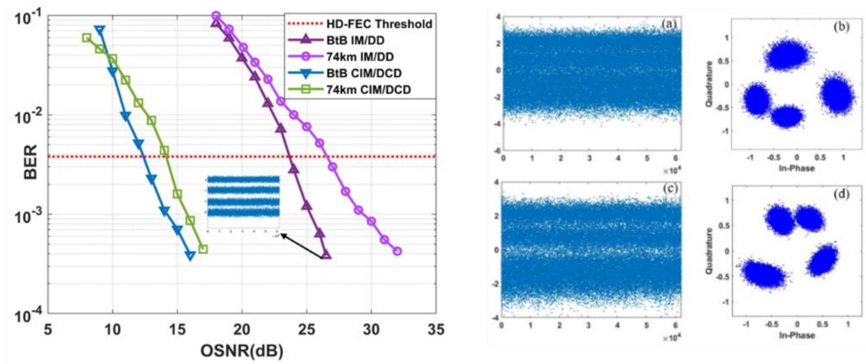

Fig. 3 BER performance over 0/74-km transmission. Inset(a-d) are corresponding recevied signal for different scheme at OSNR of 18dB (a)BtB IM/DD; (b) BtB CIM/DCD; (c)after 74-km transmission IM/DD; (d)after 74-km transmission CIM/DCD

5. Conclusions

We have proposed a CIM/DCD scheme for DMLs that can significantly enhance the receiver sensitivity without the use of local lasers. A proof-of-concept experiment with 12.5-Gb/s PAM-4 transmission over 0/74-km SSMF link has been demonstrated. Using the proposed scheme, the proposed CIM/DCD scheme shows more than 11-dB OSNR sensitivity advantage over the conventional IMDD scheme for both BtB and 74-km transmission cases. In addition, the complexity of digital data processing is dramatically reduced compared with existing coherent schemes for DMLs.

Acknowledgements

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