Nonlinearity Free Operation of SOA for Use in High-Capacity Co-Packaged Optics

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Abstract: We propose a novel concept to generate high-capacity WDM signals from single source of non-mode-locked multi-wavelength light using SOAs. Using micro-ring modulators in a way to suppress SOA nonlinearity, high-quality PAM4 signals can be generated.
OCIS codes: (060.4510) Optical communications; (130.4110) Modulators, (130.6622) Subsystem integration and techniques

1. Introduction

Recently, co-packaging optics (CPO), where photonic and electrical circuits are integrated on the same board is attracting attention to reduce the power consumption and the latency of the network in high-performance computer and datacenter [1-2]. In CPO, high-capacity WDM transmission is performed modulating multi-wavelength light (MWL) with a bunch of micro-ring modulators (MRM) [3-5]. Multi-Tbps optical I/O was realized using 256-ch 25-Gb/s signals with bandwidth density of >1Tbps/mm^2 [6]. CPO with internal light source has advantages in terms of footprint, feasibility of assembling and inspection [7, 8]. Considering the high failure rate of a laser, reducing the number of lasers is most effective to lower the failure rate of CPO. Ideally, CPO can be composed using just one set of MWL, whose output is shared by multiple modulators. In this scheme, signal power per channel decreases with the capacity unless optical amplifier such as SOA is used before or after the modulators. So far, lossless operation of a (1×8) silicon optical splitter was achieved by hybrid integration of InP-SOA [9].

If SOA is used after the modulator, signal waveform is distorted by nonlinear optical effects, i.e. self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). To mitigate these effects, low power operation is required to the SOA. Uneven channel spacing can be used to suppress the nonlinear effects [10]. However, large part of the transmission bandwidth is left unused. On the other hand, if SOA is used before modulation, SPM and XPM do not occur. If the source of MWL is so-called optical frequency comb (OFC), whose modes are phase-locked each other, amplified light is free from FWM and high quality signals are generated. Although extensively studied, the reliability OFC is still uncertain and it is more practical to use standard LDs for MWL. In this case, the amplified light suffers from extra intensity noise caused by FWM and the generated signal has low SNR. However, it is possible to suppress the FWM-induced intensity noise by using uneven channel spacing and to generate WDM signals in accordance with the definition of IEEE by using modulators with dedicated design.

In this paper, we present a novel scheme to generate high-capacity WDM signals in CPO using SOAs in a way free from optical nonlinearity. In the experiment emulating the proposed concept, we generate 8-ch 112-Gb/s PAM4 signals with quasi-equal channel spacing from a non-mode-locked MWL (8 independent LDs). The measured Transmitter and Dispersion Eye Closure Quaternary (TDECQ) of 1.3dB is well below the criteria of IEEE802.3bs.

2. Proposed concept

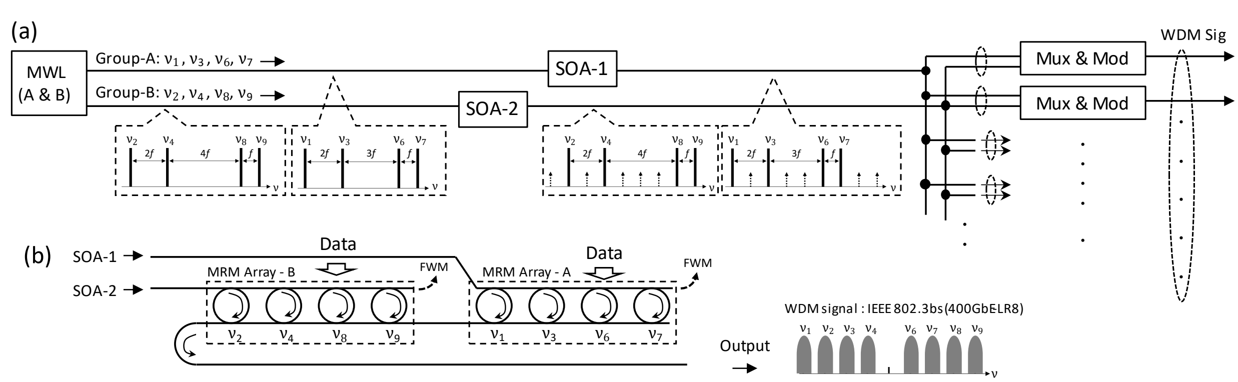

Fig. 1: (a) Conceptual diagram of a high-capacity CPO transmitter using SOAs for the amplification of multi-wavelength light. (b) The configuration of MUX-Modulator. MWL: Multi-wavelength light, MRM: Micro-ring modulator.

As an example of the proposed concept, we present in Fig.1(a) a scheme to generate a large number of 8-ch WDM signals from a single source of MWL using SOAs. It is assumed that laser frequencies are on the WDM grid given by

$$\nu_m = \nu_0 + m \times f \ (m = 1, 2, \cdots) \qquad (1)$$

, where ν_0 is the offset frequency and f is the grid spacing. Here, the eight wavelengths of MWL are divided into two groups (A and B) with uneven frequency spacings. In Group-A, laser frequencies are set to (ν_1, ν_3, ν_6, ν_7), which we call "type-A" frequency arrangement. In Group-B, laser frequencies are set to (ν_2, ν_4, ν_8, ν_9), which we call "type-B" frequency arrangement. In the two groups, four light waves are amplified by an SOA (SOA-1 and SOA-2), independently. In the SOA, many new waves are generated by FWM. However, none of them overlap with the input waves in the two (type-A and type-B) special frequency arrangements. Therefore, the amplified light is unaffected by FWM. The outputs of two SOAs are divided into multiple paths which are connected to the modulators. If the number of modulators is quite large, multi-stages of "Amp & Split" are used to supply sufficient power.

Although the outputs of two SOAs are stable, they become noisy if mixed by a normal optical coupler because the FWM products of one group interfere with the main output of another group generating high frequency beat note. To avoid this, the output of two SOAs are combined using modulators with a structure shown in Fig.1(b). The new device, which we call "MUX-modulator" consists of two sets of arrayed four MRMs (MRM array-A and MRM array-B) sharing one output port. In MRM array-A, the resonance frequencies of four MRMs are in the frequency arrangement of type-A so that only the main output of SOA-1 is data modulated and transmitted from the output port while FWM products are rejected. Similarly, in MRM array-B, only the main output of SOA-2 is modulated and FWM products are rejected. Thus, the MUX-modulator has combined functions of modulation, multiplexing and rejection of FWM products. From the output port of the MUX-modulator, 8-ch WDM signals are transmitted lying on the WDM grid between ν_1 and ν_9 with the central grid (ν_5) empty. This frequency arrangement coincides with the standard wavelength of 400GBASE-LR8 defined by IEEE 802.3bs when ν_0 = 228.2THz and f = 800GHz [11]. Furthermore, the channel count of the WDM signal can be increased to 12ch., 16ch., ⋯ adding more MRM-arrays in the MUX-modulator.

3. Experiments

We carried out a proof-of-concept experiment using a setup shown in Fig.2. The laser frequencies were on the 200-GHz WDM grid given by eq. (1) with ν_0 = 192.200THz and f = 200GHz. MWL was obtained from eight LDs, which were divide into two groups: MWL-1 with type-A frequency arrangement (ch.1~ch.4: ν_1, ν_3, ν_6, ν_7) and MWL-2 with type-B frequency arrangement (ch.5~ch.8: ν_2, ν_4, ν_8, ν_9). In each group, the outputs of four LDs were multiplexed by a (4×1) optical coupler and amplified by an SOA. The input and output power of SOA were 0dBm and 13dBm, respectively. As MUX-modulator was not available, it was emulated by a subunit consisting of a programable optical filter (POF) with two input ports and an intensity modulator. The output of two SOAs were introduced to the two input ports (port-1 and port-2) of POF. As shown in the inset of Fig.2, port-1 and port-2 had four square-shape passbands with the width nearly twice the signal baud rate at the frequencies of type-A and type-B frequency arrangement, respectively. For comparison, the performance in the even channel spacing (ch.1~ch.4: ν_1, ν_2, ν_3, ν_4; ch.5~ch.8: ν_6, ν_7, ν_8, ν_9) was also studied. The intensity modulator generated 43-Gb/s NRZ signal and 112-Gb/s PAM4 signal with an extinction ratio of ~5dB using the output from an arbitrary waveform generator (AWG). The optical spectra of the generated 8-ch 112-Gb/sPAM4 signal is shown in the inset of Fig.(2). The signals were amplified by an EDFA for quality evaluation performed with a digital communication analyzer.

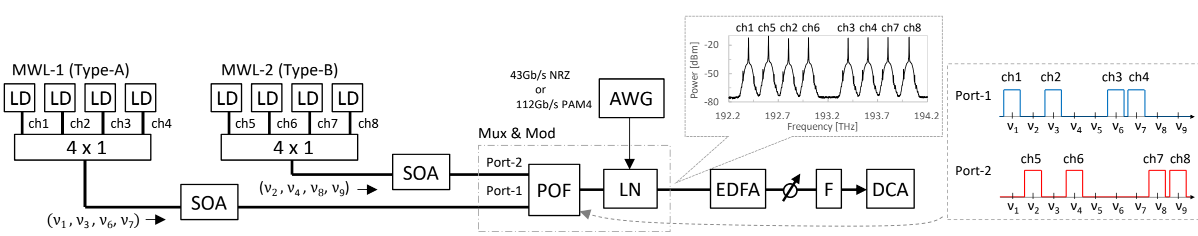

Fig. 2 Experimental setup. AWG: Arbitral waveform generator, POF: Programable optical filter, LN: LN Intensity modulator, F: Bandpass filter, DCA: Digital communication analyzer.

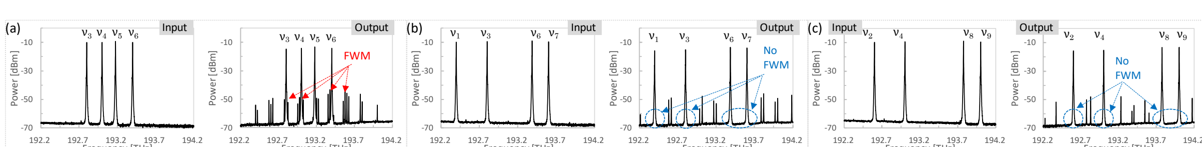

Fig. 3 Input and output spectra of SOA observed in the frequency arrangement of even channel spacing (a), type-A (b) and type-B (c).

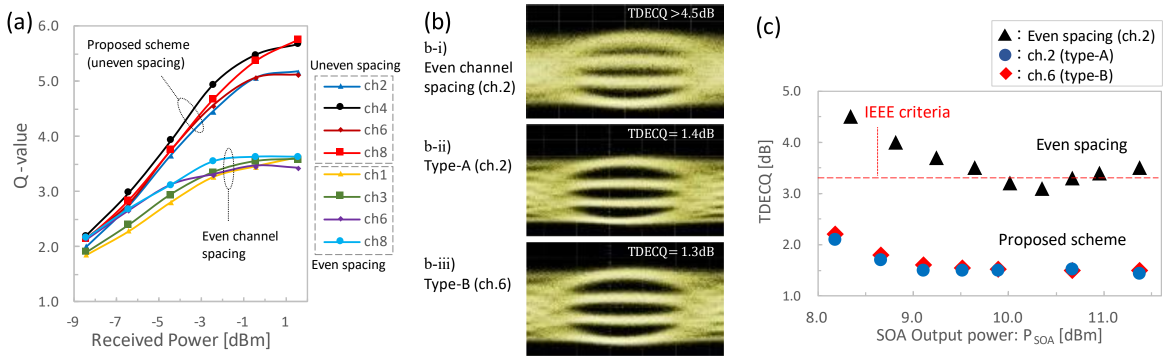

Fig.4 (a) Q-value vs Received-power measured for 43G NRZ signal in the proposed scheme and the scheme with even channel spacing, (b) Eye diagrams of 112G PAM4 signal, (c) TDECQ vs P_{SOA} measured in the proposed scheme and the scheme with even channel spacing.

First, we compare the output spectra of SOA observed in the three different frequency arrangements, where one of the laser frequencies is slightly shifted from the original value so that the FWM products do not overlap with the main output. Fig.3(a) shows the optical spectra observed when four channels are evenly spaced (ch.1~ch.4: $\nu_3 \sim \nu_6$). It is seen that new waves due to FWM are generate in the vicinity of four input waves. As a result, the amplified light suffers from additional intensity noise. Fig.4(b) and (c) show the spectra observed in the case of type-A and type-B frequency arrangement, respectively. In both cases, many new waves exist in the output of SOA. However, none of them overlap with the input waves. This guarantees that amplified light is free from quality degradation due to FWM.

Next, we evaluate the quality of 43-Gb/s NRZ (PRBS: 2^{11}-1) signal measuring the Q-value as a function of the received power. Fig.4(a) shows the performances of four channels: two (ch.2 & ch.4) from MWL-1 and two (ch.6 & ch.8) from MWL-2. For comparison, Q-values measured for four channels (ch.1, ch.3, ch.6, ch.8) in the even channel spacing are also plotted in Fig.4(a). In the case of even channel spacing, Q-values remain below 4.0, which corresponds to BER of ~3.4×10^{-5}, because SNR is degraded by the intensity noise due to FWM. The poor performance is improved in the proposed scheme adopting uneven channel spacing.

The quality of 112-Gb/s PAM4 signals was evaluated by TDECQ, which is required to be below 3.4dB by IEEE. Fig.4(b) compares the eye diagrams observed in the three frequency arrangements: even channel spacing (b-i), type-A (b-ii) and type-B (b-iii). In the case of even channel spacing, the upper eye is almost closed and TDECQ was beyond ~the measurable range (> 4.5dB). In the case of type-A and type-B frequency arrangement, eye diagrams with clear openings are observed. The measured TDECQ of 1.3~1.6dB is well below the IEEE requirement and almost equal to the values obtained in the case of single-wave light. In Fig.4(c), TDECQ is plotted as a function of the SOA output power, P_{SOA}, for the three frequency arrangements. Here, the input power of SOA is reduced to -2dBm so that TDECQ is in the measurable range. In the proposed scheme (ch.2 and ch.6), TDECQ decreases monotonously with P_{SOA} because SNR after EDFA increases with signal power. In the case of even channel spacing, TDECQ decreases with P_{SOA} only at $P_{SOA} < 10.3$dBm. At $P_{SOA} > 10.3$dBm, TDECQ increases with P_{SOA} because intensity noise caused by FWM become dominant. As a result, TDECQ below 3.4 dB is not achieved when SOA is in the full-power operation. These results suggest that SOA can be used like EDFA in our scheme.

4. Conclusion

We showed that SOA can be used to generate 112-Gb/s PAM4 WDM signals from a set of normal LDs using even channel spacing and MRMs in a way to suppress optical nonlinearity. If we assume bandwidth density of ~1Tbps/mm^2 for the CPO with 112-Gb/s PAM4 signals, 100Tbps optical I/O can be expected in the footprint of 1cm^2.

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5. References

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