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Enhancing Data Center Interconnects Efficiency with Integrated SOAs in InP Mach-Zehnder Modulators: an Experimental Validation

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Abstract: This study investigates the impact of integrated SOAs within InP IQ-MZM PICs on short-reach optical links for DCI applications. Experimental validation, focusing on BER, Q-factor and EVM results, highlights SOAs' benefits in short-reach transmission.

1. Introduction

Advancements in photonic integrated circuits (PICs) are significantly influencing the optical communications landscape. Specifically, progress in indium phosphide (InP) technology is poised to offer semiconductors suitable for integrated electro-optical Mach-Zehnder modulators (MZM) [1]. The distinctive properties of the InP substrate also allow for the incorporation of a laser source and semiconductor optical amplifiers (SOAs) onto the same PIC. Moreover, the escalating global demand for data necessitates energy-efficient and cost-effective solutions for optical links spanning 10-80 km and beyond, commonly used for inter-Data Center Interconnects (DCI) [2]. One compelling application of SOAs in conjunction with integrated modulators is enabling coherent optical transmission at high symbol rates, obviating the need for Erbium Doped Fiber Amplifiers (EDFAs) as booster amplifiers on the transmitter side of the optical link. This opens up promising avenues for short-reach and DCI applications [3]. Consequently, this study aims to experimentally assess the influence of integrated SOAs within an ultra-wideband (UWB) InP IQ-MZM PIC on a single-span, short-reach optical link tailored for DCI applications. Starting from the simulation results obtained in a previous work, where the InP MZM PIC has been characterized and then inserted in a time-domain simulator in order to emulate a DCI scenario under different transmission conditions [4], this study focuses on experimentally validating the findings elucidated in the referenced research, emphasizing the practical implementation of all pertinent elements within a short-reach, single-span DCI optical link reproduced in laboratory. The proposed experimental setup in use and the results obtained are presented in this research study, focusing on bit error rate (BER), Q-factor (Q) and error vector magnitude (EVM) vs. fiber span length L_{span} curves obtained by direct measurements, emphasizing the benefits of SOAs in short-distance transmission.

2. Experimental Setup

The device under test (DUT) is a Lumentum high-bandwidth coherent driver modulator (HB-CDM), a dual-polarization (DP) UWB InP IQ-MZM, based on the InP MZM platform presented in [5]. The simplified internal structure of the DUT, shown in Fig. 1, presents integrated circuits for four-channel modulator drivers (XI, XQ, YI and YQ MZMs) and two nested modulators (PhX and PhY MZMs), tailored to modulate both the amplitude and phase of the input light across both polarization states (X and Y). The two independent polarization outputs are then recombined in a single optical output through a polarization rotator and a polarization beam combiner (PBC). The DUT features two independent integrated SOAs at both polarization terminals: a *Pre-SOA* at the input and a *Post-SOA* at the output of each polarization branch, as depicted in Fig. 1. In order to investigate the impact of the integrated SOAs in transmission for an inter-data center solution, the HB-CDM has been inserted in an experimental laboratory setup shown in Fig. 2. The HB-CDM module is inserted in a Lumentum evaluation board

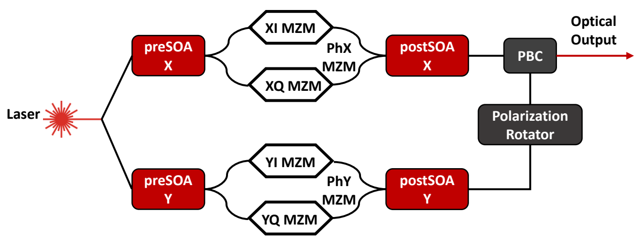

Fig. 1: Simplified internal structure of the HB-CDM with integrated SOAs.

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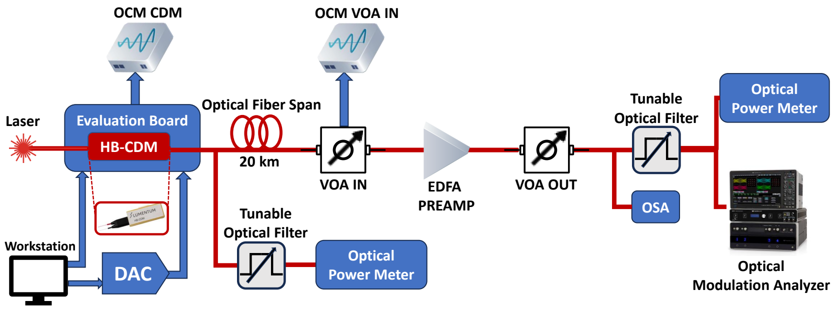


Fig. 2: Experimental laboratory setup used for performance measurements.

controlled by a workstation using USB-to-SPI communication. The evaluation board is in charge of controlling and monitoring SOAs' control currents, the electrical driver gain and the bias control differential voltages applied to electrodes of the independent drivers of the internal and nested MZMs in the HB-CDM structure. The bias-point control is managed by a proposed algorithm presented in [6]. All HB-CDM control values are monitored reading the optical channel monitor available using the evaluation board (OCM CDM). Modulation signals control is facilitated through an 8-bit, 92 GS/s digital-to-analog converter (DAC) under workstation control. Modulation signals are generated by the workstation starting from a pseudo-random binary sequence (PRBS) data generator that produces a PRBS31 ($2^{31}-1$ bits) sequence, generating independent modulation signals for each polarization branch of the modulator. Two modulation formats (DP-QPSK, DP-16QAM) at two achievable symbol rates for the DAC in use (32, 64 GBd) have been generated to be used in the experiment, spanning bit-rates from 100 towards 400 Gbit/s. A continuous wave (CW) tunable laser set at an input wavelength of 1550 nm with a launch power of 10 dBm generates the optical input. The optical launch power in output from the HB-CDM is monitored by an optical power meter. To reproduce a realistic DCI scenario, the optical modulated signal from the HB-CDM output directly feeds into an optical link, omitting a booster EDFA, which is in this case substituted by the SOAs in the HB-CDM. This link is composed by a single span of 20 km of a standard single mode fiber (SSMF) with an attenuation coefficient (α) of 0.19 dB/km, connected to a VIAVI variable optical attenuator (VOA-IN) used to emulate the increase of the span length increasing the attenuation value. Four fixed span lengths are considered for the experiment (20, 40, 60 and 80 km, corresponding to 0, 3.8, 7.6, 11.4 dB of VOA-IN attenuation, respectively), in addition to a maximum-reach L_{max} case for each modulation format and symbol rate under investigation. The OCM VOA-IN is used to monitor the optical output power of the VOA-IN ($P_{out,span}$). In order to keep $P_{out,span}$ constant for each case under test, SOA currents of the HB-CDM are varied in order to increase the SOA gain and to recover the loss introduced by the emulated DCI link. To mitigate distortion and streamline considerations, the pre-SOAs are saturated at maximum gain, while the post-SOAs are adjusted from a minimum to a maximum operating current I_{SOA}. This adjustment is uniform across both polarizations, as they have been previously balanced in output power. A VIAVI pre-amplifier (PREAMP) EDFA is connected to the VOA-IN constant output power and it is set at constant, maximum gain, in order to present a minimum noise figure (NF). PREAMP output is sent to another VIAVI VOA (VOA-OUT), which is in charge to vary the effective gain of the EDFA at receiver side by varying its attenuation, in order to keep a received output power P_{RX} constant at 0 dBm, which has been considered as a safe received output power value at receiver side for constellation diagram analysis and for a proper operation of the digital signal processing (DSP) of the coherent receiver. The optical output of the VOA-OUT is partially sent via a 90:10 optical splitter to an optical spectrum analyzer (OSA) which is in charge to perform optical signal-to-noise ratio (OSNR) measurements at receiver side, while the other optical branch is previously sent to a tunable optical filter centered at 193.5 THz and then divided between a Teledyne Lecroy Optical Modulation Analyzer (OMA) and a Keysight 8163A optical power meter via a 50:50 optical splitter for constellation diagram observation and P_{RX} power measurements, respectively. Thanks to the DSP integrated in the OMA, it has

Modulation Format	SE [bit/s/Hz]	R_S [GBd]	R_b [Gbit/s]	$P_{out,span}$ [dBm]	$\alpha_{VOA-OUT}$ [dB]	OSNR [dB]	$I_{SOA,norm}$ [%]		Q [dB]		EVM [%]		$\log_{10}$(BER)	
				20 ÷ 80 km range	20 ÷ 80 km range	20 ÷ 80 km range	@20km	@80 km	@20km	@80 km	@20km	@80 km	@20km	@80 km
DP-QPSK	3.125	32	100	-3.24	9.1	25.34	19.68	100	20.83	19.56	10.3	10.53	-21.87	-17.41
		64	200	-3.77	8.7	24.19	19.85	100	10.86	10.12	28.14	28.49	-3.59	-3.32
DP- 16QAM	6.25	32	200	-6.03	8.3	23.61	20.5	100	13.87	12.36	9.07	10.78	-6.51	-4.92
		64	400	-3.54	9.4	25.12	19.7	100	8.94	8.38	15.99	17.05	-2.71	-2.48

Table 1: Fiber span output power $P_{out,span}$ [dBm], VOA-OUT attenuation $\alpha_{VOA,OUT}$ [dB], OSNR [dB] measured at 0.1 nm resolution bandwidth, SOA normalized current $I_{SOA,norm}$ [%], Q-factor [dB], EVM [%] and estimated Pre-FEC log_{10}(BER) measured results vs. Modulation Format, Spectral Efficiency SE [bit/s/Hz], symbol rate R_S [GBd], bit-rate R_b [Gbit/s] scaled of FEC-OH 28%. Results are reported for the inter-data center interconnect span length range under test, between 20 and 80 km.

Modulation Format	R_S [GBd]	R_b [Gbit/s]	L_{MAX} [km]	$P_{out,span}$ [dBm]	$\alpha_{VOA-OUT}$ [dB]	OSNR [dB]	$I_{SOA,norm}$ [%]	Q [dB]	EVM [%]	$\log_{10}$(BER)
DP-QPSK	32	100	154.8	-16.15	0.0	13.33	100	13.47	21.22	-5.91
	64	200	145.9	-16.16	0.0	12.57	100	8.58	37.26	-2.42
DP- 16QAM	32	200	135.0	-16.5	0.73	13.71	100	10.12	16.11	-2.69
	64	400	100.0	-7.35	7.54	21.57	100	8.23	17.36	-2.43

Table 2: Maximum Reach L_{MAX} [km] and fiber span output power $P_{out,span}$ [dBm], VOA-OUT attenuation $\alpha_{VOA,OUT}$[dB], OSNR [dB] measured at 0.1 nm resolution bandwidth, SOA normalized current $I_{SOA,norm}$ [%], Q-factor [dB], EVM [%] and estimated Pre-FEC log_{10}(BER) results vs. Modulation Format, symbol rate R_S [GBd] and bit-rate R_b [Gbit/s] scaled of FEC-OH 28% under test. The reported results are measured at the maximum reach L_{MAX} affordable for each case under test.

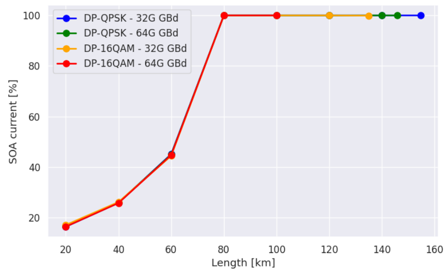
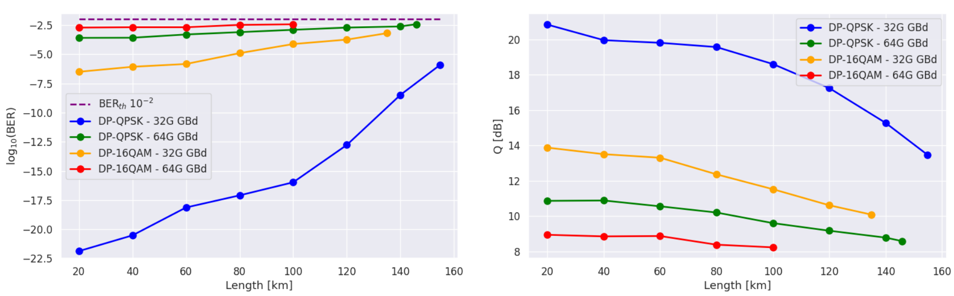


Fig. 3: Normalized SOA current [%] vs. Fiber Length [km] curves obtained by measurement, considering two modulation formats (DP-QPSK, DP-16 QAM) at two symbol rates (32, 64 GBd).

been possible to recover also the chromatic dispersion introduced by the fiber span and to consequently use it as a coherent receiver in order to collect performance measurements in terms of EVM, Q-factor and estimated BER.

3. Results

We present the results obtained after measurements for all modulation format and symbol rate cases under test. The first measurement campaign is conducted considering fiber span lengths between 20 and 80 km, in order to investigate the inter-data center interconnect scenario. Results of these first measurements are presented in Tab. 1. $P_{out,span}$ is kept constant in the inter-data center interconnect span length range, and it is chosen forcing the SOA gain in saturation, setting I_{SOA} at maximum current ($I_{SOA,norm}$ = 100%), considering a span length of 80 km, which is equivalent to set $\alpha_{VOA-IN} = 11.4$ dB, and reading the obtained $P_{out,span}$ value from the OCM VOA-IN. Then, for each modulation format and symbol rate case under test, different span lengths in the chosen 20-80 km range are taken into account increasing the attenuation introduced by VOA-IN, which is equivalent in terms of fiber loss to increase the length of the fiber span. As a consequence, I_{SOA} is also increased in order to recover the loss introduced by the increased span length, as shown in Tab. 1 and graphically in Fig. 3. Consequently, VOA-OUT attenuation $\alpha_{VOA-OUT}$ is set in order to keep the received output power constant at 0 dBm. As a consequence, also the OSNR measured at receiver side is kept constant increasing the fiber span length. In fact, considering results shown in Tab. 1 it can be noticed that $P_{out,span}$, $\alpha_{VOA-OUT}$ and OSNR values are presented as single values because they are kept constant in the 20-80 km range. It can be also observed that Q, EVM and estimated Pre-FEC log_{10}(BER) obtained by OMA measurements present only a slight difference at the two extremes of the span length range, showing a good SOA effect on efficiently recovering fiber loss. It is also interesting to notice that, observing $I_{SOA,norm}$ values at 20 km and, more in detail, in Fig. 3 at also 40 and 60 km span lengths, enhanced by markers in figure, SOA current values in use for the different modulation formats and symbol rates are almost the same in all the cases under test, making the SOA utilization for this purpose simple, effective, and consistent across different application at the same time. Finally, in order to test the maximum reach L_{MAX} affordable for each case under test, observing from Fig. 3 that SOA gain and current are set at their saturation values at a span length of 80 km, we set VOA-OUT attenuation at its minimum (0 dB), where possible, keeping SOA current at its maximum value and increasing VOA-IN attenuation at its maximum in order to keep both the received output power at 0 dBm and the estimated BER value from the OMA under a reasonable threshold of $\text{BER}_{th} = 10^{-2}$, in order to make the reconstruction of the received signal at coherent receiver end feasible. Maximum reach L_{MAX} and performance results in terms of OSNR, Q-factor, EVM and Pre-FEC log_{10}(BER) measured at maximum reach are presented in detail in Tab. 2 and graphically in Fig. 4 a) in terms of estimated Pre-FEC log10(BER) and in Fig.



a) b)

Fig. 4: a) Estimated Pre-FEC $\log_{10}$(BER) and b) Q-factor [dB] vs. Fiber Length [km] curves obtained by measurement, considering the two modulation formats (DP-QPSK, DP-16 QAM) at the two symbol rates (32, 64 GBd) under test.

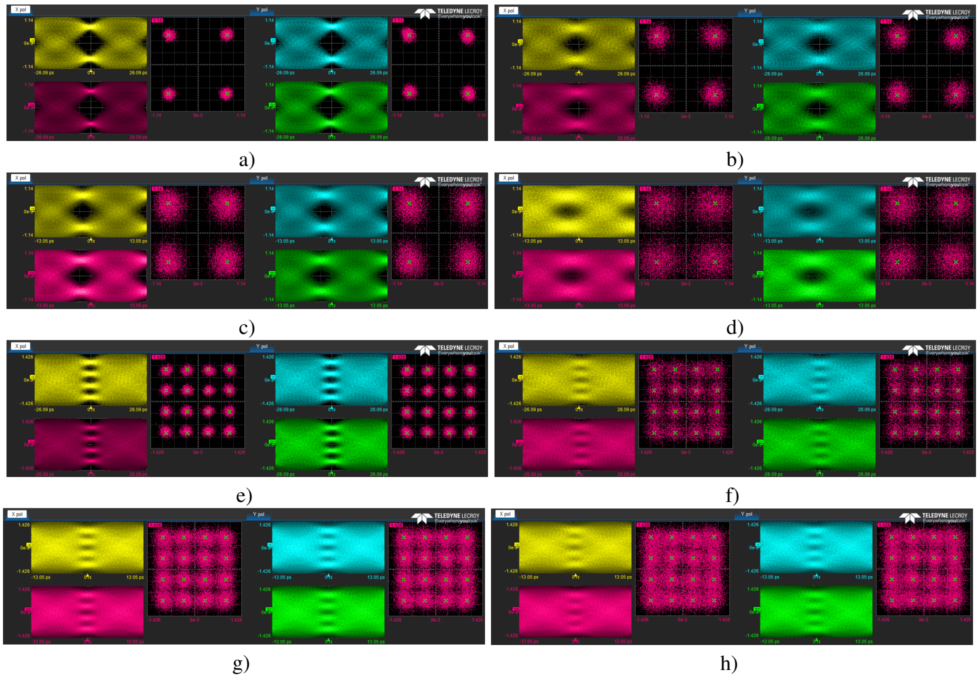


Fig. 5: Eye-diagrams and constellation diagrams OMA acquisitions for DP-QPSK @32 GBd at a) L_{span} = 20 km, b) $L_{span} = L_{MAX}$; DP-QPSK @64 GBd at c) L_{span} = 20 km, d) $L_{span} = L_{MAX}$; 16 QAM @32 GBd at e) L_{span} = 20 km, f) $L_{span} = L_{MAX}$; 16 QAM @64 GBd at g) L_{span} = 20 km, h) $L_{span} = L_{MAX}$.

4 b) as Q-factor vs. span length curves for the four cases under test. It can be easily observed that the performance are kept feasible for a correct coherent reception also for L_{MAX} which goes from a maximum value of 154.8 km for the 100 G solution (DP-QPSK @32 GBd) to a minimum of 100 km for the 400 G solution (DP-16 QAM @64 GBd), as also shown qualitatively in Fig. 5, where eye-diagram and constellation diagram acquisitions from OMA are shown for each case under test of modulation format and symbol rate, for a fiber span length of 20 km and at maximum reach. It can be observed that the constellations can be correctly reconstructed at the coherent receiver end even at maximum reach, experimentally demonstrating the promising effect of the SOA integration in InP MZMs photonic integrated circuits. Also, it can be noticed that the experimental results obtained in this article appear to confirm and strengthen the simulations obtained in [4].

4. Conclusion

Based on the experimental investigation conducted in this study, several key findings have emerged. The integration of SOAs within InP IQ-MZM PICs, as the HB-CDM under test, has shown promising benefits for short-reach optical links in DCI applications. The experimental validation, focusing on estimated BER, Q-factor and EVM, highlights the advantageous impact of SOAs on short-distance transmission for 100G, 200G and 400G solutions. Our results demonstrate that SOAs effectively mitigate fiber loss, maintaining signal integrity across varying fiber span lengths for inter-data center solutions and beyond. Notably, the experimental outcomes are consistent with and reinforce the simulations conducted in prior research, underscoring the reliability and applicability of our findings. Furthermore, the simplified and uniform adjustment of SOA settings across different modulation formats and symbol rates demonstrates the ease and effectiveness of SOA utilization in diverse applications, emphasizing the potential of cost-effective integrated SOAs within InP IQ-MZM PICs to efficiently address DCI solutions.

Acknowledgment

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