112-Gbit/s/λ PAM4 Transmission enabled by a Negatively-Chirped InP-MZ Modulator

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Abstract *A negatively-chirped InP-MZM modulated by a 1-Vpp PAM4 signal enables 112Gbit/s/λ data transmission with reduced digital processing complexity. SSMF-links longer than 3-km (KP4-preFEC) or 4-km (HD-preFEC) without digital dispersion pre/post compensation are successfully demonstrated.*

Introduction

A new generation of high-speed short reach optical transceivers operating at 100-Gbit/s, 400-Gbit/s and beyond, are urgently required due to the continuous traffic growth driven by cloud computing, big data, and smart mobile devices. However, these applications require low cost, low power consumption, and smaller transceivers to reach the largest bandwidth throughput in the limited space of data centre infrastructure. Today's 100-Gbit/s or 400-Gbit/s short reach optical transceivers rely on large lane count resulting in additional cost, power consumption, and complexity. Cost-effective and scalable solutions will become available by increasing the capacity per channel. The IEEE P802.bs 400-Gbit/s Ethernet Task Force announced a clear set of objectives, one of them being 500m, 2km and 10km transmission over single mode fibre[1]. The preferred solution for 400-Gbit/s transceivers is to transmit 100-Gbit/s/λ in a single fibre (four wavelengths required) or multiple fibres (PSM4, four fibres required)[2]. Hence, the most promising modulation format being considered, due to its higher spectral efficiency and simpler implementation, is pulse-amplitude modulation (PAM) for optical intensity-modulation/direct-detection (IM/DD). Performance and throughput of IM/DD can be improved, with digital assistance, employing an analogue-to-digital converter (ADC) after the receiver (Rx)[2]. Recently, several digitally-assisted 112-Gbit/s/λ PAM4 transmission experiments were demonstrated in the 1550nm window employing Mach-Zehnder Modulators (MZM) in $LiNbO_3$, thin-film polymer on silicon (TFPS) or InP-based EML transmitters, as summarized in Table 1. For such demonstrations, digital signal processing (DSP) is mostly implemented to mitigate system bandwidth limitations. Digital spectral shaping, i.e. Nyquist Filtering, and linear and nonlinear equalization techniques are used. It is important to note that most 2km transmission using InP-based EMLs have been demonstrated requiring more complex DSP in terms of equalizers with many taps. Long transmission, 80km, has been also demonstrated with commercial, bulky and power hungry $LiNbO_3$ based and TFPS-based MZMs with chromatic dispersion compensation (CD) techniques that make the system hardware-inefficient with increased DSP complexity.

In this paper, we maximize the transmission performance of 112-Gbit/s/λ PAM4 signals while keeping the hardware and the DSP complexity to the minimum. This is achieved, for the first time, by using dispersion tolerant negatively-

Tab. 1: State-of-art: Single Wavelength 112Gb/s @ C-band

Authors	Year	km	Gbps	FEC Thres	E/O Tech	Type	E/O BW	O/E Tech	O/E BW	DCF	Taps (Digital Assistance)
3-5Labs[4]	2015	2	112	3e-4	EML	InP	50	PIN+TIA	40	NO	25 LEQ
BellLabs[5]	2015	2	112	2e-7	MZM	$LiNbO_3$	35	PIN+TIA	45	NO (CDR)	NAN
BellLabs[6]	2016	80	112	3.8e-3	MZM	$LiNbO_3$	38	PIN+TIA	32	NO (VSB)	80 (LEQ)+ N.A (NLEQ)
ADVA[7]	2016	80	112	3.8e-3	MZM	$LiNbO_3$	27	PIN+TIA	35	YES	41 (CSF)+ MLSE 4-memory
BellLabs[8]	2016	2	112	3e-4	EML	InP	50	PIN+TIA	40	NO	3 (LEQ)
BrPhot[9]	2017	2	112	3e-4	MZM	TFPS	50	PIN+TIA	30	NO	60 (LEQ) REALTIME
BellLabs[10]	2017	80	112	3e-4	MZM	$LiNbO_3$	30	PIN+TIA	30	NO (VSB)	96 (LEQ) + 48 (NLEQ)
This WORK	2017	2	112	2e-4	MZM	InP	25	PIN	70	NO (chirp)	3 (LEQ)

DCF: Dispersion Compensating Fiber, LEQ: Linear Equalizer, NLEQ: Non-linear Equalizer, CSF: Channel Shortening Filter, MLSE: Maximum likelihood sequence estimator, VSB: Vestigial Sideband, CDR: Clock-data Recovery

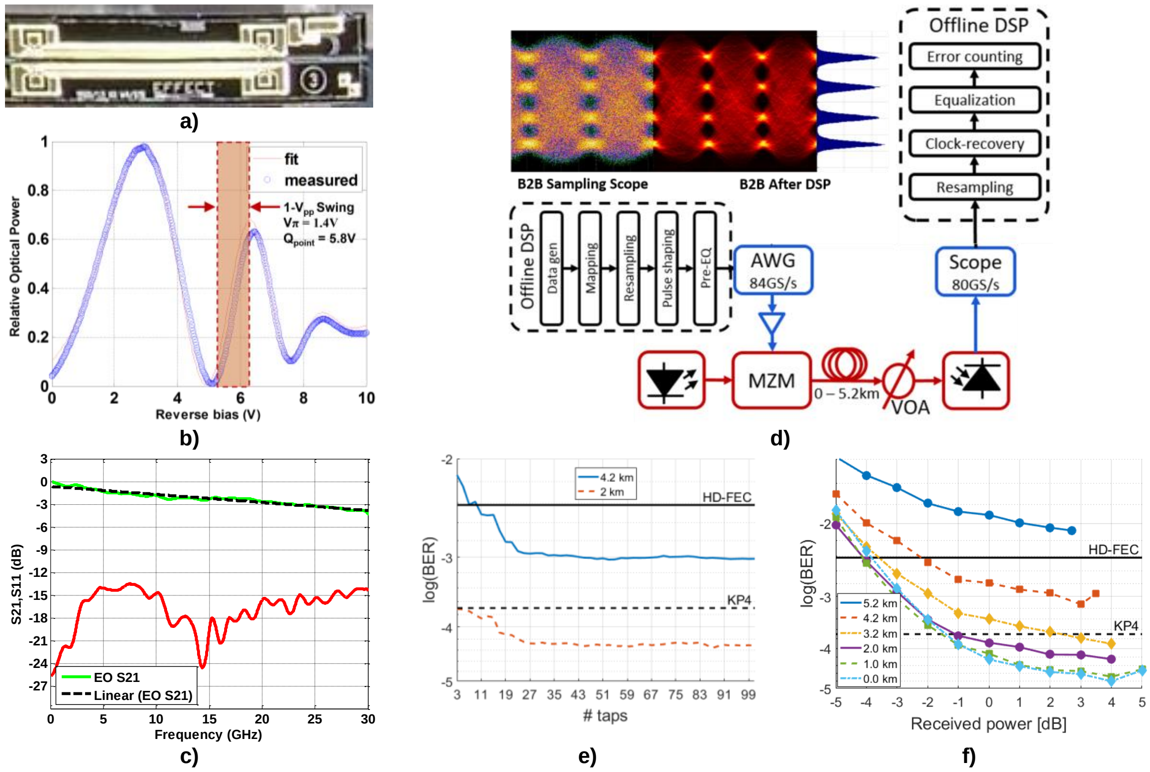

Fig. 1 a) Chirped InP-MZM, b) Normalized optical transmission characteristic of the modulator as a function of reverse bias at 1550 nm, c) Measured on chip EO response of the MZM (3dB bandwidth:25 GHz), d) Experiment setup. (Pre-EQ: pre-compensation, AWG: Arbitrary Waveform Generator, MZM: Mach-Zehnder Modulator, VOA: Variable Optical Attenuator, Scope: oscilloscope, e) Tap-sweep for a feedforward filter equalizing the received signal after 2-km and 4.2-km transmission, f) BER vs received optical power performance for different transmission lengths

chirped-MZMs, a key component in InP-monolithic multichannel integrated tuneable transmitters.

Device Characteristics

The chirped MZM chip comprises of two identical low-loss 2x2 MMI-couplers interconnected by equal length phase shifters to form an interferometer, see Fig. 1a. Optical modulation is achieved via the quantum confined stark effect (QCSE) in the InGaAsP-based multiple-quantum-well (MQW) phase shifter waveguides grown on semi- insulating (SI) InP-substrate with the MQW sandwiched between p and n doped layers in a p-i-n arrangement. The quantum wells are specifically designed to achieve the absorption band edge at ~1380 nm to achieve sufficient detuning from the wavelength of operation i.e. optical C-band.

The modulator's 1.3µm-wide deeply etched optical waveguides provide high lateral optical confinement. This results in larger electro-optical overlap and contributes to the compact waveguide routing on the chip. The total size of a cleaved modulator chip is 0.5 × 4.25 mm^2, see picture in Fig. 1a. The lower arm of the MZM has a travelling wave RF electrode (TWE) with GSG bond pads to access the chip either through high-frequency GSG probes or wire bonding. The TWE electrode and GSG bond pad designs are optimized to achieve overall device impedance close to 50 Ω and maximize the velocity matching between co-propagating RF and optical waves. As compared to the lower arm, the upper arm of the MZM has only a DC electrode which is only used to optimize the operating point of the modulator.

Fig. 1b shows the DC transfer function (normalized) of the fabricated modulator chip measured at 1550 nm for TE polarized input light from an external tuneable laser source coupled and collected using a lensed fibre. For this measurement, reverse bias was applied to the lower arm of the MZM, while the DC arm was kept fixed at 0 V. The measured device has TWE length of 2.0 mm and exhibits a switching voltage (V_π) less than 1.5 V, as shown in Fig. 1b, with DC extinction ratio (ER) >20dB. To further characterize the high-speed performance of the fabricated chips, a small signal electro-optic response was measured on-chip using a 67 GHz LCA (N4373B) from Agilent. For this purpose, the RF signal of -7 dBm and DC signal was applied to the lower MZM arm through a bias tee and a high-speed GSG probe with the DC arm kept at 0 V. To terminate the output GSG bond pad with 50 Ω another GSG probe

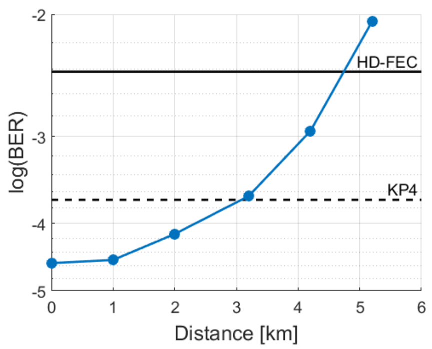

Fig. 2: BER vs distance performance (25-taps LEQ)

was used. To compensate for the RF cable losses, two tier on-wafer RF calibration was performed. Figure 1c shows the measured EO response of one of the fabricated MZM chip. The modulator has a 3-dB EO bandwidth of 25 GHz with excellent phase linearity up to 30 GHz, greatly helping to reduce DSP complexity.

Experiment setup

Fig. 1d shows the experiment setup. An 112-Gbit/s PAM-4 signal is created offline and resampled to 84 GS/s. A 19-tap filter is used to pulse shape with a raised cosine filter of roll-off 0.15. Pre-compensation[3] for system bandwidth limitations caused by various components such as DAC, RF-amplifier, MZM, receiver, and ADC is applied with a 9-tap filter. The waveform is uploaded to a Keysight M8196A arbitrary waveform generator (AWG) running at 84 GS/s. The electrical signal is amplified by an SHF807 RF-amplifier and modulated onto a 1550nm optical carrier by the MZM-PIC. The optical signal is transmitted over various lengths of fibre. A variable optical attenuator (VOA) controls the optical power into the PIN photodiode (PD). The signal is digitized by an 80-GS/s Keysight MSOV334A oscilloscope and after resampling, clock-recovery, and equalization, the error rate is counted. Fig. 1e shows a tap-sweep for 3.5 and 4 dBm input power with 2-km and 4.2-km transmission distance respectively. Only 3-taps are needed for the 2-km transmission to achieve KP4 preFEC BER levels. For completeness, 25 taps are used for all the transmission experiments, which is a good trade-off between performance and DSP complexity.

Results

Fig. 1f shows the receiver sensitivity for different transmission distances. Power penalty is negligible for 0, 1 and 2 km at HD-FEC (3.8x10-3) and KP4 (2x10-4). From 3 km onwards, performance is compromised by chromatic dispersion (CD). The feedforward equalizer can combat the power fading introduced by CD only at the cost of amplifying noise. Therefore, receiver sensitivity degrades. Severe CD is present even at a short distance due to the high signal bandwidth associated with the 56-GBaud PAM-4. The 56-GBaud PAM-4 signal with raised cosine roll-off 0.15 occupies 64.4 GHz of the optical spectrum (32.2 GHz analogue electrical BW). Fig. 2 shows that the penalty due to CD increases exponentially. Whereas the signal after 3.2 km can be recovered with a bit error rate (BER) near KP4, 5.2 km cannot be recovered with a BER below HD-FEC.

Conclusions

For the first time, successful transmission of 112-Gbit/s/λ chirped-PAM4 without DCF or digital dispersion pre/post compensation is demonstrated. More than 3-km or 4-km, under KP4 and HD-pre-FECs, respectively, is demonstrated. The negatively-chirped InP-MZM driven with only a 1-Vpp PAM4 signal enables reduced digital complexity at receiver equalization stage with only 3-taps and 25-taps for 2-km and 4-km, respectively. Such low-driving PAM4 signalling becomes attractive for high-speed driver-less transceivers. The 10-km transmission seems feasible with better channel equalization techniques, such as MLSE. The synergy between DSP and dispersion tolerant modulation techniques, such as chirped PAM4, is vital for the introduction of low-complexity digital-assisted, cost-effective and scalable 400-Gbits/s transceivers.

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