Spectrally-Efficient Single Sideband 16-QAM Nyquist-Subcarrier Modulation-Based WDM Transmission using an InP Dual-Drive Mach-Zehnder Modulator and Direct-Detection

M. S. Erkılınç[(1)], S. Pachnicke[(2)], H. Griesser[(3)], B. C. Thomsen[(1)], P. Bayvel[(1)], and R. I. Killey[(1)]

[(1)] Optical Networks Group, Department of Electronic and Electrical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK. m.erkilinc@ee.ucl.ac.uk
[(2)] ADVA Optical Networking SE, Maerzenquelle 1-3, 98617 Meiningen, Germany.
[(3)] ADVA Optical Networking SE, Fraunhoferstr. 9a, 82152 Martinsried, Germany.

Abstract *We experimentally demonstrated 16 GHz-spaced 25 Gb/s per channel WDM transmission over 242 km of standard SMF at a net information spectral density of 1.46 b/s/Hz using SSB Nyquist-shaped subcarrier modulation generated with an InP dual-drive Mach-Zehnder modulator.*

Introduction

Dense wavelength division multiplexed (DWDM) systems using direct detection and offering high information spectral densities (ISDs) ($>$1 b/s/Hz) have attracted much interest for metro/regional links (up to 500 km). In such systems, cost-effective solutions with compact footprint, low power consumption and simplified production and packaging processes are required, and can be achieved using Indium Phosphide (InP) photonic integration[1–3].

To achieve ISDs greater than 1 b/s/Hz in metro and regional applications, multi-level signalling, such as quadrature amplitude modulation (QAM), needs to be performed. An effective way to achieve this in direct detection systems is through the use of Nyquist pulse-shaped subcarrier modulation (SCM)[4], with optical single sideband (SSB) signalling implemented with DSP and an optical vector modulator. Previously, we demonstrated spectrally-efficient WDM transmission of Nyquist pulse-shaped 16-QAM SCM using $LiNbO_3$ IQ-modulators[5]. To reduce the optical complexity, and consequently the cost, further in such systems, a dual-drive Mach-Zehnder modulator (DD-MZM) instead of an IQ-modulator can be used to generate an optical SSB signal[6].

Hence, in this paper, we demonstrate the transmission of 16 GHz-spaced DWDM SSB Nyquist pulse-shaped 16-QAM SCM signals, generated using an InP-based tunable transmitter assembly (TTA). The TTA, which was developed by Oclaro, consisted of a wideband tunable DS-DBR laser and an InP dual-drive MZM. The performance of single channel and WDM signal transmission at a bit rate of 25 Gb/s per channel was assessed. The WDM signal was transmitted over up to 242 km of uncompensated standard single mode fibre (SSMF), using electronic pre-distortion, at a bit error ratio (BER) of below 3.8×10^{-3} with a net optical information spectral density of 1.46 b/s/Hz.

Experimental Setup

The optical transmission test-bed used for the experiment is shown in Fig. 1. It consisted of transmitters generating five 16 GHz-spaced 25 Gb/s per channel DWDM signals, an optical fiber recirculating loop and a direct detection receiver, based on a single-ended PIN-photodiode and a single ADC. The Oclaro TTA comprised a DS-DBR laser source tunable over the C-band (1528 to 1563 nm) operating at 1550.4 nm, and an InP DD-MZM (with a V_π of 1.9 V_{pp}, a 3dB bandwidth of 10 GHz and a DC extinction ratio of 17 dB). The optical spectrum of the single channel signal is shown in Fig. 1(a). Since only a single TTA was available, the inner three channels ($\lambda_{2,3,4}$) were generated from the output of the TTA, followed by an IQ-modulator which was driven with a tone from a signal generator at a frequency of 16 GHz and operated at its null point. A length of fibre providing a delay of 17 ns was used to decorrelate the channels before they were combined and launched into the recirculating loop. The outer channels ($\lambda_{1,5}$) were generated using a pair of discrete DFB lasers and a $LiNbO_3$ DD-MZM modulator with a V_π of 2.6 V, a 3dB bandwidth of 10 GHz and a DC extinction ratio of 18 dB. By adjusting the bias voltages, the DD-MZMs were biased close to their quadrature points to generate the SSB Nyquist pulse-shaped 16-QAM SCM signal with the desired optical carrier power, as shown in Fig. 1(b).

The driving signals for the DD-MZMs were generated offline in MATLAB. 2^{15} de Bruijn bit se-

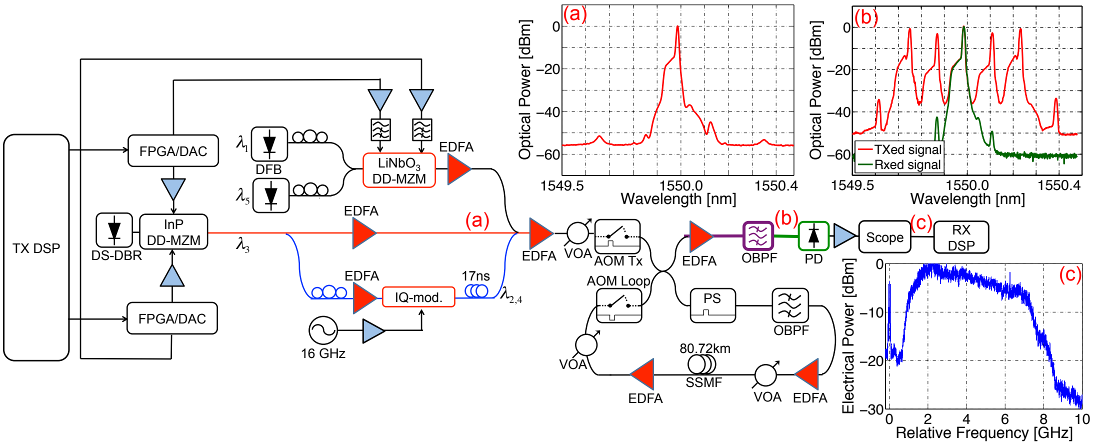

Fig. 1: Experimental setup for DWDM SSB Nyquist pulse-shaped SCM transmission. FPGA: Field programmable gate array, VOA: Variable optical attenuator, AOM: Acousto-optic modulator, PS: Polarization scrambler, PD: Photodiode. Insets: Experimental optical spectrum of transmitted (a) single channel and (b) WDM signal. (c) Received electrical spectrum. TX-DSP is shown in Fig. 2.

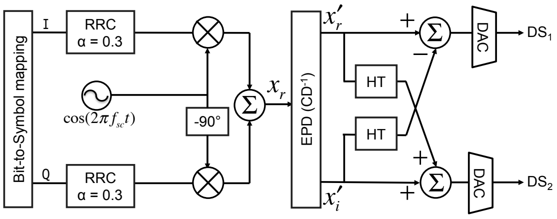

Fig. 2: Block diagram of Nyquist-SCM transmitter DSP.

quences were mapped to 16-QAM symbols, followed by root raised-cosine (RRC) pulse shaping filters with a roll-off factor of α =0.3, 256 taps and a stop-band attenuation of 40 dB. The I- and Q-baseband signals were up-converted to the subcarrier frequency (f_{sc}) of 4.68 GHz (0.75$\times f_s$) and added to each other to generate a double sideband (DSB) Nyquist pulse-shaped SCM signal at a bit rate of 25 Gb/s. Electronic pre-distortion (EPD), pre-dispersing the signal with the inverse of the transfer function of the fiber (neglecting loss and nonlinearity), was performed to mitigate the dispersion. Finally, the 6-bit quantized pre-dispersed signal combined with its Hilbert transform (HT) were uploaded to FPGA RAM memory blocks, interfaced with the DACs (Micram VEGA DACII), to drive the DD-MZMs to generate the optical SSB signal, as shown in Fig. 2.

The transmission experiment was performed using an optical recirculating loop with a single 80.7 km length span of SSMF. The fibre parameters (α, D, γ) were 0.2 dB/km, 17 ps/(nm.km) and 1.2 W^{-1}km^{-1}, respectively. An optical band-pass filter (OBPF) (Yenista Optics XTM50-Wide) with a bandwidth of 200 GHz and a filter edge gradient of 500 dB/nm was used to filter the out-of-band amplified spontaneous emission (ASE)-noise during the transmission. The total loss per circulation (31 dB), arising from the fibre loss (16 dB) plus the insertion loss of the loop components (15 dB from VOAs, PS, AOM and OBPF), was compensated by two EDFAs with a noise figure of 5 dB operating in saturation (18 dBm output power).

The channel of interest was demultiplexed using a manually tunable OBPF (Yenista Optics XTM50-Ultrafine) with a 3dB bandwidth of 14 GHz and a filter edge gradient of 800 dB/nm). A single-ended Discovery PIN photodiode (DSC10H) was used to detect the filtered optical signal, followed by an RF-amplifier. For signal acquisition, a single ADC operating at 50 GSa/s with a 3dB bandwidth of 16 GHz and a nominal resolution of 8 bits (ENOB of 5 bits at 10 GHz) was used. The received electrical signal spectrum is shown in Fig. 1(c). After normalization and resampling to 2 samples per symbol, the signal was split into two arms. A pair of matched filters was applied, followed by frequency down-conversion to generate the I- and Q-baseband signals. For clock recovery, a 5-tap FIR filter was used before the BER counter. Finally, the BER was computed by error counting over 2^{19} bits and Q^2-factor was calculated from the measured BER (See Ref.[5] for the block diagram of the receiver DSP).

Results and Discussions

In back-to-back operation, the BER with respect to optical signal-to-noise ratio (OSNR) values for the single channel case, together with the received constellation at an OSNR of 34 dB, are shown in Fig 3. The required OSNR value for 25 Gb/s SSB Nyquist pulse-shaped 16-QAM SCM signal at the HD-FEC threshold was found to be 23 dB with a 2 dB implementation penalty. This is due to the DAC/ADC quantization noise, the bandwidth of the modulator and non-ideal optical filtering at the receiver. In the WDM case, the channel spacing was set to 16 GHz, yielding

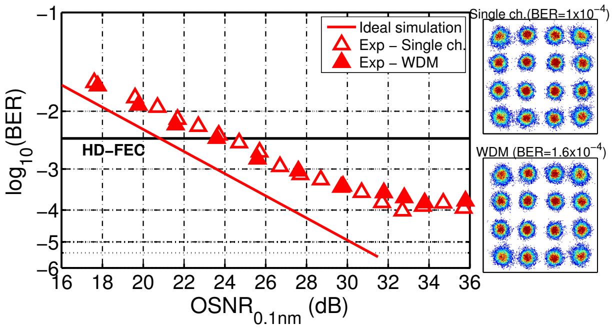

Fig. 3: BER vs. OSNR for single channel and WDM signal (left) with their constellations at an OSNR of 34 dB (right).

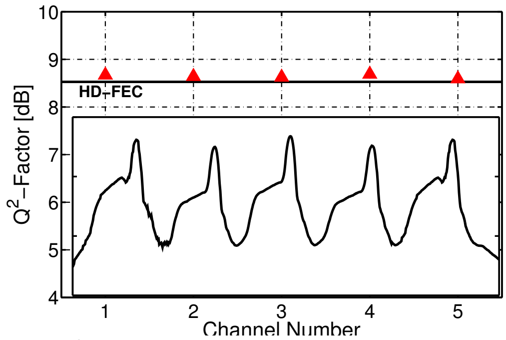

Fig. 5: Q^2-factor for each transmitted channel. Inset: Transmitted optical spectra.

a net optical ISD of 1.46 b/s/Hz assuming a 7% HD-FEC overhead. The spacing was sufficient to have no additional penalty due to the linear crosstalk between the neighbouring channels at the HD-FEC threshold, as shown in Fig. 3. Note that the non-standard channel spacing value was chosen to maximise the net optical ISD with the available components in our lab.

Using the recirculating loop, the single channel and WDM signals were transmitted over up to 484 and 242 km of SSMF, respectively. Q^2-factor values with respect to launch power per channel are shown in Fig. 4 along with the received constellations.

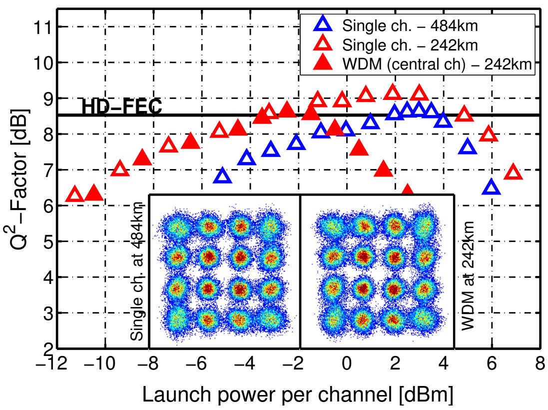

Fig. 4: Q^2-factor vs. launch power per channel and the received constellations.

The lower maximum distance for the case of WDM transmission can be explained by the additional inter-channel fibre nonlinear effects. The optimum launch power per channel in WDM transmission was found to be -2 dBm, 4 dB less than that for single channel transmission. Furthermore, all five transmitted channels, carrying 25 Gb/s SSB Nyquist pulse-shaped 16-QAM SCM signals, achieved BERs below 3.8×10^{-3} (Q^2-factor>8.52 dB) at the optimum launch power of -2 dBm per channel, as shown in Fig. 5.

Conclusions

We experimentally demonstrated spectrally-efficient WDM transmission (16 GHz-spaced five channels operating at bit rate of 25 Gb/s per channel) of SSB Nyquist pulse-shaped 16-QAM subcarrier modulation technique for metro links using an InP-based dual drive Mach-Zehnder modulator and a tunable DS-DBR laser. The maximum transmission distances at a BER of 3.8×10^{-3} were found to be 484 and 242 km for single channel and WDM signals, respectively, at a net optical ISD of 1.46 b/s/Hz. To the best of our knowledge, this is the first demonstration of InP-MZM based dispersion pre-compensated Nyquist SCM, and represents the highest information spectral density, at this distance among the reported experimental direct detection WDM demonstrations using this simple transceiver architecture.

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References

[1] R.A. Griffin et al., "InP Mach-Zehnder modulator platform for 10/40/100/200-Gb/s operation," Journal of Selected Topics in Quantum Electronics, Vol.**19**, no. 6, p. 158 (2013).

[2] N. Kikuchi et al., "High-speed InP-based Mach-Zehnder modulator for advanced modulation formats," IEEE Compound Semiconductor IC Symposium (CSICS), La Jolla, CA (2012).

[3] E. Rouvalis et al., "A low insertion loss and low V_π InP IQ modulator for advanced modulation formats," Proc. European Conference on Optical Communication (ECOC), Tu.4.4.1, Cannes (2014).

[4] J.C. Cartledge and A.S. Karar, "100 Gb/s intensity modulation and direct detection," Journal of Lightwave Technology, Vol.**32**, no. 16, p. 2809 (2014).

[5] M.S. Erkilinc et al., "Spectrally-efficient WDM Nyquist-pulse-shaped 16-QAM subcarrier modulation transmission with direct detection," to be published in Journal of Lightwave Technology.

[6] M.S. Erkilinc et al., "Dispersion-precompensated direct-detection Nyquist pulse-shaped subcarrier modulation using a dual-drive Mach-Zehnder modulator," to be presented at Opto Electronics and Communications Conference (OECC), Shanghai (2015).