Quantum Dash Mode-Locked Laser based Open-Loop Optical Clock Recovery for 160 Gb/s Transmission System

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Abstract: We report first demonstration of quantum dash mode-locked laser based open-loop optical clock recovery of 160 Gb/s RZ-OOK after 52 km transmission with 102 fs timing jitter 40 GHz clock and 2 dB BER penalty.

1. Introduction

Optical clock recovery (OCR) is one of the key functions in the optical receiver frontend for high speed optical time division multiplexing (OTDM) networks. Especially for OTDM system beyond 160 Gb/s, OCR is demanded to provide subharmonic clock with low timing jitter, e.g. timing jitter of maximally 520 fs is tolerable for 160 Gb/s [1]. Besides, fast locking time, low cost, high power efficiency, system compactness and operation simplicity have to be considered for practical implementations. To date, OCR for 160 Gb/s or higher bitrates has been demonstrated by using optoelectonic phase locked loops (OPLL) [2], self-pulsating laser diodes (SPLD) [3], and mode-locked laser diodes [4]. Among those schemes, a feedback loop is often required in the OCR based on OPLL and SPLD in order to obtain stable and low timing jitter clock. Feedback loop increases the complexity of OCR operation and the locking time, while introducing costly high speed and power hungry electronics and optical components (high speed oscillator, amplifiers, photo-detector, and so on).

Direct optical injection locking of Mode-Locked Laser Diodes (MLLD) has the potential to perform OCR directly without feedback. Especially, optical injection locking of Quantum Dash MLLD (QD-MLLD) have attracted significant interest in the application of OCR, thanks to the features of extremely narrow mode-beating spectral linewidth, broad flat optical gain spectra (>12 nm) and low current operation [5]. Such features allow low timing jitter OCR with open-loop operation (no feedback) and low power consumption. Moreover, the fast locking time of the QD-MLLD gives the opportunity to exploit the OCR for burst mode operation [6]. Recently back-to-back (B2B) OCR operation of up to 160 Gb/s OTDM signal has been demonstrated based on QD-MLLD injection locking followed by an electrical filter with high quality factor of 1000 [4]. However, the QD-MLLD based OCR operation in an optical transmission system has never been demonstrated so far.

In this paper, we demonstrate for the first time a QD-MLLD based optical open-loop sub-harmonic clock recovery for optical transmission system up to 160 Gb/s. Experimental results indicate that 40 GHz recovered clock with low timing jitter of 107fs and 102 fs for 80 Gb/s and 160 Gb/s, respectively is obtained by directly injection locking the QD-MLLD with the OTDM signal after 52 km transmission. No additional electrical filter has been employed after the photo-detection of the clock pulses. By using recovered subharmonic 40 GHz clock to drive the electro-absorption modulator (EAM) based demultiplexer, and to trigger the 40 Gb/s BER tester, BER penalty of 0.5 dB and 2 dB is achieved for 80 Gb/s and 160 Gb/s respectively after transmission.

2. Experimental setup

Fig. 1 shows the experimental setup of the QD-MLLD based OCR for high speed RZ-OOK transmission system. It consists of three major blocks: a high speed RZ-OOK transmitter, 52 km dispersion compensated transmission link, and an OTDM receiver based on QD-MLLD and EAM. In the OTDM RZ-OOK transmitter, a 160 Gb/s OTDM RZ-OOK signal is generated by optically time-multiplexing a 40 Gb/s data streams via a fiber based time interleaver. The 160 Gb/s RZ-OOK has a data pattern of 2^7-1 PRBS, which is due to the limits of the time interleaver. The high speed signal has a central wavelength of 1546.50nm and data pulse width of 1.3 ps. In order to remove the phase jumps between the adjacent bits of the OTDM signal [7], wavelength conversion is implemented to produce stable and phase coherent 160 Gb/s RZ-OOK signal. The wavelength converter (WC) is implemented by a nonlinear optical loop mirror (NOLM) as shown in Fig. 1. The 160 Gb/s OTDM signal is fed into a NOLM as the control signal, while a coherent CW light generated by an ECL laser (λprobe=1558.32nm) is used as the probe. The 160 Gb/s RZ-OOK switch ON/OFF the NOLM, and replicates its data information to the coherent CW probe light. At

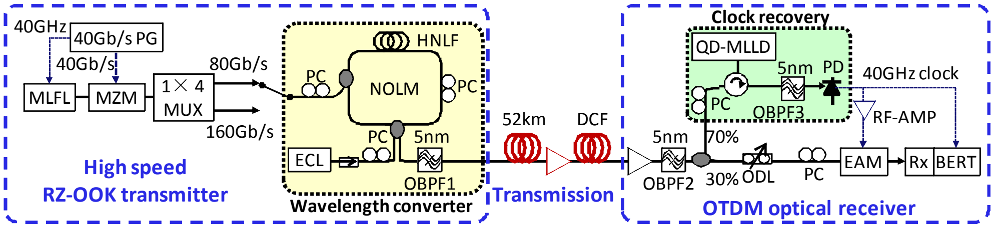
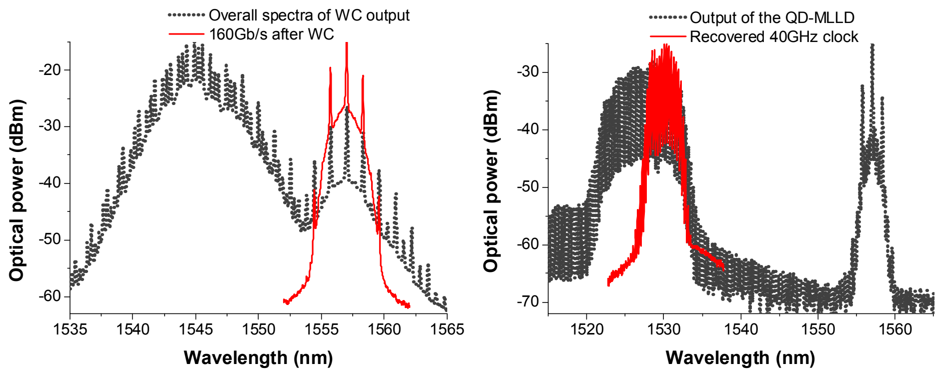


Fig.1 Experimental setup of the QD-MLLD based OCR for high speed RZ-OOK transmission system



(a) (b)

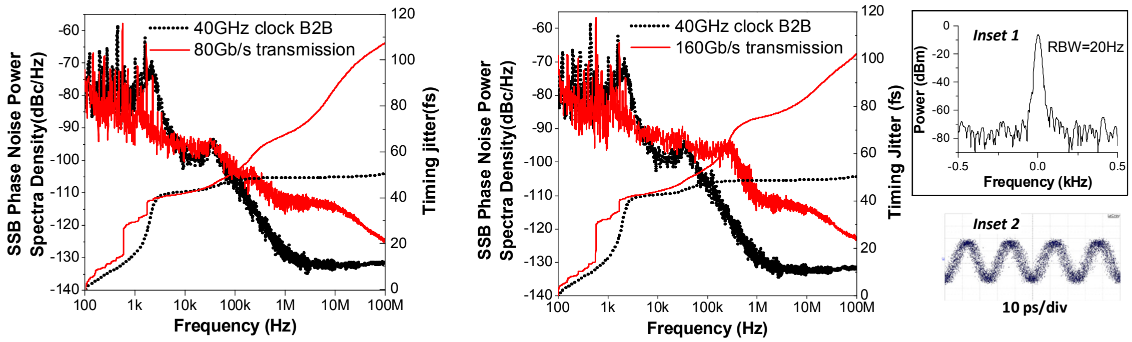
Fig.2 Optical spectra: (a) at the output of WC; (b) at the output of the QD-MLLD

the output of the NOLM, a 5 nm optical band pass filter (OBPF1) with center wavelength located at the probe wavelength is used to select out the phase coherent 160 Gb/s RZ-OOK signal. Fig 2 (a) shows the optical spectra of the original 160 Gb/s OTDM signal and the phase coherent 160 Gb/s RZ-OOK signal. After the wavelength conversion, the obtained phase coherent 160 Gb/s RZ-OOK shows strong 160 GHz harmonics without any 40GHz components.

The phase coherent 160 Gb/s signal is then launched into dispersion compensated 52 km transmission link with a launching power of 10 dBm. After the transmission, the 160 Gb/s signal is first amplified to 11 dBm and fed into the optical receiver frontend. In the optical receiver frontend, the 40 GHz sub-harmonic OCR is achieved by injection locking the QD-MLLD. The QD-MLLD is operated in an open-loop fashion with low bias current of 86 mA, temperature of 25 degrees, and injection power within the range from 9 dBm to 10 dBm. A polarization controller is required to optimize the state of polarization of injected signal. A 5 nm optical bandpass filter is used to select out part of the QD-MLLD spectrum to output the recovered 40 GHz clock. The optical spectra of the output of the injection locked QD-MLLD and the recovered 40 GHz optical sub-harmonic clock from the input 160 Gb/s signal are shown in Fig.2 (b). Note that the detuning between the recovered clock and the WC signal is more than 25nm, which indicates the large detuning wavelength range of the open-loop OCR based on injection locked QD-MLLD. The recovered 40 GHz optical clock is then detected by a photodiode (PD) and electrically amplified before driving the EAM to demultiplex the OTDM signal into 40Gb/s tributaries. The obtained 40Gb/s signals are then detected and tested in a bit error rate (BER) tester while the BERT is triggered by using the recovered 40 GHz clock.

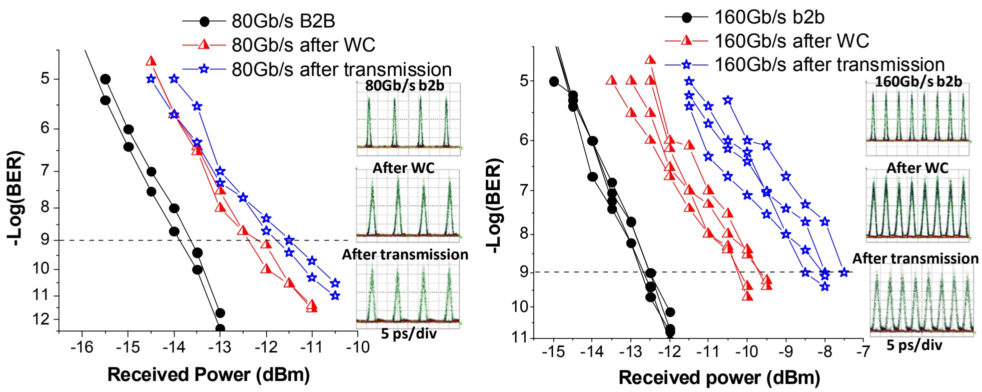
3. Results

Subharmonic OCR is implemented by injection locking the QD-MLLD with OTDM signal at both 80 Gb/s and 160 Gb/s. Fig.3 (a) and (b) show single sideband phase noise spectrum density (SSB-PSD) of the recovered 40 GHz clock from signal of 80 Gb/s and 160 Gb/s after transmission respectively. As reference the phase noise trace of original 40 GHz clock from the transmitter is also shown in Fig 3 (black dotted trace in (a) and (b)). The recovered 40 GHz clock has a low timing jitter of 107 fs and 102 fs (integrated from 100 Hz to 100 MHz) in the case of 80 Gb/s and 160 Gb/s respectively. The insets of Fig.3 show the electrical spectrum and the waveform of the electrical 40 GHz clock. The recovered clock has a line width of less than 50 Hz at -10 dB (RBW=20Hz). The OTDM signal is then demultiplexed into 40 Gb/s by using the recovered clock. BER measurements are carried out to further evaluate the quality of the recovered clock. The BER results are shown in Fig 4. Eye diagrams of corresponding OTDM signals at B2B, after WC and after transmission are shown in the insets of Fig 4. As a comparison, B2B trace of the original OTDM signal (B2B traces) and the phase coherent OTDM RZ-OOK (after WC traces) at 80 Gb/s and 160 Gb/s are taken by using the original 40 GHz clock from the transmitter to drive the EAM and trigger



(a) (b)

Fig.3 Single sideband phase noise spectral power density: (a) 80 Gb/s clock recovery; (b) 160 Gb/s clock recovery



(a) (b)

Fig.4 BER measurement results: (a) 80 Gb/s; (b) 160 Gb/s;

the BER tester. In the case of 80 Gb/s signal, 1.5 dB penalty is introduced in the WC to produce phase coherent OTDM signal when being compared to the B2B trace. The 52 km transmission link introduced extra 0.5 dB penalty compared to traces after WC. While in the case of 160 Gb/s, the WC introduced about 2 dB penalty to the phase coherent 160 Gb/s RZ-OOK, which is due to the data pulse broadening and extra amplitude noise introduced during the WC. Besides, extra 2 dB penalty is introduced after the 52 km transmission, which is because of extra timing jitter introduced to the recovered clock during the transmission link and imperfect dispersion compensation.

4. Conclusion

We demonstrated for the first time sub-harmonic OCR and demultiplexing for high speed RZ-OOK up to 160 Gb/s with 52 km transmission by using QD-MLLD and EAM. We obtained low timing jitter 40 GHz recovered clock of 107 fs and 102 fs with BER penalty of 0.5 dB and 2 dB after transmission respectively for 80 Gb/s and 160 Gb/s RZ-OOK. The OCR based QD-MLLD requires no feedback, and operates in an open-loop fashion with low bias current and even under large spectral detuning. These lead to the advantages of operation simplicity, low power consumption and the potential to integrate with EAM to build a compact OTDM optical receiver frontend.

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