320 Gb/s all-optical clock recovery and time demultiplexing enabled by a single Quantum Dash Mode-Locked Laser Fabry-Perot Optical Clock Pulse Generator

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Abstract: We present the first 320Gb/s all-optical clock recovery by exploiting single Quantum Dash MLL to generate 40GHz synchronized optical clock pulse with 71fs timing jitter. 320Gb/s all-optical demultiplexing operation with 1dB BER penalty was demonstrated.

1. Introduction

Optical clock recovery (OCR) and optical time demultiplexing (OTD) are key functions to realize optical receiver frontends for high speed optical data signal transmission systems. Especially for high speed data beyond 160 Gb/s, two main issues have to be solved for practical operation of the OCR and OTD.

First, the tolerance to timing jitter of the recovered clock becomes more stringent as the data rate increases [1]. At 160 Gb/s, the maximum tolerant timing jitter of the optical clock is 520 fs. This value decreases to 260 fs and 130 fs for 320 Gb/s and 640 Gb/s demultiplexing operation, respectively.

The second issue is that beyond 160 Gb/s, the switching window of OTD based on electro-optical-modulators (EOM) is too large to resolve the high speed modulated pulses. This leads to a larger crosstalk as the data rate increases, and thus to a larger power penalty. Ultrafast all-optical switches clocked by short optical pulses are the only viable solution to be implemented in OTD along with the appropriate switching window to minimize channel crosstalk.

An all-optical clock recovery that provides optical clock pulses with low timing jitter and pulse-width narrower than the required switching window is the key function for demonstrating optical receivers at data rate of 160 Gb/s and beyond. Besides, the compactness, fast locking time, low cost and low power consumption have to be considered for practical implementation.

Up to now, the only OCR solutions beyond 160 Gb/s that are able to produce low timing jitter and short optical clock pulses require optoelectronic phase locked loops (OPLL) [2-4]. The feedback loop increases the foot-print, the complexity, and the locking time. It requires costly and power hungry high speed electronics (oscillators, detectors, and amplifiers) and optical components (40 GHz fiber based mode locked laser driven by 40 GHz electronic clock).

Recently, 40 GHz monolithically integrated Quantum Dash Mode-Locked Laser Diodes (QD-MLLD) that exhibit extremely narrow mode-beating spectral linewidth, and broad flat optical gain spectra (>12 nm) have been demonstrated [5]. Such unique features allow for the injection locked QD-MLLD to generate short clock pulses with low timing jitter even though it is DC-biased.

Although an OCR based on QD-MLLD followed by a high speed photo-detector and an electro-optical modulator as time demultiplexing was recently demonstrated for optical signals up to 160 Gb/s [6], exploiting the potential of the QD-MLLD as optical clock pulse generator for implementing an all-optical clock recovery as well as an all-optical time demultiplexing for signals beyond 160 Gb/s has never been investigated and proved.

In this work we present the first demonstration of 320 Gb/s all-optical clock recovery and 320-to-40 Gb/s all-optical time demultiplexing by exploiting the QD-MLLD as optical clock pulse generator. Experimental results show that directly injecting 320 Gb/s data, the QD-MLLD produces 40 GHz synchronous optical clock pulses with 71 fs timing jitter and 1.9 ps pulse-width. Error free operation with 1 dB power penalty was obtained after 320-to-40 Gb/s all-optical time demultiplexing.

2. Experimental setup

Fig. 1 shows the experimental setup to demonstrate the 320 Gb/s RZ-OOK all-optical clock recovery and all-optical time demultiplexing. It consists of a 320 Gb/s RZ-OOK transmitter, an OTDM receiver which contains a QD-MLLD based clock recovery and a nonlinear optical loop mirror (NOLM) based all-optical time demultiplexing. In the transmitter, a 320 Gb/s OTDM RZ-OOK signal is generated by optically time-multiplexing a 40 Gb/s data

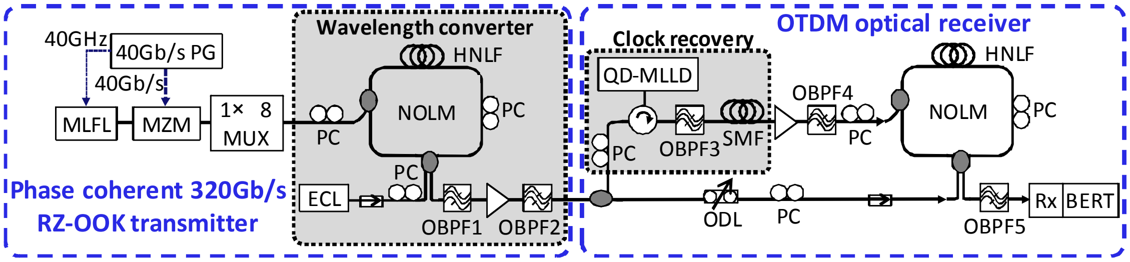
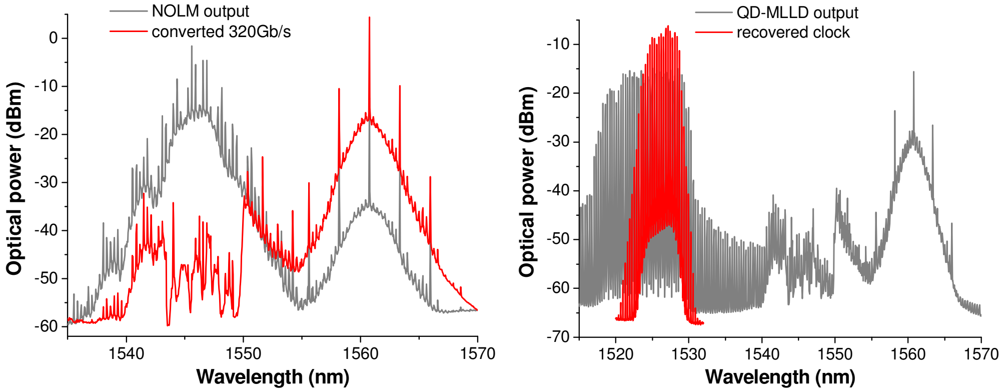


Fig.1 Experiment setup of 320 Gb/s OCR and demultiplexing using QD-MLLD and NOLM



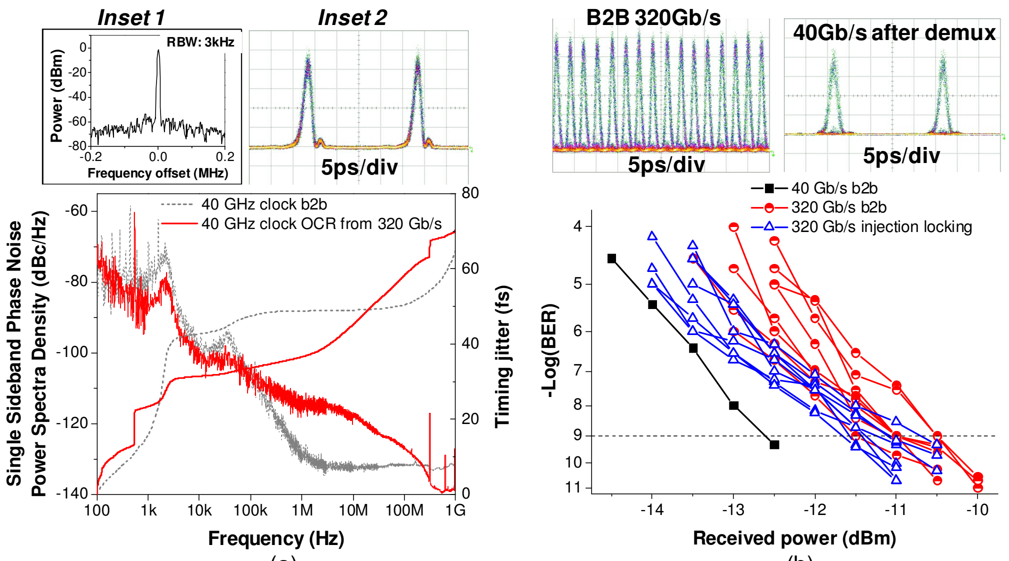
(a) (b)

Fig.2 (a) Optical spectra of the wavelength conversion; (b) optical spectra of the injection locking of QD-

streams via a fiber based time interleaver. The 320 Gb/s RZ-OOK, centered at 1546.5 nm, has a 2^7-1 PRBS data pattern due to the limits of the time interleaver. The data pulse is characterized by a 1.3 ps FWHM. In order to remove the phase jump between adjacent bits of the OTDM signal produced by the 40 GHz fiber-based MLL [7], wavelength conversion (WC) is implemented to generate stable and phase coherent 320 Gb/s RZ-OOK signal. No WC would be required if a stable OTDM source was available. The WC is based on a NOLM as shown in Fig. 1. The 320 Gb/s OTDM signal is fed into a NOLM as the control signal, while a coherent CW light generated by an ECL laser (λprobe=1560.70 nm) is used as the probe. The 320 Gb/s RZ-OOK signal switches ON/OFF the NOLM, and replicates its data information to the coherent CW probe light. At the output of the NOLM, a 6 nm optical notch filter (OBPF1) with the center wavelength at 1544 nm is used to reject the original OTDM signal and to let pass the phase coherent 320 Gb/s RZ-OOK signal. The converted 320 Gb/s signal is then amplified and filtered by 9 nm Gaussian shape optical band pass filter (OBPF2) before entering into the OTDM receiver. Fig 2 (a) shows the optical spectra of the wavelength converted and the phase coherent 320 Gb/s RZ-OOK signal. Note that the obtained phase coherent 320 Gb/s RZ-OOK shows strong 320 GHz harmonics without any 40 GHz components after the wavelength conversion. At the optical receiver side, the 40 GHz sub-harmonic OCR from the 320 Gb/s RZ-OOK is achieved by injection locking the QD-MLLD. The QD-MLLD is operated with a low DC bias current of 117 mA (no high speed electrical clock was applied), a temperature of 16 ^{o}C, and 9 dBm injection power. A polarization controller is used to optimize the polarization state of the injection signal. More details on the QD-MLLD can be found in [5]. At the output of the injection locked QD-MLLD, the recovered optical 40 GHz clock is selected out through a 5 nm optical band-pass filter (OBPF3). Owing the positive chirp of the optical pulses, 125 m SMF were employed to compress the pulses. The measured optical spectra at the output of the injection locked QD-MLLD and the recovered 40 GHz optical clock are shown in Fig. 2 (b). The 40 GHz optical clock pulse is then amplified and filtered before being fed into the NOLM to all-optical time demultiplexing of the 320 Gb/s into 8x40 Gb/s tributaries. After the all-optical time demultiplexing, the 40 Gb/s signals are then detected and analyzed by a bit error rate (BER) tester, which is clocked by using the recovered 40 GHz clock.

3. Results

Fig. 3 (a) shows single sideband phase noise spectrum density (SSB-PSD) of the recovered 40 GHz sub-harmonic clock. As reference the phase noise trace of original 40 GHz clock from the transmitter is also shown in Fig. 3 (a). The recovered 40 GHz clock has a low timing jitter of 71 fs (integrated from 100 Hz to 1 GHz). The inset 1 shows



(a) (b)

Fig.3 (a) SSB-PSD trace of the recovered clock; (b) BER results of the 320 Gb/s

the corresponding electrical spectra, the recovered clock has a linewidth <10 kHz at -20 dB (RBW is 3 kHz). The low timing jitter is in principle sufficient for optical demultiplexing 640 Gb/s data. Besides, inset 2 shows the waveform of the 40 GHz optical pulse after 125m SMF. The pulse has a FWHM of 1.9 ps, which is sufficient to optically demultiplex a 320 Gb/s RZ-OOK signal. The obtained 40 GHz optical pulses are fed into the all-optical time demultiplexer to select one of the eight 40 Gb/s tributaries at the time out of the 320 Gb/s signal. BER measurements shown in Fig 3 (b) are carried out to evaluate the quality of the recovered clock and the performance of the 320-to-40 Gb/s demultiplexing. The corresponding eye diagrams of the 320 Gb/s signal and one of the demultiplexed 40 Gb/s tributaries are shown in the insets. As a comparison, Fig.3 (b) shows the 40 Gb/s back-to-back (B2B) BER curve, and the B2B BER curves of the 320 Gb/s OTDM signal demultiplexed by the 40 GHz optical clock pulses directly provided by the transmitter. The BER curves of the 320 Gb/s demultiplexed by using the 40 GHz optical clock pulse recovered from the QD-MLLD provide similar performance as the 320 Gb/s B2B BER curves, and have only 1 dB of power penalty when compared to the 40 Gb/s B2B BER curve.

4. Conclusion

We demonstrate for the first time the capability of using the synchronous optical clock pulse provided directly by an injection locked QD-MLLD to achieve an all-optical clock recovery and an all-optical time demultiplexing operation for high speed data at 320 Gb/s. The proposed OCR does not rely on high speed expensive and power hungry optoelectronic feedback. This results in a low cost, nanosecond scale fast locking time, and low power consumption solution. Experimental results show that directly injecting 320 Gb/s data, the QD-MLLD provides low jitter 40 GHz recovered optical clock pulses with 71 fs timing jitter and 1.9 ps pulse-width. Error free operation with 1 dB power penalty after 320-to-40 Gb/s demultiplexing was measured.

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