320 Gb/s all-optical clock recovery and time demultiplexing after transmission enabled by single quantum dash mode-locked laser

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We report, to the best of our knowledge, the first demonstration of 320 Gb/s all-optical clock recovery and all-optical time de-multiplexing after 51 km transmission by exploiting single-quantum dash mode-locked laser diode (QD-MLLD). Based on injection locking of the QD-MLLD, the 40 GHz synchronized optical clock pulses were recovered from the 320 Gb/s with a pulse width of 1.9 ps and timing jitter of 135 fs, which allowed directly time de-multiplexing of 320–40 Gb/s without additional complex optoelectronic circuitry. The 320–40 Gb/s all-optical de-multiplexing was achieved with averaging a power penalty of 4.5 dB at BER of 1E-6.

Optical clock recovery (OCR) and optical time de-multiplexing (OTD) are key functions to realize optical receiver front ends for high-speed optical time-division multiplexing (OTDM) transmission systems. Especially for high-speed data beyond 160 Gb/s, several important issues have to be taken into account for practical implementation of the OCR and OTD. First, the tolerance of timing jitter in the OTD operation is reduced with the increase of the data rate [1], e.g., at 160 Gb/s, the maximum timing jitter of the optical clock allowed is 520 fs, while this value decreases to 260 and 130 fs for 320 and 640 Gb/s de-multiplexing operation, respectively. Second, beyond 160 Gb/s, the gating window of OTD based on fast electro-optical-modulators (EOM) (typically larger than 5 ps) is too large to resolve the high-speed modulated pulses. This results in inter-symbol cross talk and thus extra power penalty. Ultrafast all-optical switches clocked by short optical pulses, on the other hand, are considered a viable solution to implement OTD with the required gating window to minimize the crosstalk. An all-optical clock recovery (AOCR) capable of producing low timing jitter optical clock pulses with sufficiently narrow pulse-width to de-multiplex optical signals beyond 160 Gb/s is demanded to enable high bitrates optical signal reception. Furthermore, small foot-print, fast locking time, low cost, and low power consumption have to be considered for practical application.

To date, the only OCR solutions beyond 160 Gb/s that are able to produce short optical clock pulses with sufficiently low timing jitter require optoelectronic phase-locked loops [2,3]. However, the feedback loop introduces the operation complexity, long clock locking time and costly and power-consuming high-speed electronics (oscillators, photo-detectors, and amplifiers) and optical components (optical pulse source etc.), leading to a bulky and power-hungry system. Recently, AOCR based on injection locking of a monolithically integrated quantum dash mode-locked laser diode (QD-MLLD) has been extensively investigated [4–9]. The extremely narrow free-running mode-beating spectral linewidth (<50 kHz), and broad flat gain spectrum (>12 nm) [4] allow potential generation of short synchronized clock pulses (∼1.5 ps) with extremely low timing jitter (<100 fs) by injection locking of QD-MLLD [6,7]. In [9], error-free OCR and OTD of 160 Gb/s after transmission is reported, while in [6], by exploiting the QD-MLLD as an optical clock pulse generator, we reported for the first time (to our knowledge) that error-free 320–40 Gb/s all-optical time de-multiplexing (AOTD) operation is achieved by using the 40 GHz optical clock short pulse recovered from 320 Gb/s optical time division multi-plexed (OTDM) signal with no transmission.

In this Letter, we further investigate the operation of the QD-MLLD-enabled AOCR and AOTD with 320 Gb/s signal transmitted over 51 km fiber link. In the AOCR of 320 Gb/s with transmission, we measured high-quality 40 GHz optical clock pulse featuring a full width at half-maximum (FWHM) of 1.9 ps, signal-to-noise floor suppression ratio of 48 dB and a low timing jitter of 135 fs (all the timing jitter values in this Letter are integrated from 100 Hz to 100 MHz, according to the method reported in [10]). No less than 2 dB injection power dynamic range with clock timing jitter range from 135 to 162 fs was observed in AOCR operation. 320–40 Gb/s AOTD was implemented with averaging 1 dB power penalty at bit error rate (BER) 1E-9 in the case 320 Gb/s without transmission and averaging 4.5 dB power penalties at BER of 1E-6 in the case of 320 Gb/s with transmission.

Figure 1 shows the experimental setup to investigate the performance of the 320 Gb/s AOCR and AOTD operation after 51 km transmission by exploiting a QD-MLLD as optical clock pulse generator. At the transmitter side, a 320 Gb/s OTDM return to zero on–off keying (RZ-OOK) signal is generated by optically time-multiplexing a 40 Gb/s RZ-OOK data streams via fiber based time inter-leavers. The 320 Gb/s RZ-OOK signal has a data pattern of $2^7 - 1$ PRBS, with a center wavelength of 1551.50 nm. The data-pattern length is limited by the inter-leaver used for the time multiplexing. A PRBS pattern of $2^{31}-1$ is also feasible as it is reported in [4]. The data pulse has a FWHM of 1.3 ps. The 320 Gb/s RZ-OOK is amplified to 13 dBm and filtered by a 5 nm Gaussian shape optical bandpass filter (OBPF) before propagating through the 51 km dispersion compensated transmission fiber link. The transmission fiber link consists of a 51 km true-wave fiber (loss of 11 dB, second-order dispersion of 210.72 ps⁄nm, third-order dispersion of 2.52 ps⁄nm^2, PMD coefficient of <0.04 ps⁄km), and a section of dispersion compensation fiber (DCF) (loss of 5 dB, second-order dispersion of −210.6 ps⁄nm, third-order dispersion of −1.97 ps⁄nm^2).

Figures 2(a) and 2(b) show the optical spectrum of the 320 Gb/s signal before and after the transmission. The corresponding eye diagrams are presented in the Figs. 2(c) and 2(d). The 320 Gb/s signal before transmission has a signal-to-noise ratio (SNR) of 11.5 (measured via Agilent optical sampling scope). After transmission, the SNR of the 320 Gb/s signal dropped to 5.2. The signal-quality degradation is due to the impairments of nonoptimized transmission link, such as inter-symbol cross talk due to the imperfect dispersion compensation in the fiber link, fiber nonlinearities, cascaded optical filtering, and high-noise figure optical amplifier in the transmission link. Higher signal quality of the 320 Gb/s after transmission can be obtained if optimized dispersion compensation modules and optical amplifiers are available.

After the transmission, the 320 Gb/s signal is amplified again and filtered by a 5 nm OBPF before being sent into the OTDM receiver front end. The OTDM receiver front end consists of the QD-MLLD based AOCR, and the nonlinear optical loop mirror (NOLM) based AOTD. In the AOCR, the 40 GHz sub-harmonic clock recovery from the 320 Gb/s RZ-OOK was achieved by injection locking of the QD-MLLD. The injection power of the 320 Gb/s is 11 dBm. The QD-MLLD is operated with a DC bias current of 149 mA (no high-speed electrical clock was applied), and a temperature of 21°C, with over 12 nm broadband multiple-mode lasing spectrum centered at 1525 nm (see Fig. 3). More details on the QD-MLLD can be found in [4]. The origin of the sub-harmonic clock recovery mechanism in this experiment is still unclear. It may result from the modulation of the gain and refractive index due to the injected data signal [11,12] and the mode-locking behavior as a result of the enhanced four-wave mixing in the resonate cavity [13]. These effects will then force the QD-MLLD to synchronize the frequency of the generated clock to the incoming data signal. Note that, although the AOCR reported in this Letter is polarization-dependent, this issue can be solved by cascading a polarization-insensitive bulk-based self-pulsating laser and quantum dash/dot mode-locked laser [14]. At the output of the injection-locked QD-MLLD, the recovered optical 40 GHz clock is selected out via a 5 nm OBPF. 125 m single-mode fiber (SMF) was employed to compress the pulse width due to the positive chirp of the optical pulses [7].

Figure 4 shows the optical spectrum at the output of the injection-locked QD-MLLD and the 40 GHz optical recovered from the 320 Gb/s after transmission. The AOCR is achieved with the 320 Gb/s signal detuned over 25 nm to the QD-MLLD lasing center wavelength. A more detailed study on the injection-wavelength dependence has been presented in [15]. Figure 5(a) shows the electrical spectrum of the recovered 40 GHz clock; the clock has a linewidth of <10 kHz at −20 dB (RBW is 3 kHz) and a signal-to-noise suppression ratio of 48 dB. Figure 5(b) shows the waveform of the 40 GHz clock pulse after the pulse-compression stage. The FWHM of the clock pulse is 1.9 ps, which is sufficiently narrow enough to de-multiplex a 320 Gb/s signal.

After the pulse-compression stage, the 40 GHz optical clock pulse is amplified and used to clock the NOLM to all-optical time de-multiplex the 320 Gb/s signal into 8 × 40 Gb⁄s tributaries. The 40 Gb/s tributaries are then detected and sent to a bit-error-rate tester, which is also clocked by the recovered 40 GHz clock. BER measurements are carried out to evaluate the quality of the recovered clock and the performance of the 320–40 Gb/s de-multiplexing both in the case of 320 Gb/s signal with-out and with transmission.

Figure 6 reports the single sideband phase-noise-spectrum density (SSB-PSD) of the recovered 40 GHz sub-harmonic clock. As a reference, the phase-noise trace of 40 GHz original clock from the transmitter is also shown in Fig. 6. The original 40 GHz clock has a low timing jitter of 64 fs. The recovered 40 GHz clock has a timing jitter of 100 and 135 fs in case of 320 Gb/s AOCR without and with transmission, respectively. The injection optical powers were 10 and 11 dBm in the case of 320 Gb/s AOCR without and with transmission. It is worth noting that high-quality AOCR with a low timing jitter 40 GHz optical clock (135 fs) is still able to be achieved even with a degraded 320 Gb/s signal after transmission (SNR of 5.2).

Figure 7 shows the SSB-PSD and timing jitter of the AOCR of 320 Gb/s with transmission while varying injection signal power. The phase-noise trace of the original 40 GHz clock is shown as a reference. AOCR with injection power range from 10 to 12 dBm is achieved with timing jitter range from 135 to 162 fs, respectively. This indicates no less than 2 dB injection power dynamic range of the 320 Gb/s AOCR after transmission.

The BER results after AOTD operation are reported in Figs. 8 and 9. Figure 8 shows the BER curves of the 320 Gb/s after AOCR and AOTD operation in the case of without and with transmission, respectively. The BER curve of the 40 Gb/s RZ-OOK directly from the transmitter, which we define as back-to-back (B2B) case, is also shown in Fig. 8. Compared to the B2B 40 Gb/s BER curve, 320 Gb/s AOCR and AOTD without transmission introduced only 1 dB penalty at BER of 1E-9. While in the case of 320 Gb/s with transmission, an error floor emerged at BER of 1E-6. The error floor is understood to be due to the following factors: first, as we reported in Fig. 2, the quality of 320 Gb/s signal after transmission is degraded to an SNR of 5.2, which results in an error floor BER performance; second, the 40 GHz recovered clock has higher timing jitter (>135 fs) after transmission compared to the scenario without transmission (100 fs). This therefore leads to an extra power penalty in the AOTD operation and degraded BER performance. However, the BER after transmission is well below the forward error correction (FEC) limit of 3.8E-3, which corresponds to a post-FEC BER of less than 1E-12 [16].

Figure 9 shows the power-sensitivity measurement results at the BER of 1E-6 for all the eight 40 Gb/s tributaries after AOTD in the case of 320 Gb/s without and with transmission. The average power sensitivity in the 320 Gb/s AOCR and AOTD operation without transmission is −13 dBm at BER of 1E-6, while the power sensitivity increases to average −9.2 dBm at 1E-6 in case of the 320 Gb/s after transmission. Compared to the power sensitivity of B2B 40 Gb/s, the transmission link introduced a 4.5 dB penalty at BER of 1E-6 to the 320 GB/s AOCR and AOTD operation.

In summary, we demonstrate for the first time 320 Gb/s AOCR and AOTD operation after 51 km transmission by using the synchronous optical clock pulse generated directly by an injection-locked QD-MLLD. The proposed AOCR does not rely on high-speed expensive and power-hungry optoelectronic feedback. This leads to operation simplicity, low cost, fast locking time [17], and low power consumption. Experimental results show that by directly injection locking with the 320 Gb/s signal after transmission, the QD-MLLD was able to produce high-quality 40 GHz synchronized optical clock pulses with 135 fs timing jitter and 1.9 ps pulse width. By exploiting the short optical clock pulse, 320 Gb/s AOTD operation was successfully implemented. A 4.5 dB power penalty at BER of 1E-6 was obtained in the AOCR and AOTD operation with 320 Gb/s signal after transmission.

Figures

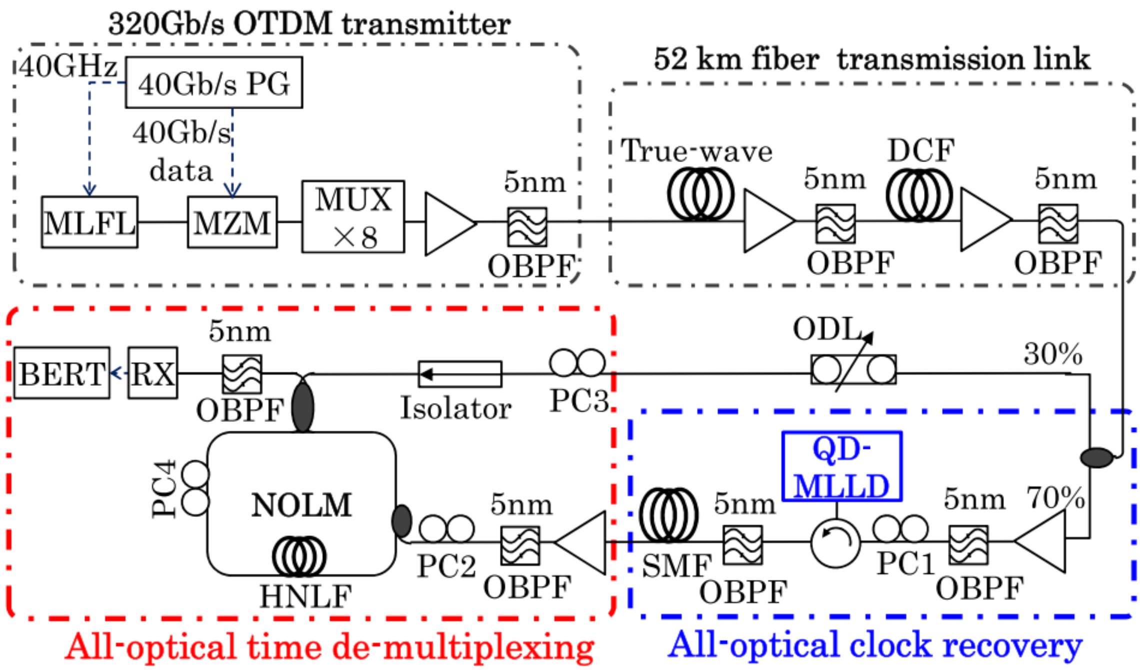

Fig. 1. Experimental setup of 320 Gb/s AOCR and AOTD after transmission using a QD-MLLD and a NOLM, MLFL, mode-locked fiber laser; PG, pattern generator; MZM, Mach–Zender modulator; MUX, time multiplexer; OBPF, optical bandpass filter; DCF, dispersion compensation fiber; ODL, optical delay line; PC, polarization controller; QD-MLLD, quantum dash mode-locked laser diode; NOLM, nonlinear optical loop mirror; HNLF, highly nonlinear fiber; RX, optical receiver; BERT, bit error rate tester.

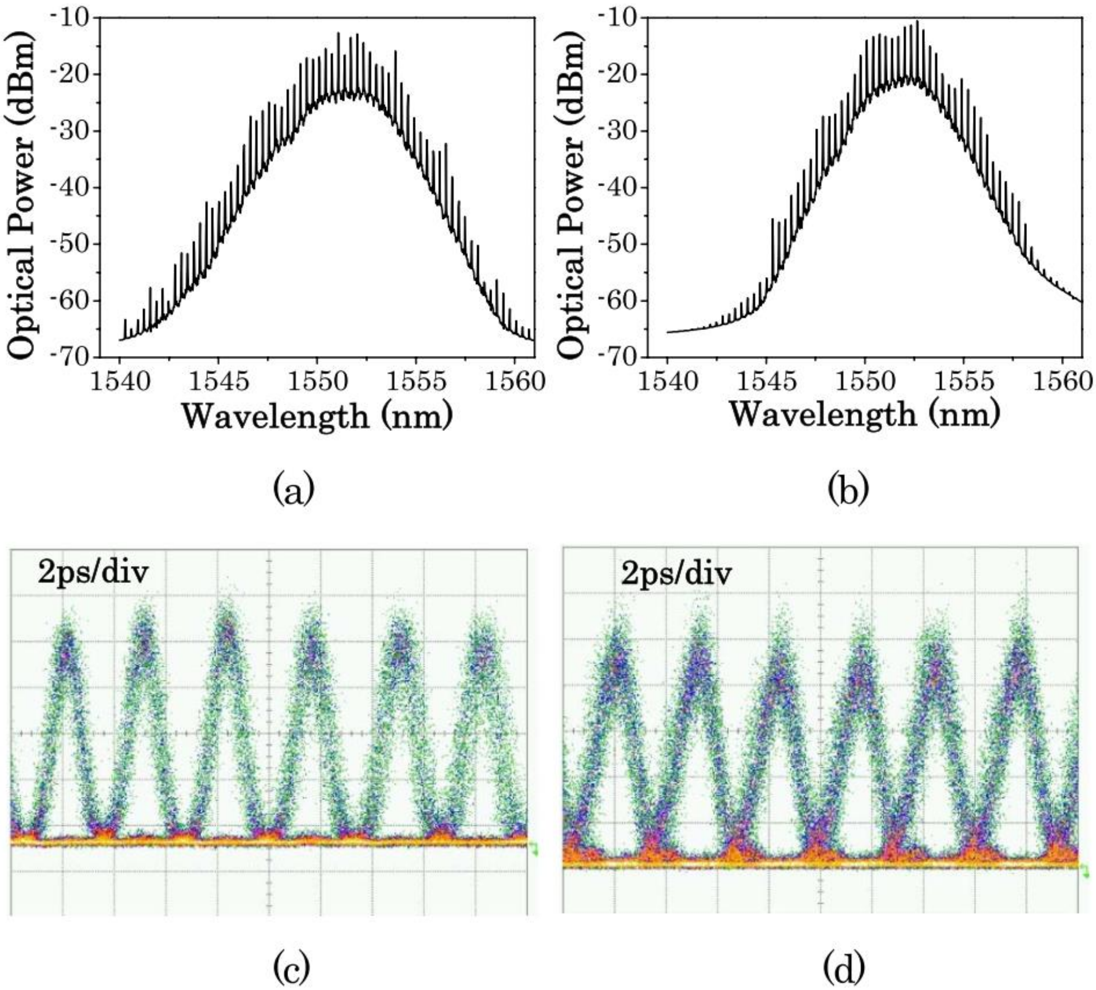

Fig. 2. Optical spectrum of the 320 Gb/s signal (a) before and after 51 km transmission link, and the corresponding eye diagrams (2 ps⁄div): (c) before and (d) after transmission.

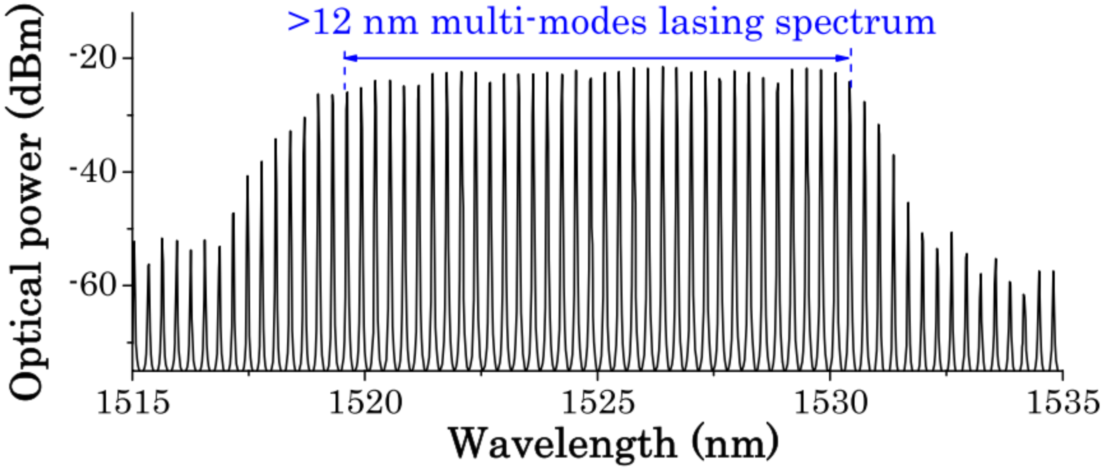

Fig. 3. Free-running optical spectrum of the QD-MLLD operated at 149 mA and 21°C.

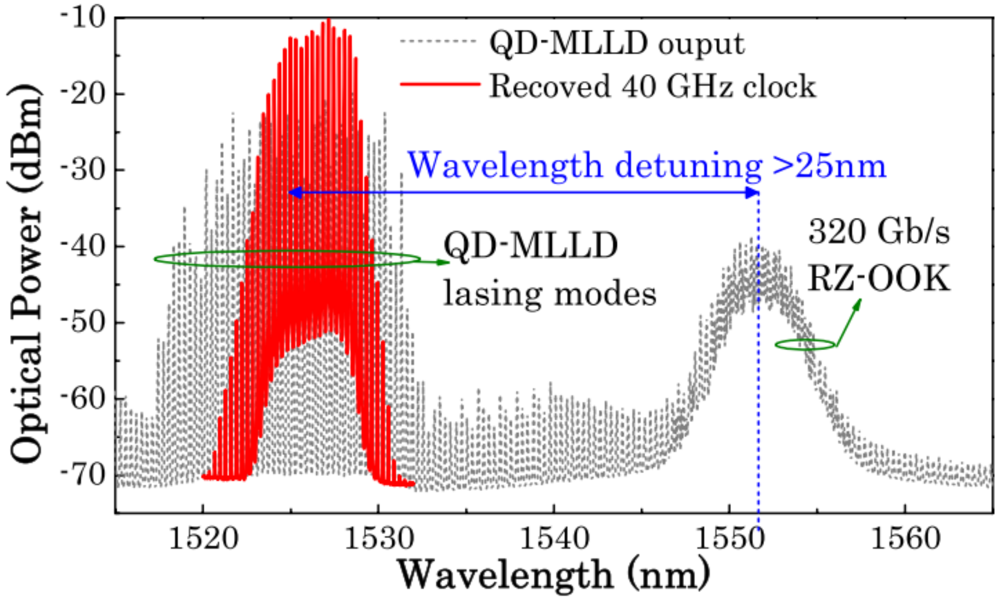

Fig. 4. Optical spectrum at the output of the injection-locked QD-MLLD and the recovered 40 GHz optical clock.

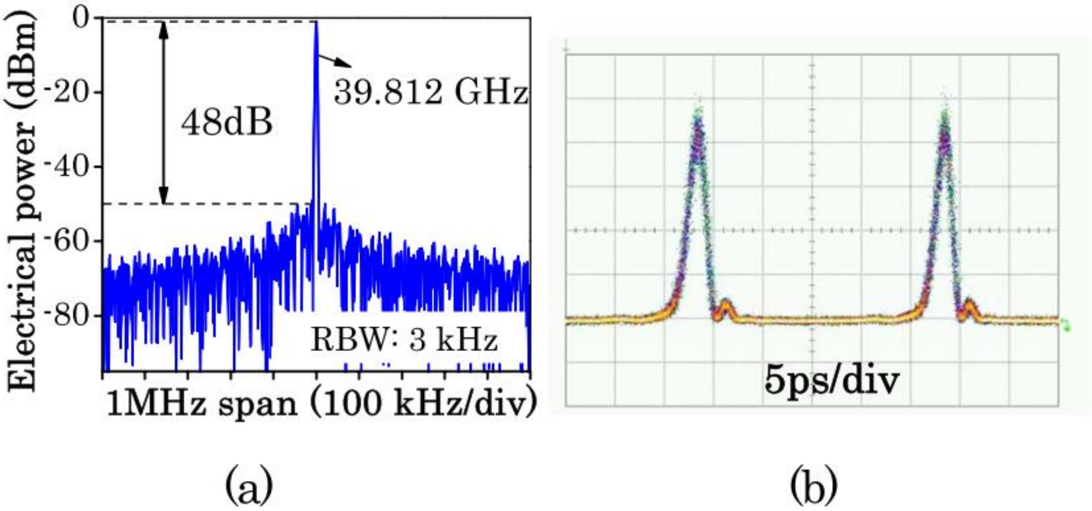

Fig. 5. (a) Electrical spectrum. (b) Waveform of the recovered 40 GHz optical clock pulse.

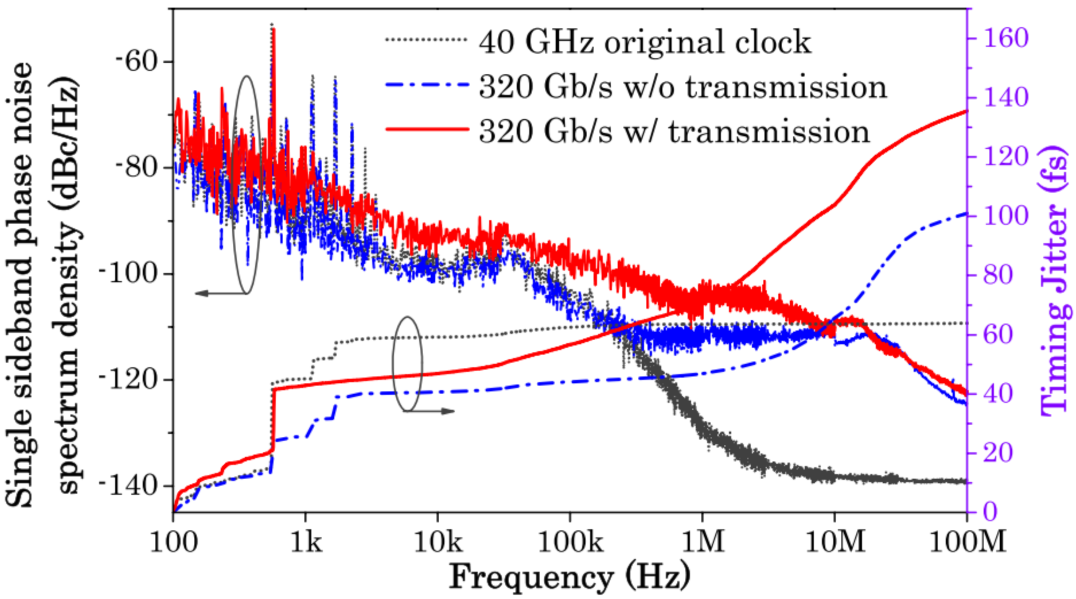

Fig. 6. Single sideband phase-noise-spectrum density (SSB-PSD) and timing jitter of the recovered 40 GHz sub-harmonic clock without and with transmission, w/o, without; w/, with.

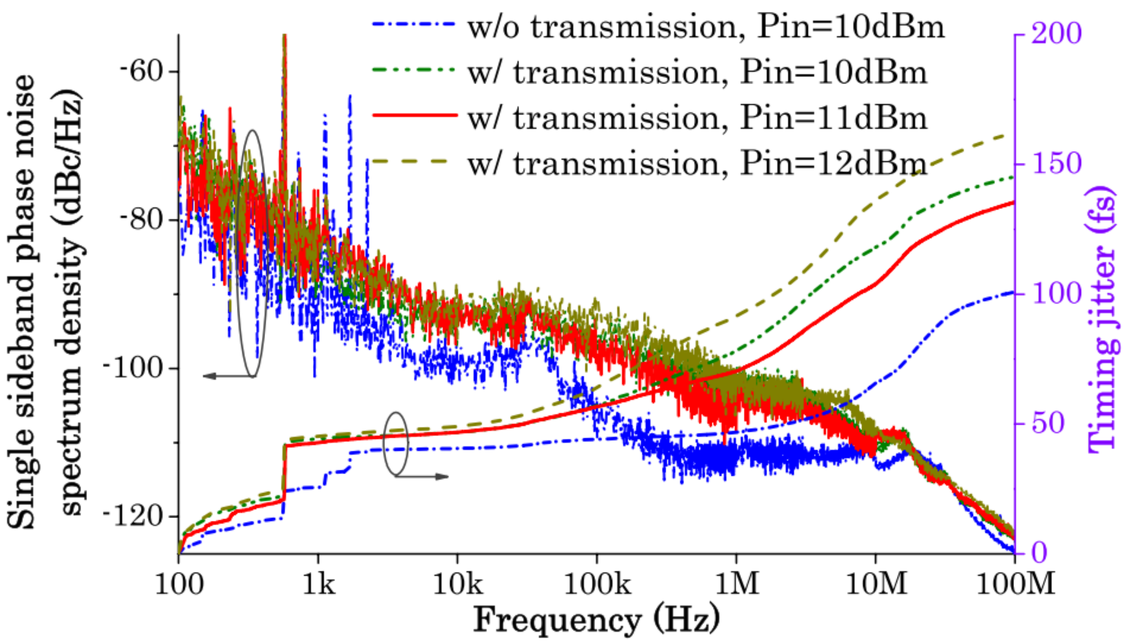

Fig. 7. Power dynamic range of the OCR after transmission: the SSB-PSD and timing jitter of recovered clock with the differ-ent injection power, w/o, without; w/, with.

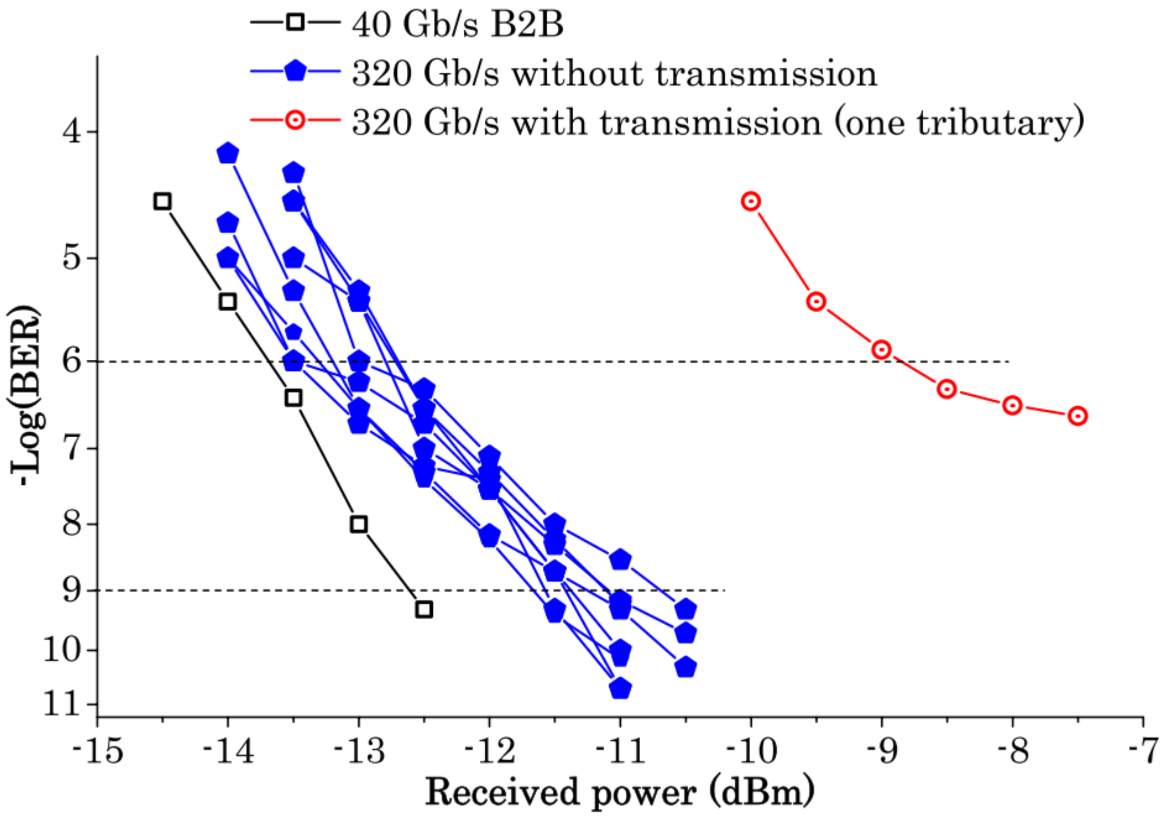

Fig. 8. BER curves of the 320 Gb/s AOCR and AOTD operation without and with transmission.

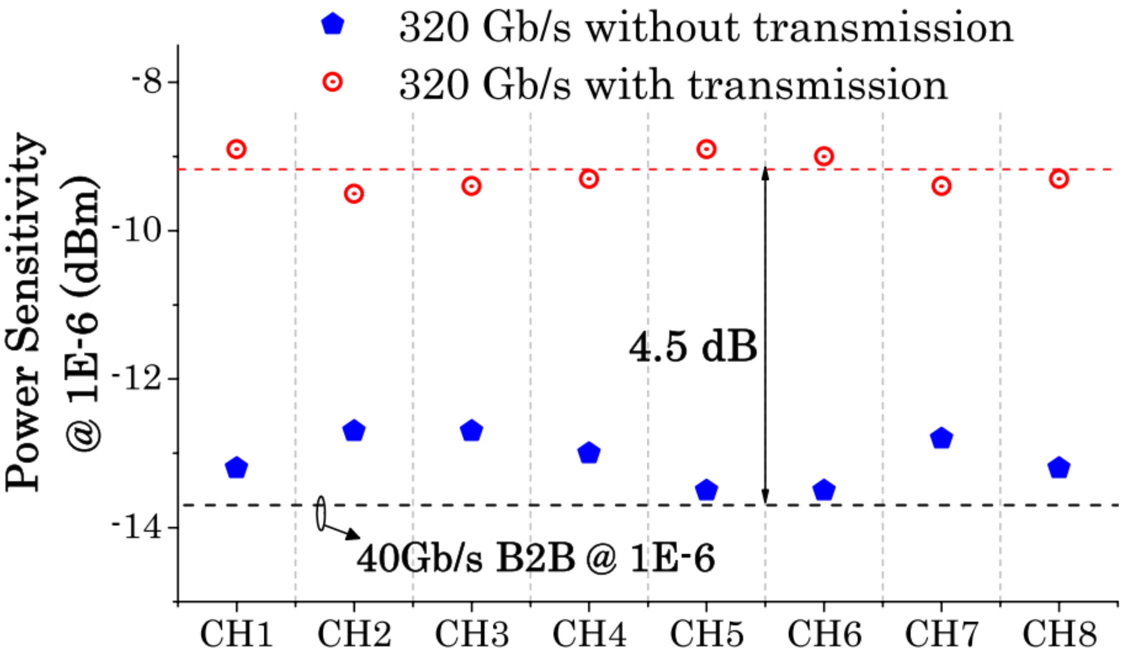

Fig. 9. Power sensitivity at BER of 1E-6 of 320 Gb/s AOCR and AOTD without and with transmission.

References

1. M. Jinno, Opt. Lett. 18, 1409 (1993).

2. H. C. H. Mulvad, E. Tangdiongga, H. de Waardt, and H. J. S. Dorren, Electron. Lett. 44, 146 (2008).

3. P. Guan, H. C. H. Mulvad, K. Kasai, T. Hirooka, and M. Nakazawa, Photon. Technol. Lett. 12, 1735 (2010).

4. G. H. Duan, A. Shen, A. Akrout, F. Van Dijk, F. Lelarge, F. Pommereau, O. LeGouezigou, J. Provost, H. Gariah, F. Blache, F. Mallecot, K. L. Merghem, A. Martinez, and Ramdane, Bell Labs Tech. J. 14, 63 (2009).

5. M. Yanez and J. Cartledge, J. Lightwave Technol. 29, 1437 (2011).

6. N. Calabretta, J. Luo, J. Parra-Cetina, S. Latkowski, R. Maldonado-Basilio, P. Landais, and H. J. S. Dorren, "320 Gb/s all-optical clock recovery and time demultiplex-ing enabled by a single quantum dash mode-locked laser Fabry–Perot optical clock pulse generator," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference, OSA Technical Digest [online] (Optical Society of America, 2013), paper OTh4D.5.

7. R. Maldonado-Basilio, S. Latkowski, S. Philippe, and P. Landais, Opt. Lett. 36, 1569 (2011).

8. M. Costa e Silva, A. Lagrost, L. Bramerie, M. Gay, P. Besnard, M. Joindot, J. Simon, A. Shen, and G. Duan, J. Lightwave Technol. 29, 609 (2011).

9. J. Luo, J. Parra-Cetina, S. Latkowski, R. Maldonado-Basilio, P. Landais, H. Dorren, and N. Calabretta, "Quantum dash mode-locked laser based open-loop optical clock recovery for 160 Gb/s transmission system," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference, OSA Technical Digest [online] (Optical Society of America, 2013), paper OTh4D.6.

10. T. R. Clark, T. F. Carruthers, P. J. Matthews, and I. N. Duling, Electron. Lett. 35, 720 (1999).

11. Y. J. Wen, D. Novak, and H. F. Liu, Electron. Lett. 36, 879 (2000).

12. A. Murakami, K. Kawashima, and K. Atsuki, IEEE J. Quan-tum Electron. 39, 1196 (2003).

13. J. Renaudier, G. H. Duan, P. Landais, and P. Gallion, IEEE J. Quantum Electron. 43, 147 (2007).

14. B. Lavigne, J. Renaudier, F. Lelarge, O. Legouezigou, H. Gariah, and G. H. Duan, J. Lightwave Technol. 25, 170 (2007).

15. J. Parra-Cetina, S. Latkowski, R. Maldonado-Basilio, and P Landais, Photon. Technol. Lett. 23, 531 (2011).

16. F. Chang, K. Onohara, and T. Mizuochi, IEEE Commun. Mag. 48(3), S48 (2010).

17. R. Maldonado-Basilio, J. Parra-Cetina, S. Latkowski, N. Calabretta, and P. Landais, J. Lightwave Technol. 31, 860 (2013).