Multi-Data-Rate System Performance of a 40-GHz All-Optical Clock Recovery Based on a Quantum-Dot Fabry–Pérot Laser


Abstract—Bit-error-rate assessment of a multi-rate all-optical clock recovery (OCR) based on a narrow linewidth mode-locked quantum-dot (QD) Fabry–Pérot laser is presented in this letter. OCR has been achieved without external feedback. We use a QD Fabry–Pérot semiconductor laser designed for 40-GHz clock extraction. We then present OCR performance with 40-, 80-, and 160-Gb/s input data signal and demonstrate that clock recovery has been obtained thanks to subharmonic locking process. Results are presented through penalty measurement using an original characterization based on recovered clock remodulation with electrical data from the transmitter. This technique allows us to evaluate the quality of the recovered clock.

Index Terms—Clock synchronization, error analysis, optical communication, semiconductor lasers.

I. INTRODUCTION

Optical transmission systems beyond 40 Gb/s require complex arrangements to carry out the optical clock extracting [1], [2] needed for signal processing like optical time-domain signal demultiplexing [3] or all-optical regeneration [4]. Mode-locked (ML) semiconductor lasers have been often employed for direct [5] or subharmonic optical clock recovery (OCR) [6], [7], and particularly for the recovery of a 40-GHz clock from a 160-Gb/s data stream [8]. In this letter, an ML quantum-dot (QD) Fabry–Pérot laser (FPL) is used for the all-OCR operation. Such a laser, exhibiting an extremely narrow mode-beating spectral linewidth, has previously been shown to be able to recover optical clock with jitter performances compatible with ITU G285-1 recommendations for 40-GHz clock recovery [9]. In this experimental report, we demonstrate that ML-QD-FPL can also be used for multi-data-rate OCR at 40, 80, and 160 Gb/s. The method consists of recovering the optical clock with the laser by injecting an optical data stream. The optically recovered clock is remodulated with data for then being coded. Thus, the quality of the recovered clock can be evaluated from bit-error-rate (BER) measurements from the remodulated signal [10]. Such an experiment gives us, in a system environment, a method both of evaluating the quality of the optically recovered clock and of characterizing the clock recovery performance.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The transmitter unit (Tx) consists of an actively fiber-ring laser (Pritel Inc) which generates 1.5-ps optical pulses at the standard frequency of 42.66 GHz. This optical clock is then modulated with electrical data at 42.66 Gb/s in an electrooptic modulator (EOM) to create an optical data stream at 1550 nm. This is followed by an optical time-division-multiplexing (OTDM) stage consisting of an optical clock multiplier (OCM) also from Pritel Inc., which generates optical data trains at 85.32 and 170.64 Gb/s. While preserving the pseudorandom bit sequence (PRBS) for BER testing, we use a 2^23 − 1 PRBS. This arrangement makes it possible to test the clock recovery at three different input bit rates with the same PRBS length.

The clock recovery section consists of a self-pulsating ML-QD-FPL with a peak emission wavelength around 1570 nm (L-band). Varying the current and temperature of the laser allows the locking of the self-pulsating signal to the repetition frequency of 42.66 GHz, in a range of 20 MHz, obtaining the clock extraction from the optical data signal. The operating laser parameters have been chosen in order to recover the clock...
previously at 42.66 GHz and are not optimized to achieve the best mode-locked spectral linewidth. In the best configuration, corresponding to a passively mode-locked frequency at 42.71 GHz, a linewidth of 10 kHz has been measured.

Once recovered, this optical clock is then remodulated at 40 Gb/s with nondegraded data from the transmitter for BER evaluation. In this way, the error detection process allows us to evaluate the optical data stream quality. Electrical data used for remodulation are nondegraded, which implies that data quality on the receiver corresponds to the quality of the recovered optical clock. Experimentally, we use the electrical data at 42.66 Gb/s directly taken from the transmitter to remodulate the recovered clock in an EOM. An optical delay line, placed before the modulator, allows us to synchronize clock and data.

Therefore, by synchronizing the receiver with the electrical clock from the transmitter, it is possible to measure the introduction of extra errors arising from clock recovery. The benefit of this technique is that it allows impairments investigations of the OCR by timing jitter, optical noise, or PDL, to appear as a BER penalty at the receiver. BER versus optical signal-to-noise-ratio (OSNR) measurements are made by adding optical noise ahead of the receiver. The OSNR are measured in a 1-nm bandwidth at 40 Gb/s.

III. MULTI-RATE CLOCK RECOVERY

Given that nominal transmitter bit rate is at the standard 42.66 Gb/s, then the bit rates applied to the clock recovery stage are exactly 42.66, 85.32, and 170.64 Gb/s. Fig. 2 shows temporal traces corresponding to generated optical signal at 40 and 160 Gb/s (autocorrelator and oscilloscope traces) and remodulated optically recovered clock from 40- and 160-Gb/s input (oscilloscope traces). The extinction ratio of the remodulated recovered clocks is up to 15 dB. The pulselength of the recovered clock pulses is 4 ps. It is important to note that the optical time multiplexing is carried out in such a manner that there is no 40-GHz component at 80 or 160 Gb/s. This point has been verified by checking carrier frequency suppression with the RF spectrum analyzer. Given this, the clock recovery from 80 and 160 Gb/s is due to the subharmonic locking process. Fig. 3 shows the output laser for optical data injection at 40 and 160 Gb/s. For the clock recovery at 160 Gb/s, the locking process is clearly obtained by phase correlation of the Fabry–Pérot modes, induced by 160-GHz internal carrier density modulation [11] as there is no 42.66-GHz frequency component in the unlocked case.

For the experiment, data optical power injected into the ML-QD-FPL for clock recovery operation is in the 5- to 10-dBm range for all bit rates. The polarization of the injected signal is also controlled to minimize well-known polarization dependency in QD structures. Using this, we obtained a very stable clock recovery operation. Furthermore, the laser driving current was 470 mA and the temperature was controlled at 29.2 °C. We determine that the ML-QD-FPL is still locked with the input data for temperature variations of 0.5 °C and driving current variations of 50 mA.

IV. BER RESULTS

We measured the receiver sensitivity with remodulated optically recovered clock for $2^{27} - 1$ PRBS sequence length. It should be noted that the OCM used does not maintain the PRBS properties when used with sequence lengths longer than $2^{27} - 1$. From Fig. 4, it can be seen that the performances for the three bit rates used are almost identical, with a penalty of less than 1 dB at a BER of $10^{-9}$. These results confirm experimentally that ML-QD-FPL lasers can perform clock recovery at different bit rates in a system environment. It also demonstrates that subharmonic synchronization (80 and 160 Gb/s producing a clock at 40 GHz) is possible without degrading the quality of the recovered clock. For this study, the receiver sensitivity reference has not been done with a return-to-zero (RZ) signal at 42.66 Gb/s with the same pulselength. As a reference, we give two different receiver sensitivity results: the first one with Pritel source pulses (1.5-ps pulselength), which presents a negative penalty of 1 dB, and the second one with 33% RZ format (8-ps pulselength), which presents a positive penalty of 1 dB.

Fig. 2. Temporal traces of input data signals at 40 and 160 Gb/s, and remodulated clock at 40 Gb/s for BER measurement.

Fig. 3. RF spectrum measured at the clock recovery output (ML-QD-FPL) for 40 Gb/s injected: (a) when clock recovery is unlocked to the data carrier frequency and (b) when it is locked. For 160-Gb/s input: (c) for free running laser (no injected carrier frequency at 40 GHz) and (d) when the laser is locked by subharmonic process.
be certainly improvable by choosing a mode-locked laser operating point with pulsating frequency closer to the injected data bit rate.

V. CONCLUSION

All-OCR using an ML-QD-FPL has been successfully demonstrated at 160 Gb/s, without external feedback. The compactness, stability, and robustness of the laser make it a strong candidate for OCR and high-bit-rate OTDM applications.

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REFERENCES