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Up to 427 GHz All Optical Frequency Down-Conversion Clock Recovery Based on Quantum-Dash Fabry–Perot Mode-Locked Laser

Marcia Costa e Silva, Alexandra Lagrost, Laurent Bramerie, Mathilde Gay, Pascal Besnard, Michel Joindot, Jean-Claude Simon, Alexandre Shen, and Guan-Hua Duan

Abstract—This paper reports on all optical frequency down conversion clock recovery based on Quantum-Dash Fabry–Perot mode-locked laser diode (QD-MLLD). A first section is dedicated to the generation of a tunable repetition rate pulse source based on a first QD-MLLD. The principle is to select three lines in the QD-MLLD spectrum with a filtering technique; the lines spacing are properly chosen to generate the desired repetition rate. In this paper, a frequency of 427 GHz was reached and observed with an optical sampling oscilloscope. Moreover, an encoded 170.8 GHz pulse source was characterized showing no penalty in comparison with our reference obtained by Optical Time Division Multiplexing (OTDM), which confirms the quality of the optical clock. In a second section, we show a clock frequency down conversion based on a second QD-MLLD, which is optically injected by a pulse source, whose repetition rate is 10 times higher than its self pulsating frequency. The 42.7 GHz down converted clock is then encoded and analyzed showing no penalty in comparison to a standard 42.7 Gbit/s reference, demonstrating its quality. Finally, in a third section, we demonstrate sub-harmonic clock recovery with a QD-MLLD, when a data stream is injected. We measure a penalty of 0.3 dB when compared to a standard 42.7 Gbit/s reference.

Index Terms—Clock-recovery, mode-locked lasers, optical communications, quantum dot devices.

I. INTRODUCTION

THE ever increasing demand for capacity motivates scientists to explore different alternatives in order to increase bit rates in optical communications. The development of high performance, reliable and low-cost devices has been the key for this improvement over the years and nowadays improving some existing devices is one way to achieve this goal. Semiconductor Mode-Locked Laser Diodes (MLLD) appear as a versatile device in optical communication. For several years the use of this kind of laser source has been demonstrated for different applications such as a high repetition rate source [1]–[4], wavelength

tunable transmitter [5], generation of millimeter wave signals [6], and also as an optical clock recovery [7]–[9].

The MLLD based on Quantum Dot and Quantum Dash structures (QD) [10]–[13], brought a remarkable improvement of the optoelectronic properties, owing to the three dimensional carrier confinement leading mainly to a broad gain bandwidth and a low phase noise level [12], [14]. QD lasers are expected to present lower threshold current, lower chirp, higher gain, and higher thermal stability than bulk-based devices or even quantum well (QW) devices [15], [16]. All these improvements in laser structure allowed significant advances in the generation of a train of pulses at high repetition rate [17].

Some important results have been published for passive mode locking regime as the generation of high bit rate pulse train as high as 346 GHz in [18] and the generation of subpicosecond pulses at high repetition rate [19], [13], [20]. In an active mode locking regime, the QD-MLLD has been investigated as a powerful device for different applications in optical telecommunications, as an all optical clock recovery for 40 Gbit/s [21], [22] and a clock recovery at 40 Gbit/s for RZ, NRZ and DPSK signals [23], which indicates that this kind of technique can be tested for advanced modulation formats. As far as high bit rate transmissions are concerned, different configurations can be reported: as a 160 Gbit/s source in a OTDM configuration [24]; as a unique source to generate different wavelength-division-multiplexing channels for access network applications [25]; and as a high repetition rate pulsed signal generator up to 170.8 GHz and higher by a simple spectral filtering method, taking advantage of the wide spectrum of the laser [26].

In this work we present the use of QD-MLLD in an active mode locking regime: as a very high repetition rate source and as a 42.7 GHz down-conversion clock recovery using two QD structures. The devices used in this paper were fabricated by Alcatel-Lucent-Thales III-V laboratory. Fig. 1 depicts the laser structure, which is similar to the one described in [27]. The active region is composed of Quantum Dash layers with InGaAsP Quantum Well in a Fabry–Perot (FP) structure. It is a buried hetero-structure and its FP cavity length is one millimeter, for a Free Spectral Range of 42.7 GHz. A temperature probe and a Peltier cooler have been integrated to the chip into a butterfly module. These lasers can be passively or actively mode-locked depending on applications. The optical spectrum is quite flat, with about a 13 nm width at 10 dB loss for both studied lasers and is centered at 1555 nm for the high repetition rate pulse source application and at 1560 nm for sub-harmonic clock re-

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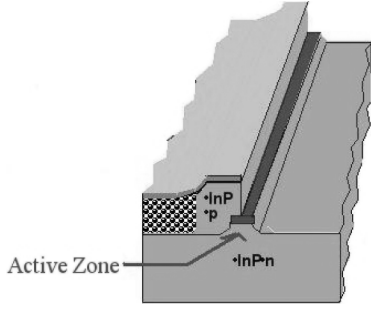


Fig. 1. Schematic sketch of the laser structure.

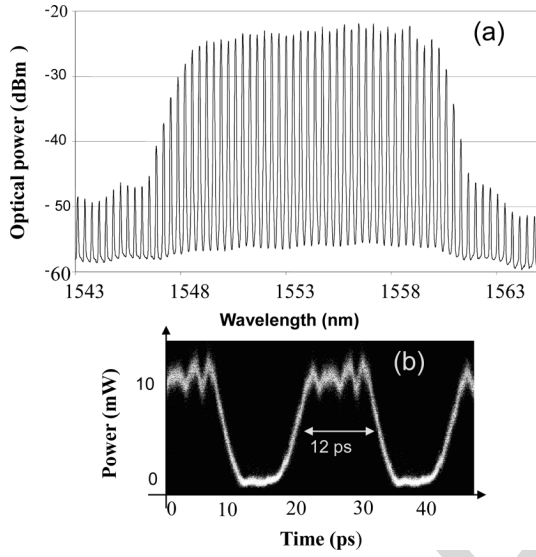


Fig. 2. Optical spectrum and corresponding eye diagram.

covery application. Fig. 2 shows the optical spectrum (a) and the pulse shape (b) for the laser used as a high repetition rate pulse source. The pulse exhibits a large full width at half maximum (FWHM) of about 12 ps. The pulse is not Fourier transform-limited due to the high level of chirp in the laser and to chromatic dispersion in the fiber pigtail.

This paper is divided in three sections. The first one is devoted to the high repetition rate pulse source, using a first QD-MLLD, which can be called a tunable repetition rate pulse source. The principle is to select three lines in the QD-MLLD spectrum with a filtering technique; the line spacing is properly chosen to generate the desired repetition rate. The maximum frequency reachable with this laser is studied. Moreover, the quality of the repetition rate pulse source was assessed through BER measurements.

The second section details how a QD-MLLD can be used as an all optical clock frequency down-conversion. Thanks to the tunable repetition rate source, we assess its capacity to convert a clock at $N \times 42.7$ GHz towards a clock at 42.7 GHz. The quality of the encoded down-converted clock at 42.7 GHz is also assessed through BER measurements. Finally, in a third section, we study down-conversion clock recovery in the QD-MLLD, when a data stream is injected.

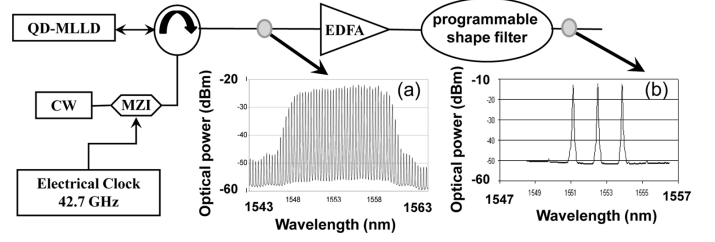


Fig. 3. Experimental setup of the pulse stream generation.

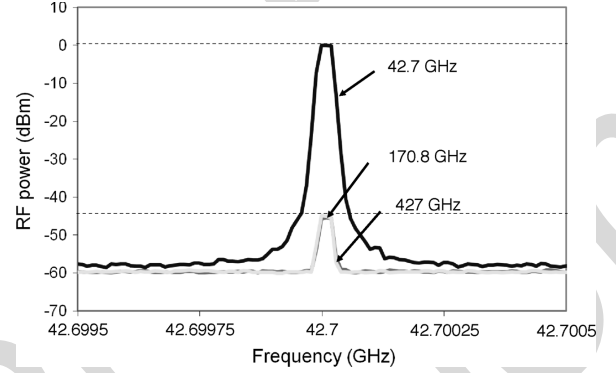


Fig. 4. RF spectrum for generated pulse stream at 42.7 GHz for three different frequencies: 42.7 GHz, 170.8 GHz and 427 GHz.

II. TUNABLE REPETITION RATE PULSE SOURCE

This part is dedicated to the generation of repetition rate pulse source at various frequencies by using a Quantum-Dash mode-locked laser diode and an optical filter.

A. Experimental Setup

Fig. 3 depicts the experimental setup. The laser is actively mode-locked by seeding a train of pulses from an optical clock. For that, a RZ 33% 42.7 GHz optical clock signal is generated at 1535 nm with a LiNbO₃ modulator and is injected inside the cavity of the QD-MLLD module through an optical circulator. Spectrum (a) in Fig. 3 shows the wide spectral comb of the QD-MLLD centered at 1555 nm with a 13 nm (1.6 THz) width at 10 dB. The signal of the laser is injected into an optical amplifier and passes through a tunable spectral filter (*Waveshaper Finisar*TM) [28]. Three spectral lines were selected, according to the desired frequency. For example, three lines separated by 341.6 GHz (8×42.7 GHz) are selected as shown in the spectrum (b). We note that the lines do not exhibit residual spurious spectral components at the fundamental clock frequency spacing of the QD-MLLD.

Fig. 4 illustrates the beating spectra at 42.7 GHz for 3 different frequencies generated at: 42.7 GHz, 170.8 GHz and 427 GHz measured by means of a high-speed photodiode followed by an electrical spectrum analyzer (ESA), with a resolution bandwidth set to 1 kHz and video bandwidth set to 300 kHz. For frequencies greater than 42.7 GHz, RF component is suppressed by more than 40 dB, confirming the purity of the generated signals.

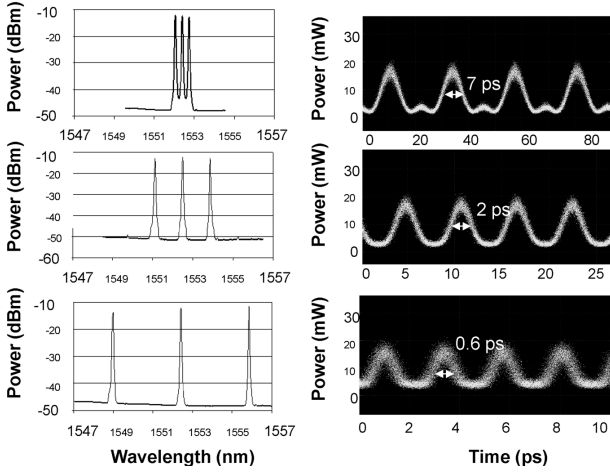


Fig. 5. Generated clock for three different frequencies: 42.7 GHz; 170.8 GHz and 427 GHz.

B. High Repetition Rate Pulse Source Generation

The waveform delivered by the tunable repetition rate pulse source is observed using an optical sampling oscilloscope (OSO) with a temporal resolution of one picosecond. An optical spectrum and temporal shape is shown in Fig. 5 for three generated clocks at 42.7 GHz, 170.8 GHz and 427 GHz. The FWHM of pulses are 7, 2 and 0.6 ps respectively. The timing jitter of the tunable repetition rate pulse source seems to be below the oscilloscope resolution. Further investigation of timing jitter was not possible in this work. However, studies with similar laser show a rms jitter below 200 fs [21], [29].

Unfortunately, the oscilloscope bandwidth is not sufficient to characterize high repetition rate pulse source. In particular, due to low frequency sampling of the OSO, some unexpected events can not be observed. That is why we devoted the next section to the assessment of the encoded high repetition rate pulse source at 170.8 GHz through bit error rate measurement to confirm the stability of this pulse source.

C. Bit Error Rate Measurements

We assessed the clock quality in a back to back experiment, in order to demonstrate the stability of the generated clock signal. We compared the proposed 170.8 GHz generated clock when modulated at 42.7 Gbit/s with an available reference 170.8 Gbit/s signal obtained by the OTDM method and described in previous work [24].

Fig. 6 illustrates the experimental setup. The 170.8 GHz clock was first encoded at 42.7 Gbit/s by a Mach-Zehnder intensity modulator (MZI). This does not lead to a true PRBS modulation as each bit of the sequence is repeated four times. However, after demultiplexing for BER analysis, the PRBS sequence is recovered on each tributary. This experiment allows the quality of the optical clock to be assessed. As shown in the upper part of Fig. 6, the modulation at 42.7 Gbit/s over the signal at 170.8 GHz will vanish half of the pulses at 170.8 GHz. We do the analysis of one undistorted bit out of four at 42.7 Gbit/s. The optical time domain demultiplexer box consists of an electro absorption modulator driven by the clock recovered at 42.7 GHz and a

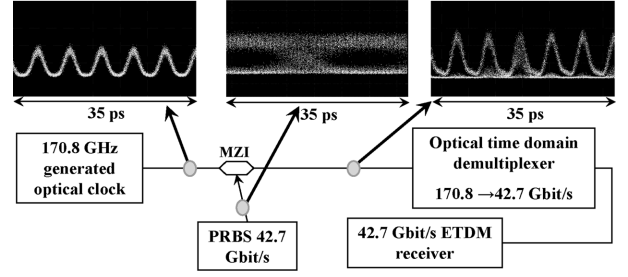


Fig. 6. Experimental setup for data encoding and BER analysis of the 170.8 GHz generated clock.

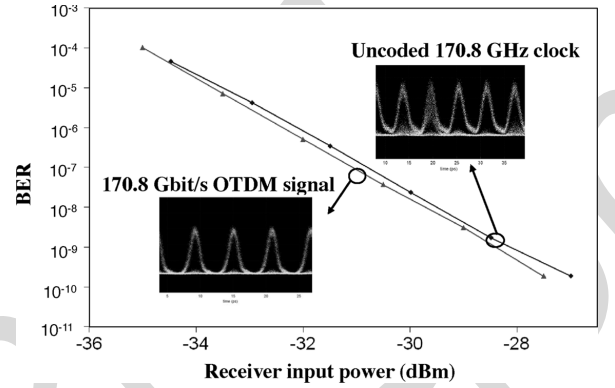


Fig. 7. BER versus receiver input power of the encoded 170.8 GHz generated clock and the 170.8 Gbit/s OTDM signal.

delay line selecting the tributary to be analyzed in a 42.7 Gbit/s ETDM receiver. The clock recovery we used is the QD-MLLD as shown in next section. The OTDM 170.8 Gbit/s signal used as a reference is generated by a 42.7 GHz signal. This last signal is itself obtained from a QD-MLLD and is modulated by a MZI with a 42.7 Gbit/s $2^7 - 1$ length pseudo-random binary sequence (PRBS). The 42.7 Gbit/s data stream is then multiplexed by a bit-rate multiplier (BRM), which multiplies 4 delayed versions of this signal to generate a 170.8 Gbit/s. The choice of the PRBS length is due to the BRM device, which guarantees, thanks to a proper optical delay line in each multiplexing arms, a true PRBS length of $2^7 - 1$ at 170.8 Gbit/s. An encoded 170.8 GHz pulse source and 170.8 Gbit/s OTDM signal were compared by analyzing the bit error rate.

The BER versus receiver input power is plotted in Fig. 7 for both cases. In the case of the 170.8 GHz generated clock, we don't observe error floor, which confirms the stability of active mode locking of QD-MLLD. Indeed unexpected events would have generated errors. Finally, we observe that the curves of reference (OTDM signal) and of analyzed signal (generated pulse source) are really close (less than 0.2 dB shift at $\text{BER} = 10^{-9}$). If this experiment is not a full validation of the clock locking on an encoded signal case, this confirms the quality of the optical clock in terms of amplitude noise and timing jitter for telecommunication applications.

III. ALL OPTICAL CLOCK FREQUENCY DOWN-CONVERSION

In this part, we show the ability of the Quantum Dash Fabry-Perot mode locked laser diode to generate a 42.7 GHz clock from a $N \times 42.7$ GHz incident pulse stream [30], [31]. To

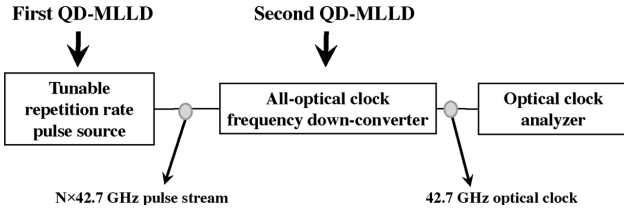


Fig. 8. Block setup for all optical clock frequency down conversion analysis.

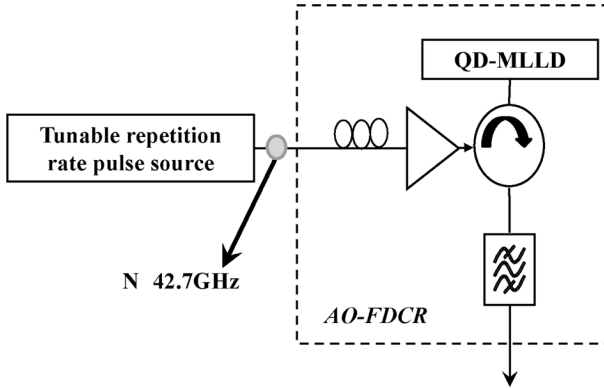


Fig. 9. Experimental setup of the all optical clock frequency down-conversion.

reach this goal, a second QD-MLLD will be used for all optical clock frequency down-conversion.

A. Experimental Setup

The experimental setup, as shown in Fig. 8 is divided into three blocks. The first one consists of the tunable repetition rate pulse source already described in the first part. We will now describe the two other blocks.

1) *All Optical Clock Frequency Down-Conversion*: The second block, depicted in Fig. 9, is the all optical clock frequency down-converter. It consists of a second QD-MLLD. The optical signal injected in the laser will lock the laser at a subharmonic frequency.; it is investigated here for very high clock rates. The residual incident pulse stream at 1555 nm is eliminated by optically filtering the peak emission wavelength around 1560 nm. Mode-locking of the laser is ensured by adjusting the polarization state, the temperature and the current of the laser. The average input power in the QD-MLLD is constant and is around 5 dBm, thanks to the polarization-maintaining optical amplifier placed before the QD-MLLD. Finally, when the $N \times 42.7$ GHz pulse stream is injected into the laser cavity, we obtain a 42.7 GHz synchronized down-converted clock at 1560 nm. The clock frequency down-converter robustness to optical input power was not evaluated in this experiment.

Fig. 10 shows the optical spectrum (a) and the pulse shape (b) for the QD-MLLD used as a clock down-converter. The optical spectrum is clearly centred at 1560 nm and is quite flat, with about 13 nm width at 10 dB loss. The pulse exhibits a large FWHM of about 17 ps. Let us notice that at this wavelength range, the OSO specifications are not guaranteed.

In order to assess the all optical frequency down-conversion scheme, the down converted signal is encoded and analyzed.

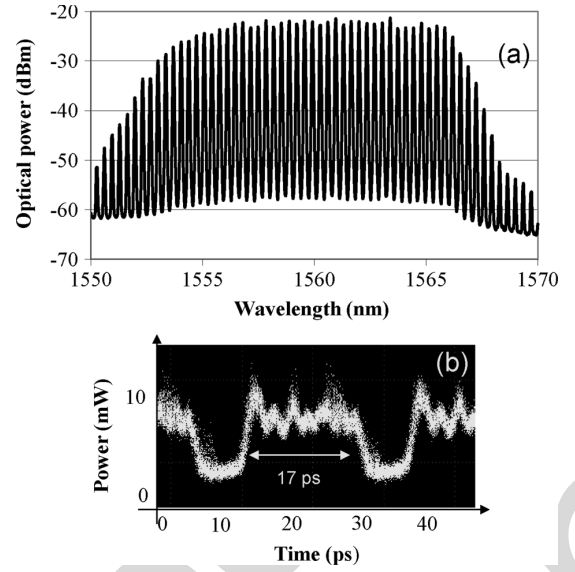


Fig. 10. Optical spectrum and corresponding eye diagram for QD-MLLD used in all optical clock frequency down-converter.

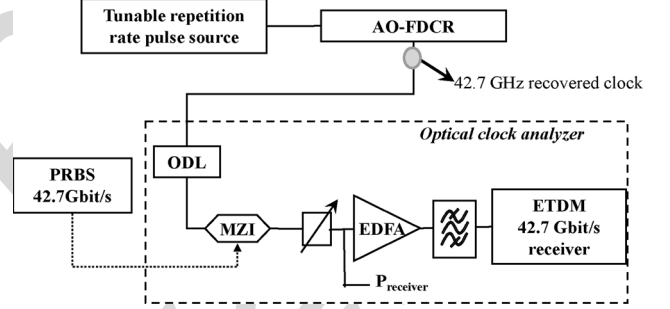


Fig. 11. Experimental setup for the analysis of the converted clock.

2) *Analysis of Recovered Clock*: The final step consists in analyzing the optical clock quality with a bit error rate measurement. The experimental setup of this step is shown in Fig. 11. The down-converted signal is modulated at 42.7 Gbit/s by a $2^{15} - 1$ PRBS using a MZI modulator. An optical delay line (ODL), placed before the modulator, ensures that clock and data are in phase. The modulator output signal is sent to an optical receiver for BER measurements, which allows to check whether the down-converted recovery clock is correctly locked. As a matter of fact, if it were not the case, we would have measured an error floor.

B. Results

Fig. 12 shows the RF spectrum of the beating of the QD-MLLD in the free running regime and in a mode-locked regime (when injected by a signal at 427 GHz). This signal is measured by a high-speed photodiode followed by an electrical spectrum analyzer (ESA), with a resolution bandwidth of 1 kHz. The free running regime spectrum linewidth is about 20 kHz showing good accordance with previous measurements performed at Alcatel-Thales III-V Laboratory with such a structure [29]. When QD-MLLD is actively locked, we obtained a -3 dB linewidth of 8 kHz in comparison to 20 kHz in

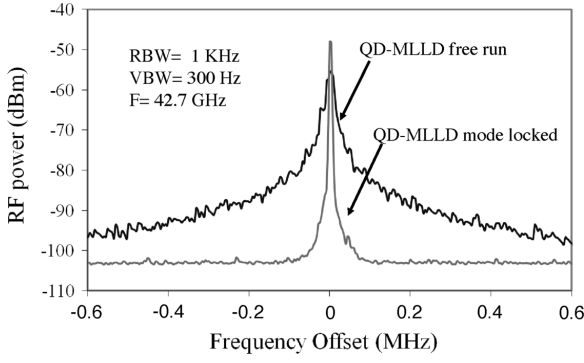


Fig. 12. RF spectrum of the all optical clock frequency down-converter with and without optical mode locking when a signal at 427 GHz is injected.

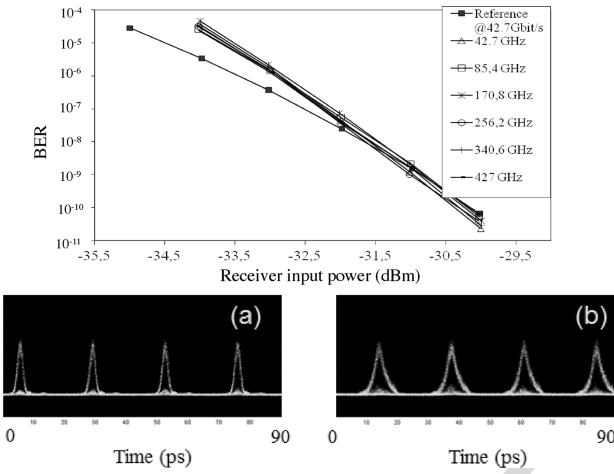


Fig. 13. BER versus the receiver input power for different frequencies of the transmission optical signal. Eye diagram for (a) 42.7 Gbit/s reference and (b) 42.7 Gbit/s clock recovered.

free running regime. This first measurement confirms that the QD-MLLD locks on injected signal.

BER measurements versus the receiver input power are then given in Fig. 13 for 6 different frequencies of the transmitted pulse stream. The reference BER curve is obtained by directly connecting the pulse stream generator output to the optical clock analyzer block.

Fig. 13 shows the eye diagrams of the 42.7 Gbit/s reference signal (a) and of the encoded down-converted clock (b). Note that the pulsewidth of both signals are slightly different (5 ps for the recovered clock and 2 ps for the 42.7 Gbit/s reference). The BER curves in Fig. 13 show that there is no error floor. This confirms that the down-converter is able to lock in the same condition for $N \times 42.7$ GHz incident frequency with a value of N as large as 10. Moreover, we obtain no penalty for BER less than 10^{-8} . For BER higher than 10^{-8} , penalty appears, this is probably due to slight differences in the temporal shape of both signals.

We note that, as shown previously in the paper, spurious lines of the incident signal are suppressed by more than 40 dB, ensuring that there is no sub-harmonic synchronization of the down-converter at the original clock frequency.

This sub-synchronization at high frequency can be explained by the strong correlation between the phases of the laser modes.

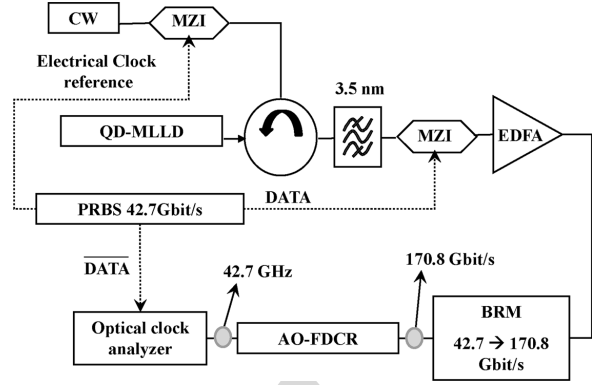


Fig. 14. Experimental setup of the AO-FDCR used as a clock recovery of an OTDM 170.8 Gbit/s.

The strong phase correlation is due to the enhanced four-wave-mixing (FWM) in this QD structure [29]. This non-linear effect appears to be the major phenomenon leading to the mode-locking of the QD laser [32]. Consequently the $N \times 42.7$ GHz signal modulates the gain section of the QD-MLLD. We assume that this modulation locks in phase the spectrum lines spaced by $N \times 42.7$ GHz. Thanks to FWM, all spectrum lines of the laser are afterward locked in phase. Our experimental results demonstrate the possibility to lock the QD-MLLD with an injected signal modulated at 10 times its own frequency.

IV. ALL OPTICAL FREQUENCY DOWN-CONVERSION CLOCK RECOVERY

The principle of clock recovery using a long cavity Fabry Perot Mode Locked multimode laser was studied in [33] and at a subharmonic frequency in [34], [35]. In this section, we characterize the quality of the down-converter when a data stream is injected into the device instead of a clock signal as studied in the previous section. We thus now call the device an All Optical Frequency Down-conversion Clock Recovery (AO-FDCR). This experiment was performed with the two bit rates available in this work: 42.7 and 170.8 Gbit/s.

A. Experimental Setup

Fig. 14 shows the experimental setup. An electrical clock at 42.7 GHz drives all the system and visualization equipment. The first QD-MLLD generates a 1.5 ps pulse stream at 42.7 GHz modulated through a MZI modulator at 42.7 Gbit/s with a PRBS sequence. For the case of 170.8 Gbit/s, a BRM is inserted for the OTDM stage. A $2^7 - 1$ sequence was used at 170.8 Gbit/s (due to the BRM limitation as explained earlier in the paper). The generated data stream is then inserted into the AO-FDCR block and the recovered clock is analyzed in the optical clock analyzer described in the last section.

B. BER Measurements

BER versus receiver input power is plotted in Fig. 15. The two triangle curves correspond to results obtained in the previous experiment when a pulse stream is injected. The two other curves correspond to BER results when a data stream is injected. A penalty of only 0.3 dB for a BER of 10^{-9} is observed in the case of data stream injection in comparison to pulse stream injection.

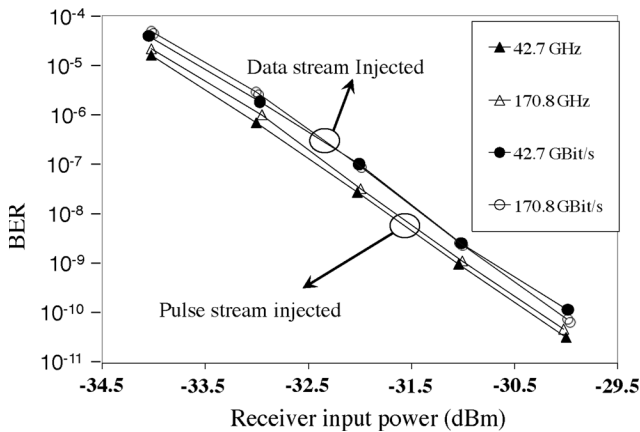


Fig. 15. BER versus receiver input power of encoded optical clock recovery with different input signals: the pulse stream (triangles) or the data stream (circles).

Moreover, 42.7 and 170.8 Gbit/s curves are superposed showing that the clock recovery quality does not depend on the bit rate. We want to notice here that no phase jump is observed on the recovered clock when it is properly locked. A possible explanation is the really narrow linewidth of some kHz of this laser [29], [9], thus indicating a strong correlation between modes. It is believed that this strong phase correlation is due to the enhanced four wave-mixing in this QD structure, due to the short lifetime of the electrons at the excited state in the conduction band. However it is not possible to know upon which 42.7 Gbit/s tributary of the 170.8 Gbit/s signal, the AO-FDCR locks. In an optical demultiplexing application case, this would imply the use of a Multiple-Input Multiple-Output (MIMO) technique to properly address each OTDM channel at the output receiver.

This experiment thus validates the use of this kind of laser as a clock recovery with data stream up to 170.8 Gbit/s.

V. CONCLUSION

In the first section of this paper, we have shown experimentally the potential of QD-MLLD for the realization of a high repetition rate source. Thanks to a spectrum filtering technique, we generated a tunable repetition rate pulse source up to 427 GHz. We have investigated the quality of 170.8 GHz pulsed source through BER measurement showing no penalty in comparison to a 170.8 Gbit/s OTDM signal. These results confirm the ability of the QD-MLLD to be used as a high repetition rate source for telecommunication applications. The repetition rate of this source is only limited by its spectrum bandwidth; 1.2 THz optical source was shown in our previous work [26].

In the second section we performed all optical clock down-conversion using QD-MLLD showing the possibility to lock the QD-MLLD with an injected signal modulated at 10 times its own frequency. The quality of the down-converted clock is analyzed through BER measurements: no penalty is observed for BER less than 10^{-8} . Finally, in all optical down-conversion clock recovery section, we have measured a slight penalty of 0.3 dB when a data stream is injected. These results show the potential of QD-MLLDs to perform both clock recovery and frequency down-conversion functions. QD-MLLDs could be key components for future 400 Gigabit Ethernet networks.

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