Optical Clock Synchronization for O-band Directly Modulated Laser Based Data Center Interconnection

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Abstract: We show that clock synchronized transmission has reduced receiver-side jitter that limits DMLs' performance compared to conventional clock and data recovery. We access transmission quality using 35-GHz-bandwidth DMLs at 1271 and 1373 nm.

1. Introduction

The drastic increase of intra and inter-data center (DC) traffic demands transceiver hardware that can scale both data rate and transmission distance efficiently [1]. Direct modulation direct detection (DM-DD) represents the simplest transceiver hardware, with ultra-low power consumption and small size. Recent research has demonstrated >100-GHz-bandwidth directly modulated lasers (DML) for up to 250 Gb/s per wavelength data rate for short (2 km) reach intra-DC interconnection [2,3]. Besides scaling up baud rate, coarse wavelength division multiplexed (CWDM) DML arrays have also drawn strong interest due to the potential cost and power consumption advantages of using low-speed electronics [4,5]. Coarse WDM of 4 DMLs operating at the telecom O band (1270-1330 nm) has been demonstrated for up to 10 km transmission distance, which could expand be to 1350-1370 nm region, enabling 8 or even 10 CWDM channels for >800 Gb/s.

Whilst most DML-based system demonstrations have focused on increasing data rate and distance, one lesser studied aspect is the impact of clock recovery quality, which is important for several reasons. Firstly, high data rate signals using either high baud rate or high order modulation formats (e.g. PAM4 and PAM8) are more susceptible to clock jitter. Secondly, it is well known that the pattern dependent effect in DML degrades signal jitter with the increased pattern length [6]. For standard transceivers that recover clock from the received waveforms, this leads to a degradation of the clock quality that increases bit error ratio (BER). Thirdly, as the operating wavelength moves to the edge of the O band (e.g. 1270 nm and 1370 nm), the fiber dispersion is no longer negligible for >10km transmission, which distorts the waveform and consequently degrades quality of the recovered clock. While digital signal processing (DSP) has been investigated to improve clock and data recovery (CDR) quality [7], this comes at the cost of increased system complexity and power consumption. To minimize added system complexity, an alternative approach can be to distribute clock signals for phase and frequency synchronization, for example through control plane fibers [8], different cores in a multi-core fiber [9], or different wavelengths [10].

In this paper, we use the low-loss C-band to transmit clock synchronization signals and the low-dispersion O-band for DML-based data transmission, showing that the optical clock synchronization approach can significantly outperform the conventional clock recovered approach in DML-based transmission systems. We test the system performance at the 'extreme' wavelengths of 1270 nm and 1370 nm and report for the first time the joint impact of dispersion, modulation chirp and pattern length on clock and data transmission.

2. Experimental setup

Fig. 1 shows the experimental setup that consists of an optical clock generation node, CWDM transmitter and receiver node. Similar to [8], an optical clock is generated by modulating a continuous wave (CW) laser with a Mach-Zehnder modulator (MZM) biased at quadrature. The MZM was driven by an 800 MHz square wave clock and was amplified to 15 dBm before splitting into two branches using a 10:90 coupler. 10% of the optical clock was detected by a slow photodetector (PD) as the reference clock for the transmitter FPGA (Xilinx VCU108). The GTY digital transmitters output two independent 25.6 Gbps non-return-to-zero (NRZ) signals, which were amplified to 14 dBm to drive two DMLs centered at 1271 nm and 1373 nm. Both $PRBS2^7$-1 and $PRBS2^{15}$-1 were used to test the impact of pattern dependent effect. Both DMLs were biased at around 55 mA and exhibit about 30 GHz small-signal bandwidth (spectra shown in Fig.1a and Fig.1b). The DMLs' outputs are combined by a 6-channel coarse wavelength multiplexer (CMUX) with 20 nm channel spacing for each channel. The output of the CMUX was combined with 90% of optical clock and launched into a 10 km SSMF. At the receiver side, the clock signal was recovered using a C-band 0.8-nm-bandwidth optical bandpass filter (OBPF) followed by a photodiode before feeding the 800 MHz reference clock to the receiver-side FPGA. The modulated signal at 1271/1373 nm was

extracted using coarse wavelength demultiplexer (CDMX) and fed into PD followed by transimpedance amplifier and sent to GTY receiver.

The on-board clock and data recovery modulate upconverts the 800 MHz reference clock to 25.6 GHz and keeps optimize sampling clock phase over time ($\Phi_{\lambda 1}(t)$) by comparing data transition, as shown by the orange and blue curves in Fig. 1c. Due to the low dispersion of SSMF at the O-band, the laser wavelength variation imposes only a small change of group velocity delay. Further, as clock and data are transmitted through same fiber, the temperature dependent propagation delay variation does not shift the relative time delay between data and the clock, and therefore does not affect the sampling phase. Therefore, it is possible to estimate the optimum sampling phase at the beginning of the measurement, lock the phase and re-use it for later measurement, as shown by the black curve in Fig. 1c. In this proof-of-concept experiment, we only test different wavelength channels individually, however, this concept can also be applied when simultaneously detecting multiple wavelengths.

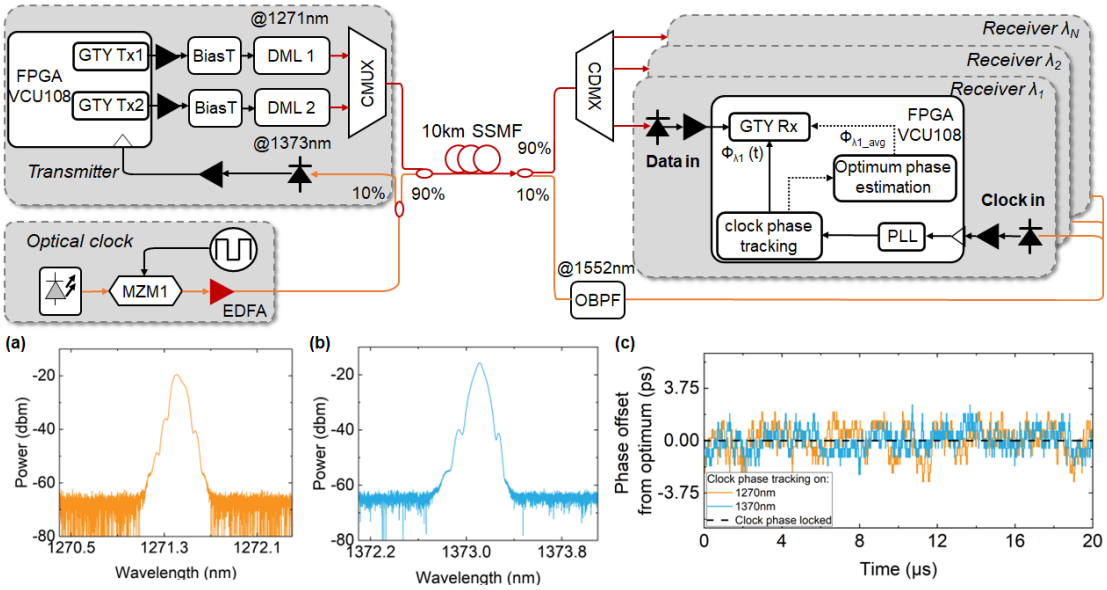

Fig. 1. Conceptual diagram. Optical spectrum after 10 km SSMF transmission (a): 1270 nm; (b): 1370 nm; (c): Sampling clock phase variation over time.

3. Results and Discussion

Fig.2a and Fig.2b show the eye diagrams of the 1271 nm and 1373 nm DML channels before and after SSMF transmission. Both DMLs exhibited similar performance at the back-to-back (BtB), with a root-mean-squared (rms) jitter of 3.3 ps and a peak-to-peak jitter of 17 ps, measured by a sampling oscilloscope. The small normal dispersion at 1271 nm in conjunction with positive chirp resulted in compressed pulses after 10km SSMF transmission, leading to maintained jitter and an improved eye opening. The 1373 nm signal, however, had a reduced eye opening and higher rms and higher peak-to-peak jitter due to the anomalous dispersion induced broadening. These results indicate that the impact of dispersion is non-negligible at the edge of the O-band and clock signals recovered from dispersion impaired DML waveforms may lead to degraded clock jitter and system performance. As this effect is already obvious in our proof-of-concept study using 25.6 Gb/s OOK, it can be expected that the clock degradation will be worse in high baud rate systems.

To compare the clock quality of the conventional data recovered clock and our proposed distributed clock approach, we measure the phase noise of the clock component of the modulated signals and the distributed clock. Due to the availability of a 25GHz CDR, we estimate the recovered clock phase noise by extracting clock component from the data using a 50-MHz-bandwidth narrowband cavity filter [11] and PRBS2^7-1. This ensures only one clock tone falls into the filter bandwidth and provides a good approximation of a CDR. In fact, this eliminates any pattern induced jitter (e.g. the large peak-to-peak jitter), which might be present in comparator based CDR. The phase noise was scaled down to 800 MHz to directly compare with the optical distributed clock in Fig.2c. The optically distributed clock exhibited 15 dB lower phase noise compared to the recovered clock (at -10 dBm received optical power) and the integrated rms jitter (100 Hz to 30 MHz) was only 0.16 ps, as opposed to 0.8 ps (1271 nm) and 1.9 ps (1373 nm) for the recovered clock. The high frequency (>100 kHz) phase noise of the recovered clock also depends on received power due to the receiver thermal noise. Using 1271 nm signal as example, the integrated

jitter increased from 0.8 ps to 2.3 ps with the power reduced from -10 dBm to -18 dBm. The phase noise of distributed clock, however, is independent of signal power, ensuring stable and high-quality clock.

Fig. 2d measures tolerance to clock phase offset using bit error rate (BER) at different sampling phase for both channels when transmitting PRBS2^7-1 and PRBS2^{15}-1. The received power of 1271 nm and 1373 nm are adjusted to -14 dBm and -8 dBm, respectively for fair comparison as 1373 nm channel suffers from pulse broadening. For 1271 nm channel, the BER remains below 10^{-6} when sampling phase offset is within 10 ps for both PRBS2^7-1 and PRBS2^{15}-1. The error floor is slightly higher when transmitting PRBS2^{15}-1 due to pattern dependent effect [6]. For 1373 nm channel, the sampling phase offset tolerance window is only 4 ps and 2 ps for PRBS2^7-1 and PRBS2^{15}-1 due to pulse broadening as shown in Fig. 2b. This offset can be easily corrected using techniques such as clock phase caching [8] to ensure stable operation in temperature varying environment.

Finally, we measured the BER at different optical power under two scenarios: when i) sampling clock phase tracking is enabled and (solid line) ii) sampling clock phase locked (dashed line). Fig.2e and 2f show that when clock phase tracking is enabled, receiver sensitivities for BER=10^{-6} and BER=3.8×10^{-3} are -15.5 dBm and -18.5 dBm for 1271 nm channel and -8.5 dBm and -11.5 dBm for 1373 nm channels, respectively when transmitting PRBS2^7-1 and PRBS2^{15}-1. This indicates that pattern dependent effect is neglectable when optimum sampling phase is found. By comparing the solid and dashed lines, we obtained that the power penalty is less than 0.3 dB for both wavelengths, which indicates that the sampling clock phase tracking can be potentially switched off once optimum phase is determined, therefore, a potential reduced power consumption.

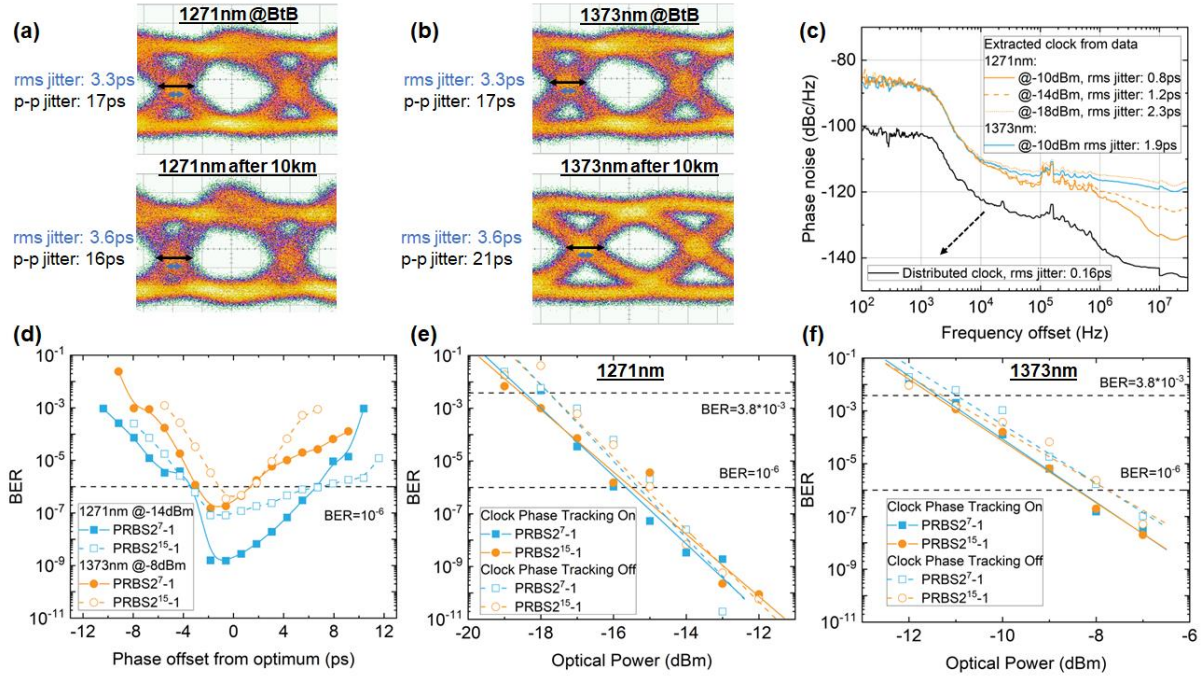

Fig. 2. Optical 25.6Gbps OOK eye diagram (a) 1271 nm; (b): 1373 nm; (c) Phase noise measurement of recovered clock and distributed clock; (d) BER at different sampling clock phase; BER at different received optical power of (e) 1271 nm and (f) 1373 nm.

4. Conclusion

We co-transmit optical clock with DML-based O-band CWDM signals. The separation of clock and data transmission prevents degradation of the clock quality due to the interplay between modulation dynamics and fiber dispersion compared to conventional CDR, enabling high performance for DML-based systems.

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