Generation of Return-to-Zero Optical Pulses Using Directly Modulated Chirp Managed Laser

Wei Jia, *Student Member, IEEE*, and Chun-Kit Chan, *Senior Member, IEEE*

***Abstract*— We propose and experimentally demonstrate the generation of return-to-zero (RZ) optical pulses with duty cycles of 33% and 67% using a directly modulated chirp managed laser (CML) driven by a sinusoidal signal at half pulse rate. No external pulse carver is required. The transmission performance of a 10-Gb/s RZ differential phase-shift keying (RZ-DPSK) signal based on CML pulses is also investigated. It shows comparable fiber chromatic dispersion tolerance and fiber nonlinearity robustness in single-channel test, compared with the conventional RZ-DPSK signal generated, via an external pulse carver.**

***Index Terms*— Chirp managed laser (CML), direct modulation, return-to-zero (RZ) pulse.**

I. Introduction

RETURN-TO-ZERO (RZ) optical pulses have been widely used in high-speed optical fiber transmission systems with on-off keying (OOK) and differential phase-shift keying (DPSK) modulation formats, with the advantages of high robustness to inter symbol interference (ISI) and nonlinear distortions [1]. Conventionally, a sinusoidally-driven Mach–Zehnder modulator (MZM) was used as an external pulse carver to generate the RZ optical pulses. An alternative method was based on an optical phase modulator (PM) followed by an optical delay interferometer (DI) [2]. Mode-locked laser using electro-absorption modulator (EAM) as a mode locker was another candidate [3]. However, external modulators suffered from the drawbacks of high cost, high insertion loss and large driving voltage.

In this letter, we demonstrate a cost-effective approach to generate high-speed RZ optical pulses using a single chirp managed laser (CML), which integrates a directly modulated distributed feedback (DFB) laser (DML) and a DI periodic filter in a single laser package [4], without any external modulator for pulse carving, for metro or access network. Both 33%-duty-cycle and 67%-duty-cycle RZ optical pulses have been generated simultaneously at the two output ports of the DI in the CML. The frequency of the sinusoidal driving signal is half of the repetition rate of the output RZ optical pulses. The transmission performances of 10-Gb/s CML-based RZ-DPSK signals with duty cycles of 33% and 67% have also been investigated. 70-km and 50-km error-free SSMF transmissions have been achieved for the 10-Gb/s 33%-duty-cycle and 67%-duty-cycle CML-based RZ-DPSK signals, respectively, while those based on MZM pulse generation could be transmitted up to 60 km. The former case also showed comparable fiber nonlinearity robustness in single-channel test, compared with the latter approach. With the recent development of 40-GHz DML technology [5], the proposed technique could generate ultra high-speed RZ pulses.

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The authors are with the Department of Information Engineering, Chinese University of Hong Kong, Shatin, N.T., Hong Kong (e-mail: jw009@ie.cuhk.edu.hk; ckchan@ie.cuhk.edu.hk).

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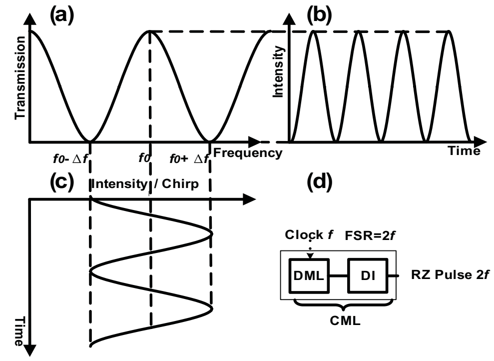


Fig. 1. Proposed scheme and operation principle of RZ pulse generation based on CML. (a) Transmission function of DI. (b) CML output. (c) DML output. (d) Structure of CML.

II. Operation Principle

Fig. 1 depicts the proposed scheme and the operation principle of RZ pulse generation based on a CML. Fig. 1 (d) illustrates the structure of CML consisting of a DML and a DI. A RZ pulse at a pulse rate of $2f$ Hz can be generated by directly modulate the built-in DML with a sinusoidal clock at a frequency of f Hz, and carefully set the frequency offset position of the built-in DI, which has a free spectral range (FSR) value of $2f$ Hz, as shown in Fig. 1(a). The built-in DML is biased high above the threshold with the benefits of high output power, wide modulation bandwidth and suppression of transient chirp [6]. Fig. 1(c) shows the intensity and chirp characteristics of the built-in DML output signal. The laser generates an accompanying adiabatic chirp which follows the changes in the intensity waveform. The peak level is blue shifted relative to the bottom level [6]. The frequency deviation of $2\Delta f$ (in Hz) between the peak level and the bottom level of the DML output signal equals the FSR of the built-in DI. If the DI is biased at the peak of its transmission function, the 33%-duty-cycle RZ pulse at the pulse rate of $2f$ Hz is produced, as depicted in Fig. 1(b). If the DML output signal is biased at the DI's transmission minimum, it generates the 67%-duty-cycle RZ pulse at the pulse rate of $2f$ Hz.

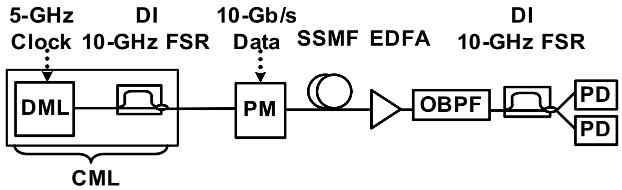
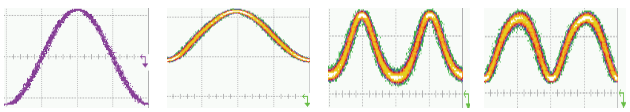


Fig. 2. Experimental setup of the 10-Gb/s CML-based RZ-DPSK transmission system.



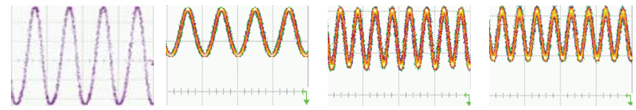
(a) (b) (c) (d)

Fig. 3. Eye diagrams of (a) 5-GHz sinusoidal driving signal, (b) 5-GHz DML output signal, (c) 10-GHz 33%-duty-cycle RZ pulse, and (d) 10-GHz 67%-duty-cycle RZ pulse. Time scale: 50 ps/div.

III. Experiment and Results

We have experimentally demonstrated the generation and transmission of the 10-Gb/s RZ-DPSK signal using a CML, as shown in Fig. 2. We employed a commercially available DML module (NEL: NLK5C5EBKA) and a commercially available DI to simulate the CML in the experiment. The input impedance, threshold current and cut-off frequency of the DML were 50 ohms, 15 mA and 18 GHz, respectively. The DI had a FSR of 10 GHz. The DML was directly modulated with a 5-GHz sinusoidal signal. The driving voltage V_{pp} was 2.3 volts, and the laser was biased at 80 mA. A $LiNbO_3$ single-waveguide PM was then employed so as to modulate the generated RZ pulses with a 10-Gb/s $2^{31}-1$ pseudo-random bit sequence (PRBS) data. The central wavelength of the generated RZ-DPSK signal was around 1551.3 nm. The measured powers of the DML output signal, the 33%-duty-cycle RZ pulse and the 67%-duty-cycle RZ pulse were 6.7 dBm, 3.0 dBm and 3.2 dBm, respectively. The linear transmission system was composed of a piece of standard single-mode fiber (SSMF) and an erbium-doped fiber amplifier (EDFA) was inserted after fiber to boost up the optical power. A tunable optical band pass filter (OBPF) with ~1.0-nm bandwidth was placed after the EDFA to eliminate the excessive amplified spontaneous emission (ASE) noise. At the receiver, the transmitted RZ-DPSK signal was demodulated by another DI with a FSR of 10 GHz.We used a 12.5-GHz photo-detector (PD) for bit-error-rate (BER) measuring and a 40-GHz PD for eye diagrams recording at the same time for convenience. Fig. 3 shows the back-to-back (BtB) eye diagrams of the 5-GHz sinusoidal driving signal, the 5-GHz DML output signal, the 10-GHz 33%-duty-cycle RZ pulse and the 10-GHz 67%-duty-cycle RZ pulse. The extinction ratios (ERs) of the 33%- and the 67%-duty-cycle RZ pulses were 10.8 dB and 9.8 dB, respectively. Under a higher driving voltage of 2.7 volts, the respective ERs were 12.7 dB and 8.3 dB, while under a lower driving voltage of 1.7 volts, the respective ERs were 4.6 dB and 11.3 dB.

Fig. 4 shows the BtB eye diagrams of the 20-GHz sinusoidal driving signal, the 20-GHz DML output signal, the 40-GHz 33%-duty-cycle RZ pulse and the 40-GHz 67%-duty-cycle RZ pulse. The laser was biased at 120 mA and the driving voltage was 5.1 volts. The DI here had a FSR of 40-GHz. The ERs of the 33%- and the 67%-duty-cycle RZ pulses were 5.6 dB and 4.1 dB, respectively. The ER of the CML-based RZ pulses could be further enhanced by using DML with higher frequency modulation (FM) efficiency and DI with higher ER. Though the work in [7] realized 80-km SSMF transmission, it could only generate 10-Gb/s RZ-DPSK or 10-Gbaud RZ-DQPSK signal, based on the CML with 10-GHz modulation bandwidth. However, the proposed scheme could generate 20-Gb/s RZ-DPSK signal or 20-Gbaud RZ-DQPSK signal using the same module.



(a) (b) (c) (d)

Fig. 4. Eye diagrams of (a) 20-GHz sinusoidal driving signal, (b) 20-GHz DML output signal, (c) 40-GHz 33%-duty-cycle RZ pulse, and (d) 40-GHz 67%-duty-cycle RZ pulse. Time scale: 50 ps/div.

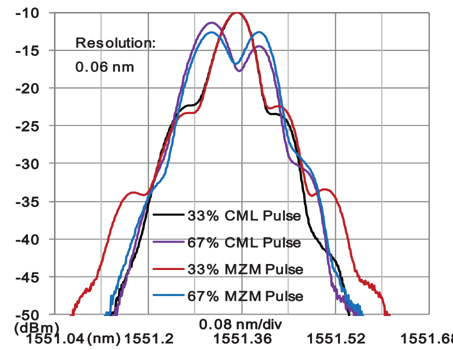


Fig. 5. Optical spectra of 10-GHz CML- and MZM-based RZ pulses.

In the control experiment, we employed a DFB laser for continuous wave (CW) light and a MZM as the pulse carver to generate the 10-GHz 33%-duty-cycle RZ pulse or 67%-duty-cycle RZ pulse. The insertion loss of the MZM was around 7 dB. Their respective driving voltages were 7.6 volts and 6.2 volts, while their respective ERs were 6.9 dB and 12.0 dB. The low ER of 33%-duty-cycle RZ pulse was due to the limited dynamic range of the modulator driver amplifier. Fig. 5 shows the respective optical spectra of the 10-GHz RZ pulses based on CML and MZM. The 10-GHz 33%-duty-cycle CML-based pulse exhibited slightly more compact spectrum, as compared to that based on MZM. The 10-GHz 67%-duty-cycle CML-based pulse exhibited the carrier-suppressed property with two 10-GHz-separated peaks, similar to that based on MZM, except that the two peaks were unequal in power, due to the residual intensity modulation of DML output signal.

We have compared the transmission performances of fiber chromatic dispersion and nonlinearity tolerances between the 10-Gb/s CML-based RZ-DPSK signal and the MZM-based RZ-DPSK signal using single detection. The driving voltage of the DML was tuned to generate the 33%-duty-cycle CML pulse with ER of 6.8 dB and the 67%-duty-cycle CML pulse with ER of 11.3 dB, separately, for fair comparison with the MZM cases. The DML bias was set to be 120 mA when

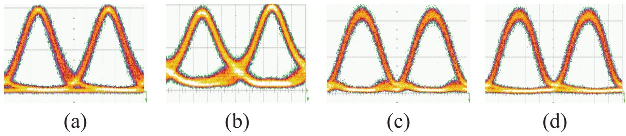


Fig. 6. Eye diagrams of demodulated 10-Gb/s RZ-DPSK signals based on CML. (a) 33% at one port of DI. (b) 33% at the other port of DI. (c) 67% at one port of DI. (d) 67% at the other port of DI. Time scale: 20 ps/div.

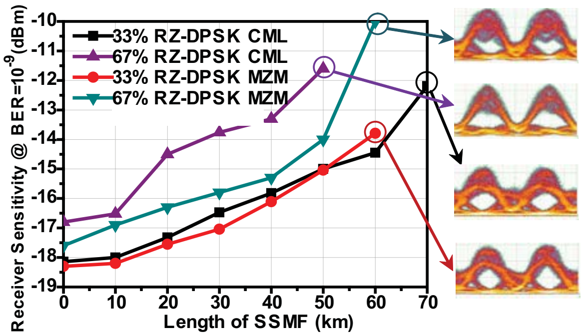


Fig. 7. Measured chromatic dispersion tolerance for 10-Gb/s RZ-DPSK signals based on CML and MZM. Insets show the respective eye diagrams after SSMF transmission using 40-GHz PD. Time scale: 20 ps/div.

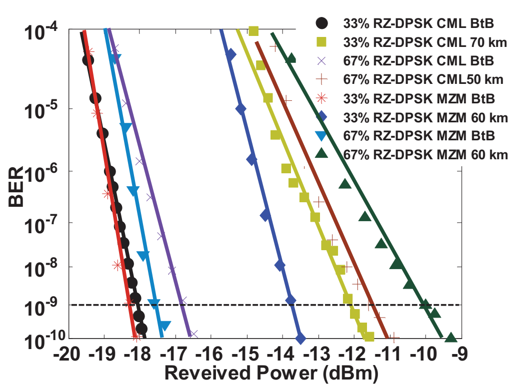


Fig. 8. BER measurements for 10-Gb/s RZ-DPSK signals based on CML and MZM. Time scale: 20 ps/div.

generating the 67%-duty-cycle CML pulse so as to suppress the inequality of the two spectral peaks shown in Fig. 5, and Fig. 6 shows the BtB eye diagrams of demodulated 10-Gb/s CML-based RZ-DPSK signals with duty cycles of 33% and 67% at the two output ports of the DI at the receiver. The uneven bottom line in Fig. 6(b) was attributed to the low ER of 33%-duty-cycle RZ pulse.

Fig. 7 depicts the receiver sensitivities at BER $= 10^{-9}$, measured after various lengths of SSMF transmission. The insets show the respective eye diagrams of the RZ-DPSK signals after SSMF transmission using the 40-GHz PD. The intensity noise shown in the eye diagrams would be alleviated by using a 12.5-GHz PD. Fig. 8 shows the measured BER performances. 70-km and 50-km error-free SSMF transmission with respetctive power penalties of 6.0 dB and 5.2 dB were achieved for the 10-Gb/s CML-based RZ-DPSK signals with duty cycles of 33% and 67%, while the MZM based ones could be transmitted up to 60 km with respective power penalties of 4.5 dB and 7.6 dB, with reference to their BtB receiver sensitivities.

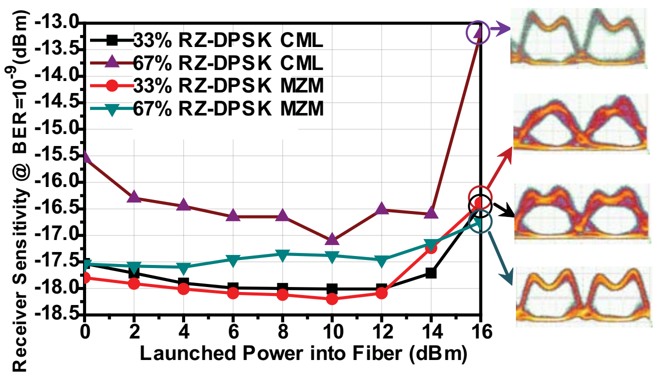


Fig. 9. Measured nonlinearity tolerance for 10-Gb/s RZ-DPSK signals based on CML and MZM. Insets show the respective eye diagrams at launch power of 16-dBm using 40-GHz PD. Time scale: 20 ps/div.

We have further measured and compared the nonlinearity tolerances of the 10-Gb/s RZ-DPSK signals based on CML and MZM in single-channel test. One span of 80-km SSMF was used. The chromatic dispersion of the SSMF was compensated with a dispersion compensation module. The power launched into the SSMF was varied from 0 dBm to 16 dBm and the results were shown in Fig. 9. The CML-based RZ-DPSK signals demonstrated comparable tolerance to high launch power, compared with the MZM-based ones. With reference to their receiver sensitivities at 0-dBm launch power, the 33%-duty-cycle and 67%-duty-cycle CML-based RZ-DPSK signals, as well as the 33%-duty-cycle and 67%-duty-cycle MZM-based RZ-DPSK signals, suffered from power penalties of 1.1 dB, 2.4 dB, 1.4 dB and 0.8 dB, respectively, at launch power of 16 dBm. Their respective eye diagrams were shown in the insets of Fig. 9, using the 40-GHz PD.

IV. Conclusion

We have proposed and experimentally demonstrated the generation of 33%-duty-cycle and 67%-duty-cycle RZ optical pulses based on a CML, driven by a sinusoidal signal at half pulse rate, without any external pulse carver. Their single channel 10-Gb/s RZ-DPSK transmission performances have been experimentally characterized.

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