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Simultaneous prescaled and frequency-doubled clock recovery using an injection-locked optoelectronic oscillator

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ABSTRACT

A frequency-doubling optoelectronic oscillator (FD-OEO) using tandem Mach–Zehnder modulators (MZMs) biased at the peak transmission point is proposed and experimentally demonstrated. Multi-functional operations of nearly chirp-free frequency-doubled optical clock (FD-OC) recovery, low-duty-cycle prescaled OC recovery and error-free fourfold demultiplexing of a 100-Gb/s optical time division multiplexing (OTDM) signal are achieved simultaneously with the proposed FD-OEO composed of low-frequency devices. As an intrinsic property, prescaled electrical clock (EC) with 167.15-fs root-mean-square (RMS) timing jitter is extracted.

1. Introduction

Clock recovery (CR) is essential to perform operations such as modulation format conversion, optical logic gate, optical sampling, synchronous modulation, 3R regeneration (reamplifying, reshaping and retiming), signal detection, add-drop multiplexing and demultiplexing of an OTDM signal with a high aggregated rate at the nodes or terminals in optical networks. Among the various schemes, optoelectronic oscillators (OEOs) are reported as the promising candidates for the remarkable ability of cost-effective and low-phase-noise CR with simultaneous modulation format conversion or twofold demultiplexing of an OTDM signal, which extremely facilitates the signal processing in the networks [1–4].

A conventional OEO has a single-loop feedback structure mainly composed of an electrooptic modulator, a photodetector (PD), a high-Q electrical bandpass filter (EBPF) and an electrical amplifier (EA). The OEO will be a self-starting oscillator with a free oscillation frequency determined by the center frequency of the EBPF and the equivalent electrical path length of the loop when injected with a continuous wave (CW) laser, and can be injection locked when injected with a data signal with frequency around the free oscillation frequency [5]. Once the OEO is injection locked, a resultant clock can be extracted. Recently, FD-OEOs have been proposed to enable FD CR with low-frequency devices, effectively enlarging the maximum operational frequency of the conventional OEOs used for only prescaled CR. The reported high-quality FD-OEOs are mainly based on polarization modulators (PolMs) or dual-parallel Mach–Zehnder modulators (DPMZMs) [5–9]. However, the PolM based FD-OEOs are sensitive to environmental disturbance due to the polarization control based working principle, while the DPMZM based FD-OEOs usually operate with the help of a segment of high nonlinear dispersion-shifted fiber (HNL-DSF) and an additional high-power erbium-doped fiber amplifier (EDFA), or a chirped fiber Bragg grating (CFBG) requiring some accurate dispersion, which extremely increase the system complexity and power consumption, and decrease the system reliability and flexibility. Besides, these previously reported schemes are not demonstrated to be capable of providing low-duty-cycle and high-extinction-ratio (ER) OC with simultaneous multi-fold demultiplexing of a high-speed OTDM signal.

In this study, we propose and experimentally demonstrated a tandem-MZM based FD-OEO. Both of the employed MZMs are biased at the peak transmission point. With low-frequency electrical devices, the proposed FD-OEO can simultaneously perform multifunctional operations involving high ER FD-OC recovery, low-duty-cycle prescaled OC recovery and error-free fourfold demultiplexing of an injected 100-Gb/s OTDM signal. The duty cycles and ERs are measured to be 33% and 27.5 dB for the FD-OC, and to be 16.5% and 26.8 dB for the prescaled OC, respectively. Moreover, both the extracted FD-OC and prescaled OC are nearly chirp free. The power penalty at a bit error rate (BER) of 10^{-9} is 0.8 dB for the best demultiplexed tributary and 1.1 dB for the worst one. Integrating from 100 Hz to 10 MHz, the RMS timing jitter of the extracted EC is measured to be 167.15 fs.

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2. Working principle

The schematic diagram of the proposed multifunctional FD-OEO is shown in Fig. 1. It is a dual-loop feedback structure mainly composed of two MZMs (MZM1 and 2), a PD, a high-Q electrical EBPF, a frequency divider, two phase shifters (PSs) and two EAs. The complex amplitude at the output of the MZM1 can be expressed as

$$\begin{aligned} E_{out1} &= \frac{E_{in}}{2}\{\exp(j(\pi/V_\pi)V_{bias})\exp[j(\pi/2V_\pi)V\ \sin(2\pi f t)] \\ &\quad + \exp[-j(\pi/2V_\pi)V\ \sin(2\pi f t)]\} \\ &= E_{in}\ \cos[(\pi/2V_\pi)V\ \sin(2\pi f t) + (\pi/2V_\pi)V_{bias}]\exp(j(\pi/2V_\pi)V_{bias}) \end{aligned} \tag{1}$$

where E_{in} represents complex amplitude of the injected CW laser; V, f and V_{bias} represent the amplitude, frequency of the radio frequency (RF) driving signal and the direct current bias voltage applied to the MZM1, respectively; and V_π represents the half-wave voltage of the MZM1.

As can be seen from Eq. (1), when MZM1 is biased at the peak transmission point and is driven by RF with a peak-to-peak voltage of twice of the half-wave voltage and a frequency of f, the injected CW laser will be carved into a chirp-free frequency-doubled pulse train (FD pulse) with a repetition rate of $2f$ and a duty cycle of 33% by MZM1. The simulated waveform of the generated FD pulse, essentially an on-off window, together with its chirp is shown in Fig. 2(a). The FD pulse is further amplitude modulated by the subsequent MZM2. The same to MZM1, when MZM2 is biased at the peak transmission point and is driven by RF with a peak-to-peak voltage of twice of the half-wave voltage but with a frequency of $0.5f$, the MZM2 can also provide a chirp-free 33% switching window but with a repetition rate of f. Then, by adjusting the phase shifters between RF applied to MZM1 and 2, chirp-free pulse with a repetition rate of f can be selected out. Fig. 2(b) presents the simulated waveform and chirp of the selected pulse at the output of the MZM2. The duty cycle is calculated to be 15%, which is low enough for fourfold demultiplexing of an OTDM signal.

As an oscillator, it has been demonstrated that the OEO can be injection-locked by an external frequency which is close to its intrinsic free-running frequency or its high order harmonics [1]. In practice, a base clock component, even though very weak, is always observed in a high-speed OTDM signal due to the non-ideal optical signal multiplexing. Firstly, the base clock component is converted into electrical signal by a wideband PD when injected into the FD-OEO, and then, filtered by a narrowband EBPF with a center frequency around the base clock component, the based clock is fed back to the two MZMs via two EAs to form closed dual loop. Adjusting the phase shifters in the loop and the bias voltages of MZMs, MZM1 and 2 driven by this filtered clock component can provide FD and base-frequency on-off windows described above, respectively. The generated base-frequency on-off window with low duty cycle is subsequently applied to the high-speed OTDM signal injected later, resulting in the fourfold demultiplexing. Due to the much stronger clock component contained in the demultiplexed tributary, the FD-OEO can be finally injection-locked by this clock component via the sustained positive feedback process.

3. Experimental results

As shown in Fig. 1, a 4 × 25-Gb/s return-to-zero on-off keying (RZ-OOK) signal is generated by a home-built transmitter mainly composed of a 25-GHz 2-ps optical pulse generator [10], a 25-Gb/s electrical pulse pattern generator (PPG) with a pseudo random binary sequence (PRBS) length of $2^{31}-1$, a 25-GHz RF source for driving the PPG and the 22-dBm EA applied to the 2-ps pulse generator, a MZM for modulation and a passive polarization-maintaining 1 × 4 optical multiplexer (OMUX). The generated 100-Gb/s RZ-OOK signal together with a CW laser at 1544 nm is injected into the proposed FD-OEO. The average optical power of the 100-Gb/s signal and CW laser are 6.3 dBm and 6.8 dBm, respectively. Both MZM1 and 2 (Sumitomo single electrode intensity modulator) are biased at the peak transmission point and are driven by RF with peak-to-peak voltages of approximately 10 V, which is twice of the half-wave voltage. The erbium doped fiber amplifier (EDFA) in the loop is employed to ensure the net gain of the loop is higher than loss. The subsequent OBPF1 with a 3-nm bandwidth is used to select the amplitude-modulated OOK signal and suppress the amplified spontaneous emission (ASE) noise introduced by the EDFA. With the help of a 50-GHz PD, the selected OOK signal is firstly converted into electrical domain and then filtered by the EBPF with 10-MHz bandwidth and 25-GHz center frequency. Finally, the filtered clock component is fed back to MZM1 and 2 via a RF power splitter and two EAs to form the closed dual loops. We should note that a frequency divider is employed before EA2, guaranteeing the frequency of RF applied to MZM2 is half of that applied to MZM1. Then, by carefully adjusting the phase shifters, the OEO can be injection-locked by the selected clock component. Thus, according to the afore-mentioned theoretical analysis, twofold demultiplexing and FD-OC recovery (by carving the injected CW laser) can be achieved simultaneously by the FD on-off window provided by MZM1. Further, fourfold demultiplexing and prescaled OC recovery (obtained by carving the FD-OC) can be achieved simultaneously after MZM2. The demultiplexed tributary and OC are separated by OBPF2 and 3 outside of the loop and are measured with an optical sampling oscilloscope and an optical spectrum analyzer, respectively.

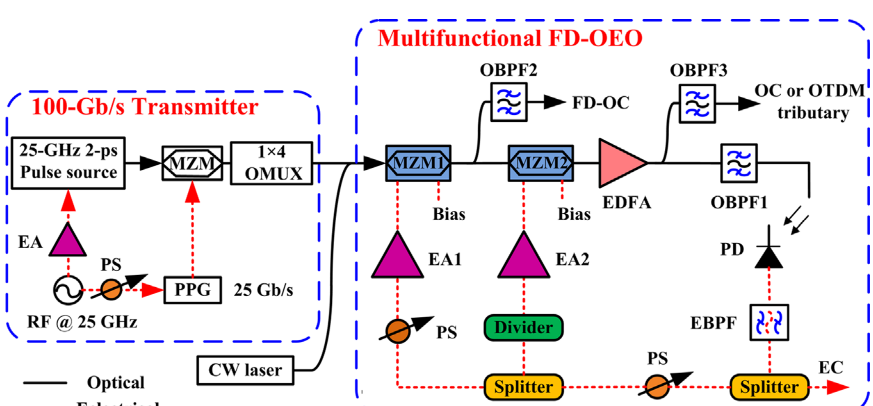

Fig. 1. Schematic diagram of the proposed multifunctional FD-OEO.