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Optical clock recovery with dual-wavelength output from degraded RZ and NRZ signals

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ABSTRACT

A novel scheme to implement clock recovery from degraded signals is proposed and demonstrated based on an optoelectronic oscillator and a dual-wavelength mode-locked fiber ring laser with distributed dispersion cavity. The scheme can obtain wavelength-tunable optical clocks at two wavelengths, which is highly desirable for composite optical logic gates, cascaded optical signal processing modules or optical signal processing modules that need synchronized pulses at multiple wavelengths. In addition, the scheme can operate in both RZ and NRZ systems. The feasibility of the method is demonstrated by an experiment, in which dual-wavelength 10-GHz optical clock with a timing jitter less than 170 fs is obtained from 10-Gb/s degraded RZ and NRZ signals. The optical clocks can be tuned from 1530 to 1565 nm.

1. Introduction

Optical clock recovery from data signals is essential for optical signal processing applications in digital communication systems, such as 3R (reamplifation, retiming, and reshaping) regeneration, format conversion, optical logic gates, and signal demultiplexing [1]. Previously, optical clock recovery from a high-speed digital signal was reported using injection-locked mode-locked lasers [2–4], self-pulsing lasers [5], phase-locked loops [6] or optoelectronic oscillators (OEOs) [7–9]. These techniques, however, can only achieve optical clock at a single wavelength. For composite optical logic gates or cascaded optical signal processing modules, optical clocks at multiple wavelengths are required to avoid interference between different units. Multiwavelength optical clocks are also essential for OTDM-to-WDM conversion [10], optical serial-to-parallel conversion [11], and optical analog-to-digital conversion [12]. Since the optical signal for processing may be distorted by long-distance fiber transmission, it would be highly desirable that the clock recovery module has the capability to perform clock extraction from a degraded signal. In addition, the previous schemes can only operate in either return-to-zero (RZ) or non-return-to-zero (NRZ) systems. Since the two modulation formats may be selectively used in the future optical networks, it would be interesting to develop a scheme that can operate in both RZ and NRZ systems.

In this paper, we propose and demonstrate a novel scheme to realize optical clock recovery, which consists of an OEO and a dual-wavelength mode-locked fiber ring laser (MLFRL) with a distributed dispersion cavity. The combination of the two parts enables the extraction of high-quality optical clocks at multiple wavelengths from degraded RZ and NRZ signals. The wavelengths of the recovered optical clock can be tuned in the operating wavelength range of an erbium-doped fiber amplifier (EDFA). An experiment is performed, dual-wavelength 10-GHz optical clocks with timing jitter less than 170 fs are successfully recovered from 10-Gb/s degraded RZ and NRZ signals.

2. Principle

Fig. 1 shows the schematic of the proposed optical clock recovery system, which is composed of an OEO and a dual-wavelength MLFRL with a distributed dispersion cavity.

The OEO is constructed from a Mach–Zehnder modulator (MZM), a photodetector (PD), an electrical amplifier (EA), a narrow-bandwidth electrical bandpass filter (EBPF) and an electrical phase shifter (PS). An optical bandpass filter (OBPF1) is inserted to make sure that only the input data can enter into the OEO loop. The net gain of the loop is controlled to be greater than unity. If a continuous-wave (CW) lightwave is introduced into the modulator, the OEO will operate at free-running mode [8]. The center frequency ($f = m/\tau$, where m is an integer and τ is the loop delay), is determined by the center frequency of the EBPF and the loop delay. If an incoming data signal contains a clock with a frequency near the oscillating frequency is injected, the OEO will be injection locked by the clock component in the data signal. Clock recovery is then performed.

The dual-wavelength MLFRL shares the MZM with the OEO, which acts as the optical mode-locking element. Due to the polarization

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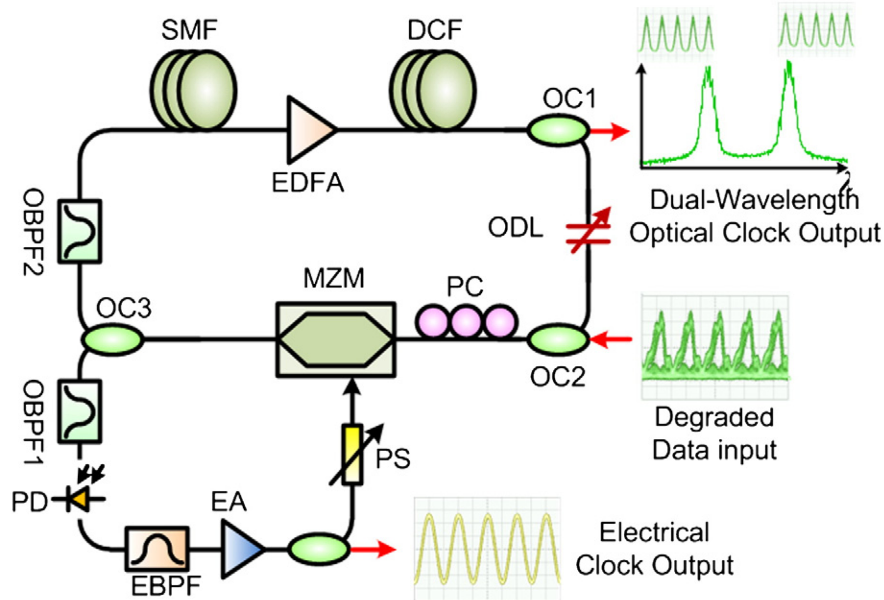

Fig. 1. Schematic of the proposed optical clock recovery system. SMF: single-mode fiber; EDFA: erbium-doped fiber amplifier; DCF: dispersion-compensating fiber; OC: optical coupler; ODL: optical delay line; PC: polarization controller; MZM: Mach–Zehnder modulator; OBPF: optical bandpass filter; PS: phase shifter; EA: electrical amplifier; EBPF: electrical bandpass filter; PD: photodetector.

dependence of the MZM, a polarization controller (PC) is incorporated at its input for performance optimization. The gain of the MLFRL is provided by an EDFA. The EDFA includes two polarization-independent isolators, which ensures the unidirectional operation. A tunable OBPF (OBPF2) is inserted to restrict the work bandwidth of the laser, which is also used to remove the data signal from the MLFRL. A tunable optical delay line (ODL) is used to adjust the cavity length. Intracavity group velocity dispersion was introduced by two dispersive elements, i.e. a length of single-mode fiber (SMF) and a length of dispersion-compensating fiber (DCF), placed before and after the EDFA, respectively.

The principle of the dual-wavelength clock recovery is described as follows. When a RZ signal with a data rate near the oscillating frequency of the OEO is injected into the scheme, the OEO would be injection locked since the RZ signal contains a strong clock component. A high spectral purity electrical clock will be obtained, which is then fed back into the RF port of the MZM. Since the MZM is also the mode-locking element in the cavity of the MLFRL, the MLFRL would be mode-locked and synchronized to the electrical clock. Due to the dispersive cavity, simultaneously multi-wavelength mode-locking is allowed [13,14]. The bandwidth of OBPF2 is selected to allow that only two wavelengths can oscillate. The gain competition between the two wavelengths, introduced by the strong homogeneous line broadening and cross-gain saturation in the erbium-doped fiber (EDF), is partly suppressed by the distributed dispersion cavity. With the distributed dispersion cavity, pulses at different wavelengths are separated in the time domain by the dispersive element before the EDF. Although the fluorescence lifetime of erbium ions in a glass host is very long, the gain recovery time of an EDFA can be controlled to be the order of nanoseconds by using short optical pulses to rapidly saturate the amplifier gain [15], which is always the case when the EDFA is applied as the gain provider in a MLFRL. Therefore, the short optical pulses split by tens of picoseconds would get some separated gain in the EDF, and the gain competition between the two wavelengths is reduced. Then, the split pulses are recombined or mismatched with exactly integral bit periods by the second dispersive element placed after the EDF. This method, although not eliminate the cross-gain saturation in the EDF, is sufficient to guarantee stable dual-wavelength lasing in the MLFRL, as experimentally validated in [16]. Optical clocks at two wavelengths are thus generated. Due to the dispersive cavity, smoothly wavelength tuning can be achieved by changing the cavity length [13,14], which is implemented by adjusting the tunable optical delay line.

Since the OEO is an oscillator with a very high Q value, the clock extraction can be performed as long as the injection signal has a distinct clock component [8]. Therefore, the clock recovery can be performed on a degraded signal if the distinct clock component is not eliminated.

It is well known that the electrical spectrum of an ideal NRZ signal contains no clock components. In the real case, however, a weak clock component always exists due to the imperfect multiplexing in the electrical domain to generate the high data rate electrical NRZ signal. Once the clock component is present, it would be captured and amplified by the OEO. The amplified clock component is then fed back into the MZM and modulates the later injected NRZ signal. With the modulation, the clock component in the injection signal is greatly enhanced. This positive feedback finally lead to an oscillation [7,17]. Thus, clock recovery from the NRZ signal can also be performed. Since the major sources for signal degradation, such as chromatic dispersion and nonlinear effects, would enhance the clock component in the NRZ signal [18,19], the scheme can extract clocks from degraded NRZ signal.

3. Results and discussions

An experiment is carried out based on the setup shown in Fig. 1. The parameters of the devices used in the experiment are as follows. The $LiNbO_3$ MZM has a bandwidth of 12.5 GHz and a half-wave voltage of 6 V. The PD has a bandwidth of 10 GHz. The bandwidth of the EBPF is 15 MHz centered at 9.953 GHz. The 3-dB bandwidths of OBPF1 and OBPF2 are 0.6 and 2.8 nm, respectively. The output saturation power of the EDFA is 16.6 dBm. The dispersion of the SMF and DCF is 33 and −96.2 ps/nm at 1550 nm, respectively. The coupling ratios of the three couplers, i.e. OC1, OC2 and OC3, are 9:1, 5:5 and 7:3. The waveforms are observed by a high-speed sampling oscilloscope (Agilent 86100A) and the spectra are measured by an