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Clock Recovery by a Fiber Ring Laser Employing a Linear Optical Amplifier

E. Tangdiongga, J. P. Turkiewicz, G. D. Khoe, *Fellow, IEEE*, and H. de Waardt

***Abstract*—We report on subharmonic optical clock recovery (OCR) at 10 GHz from 160-Gb/s optical time-division multiplexed signals. The OCR circuit is based on a passively mode-locked principle in a fiber ring laser that utilizes fast gain dynamics of a linear semiconductor optical amplifier. To decrease the jitter amount in the clock pulse considerably, postelectrical signal processing is performed. The recovered clock is a 1.8-ps 10-GHz pulse train with 0.37 pulsewidth–bandwidth product.**

***Index Terms*—Clock recovery, erbium-doped fiber amplifier (EDFA), ring laser, semiconductor optical amplifier (SOA), time-division multiplexing.**

I. Introduction

It is widely recognized that for the realization of ultrahigh-speed optical time-division multiplexed (OTDM) systems, optical clock recovery (OCR) is an essential issue. In order to ensure error-free data (de)multiplexing it is of crucial importance that an OCR is capable to generate high quality clock pulses in the presence of jittered data signal [1]. For the purposes of signal termination and add–drop multiplexing, recovered clock frequencies should be at subharmonics to the frequencies of transmitted optical data.

Among the many methods proposed and demonstrated so far, optical mode-locking using a semiconductor optical amplifier (SOA) in a fiber ring is a promising method because of its capability to generate high-intensity ultrashort optical pulses. This method is cost-effective and generally reliable because it uses widely available and matured standard pigtailed optical devices.

Recently, linear optical amplifiers (LOAs) have been introduced to address the need for low-cost and successful multichannel amplification in metro-size wavelength-division-multiplexing networks [2], [3]. Although the LOAs are primarily designed for linear operation due to their excellent immunity against crosstalk and small signal distortions, these devices have been successfully tested to perform nonlinear operation as a wavelength converter [4].

In this letter, we demonstrate another nonlinear application of LOAs, i.e., subharmonic clock recovery at 10 GHz. Fig. 1 presents a schematic of the proposed clock recovery. The clock recovery is based on a hybrid combination of optical and electronic signal processing. The optical part is carried out by injecting optical data pulses into a mode-locked fiber ring laser, as in [5], that utilizes the fast gain dynamics of an LOA. In addition, the electronic part is performed to decrease considerably the jitter amount in the clock pulses so that the clock can meet the requirements of successful OTDM switching. The input signal to the OCR scheme is 16 OTDM data channels of 10 Gb/s each. Results of experiments are presented and discussed in this letter. Of crucial importance for recovered clock signals are pulsewidth, jitter performance, and locking range.

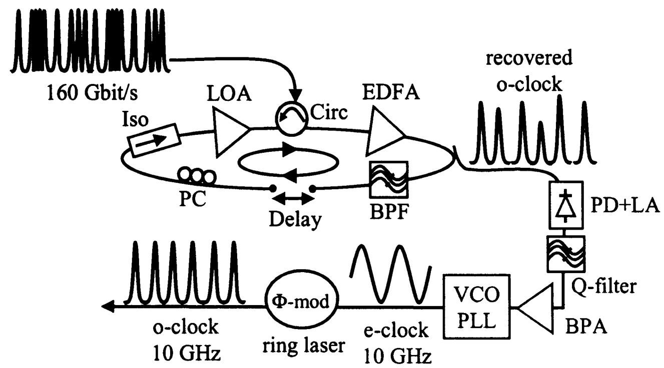

Fig. 1. Experimental setup for subharmonic 10-GHz OCR.

II. OTDM Transmitter and Clock Recovery

In OTDM transmission systems, periodic pulse train of a laser source is divided in several branches by an optical coupler to form OTDM channels. Each channel has an optical gate by which electrical data is put onto an optical carrier. A data pulse is delayed before being interleaved in time with other pulses to produce a single data stream. Proper delays in each branch prevent optical crosstalk among OTDM data channels. For our experiments, we used a combination of a single optical gate and optical multipliers to emulate high-capacity OTDM data stream. A 1.6-ps pulse 10-GHz ring laser operating at 1.55 μm was used as a pulsed light source. After intensity modulation at a base rate of 10 Gb/s with a pseudorandom binary sequence (PRBS) of 2^7-1, the signal was optically multiplexed to 160 Gb/s using four optical multipliers. In each optical multiplier, the signal was split in two branches with one arm longer than the other. The length difference was chosen as such that the bit-interleaving occurs at a double bit rate of the input. To ensure a multiplexed true PRBS data stream, the bit sequences were phase decorrelated by shifting them against each other by $(2^7-1)/n$ bit periods with $n = 2, 4, 8, 16$. An optical modulator and four multipliers caused a total optical loss of about 30 dB. Therefore, we used an optical amplifier before and after the multipliers. This was followed by a filter of 2.1 nm that suppresses the outband amplified spontaneous emission (ASE) noise before a transmission

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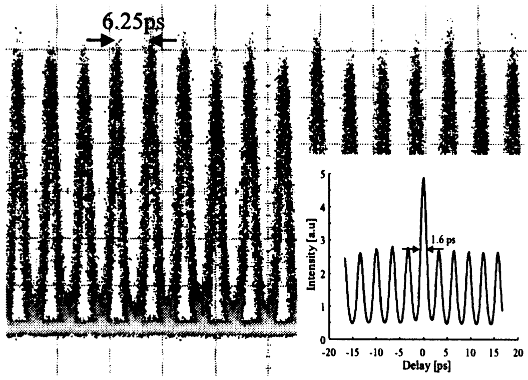

Fig. 2. Eye pattern of 160-Gb/s OTDM input signal for clock recovery and its autocorrelation profile (inset).

fiber. The eye pattern observed with an ultrahigh-speed optical sampling scope and the autocorrelator (AC) trace of 160-Gb/s OTDM signal are presented in Fig. 2. A small time variation in the channel allocation and a high extinction ratio in the AC trace indicated that the transmitter alignment of the 16 10-Gb/s OTDM channels is close to an ideal one. The average full-width at half-maximum (FWHM) of a single optical pulse was measured at approximately 1.6 ps. The AC side lobes are a result of the interpulse cross correlation of the (pseudo)random nature of the OTDM data bits.

The operation of the subharmonic OCR relies on the fast gain compression of the LOA by the incoming data stream. The LOA gain compression results in optical phase modulation in the cavity and mode-locks the fiber laser. The 16-channel OTDM signal was coupled into a ring laser by an optical circulator (Circ). The laser ring cavity was constructed entirely from fiber-pigtailed components. An optical source was provided by the ASE of the LOA. An optical isolator (Iso) was put before the LOA to ensure unidirectional mode-locked oscillation and to minimize spurious cavity reflections. An additional optical gain was provided by an erbium-doped fiber amplifier (EDFA) that compensates for gain fluctuations of the LOA under pulsed external signals. After the EDFA, a 50/50 fused optical fiber coupler was used to lead the mode-locked pulse train out from the ring cavity. A bandpass filter with 5-nm FWHM bandwidth selected the central wavelength of the mode-locked signal. A tunable optical delay was responsible for precise matching of the repetition frequency of the clock recovery circuit to the incoming data pattern. The cavity fundamental frequency of the LOA ring was 8.05 MHz and the in-cavity power was +7.8 dBm. This high in-cavity power for locking was necessary since the LOA had been optimized for high input saturation power as required for linear optical operations. To improve the clock performance furthermore, the o-clock pulses were converted to electrical signals by a 12-GHz photodetector, equalized by a limiting amplifier (LA), filtered by a high-Q filter, and amplified by a bandpass amplifier (BPA) which gave a Q value of more than 35 dB. The 10-GHz e-clock was further processed by a feedback electronics which is based on voltage-controlled oscillator phase-locked loop (VCO-PLL) signal processing. The output signal was reconverted to o-clock pulses by

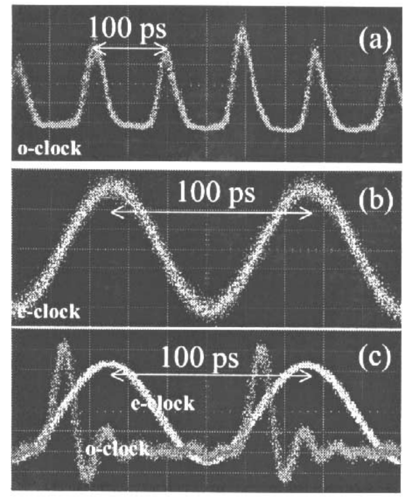

Fig. 3. Temporal response of the subharmonic clock recovery: (a) Recovered o-clock, (b) e-clock of BPA output, and (c) e-clock of PLL output and regenerated o-clock.

a fiber ring laser, which has a phase modulator in its cavity. The fundamental frequency of this output laser was 3.6 MHz.

The LOA used in this experiment is a metal–organic chemical vapor deposition-grown InP-based semiconductor device that integrates an active waveguide and a vertical-cavity surface-emitting laser (VCSEL) on the same chip [2]. The VCSEL has been elongated to coincide with the active waveguide along its entire length. This way, the active region of the device is shared among VCSEL and amplifier. The VCSEL lasing action causes a flat gain response for input powers smaller than the maximum linear power P_{lin}. Since there is no gain change for small input signals, there will not be a phase shift in the optical ring. Only high-intensity input signals ($> P_{\mathrm{lin}}$) is the cause of the optical gain change. This discrete phase shift results in an improved locking performance of one of the ring's longitudinal modes.

III. Results and Discussions

In order to achieve oscillation in the ring, we adjusted the delay so that the fundamental frequency of the fiber ring is a subharmonic of the line frequency of data pattern. For a certain value of delay, the ring circuit generated mode-locked pulse trains with a measured FWHM of 8–10 ps. However, as expected, the pulse was not transform-limited due to an excessive amount of chirp and its temporal response had a substantial amount of jitter [see Fig. 3(a)]. To improve its jitter performance, the clock was processed in the electrical domain. The output of BPA is shown in Fig. 3(b). The amplitude jitter was considerably reduced thanks largely to the LA. However, the time jitter was still larger than the requirement for optical switching. To minimize the jitter value furthermore, a VCO-PLL was added to the signal processing and its output was used as a driving signal of an output laser. The results are displayed in Fig. 3(c). The electrical and optical clock were of excellent quality. A time-precision scope showed time jitter of less than 200 fs. This jitter value is in the order of the scope jitter resolution. To evaluate the clock performance in more detail, we estimated the jitter based on its single

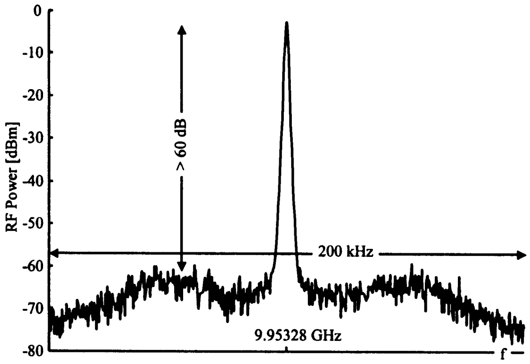

Fig. 4. RF spectrum of the recovered e-clock, 200-kHz span, and 1-kHz resolution bandwidth.

sideband (SSB) phase noise spectrum. The noise spectrum appears in the radio-frequency (RF) spectrum on the wing of the clock frequency peak. Fig. 4 shows the RF spectrum of the regenerated e-clock used as the input to the ring laser. Taking into account the 1-kHz resolution, the e-clock SSB phase noise power was approximately -90 and -110 dBc/Hz for 10- and 100-kHz frequency offsets, respectively. The calculation was done by integrating the measured phase noise over a specified frequency band. The integration region was chosen from 100 Hz to 10 MHz [6]. The jitter calculation resulted in a root mean square (rms) time jitter in the order of 50–60 fs. This value is much lower than the minimum value required for all-optical switching. Optical and RF spectrum of the o-clock pulse of the ring laser are presented in Fig. 5. The mode-locked optical spectrum was relatively symmetric around 1551.5 nm. The same performance was also obtained within a 10-nm wavelength range. The side-mode suppression was above 30 dB, which corresponds to an optical side-mode suppression of 60 dB, which is typical value of present ring lasers. The pulsewidth measured with the AC was 1.8 ps. The pulsewidth–bandwidth product of the pulse was approximately 0.37, which is very close to that of a squared hyperbolic secant profile. We tested the locking range by slightly tuning the channel rate around 10 Gb/s after the mode-locking was achieved. The locking range was measured to be less than 5 MHz. It is important to note that the setup did not employ any form of stabilization mechanism. We expect that based on its pulse performance and the use of standard pigtailed devices, the proposed OCR is a strong candidate for the clock recovery in ultrahigh capacity OTDM networking.

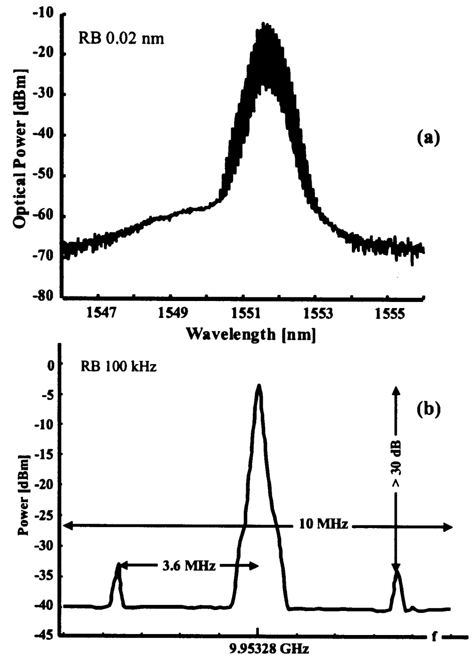

Fig. 5. Recovered subharmonic o-clock at 10-GHz repetition rate (a) optical spectrum, and (b) RF spectrum.

IV. Conclusion

We have demonstrated OCR at a subharmonic frequency of 10 GHz from 160-Gb/s OTDM signals. An optical pulse train of 100-ps periodicity is successfully recovered, reshaped, and regenerated with extremely low amplitude variation and time jitter. The measured jitter of less than 200 fs is very much limited by the resolution of the measuring instrument. We believe that the recovered clock performance enables error-free ultrafast add–drop switching in OTDM networks.

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