All-Optical Clock Recovery Using Erbium-Doped Fiber Laser Incorporating an Electroabsorption Modulator and a Linear Optical Amplifier

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***Abstract*—We demonstrated a 10-GHz all-optical clock recovery system using an erbium-doped fiber laser that incorporates an electroabsorption modulator and a linear optical amplifier. Stable pulses with peak power of 200 mW and pulsewidth of 6 ps are obtained. The output power and the pulsewidth of the recovered clock pulses are independent of the input data pattern. Stable optical clock can still be observed when the input data rate varies by more than 60% of the fundamental frequency without any optical tunable delay line inside the laser cavity. The scheme is essentially wavelength transparent for the whole C-band which recovers clock pulses from input data wavelength between 1525 and 1565 nm.**

***Index Terms*—All-optical devices, clock synchronization, optical fiber communications, optical fiber lasers.**

I. INTRODUCTION

ALL-OPTICAL clock recovery circuits which recover timing information from an incoming optical data stream to produce an optical clock without an intermediate electronic stage is a key component for optical data regeneration and optical time-division-multiplexing demultiplexing in optical communication systems. Several technologies, including tank circuit, injection locking with semiconductor laser, and erbium-doped fiber (EDF) laser, or semiconductor-optical-amplifier-based fiber mode-locked lasers and all-optical phase-locked loop, had been proposed to address this issue [1]–[5]. Among these technologies, the fiber-laser-based system enables the clock recovery system to operate over a wide wavelength range and data rate. It can generate high-intensity ultrashort optical clock pulses with low timing jitter [1], [4], [5]. However, most reported fiber-laser-based techniques are sensitive to the polarization state of the incoming data and the performance characteristics are nonuniform for the data signal at different wavelengths. In addition, the output clock pulses are of limited extinction ratio.

In this letter, we demonstrate a clock recovery circuit based on an active mode-locked fiber ring laser using an electroabsorption modulator (EAM) as the active mode locker. The 10-GHz active mode-locked fiber laser incorporates an EAM, a linear optical amplifier (LOA), and an EDF amplifier [6]. The LOA provides linear operating output power up to 10 dBm and a flat gain from 1530 to 1562 nm [7]. The much shorter life time of the excited states of the LOA compared with that of the EDF has prevented the mode-locked laser from entering the Q switching and passive mode-locking regimes. The mode-locked laser can output 2.4-ps pulses with very high stable peak power. Optical clock recovery is realized by replacing the external RF modulation of the EAM with a dc bias and injecting modulated data signal to the EAM. Mode locking of the laser is achieved by the injected optical data signal via cross-absorption of the saturated EAM. As a result, stable clock signals synchronized to the incoming data are generated [8]. Experimental results show that 10-GHz stable optical clock with peak power of 200 mW and pulsewidth of 6 ps is obtained. Stable optical clock can still be observed when the input data rate varies within 3 MHz (more than 60% of the fundamental frequency) without any optical tunable delay line inside the laser cavity. Recovered clock can operate at different output wavelengths and the timing jitter of the clock is 477 fs measured using Agilent Electrical Spectrum analyzer. The operating wavelength for the incoming data signal can cover the entire C-band. This is an important property especially for dynamic reconfigurable all optical networks.

II. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1 shows the configuration of the proposed all-optical clock recovery circuit. The cavity gain of the fiber ring laser is provided by the LOA and EDF. The LOA operates at a driving current of 233 mA with a gain of $\sim$13.5 dB and the saturation output power is 13 dBm. The 12-m-long EDF was pumped by a 300-mW 980-nm pump laser through the 980-nm/1550-nm wavelength-division multiplexing. Isolators are used for unidirectional oscillation and a 6-nm tunable bandpass filter with center wavelength of 1556.3 nm is used for wavelength selection. The out-of-band rejection of the bandpass filter is 20 dB. A polarization controller is used to optimize the polarization

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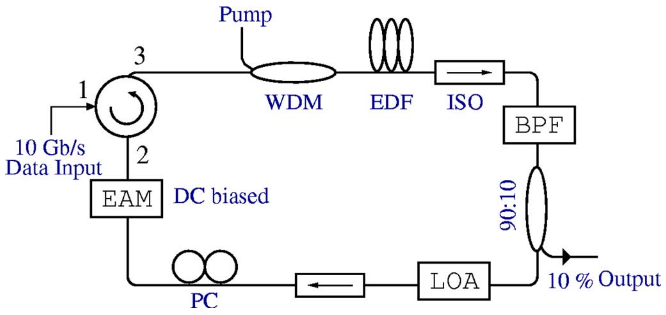

Fig. 1. Experimental setup of the all-optical clock recovery circuit. PC: polarization controller. BPF: 6-nm tunable bandpass filter. ISO: isolator.

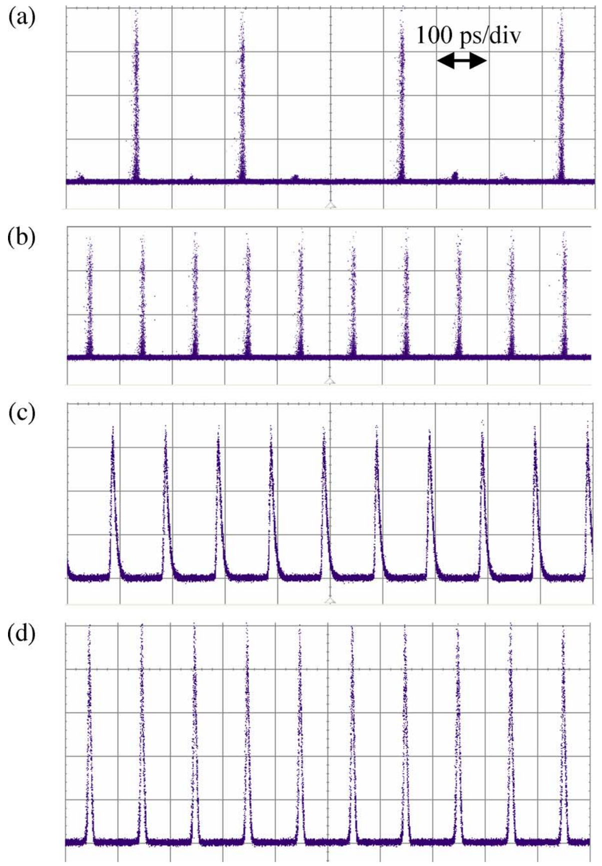

Fig. 2. Timing diagram of input data and recovered optical clock, (a) 10-Gb/s input data pattern 1001001010, and (b) the 10-Gb/s PRBS input signal. (c) Recovered 10-GHz optical clock with pulsewidth 10 ps and peak power (150 mW) using a fixed data pattern in (a). (d) Recovered 10-GHz optical clock using PRBS as shown in (b).

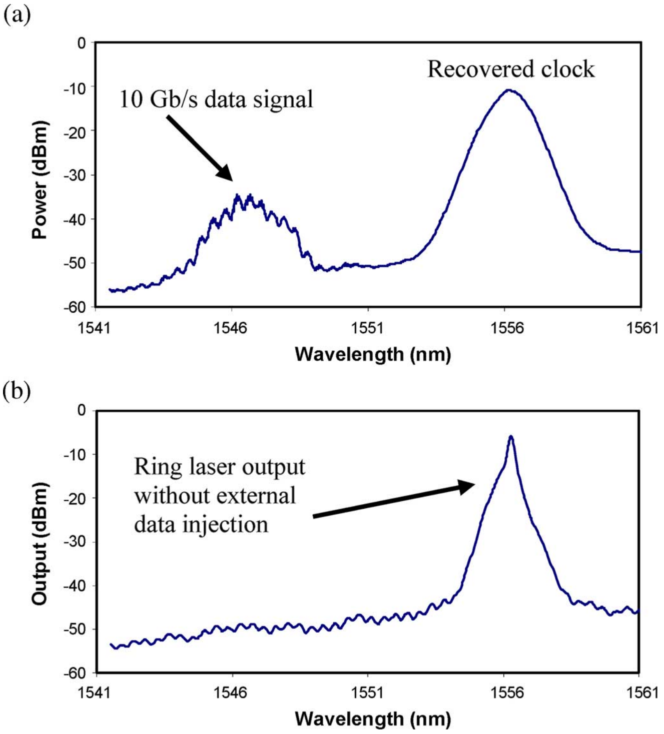

Fig. 3. Output optical spectrum of the clock recovery circuit (a) with PRBS data input, and (b) without input signal.

state of the cavity modes because the EAM has a small polarization-dependent loss. Modulated data is injected to the EAM through a circulator. The cavity length is about 40 m corresponding to a fundamental cavity mode of 4.87 MHz. Ten percent of the cavity energy of the mode-locked laser system was coupled to the output through the 90 : 10 coupler. Clock recovery is achieved by synchronization and stabilization of the fiber mode-locked laser by the externally injected data. The EAM acts as a mode-locker driven by external input data stream and it is biased at a dc voltage of -1.015 V. In the experiment, 10-Gb/s data stream is injected into the EAM through a circulator. The 10-Gb/s data stream counterpropagates with the lasing direction inside the laser cavity and forces the transmission of the EAM to vary with the input data stream which enables active mode locking of the fiber ring laser by the external data. Hence, optical clock pulses synchronized to the incoming data are generated.

To evaluate the performance of the clock recovery circuit, a 10-Gb/s return-to-zero data stream was produced by modulating the output of a 10-GHz semiconductor mode-locked laser source using a LiNbO$_3$ Mach–Zehnder modulator and a pulse pattern generator. The modulated light was injected to the ring laser and the injected power of the data signal is 3.5 dBm. The output pulses were measured using a YOKOGAWA Optical Sampling Oscilloscope (OSO) (model AQ7750) and the optical spectrum of the output pulse was taken from a ANDO optical spectrum analyzer (model AQ 6317B). We use fixed as well as pseudorandom data patterns to demonstrate the clock recovery operation of the circuit. Fig. 2(a) shows a portion of the 10-Gb/s input data pattern used; "1001001010". Fig. 2(b) shows the 10-Gb/s pseudorandom data pulses of length $2^{20} - 1$. Fig. 2(c) is the recovered 10-GHz optical clock when the input data is the fixed data pattern, as shown in Fig. 2(a). Fig. 2(d) shows the 10-GHz recovered optical clock corresponding to the pseudorandom binary sequence (PRBS) input data, as shown in Fig. 2(b). The output peak power and the pulsewidth of the optical clock are 200 mW (2 W inside the cavity) and 6 ps, respectively. From Fig. 2, the optical clock is recovered successfully. The output clock is very stable with timing jitter measured to be 477 fs using an electrical spectrum analyzer. A stable optical clock can still be observed when the input data rate varies within 3 MHz (more than 60% of the fundamental frequency) without any optical tunable delay line inside the

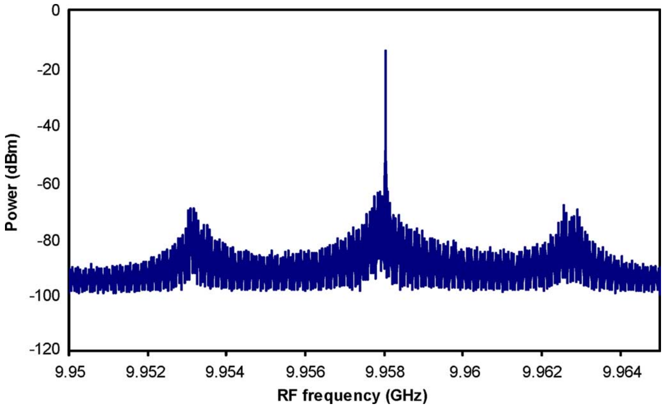

Fig. 4. Output RF spectrum with the resolution bandwidth 10 kHz.

TABLE I
OUTPUT PULSEWIDTH AND POWER VARIATION VERSUS DIFFERENT DATA LENGTH WHEN THE OUTPUT WAVELENGTH IS FIXED

	Fixed	PRBS						
Bit Length	**199 Bits**	2^7-1	2^9-1	$2^{11}-1$	$2^{15}-1$	$2^{20}-1$	$2^{23}-1$	$2^{31}-1$
Pulsewidth (ps)	6.95	6.94	6.99	6.94	6.87	6.95	6.86	6.9
Power (dBm)	–3.5	–3.59	–3.32	–3.22	–3.18	–3.34	–3.39	–3.34

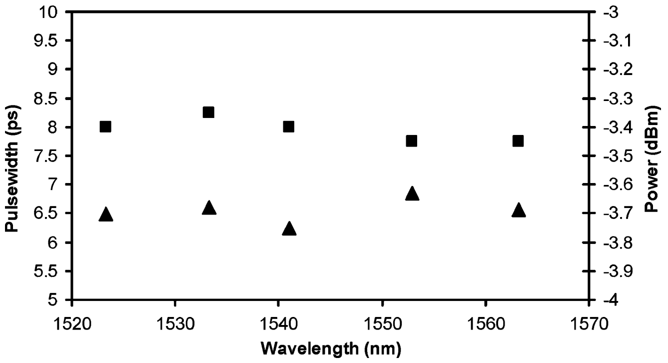

Fig. 5. Pulsewidth (triangles) and output power (squares) of recovered clock pulses versus wavelength of the input data.

laser cavity. Fig. 3(a) shows the output spectrum when the input data rate is 9.9580 GHz. The wavelength of the input data stream and the optical clock are 1546.64 and 1556.19 nm, respectively. The optical spectrum bandwidth of the recovered clock is measured to be 1.87 nm while the pulsewidth taken from the OSO is 6 ps (assuming a Gaussian envelope). The time-bandwidth product is 0.7 which indicates that the output clock pulses were significantly negatively chirped [6]. Fig. 3(b) shows the output spectrum of the laser cavity without data injection. The spectral bandwidth is 0.28 nm which is much narrower than that with data injection. The laser is not mode-locked in this case. Thus, the input data stream drives the EAM and forces the laser system into active mode-locking. Fig. 4 gives the corresponding RF spectrum with a resolution bandwidth of 10 kHz. The sidemode suppression ratio is better than 55 dB.

Table I shows the output power and pulsewidth of the recovered clock signal from a fixed data pattern and from different lengths of PRBS. The length of the PRBS tested ranges from $2^7 - 1$ to $2^{31} - 1$. The mean value of the pulsewidth of the clock pulses recovered is 6.93 ps and the maximum pulsewidth variation for different lengths of injected data signal is within ± 0.07 ps. The mean output power is -3.4 dBm with variations within ± 0.2 dB for different lengths of input data stream. The results show that the output clock pulsewidth and power remain constant for different length of input data stream.

Fig. 5 shows the output pulsewidth variation of the recovered clock versus the input wavelength of the injected data stream. The wavelength of the input data stream varies from 1523 to 1565 nm which covers the whole C-band. The average output pulsewidth is 6.5 ps and the average output power is -3.4 dBm with only very small variation.

III. CONCLUSION

We demonstrated a 10-GHz all-optical clock recovery using an EDF laser that incorporates an EAM and an LOA. Cross-absorption saturation of the EAM by an injected optical data signal was used to actively mode-lock the fiber laser cavity to recover the optical clock. Stable pulses with peak power of 200 mW and pulsewidth of 6 ps are obtained. The timing jitter is 477 fs. Stable optical clock can still be observed when the input data rate varies within 3 MHz (more than 60% of the fundamental frequency) without any optical tunable delay line inside the laser cavity. The clock recovery circuit can be used for input wavelength of the data stream across the entire C-band. Output clock pulses do not vary with input wavelength once the power of the injected data is able to mode-lock the fiber laser. The system can also operate at different output wavelengths if a tunable optical delay line is incorporated. Since there is no electronic-based component involved in the system, the configuration can potentially operate at much higher speeds if a high-speed EAM is used.

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