A Self-Started Laser Diode Pulsation Based Synthesizer-Free Optical Return-to-Zero On–Off-Keying Data Generator

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***Abstract*—A synthesizer-free return-to-zero on–off-keying (RZ-OOK) data generator is demonstrated by gain-switching a Fabry–Perot laser diode (FPLD) and driving a data-stream generator with a self-started opto-electronic oscillator (OEO). By self-feedback triggering the FPLD with the OEO, the FPLD with a modulation bandwidth of only 4 GHz can be self-pulsating to generate clock signal and return-to-zero (RZ) carrier at a repetition frequency of 10 GHz. The self-pulsated FPLD exhibits a pulsewidth of 19 ps associated with a pulse on/off extinction ratio of 7.7 dB and a timing jitter as low as 424 fs. Under self-started pulsation, the spectral linewidth enhancement factor of such a gain-switching FPLD is 12.8, which induces a dynamic frequency chirp ranging from $+6$ to -5 GHz within 30-ps duration. The corresponding chirp parameter of -0.22 is reported for such an OEO driven FPLD based RZ-OOK data generator. The lowest phase noise of -131.8 dBc/Hz at 10-MHz offset from 10-GHz carrier, and the maximum output power of 23 dBm is obtained after amplification. The generated RZ pulsed carrier exhibits a carrier-to-noise ratio of 53 dB and a harmonic suppression ratio up to 52 dB. Such a self-started OEO triggered FPLD is a new approach to the synthesizer-free optical clock and RZ-OOK data generation.**

***Index Terms*—Chirp and jitter, Fabry–Perot laser diode (FPLD), on–off-keying (OOK), opto-electronic oscillator (OEO), return-to-zero (RZ), self-started pulsation, synthesizer free.**

I. Introduction

THE stabilized optical pulse clock at a high-repetition rate with ultra-low timing jitter is mandatory to enhance the transmission performance and to promote the optical network flexibility, which essentially helps to realize the high bit-rate and error-free transmission in optical-time-division-multiplexing (OTDM) networks. In addition to the commercially available synthesizers, the self-starting opto-electronic oscillator (OEO) is an alternative to create the high-purity signals and high repetition-rate optical pulse clock without using any signal generator for versatile applications [1]–[4]. The concept of the OEO was originally proposed by Kersten [5] in 1978. The first experimental demonstrations were reported by Schlaak *et al.* [6] using a waveguide modulator and by Damen *et al.* [7] using a laser diode in 1980. Thereafter, numerous investigations focus on developing versatile OEO architectures by using a electrical comb generator [8], a dual RF drive Mach–Zehnder intensity modulator (MZM) [9], an electroabsorption modulator [10], a broadband polymer electrooptic modulator [11], an $LiNbO_3$ phase modulator [12], and an injection-locked dual loop [13]. Recently, Nakazawa *et al.* also proposed an OEO ring cavity consisting of a gain-switched vertical-cavity surface-emitting laser (VCSEL) at 850 nm and a single-mode photonic crystal fiber, which generated a 10-GHz optical pulse-train with timing jitter as low as 1.2 ps [14]. In comparison with the conventional nonreturn-to-zero (NRZ) data format, the pulsed return-to-zero on–off-keying (RZ-OOK) is a preferable data format with immunity to linear and nonlinear dispersion during high-speed and long-haul transmission. Traditionally, the RZ-OOK stream was demonstrated by modulating the optical pulse-train with the pseudorandom binary sequence (PRBS) data generator driven with additional microwave clock at punishments of increasing cost and complexity [15], [16]. The use of a self-feedback OEO for generating an RZ-OOK data stream has never been reported previously.

Without using any external microwave frequency source in this work, we combine a self-feedback OEO configuration with a 1550-nm fiber-pigtailed Fabry–Perot laser diode (FPLD) packaged in a 5.6-mm transistor outline can (TO-56 can) [17], where the FPLD incorporated OEO forces its gain-switched pulsation self-started at 10 GHz to demonstrate the synthesizer-free RZ-OOK data generator at 10 Gbit/s. The self-pulsating technique effectively overcomes inherent limitation on direct-modulation bandwidth of the FPLD packaged with a TO-56 can, such that the self-started gain-switching FPLD can easily exceed the intrinsic bandwidth of 4 GHz set by the bonding wires of the TO-can module. We discuss the linewidth enhancement factor and chirp parameter of the OEO self-started gain-switching FPLD and also investigate the self-starting threshold at versatile feedback conditions, which facilitates to promote the sub-picosecond timing jitter and to enhance the on/off extinction ratio of gain-switched pulse. The shortening on OEO driven gain-switching FPLD pulsewidth at extremely low-power amplified output is demonstrated. Moreover, the single-sideband (SSB) phase noise, the carrier-to-noise ratio (CNR), and the second-order harmonics suppression ratio are also elucidated.

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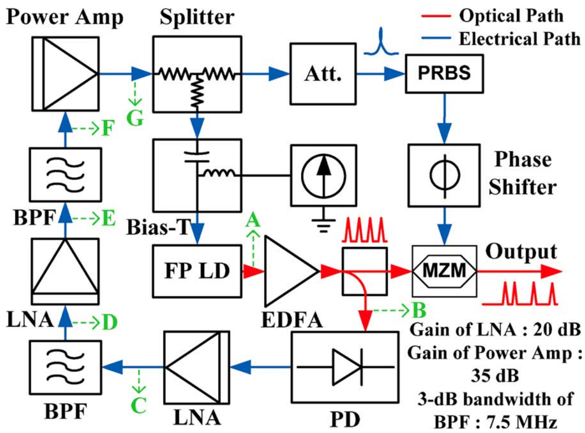

Fig. 1. Schematic diagram of the self-starting OEO with gain-switching FPLD based synthesizer-free RZ-OOK data generator. Bandpass filter: BPF. Low-noise amplifier: LNA.

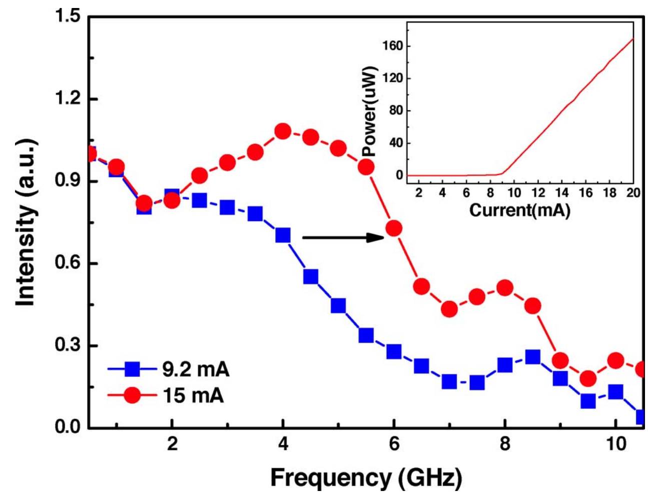

Fig. 2. Frequency response and power-current curve of the FPLD at 1550 nm.

II. Experimental Setup

Fig. 1 illustrates the experimental setup of an OEO constructed using a 1550-nm FPLD without microwave signal generator for synthesizer-free RZ-OOK data generation. The gain-switching FPLD can only be self-started by the opto-electronic feedback from the FPLD, which is directly modulated at nearly or above threshold current condition. To assist the pick-up of 10-GHz feedback from FPLD noise, a C-band erbium-doped fiber amplifier (EDFA) is used to amplify the weak output of FPLD before gain switching. There is no additional loss occurred on the OEO driven FPLD except the 50% coupler used for self-feedback triggering the OEO itself. The EDFA amplified in the OEO loop is for amplifying the FPLD output to initiate self-oscillation process, but not for compensating the insertion loss.

An ultrafast photodetector (New focus 1434 with a cutoff frequency of 25 GHz) with associated pre-amplifier (New focus 1422), two sets of low-noise amplifiers, and microwave bandpass filters (Filtronic W5258) at a central frequency of 9.953 GHz is configured to extract the 10-GHz feedback, and a 35-dB gain power amplifier is employed to drive the FPLD for gain-switching operation via a bias-tee circuit. When the bias current of the FPLD is below threshold, even a weak gain-modulation cannot be triggered by the OEO, as no clock signal is filtered for the optical pulsation. By increasing the FPLD bias beyond threshold, the continuous-wave output of the FPLD transfers into the small-signal oscillation due to a sufficient gain-modulation via the feedback from OEO. The weak 10-GHz signal in the self-feedback OEO loop turns to gain-switch the FPLD itself eventually. Two sets of the microwave bandpass filters and amplifiers are mandatory to build up the feedback loop for self-starting and re-modulating the FPLD. The stabilized gain-switching FPLD pulse-train is obtained when the gain of the 10-GHz clock in the feedback OEO loop is sufficiently large and is coincident with the relaxation oscillation frequency of the FPLD.

By using the microwave clock extracted from the OEO before driving the gain-switched FPLD, the PRBS data generator can be trigged to deliver the electrical NRZ data stream with a pattern length of $2^{31} - 1$. The optical NRZ data stream is simulated by externally encoding the optical pulse-train from the OEO driven gain-switching FPLD with an amplified PRBS pattern at 10 Gbit/s through an MZM. Fig. 2 shows the frequency response of FPLD with bias currents of 9.2 and 15 mA, and the modulation bandwidth of about 4 and 6 GHz is originating from the FPLD bandwidth, the cutoff frequency set by the TO-56 can package, and the other parasitic components. However, a visible relaxation oscillation is still observable at around 10 GHz. The inset of Fig. 2 depicts that the power-current response of the FPLD with threshold current is nearly 9.2 mA.

III. Results and Discussions

The OEO is self-started by increasing the bias current of FPLD beyond 12 mA, such that the gain-switching operation is automatically triggered to deliver the return-to-zero (RZ) pulsed carrier. The PRBS data generator is concurrently trigged by the microwave clock extracted from the OEO to deliver the electrical NRZ data stream at 10 Gbit/s. Fig. 3 illustrates the RZ-OOK data trace output from the PRBS driven MZM with a specific pattern of 10101110. Such an RZ-OOK data generator is completely synthesizer free; however, there is an intrinsic limitation on switching the gain characteristics of the FPLD. Typically, such an RZ-OOK generation cannot be automatically turned on when the bias current of the FPLD is close to the threshold condition. In the experiment, the gain-switching FPLD fails to self-start at a bias current less than 12 mA since there is no 10-GHz feedback signal picking up from the FPLD noise spectrum by the OEO circuitry. Although an inline EDFA has been inserted to enlarge the output power of the FPLD, the OEO driven gain-switching FPLD must be operated beyond threshold to trigger a sufficiently short RZ pulsed clock. Apparently, such an operation is contrary to the optimized condition for gain switching a free-running FPLD at slightly below threshold current. Nevertheless, the OEO driven gain-switching FPLD can respond to the incoming “on” bits consecutively, thus providing the RZ-OOK data with a greater modulation depth and a sharper bit-shape. Some parameters of the generated RZ clock due to such an extraordinary operation is found to strongly correlate with the bias current, which are discussed below.

First of all, the red-shifted spectrum of the OEO driven gain-switching FPLD self-started is observed by detuning the inline

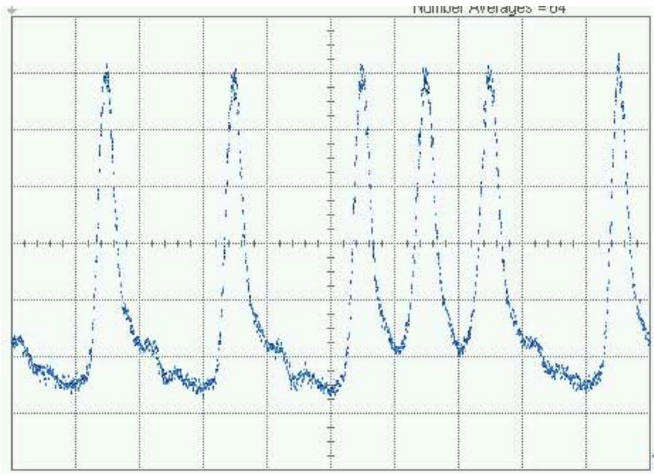

Fig. 3. Specific 10101110 RZ-OOK data stream obtained after the PRBS driven MZM.

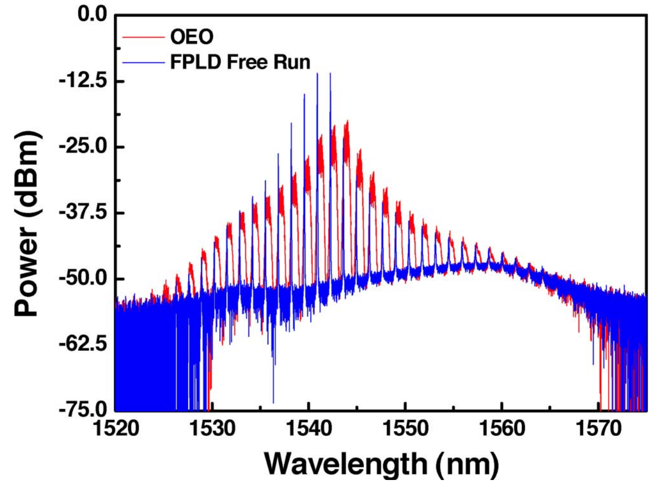

Fig. 4. Optical spectrum and mode spacing of OEO-driven gain-switching FPLD.

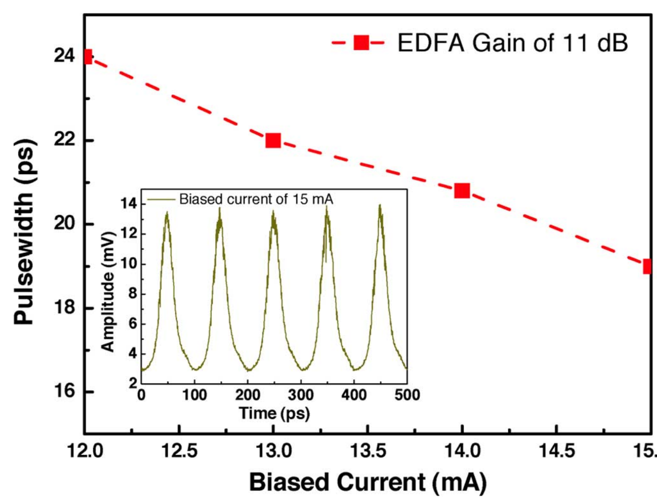

Fig. 5. Pulsewidth and output waveform of the OEO driven gain-switching FPLD at 10 GHz.

EDFA gain and the FPLD bias, which is mainly attributed to the dependence between the transient carrier concentration and the temporally changed refraction index. The correlation between the wavelength variation and the instantaneous change on the refractive index is described as $\lambda(t) = [n(t) * \lambda_0]/n_0$, where $n(t)$ and n_0 are the refractive indices at time t and 0, respectively. In a gain-switched FPLD, the carrier-induced refractive index change and the wavelength variation can generally be correlated by [18]

$$\Delta\lambda = \lambda_{\text{free-run}} - \lambda_{\text{gain-switching}} = \frac{\lambda_0}{n_0}\frac{dn}{dN}\Delta N \tag{1}$$

Typically, the dn/dN is $-(2-3)\times 10^{-20}$ for a general InGaAsP FPLD [21]. As predicted by (1) with a carrier density variation of $\Delta N = N_{\text{initial}} - N_{\text{final}}$ and the negative dn/dN, the FPLD spectrum red shifts toward longer wavelength after gain-switching, as shown in Fig. 4. In comparison with a free-running FPLD, the OEO-driven gain-switching FPLD exhibits a red-shifted wavelength up to 3.2 nm, and the linewidth enhancement factor can be rewritten as

$$\begin{aligned}\alpha &= -2k\frac{d\mu/dn}{dg/dn}\\ &= -\frac{2k}{a}\frac{\Delta\lambda}{\Delta n}\frac{\mu_0}{\lambda_0}\\ &= -\frac{4\pi}{a}\frac{\Delta\lambda}{(\tau_c/qV)(I-I_{\text{th}})}\left(\frac{\mu_0}{\lambda_0}\right)^2\\ &= \frac{-4\pi\cdot qV\cdot\Delta\lambda}{a\cdot\tau_c\cdot(I-I_{\text{th}})}\left(\frac{\mu_0}{\lambda_0}\right)^2.\end{aligned} \tag{2}$$

With (2), the linewidth enhancement factor of the OEO driven gain-switching FPLD is calculated by assuming the cavity length (L) as 600 μm, the width (W), and the depth (d) of the active region in FPLD as 1.5 and 0.2 μm, respectively, the differential gain $(a = dg/dn)$ as 2.5×10^{-20} m^2, the electron charge (q) as 1.6×10^{-19}, and the carrier lifetime (τ_c) as 2 ns, respectively. The linewidth enhancement factor of OEO driven gain-switching FPLD at a bias current of 15 mA is determined as 12.8, which is obtained under a transient current of $I(t) = I_b + I_m\sin(wt)$, where I_b is the bias current of FPLD and I_m is the modulated current at an angular frequency of w. Due to the band-filling effect, the OEO driven gain-switching FPLD reveals a optical spectrum with a 3-dB linewidth broadening by at least 12.5 times when changing the operation condition from a free-running (36 pm) to gain-switching (0.46 nm) mode.

The pulsewidth of the OEO driven gain-switching FPLD shown in Fig. 5 is obtained by the digital sampling oscilloscope (Agilent 86100 A + 86116 A with a detecting bandwidth of 63 GHz). When enlarging the gain-switching FPLD output power up to -1.5 dBm by setting the inline EDFA gain as 11 dB, the OEO driven gain-switching pulsewidth is greatly shortened from 24 to 19 ps as the bias current increases from 12 to 15 mA. The inset of Fig. 5 depicts the oscilloscope trace for the perfect OEO-driven gain-switching FPLD pulse-train self-triggered at 10 GHz. In the following, we further discuss the relationship between pulsewidth and bias current of the OEO driven gain-switching FPLD. In general, the gain-switching

FPLD output can be carried out by a set of nonlinear rate equations in (3) [18]

$$\frac{dn}{dt} = \frac{I(t)}{qV} - g_0(n-n_t)S - \frac{n}{\tau_c}$$
$$\frac{dS}{dt} = \Gamma v_g g_0(n-n_t)S - \frac{S}{\tau_{\rm ph}} + \frac{\beta\Gamma n}{\tau_c} \quad (3)$$

where n and S denote the carrier and photon densities in the gain-switching FPLD cavity n_t, the transparency carrier density g_0, the differential gain β, the spontaneous coupling factor q, the electron charge V, the active layer volume $I(t)$, the transient bias current v_g, the group velocity Γ, the optical confinement factor, and τ_c and $\tau_{\rm ph}$, the carrier and photon lifetimes, respectively. For the gain-switching FPLD, the current density $I(t)$ is described by an electric pulse-train, and the photon lifetime $\tau_{\rm ph}$ is given by $\tau_{\rm ph} = [v_g(\alpha_i + \alpha_m)]^{-1}$, where α_m and α_i denote the mirror and internal losses, respectively.

In principle, the pulsewidth of the OEO driven gain-switching FPLD can be roughly estimated by using two combined exponential curves with time constants of τ_r and τ_f on rising and trailing edges of $S(t)$, respectively. Theoretically, the rise time can be obtained by deriving the following equation: $\Gamma\nu_g g_0(n - n_t)S = \Gamma\nu_g g_0[n(t) - n_{\rm th} + \Delta n]S = \Gamma\nu_g g_0[n(t) - n_{\rm th} + (\Gamma\nu_g g_0\tau_{\rm ph})^{-1}]S$ such that the rise time can be described as $\tau_r = [(dS/dt)/S]^{-1} = \{\Gamma\nu_g g_0[n(t) - n_{\rm th} + (\Gamma\nu_g g_0\tau_{\rm ph})^{-1}]\}^{-1}$. In general, τ_f is approximately $3\tau_r$ and the OEO driven gain-switching FPLD pulsewidth is given as (4)

$$\tau_r + \tau_f = qV/[\Gamma v_g a\tau_s(I - I_{\rm th})] + \tau_f. \quad (4)$$

Only when increasing the FPLD bias current from 9.2 to 12 mA, the gain-switching FPLD can be self-started to deliver an optical pulse-train at 10 GHz. A further reduction on pulsewidth relies strictly on increasing the bias current, and the minimum requested bias current is 1.2 times the threshold current. To function as a synthesizer-free optical clock, it is mandatory to characterize the spectral purity of the 10-GHz microwave clock extracted from the OEO driven gain-switching FPLD. After amplification, the maximum output power at the FPLD bias current of 15 mA is 23.2 dBm.

Under a spectral analysis with a resolution bandwidth of 10 Hz, the CNR and second-order harmonic suppression ratio of the extracted 10-GHz microwave clock are 53 and 52 dB, respectively, which shows an SSB phase noise of −131.8 dBc/Hz at 10-MHz offset from the carrier. The CNR can be enhanced up to 60–65 dB by setting the resolution bandwidth as 1 Hz. The SSB phase noises measured at different nodes in the OEO feedback loop were shown in Fig. 6 to understand the noise-suppressing performance of each OEO element. In addition, the related timing jitter is calculated from the integral of the SSB phase-noise spectrum versus frequency measured at a specified node using the following equation [20]:

$$\sigma(f) = \left[2\int_{f_L}^{f_H}\left(10^{L_n(f)/10} - 10^{L_1(f)/10}\right)\Big/(n^2-1)df\right]^{1/2}\Bigg/2\pi f_R \quad (5)$$

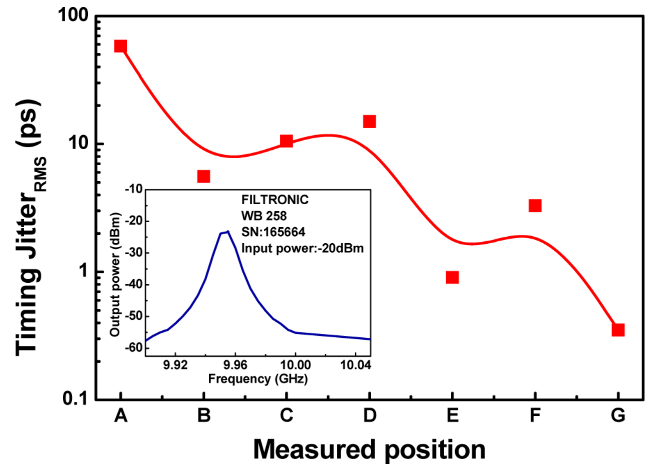

Fig. 6. Calculated timing jitter from gain-switching FPLD (15-mA bias) at different nodes in the OEO feedback loop. The A–G checking points are defined as the different nodes shown in Fig. 1.

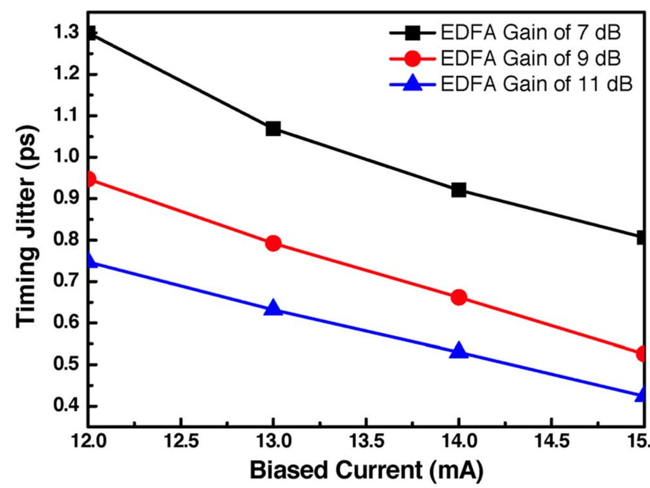

Fig. 7. Measured timing jitter of optical pulse-train at different driving currents and optical injection powers.

where f_R is the repetition rate, $L_n(f)$ is the SSB phase noise of the nth harmonic frequency component of the OEO triggered gain-switching FPLD, n is the harmonic number of the SSB phase noise, and f_H and f_L are the lower and higher limits of integration. With an integrating range from 10 Hz to 100 MHz, the minimized timing jitter of 352 fs can be obtained. The inset of Fig. 6 also shows the bandpass filtered spectrum with a quality factor of $Q = f/f_{\rm FWHM} = 1.3 \times 10^3$, where the passband of 7.5 MHz is still too wide to restrict the noise in the OEO feedback loop and inevitably degrades the phase-noise performance. Such a shortcoming can be improved if a high-Q filter and a high-gain and low thermal-noise amplifier are available.

The measured timing jitter of the self-started gain-switching pulse is plotted as a function of the injection current and is shown in Fig. 7. The OEO feedback circulating loop plays an important role on suppressing the phase noise and corresponding jitter. Therefore, the timing jitter is greatly reduced with increasing bias current of the OEO driven gain-switching FPLD. If the output power by tuning the EDFA gain is enlarged, the timing jitter further indicate a decreasing trend as a larger 10-GHz feedback signal filtered from noise can be provided by increasing the EDFA gain, such that the self-starting oscillation

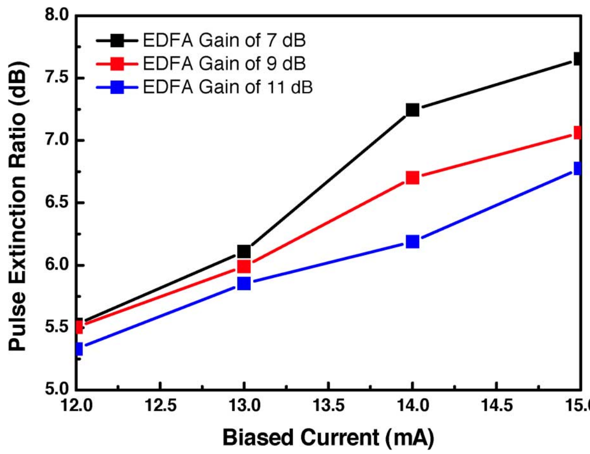

Fig. 8. Pulse on/off extinction ratio in OEO dependence on the bias current and optical injection power.

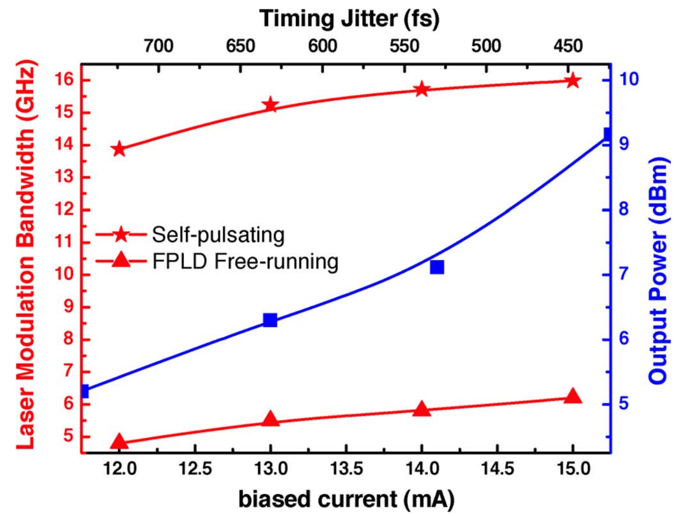

Fig. 9. Calculated modulation bandwidths of the free-running and self-pulsated gain-switching FPLD, and their corresponding output powers and timing jitters as a function of the FPLD bias current.

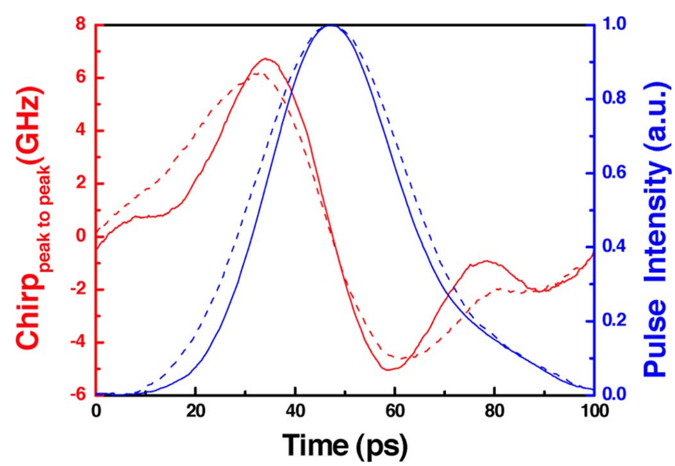

Fig. 10. Optical pulses (blue line in online version) and corresponding peak-to-peak chirps (red line in online version) of the pulse-train at bias current of 12 (dashed line) and 15 mA (solid line).

is easier to be established. Nonetheless, the EDFA is also an active device with considerable noise figure up to 5–6 dB, which somewhat degrades the noise performance of the self-started gain-switching FPLD even with high-gain amplification. A minimized timing jitter of 424 fs is achieved at the FPLD bias current of 15 mA and at the EDFA output power of −1.5 dBm.

Obviously, the cavity gain in the self-started OEO feedback loop must be appropriately enlarged to minimize the timing jitter of the RZ pulsed carrier for a further RZ-OOK data-stream generation. On the other hand, the pulse on/off extinction ratio (defined as the ratio of pulse amplitude to dc offset level) of the optical pulse-train generated from such a self-started OEO is also a key parameter for estimating the intensity noise performance of the RZ-OOK data stream. For obtaining a high on/off extinction ratio in our case, the precise control on the EDFA gain is mandatory to avoid additional spontaneous emission noise accompanied with the generated RZ pulsed carrier. However, such an issue on the optimization of the pulse on/off extinction ratio was seldom discussed in previous reports.

The pulse on/off extinction ratio at versatile operating conditions shown in Fig. 8 reveals an increasing trend with enlarging FPLD bias, which is attributed to the larger microwave signal feedback into the OEO loop for clock extraction. By selecting the EDFA gain as 7, 9, and 11 dB, the pulse on/off extinction ratio increases from 5.5 to 7.7, 5.4 to 7.1, and 5.3 to 6.7 dB, respectively. The increasing EDFA gain essentially enhances the optoelectronic conversion to reduce the self-staring threshold current effectively. However, the spontaneous emission of the EDFA dominates to distort the gain-switching pulse, in which the induced dc level inevitably suppresses the pulse on/off extinction ratio by 1.4 dB at least.

Subsequently, the EDFA gain is appropriately decreased and the FPLD bias is increased accordingly to promote the amplification on the gain-switched pulse-train. As the EDFA gain decreases from 11 to 7 dB, the pulse on/off extinction ratio is greatly enhanced from 6.8 to 7.7 dB. We conclude that the optimization on EDFA gain is more pronounced than the bias for adjusting better pulse quality. As mentioned above, we have increased the bias current to suppress the timing jitter. Assuming that the optical confinement factor Γ is 0.5, the internal loss α_i is 1000 m^{-1}, and the facet reflective R is 30%, the calculated modulation bandwidth and output power [21] from the self-starting OEO under gain-switching operation as a function of the FPLD bias and the timing jitter are shown in Fig. 9. The simulated laser modulation bandwidth is increased from 13.9 to 16 GHz, whereas the timing jitter concurrently decreases due to the enhanced carrier accumulation in the gain-switching FPLD.

Fig. 10 illustrates the optical pulse-train shapes and corresponding frequency chirps at bias current of 12 and 15 mA. The chirped frequency deviation of the OEO driven gain-switching FPLD pulse-train is positive at the rising edge ($\delta\phi/\delta t < 0$) and is negative at the falling edge ($\delta\phi/\delta t > 0$), thus leading to a negative chirp parameter C. Assuming the optical field of the gain-switching FPLD, $U(z,t)$ at $z = 0$ exhibits a linearly chirped Gaussian shape as given by [21]

$$\begin{aligned} U(0,t) &= |U(0,t)| \cdot e^{i\phi t} \\ &= |U(0,t)| \cdot e^{i\left[\phi_0 + \frac{\partial\phi}{\partial t}(t-t_0) + \frac{1}{2}\frac{\partial^2\phi}{\partial t^2}(t-t_0)^2\right]\cdot t} \\ &= |U(0,t)| \cdot e^{\left[-\frac{iC}{2}\cdot\frac{t^2}{t_0^2}\right]} \end{aligned} \tag{6}$$

$$\phi(t) = \left[\phi_0 - \delta w(t-t_0) - \frac{1}{2}\frac{d\delta w}{dt}(t-t_0)^2\right]\cdot t = -\frac{C}{2}\frac{t^2}{t_0^2} \tag{7}$$

where ϕ is the phase of $U(0,t)$ and t_0 represents the gain-switching FPLD pulsewidth. The frequency change is related to the phase derivative given by

$$\delta w = \frac{\partial\phi}{\partial t} = -\frac{C}{2}\cdot 2\cdot\frac{t}{t_0^2} = -C\cdot\frac{t}{t_0^2} \Rightarrow \frac{d\delta w}{dt} = \frac{\partial^2\phi}{\partial t} = -C\frac{1}{t_0^2} \Rightarrow C = -\delta w\cdot\frac{t_0^2}{t} \approx \frac{\delta w}{\Delta t}\cdot t_0^2. \tag{8}$$

With a chirp parameter analyzer, the maximum deviation of the chirped frequency (defined as $\delta\omega$) are -10.7 and -11.8 GHz within the pulse durations of 24 and 19 ps at bias currents of 12 and 15 mA, which corresponds to an increment on the negative chirp parameter by 10%. In principle, the frequency chirp of the FPLD is $\Delta\nu(t) = [d\phi(t)/dt]/2\pi = -\alpha[dlnP_{\rm out}(t)/dt]/4\pi$ [22], where ϕ is the phase of the output electric field and $P_{\rm out}(t)$ is the output power of the gain-switching FPLD, respectively. Since the pulse on/off extinction ratio is positively proportional to the bias current of the gain-switching FPLD, the dynamic chirp of the OEO-driven gain-switching pulse therefore shows a similar trend. Nonetheless, the linewidth enhancement factor concurrently decreases with increasing bias, which plays a less pronounced role than the pulse on/off extinction ratio for chirp degradation. Under a constant gain-switching FPLD bias of 15 mA, the chirp can be reduced by increasing the output power of the EDFA in the OEO feedback loop from -4.9 to -1.5 dBm. In brief, both the pulsewidth and timing jitter are decreased by increasing the bias current and by the remaining constant EDFA gain, whereas the pulse on/off extinction ratio and chirp parameter arise accordingly.

In view of previous reports, most research was focused on either the optical pulse-train or the microwave signal generated from such kinds of self-started OEOs using different methods. There are only two groups simultaneously discussing the parametric performances of optical pulse-train and microwave signals [10], [14], but neither one discussed the possibility of the RZ-OOK data generation in reports. To compare, Table I lists the parameters regarding the performance of the optical pulse-train and the microwave clock generated using different methods. At the same repetition rate of 10 GHz, our proposed approach shows a shorter pulsewidth (19 ps), a lower timing jitter (0.424 ps), a higher CNR (53 dB), and a better SSB phase noise (-131.8 dBc/Hz) than previous studies. Moreover, the on/off extinction ratio of the RZ pulsed carrier generated from such a self-started OEO driven gain-switching FPLD is preliminarily reported. Up to now, there is no demonstration on the RZ-OOK data-stream generation by using the synthesizer-free OEO driven gain-switching FPLD beyond 10 GHz.

In contrast to the FPLD based all-optical NRZ-to-RZ data format conversion technology reported previously [23], [24], the proposed optical RZ-OOK data generator is not only a completely synthesizer-free and self-pulsating architecture, but also an electrical-to-optical OOK transmitter without the need of addition injection from the dropped optical NRZ data stream.

TABLE I
PARAMETRIC COMPARISON ON THE OPTICAL PULSE-TRAIN AND THE MICROWAVE CLOCK GENERATED USING DIFFERENT METHODS

	Lasri et al. [10]	Hasegawa et al. [14]	Our case
Method	DFBLD-EAM	VCSEL	FPLD
Repetition Rate	10 GHz	10 GHz	10 GHz
Pulsewidth	20 ps	32 ps	19 ps
Timing jitter	-	1.2 ps	0.424 ps
Pulse on/off ER	-	-	7.7 dB
CNR	-	49.5 dB	53 dB
SSB phase noise at 10 MHz offset	-123 dBc/Hz	-90 dBc/Hz	-131.8 dBc/Hz

No matter the data format generator or convertor requires a microwave clock for driving the PRBS data generator, which is bulky and cost ineffective. The proposed RZ-OOK scheme is exempt from the use of a synthesizer, electrical RZ generator, and external optical injection in current optical NRZ-to-RZ converters. Future development on such kinds of self-started OEO triggered FPLDs will offer a new approach to the synthesizer-free optical clock and RZ-OOK data generation.

IV. CONCLUSION

Without using any external signal generators, we have demonstrated the self-started microwave clock and RZ pulsed carrier from a gain-switching FPLD at 1550 nm, which is achieved by using a self-feedback configured OEO to function as a synthesizer-free RZ-OOK data generator at 10 Gbit/s. Such a self-feedback gain-switching operation essentially overcomes the electrical modulation bandwidth of the commercial FPLD below 4 GHz. With continuous feedback and large gain in the feedback loop, the OEO driven gain-switching FPLD pulse-train repeated at 10 GHz is generated with shortened pulsewidth, timing jitter, and pulse on/off extinction ratio of 19 ps, 424 fs, and 7.7 dB, respectively. The chirp parameter and linewidth enhancement factor of the OEO driven gain-switching FPLD pulse are -0.22 and 12.8, respectively. The timing jitter in terms of laser modulation bandwidth in the OEO feedback loop is analyzed, and the self-started pulse on/off extinction ratio can be promoted by decreasing the EDFA gain and increasing the FPLD bias. For the OEO driven gain-switching FPLD, the measured output power can be as high as 23 dBm, and the SSB phase noise at 10-MHz frequency offset is as low as -131.8 dBc/Hz. The related CNR and the harmonics suppression ratio are determined as 60–65 and 52 dB, respectively. The OEO triggered gain-switching FPLD can generate RZ pulsed carrier with the lowest phase noise and jitter comparable to a commercial synthesizer in which the pulse on/off extinction ratio is greatly enhanced and the chirp can be minimized concurrently.

REFERENCES

[1] J. Lasri, P. Devgan, R. Tang, and P. Kumar, “Self-starting optoelectronic oscillator for generating ultra-low-jitter high-rate (10 GHz or higher) optical pulses,” *Opt. Exp.*, vol. 11, no. 12, pp. 1430–1435, June 2003.
[2] M. F. Lewis, “Novel RF oscillator using optical components,” *Electron. Lett.*, vol. 28, no. 1, pp. 31–32, Jan. 1992.
[3] X. S. Yao and L. Maleki, “Optoelectronic microwave oscillator,” *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 3, no. 8, pp. 1725–1735, Aug. 1996.

[4] Y. Ji, X. S. Yao, and L. Maleki, "Compact optoelectronic oscillator with ultralow phase noise performance," *Electron. Lett.*, vol. 35, no. 18, pp. 1554–1555, Sep. 1999.

[5] R. Th. Kersten, "Ein optisches Nachrichtensystem mit Bauelementen der integrierten Optik für die Übertragung hoher Bitraten," *Arch. Elektrotech.*, vol. 60, no. 6, pp. 353–359, Sep. 1978.

[6] H. F. Schlaak, A. Neyer, and W. Sohler, "Electrooptical oscillator using an integrated cutoff modulator," *Opt. Commun.*, vol. 32, no. 1, pp. 72–74, Oct. 1980.

[7] T. C. Damen and M. A. Duguay, "Optoelectronic regenerative pulser," *Electron. Lett.*, vol. 16, no. 5, pp. 166–167, Feb. 1980.

[8] C. Lin, P. L. Liu, T. C. Damen, D. J. Eilenberger, and R. L. Hartman, "Simple picosecond pulse generation scheme for injection lasers," *Electron. Lett.*, vol. 16, no. 15, pp. 600–602, Jul. 1980.

[9] X. S. Yao and L. Maleki, "Multiloop optoelectronic oscillator," *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[10] J. Lasri, P. Devgan, R. Tang, and P. Kumar, "Ultralow timing jitter 40-Gb/s clock recovery using a self-starting optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 16, no. 1, pp. 263–265, Jan. 2004.

[11] D. H. Chang, H. R. Fetterman, H. Erlig, H. Zhang, M. C. Oh, C. Zhang, and W. H. Steier, "39-GHz optoelectronic oscillator using broad-band polymer electrooptic modulator," *IEEE Photon. Technol. Lett.*, vol. 14, no. 2, pp. 191–193, Feb. 2002.

[12] T. Sakamoto, T. Kawanishi, and M. Izutsu, "Optoelectronic oscillator using a $LiNbO_3$ phase modulator for self-oscillating frequency comb generation," *Opt. Exp.*, vol. 31, no. 3, pp. 811–813, Mar. 2006.

[13] W. Zhou and G. Blasche, "Injection-locked dual opto-electronic oscillator with ultra-low phase noise and ultra-low spurious level," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, pp. 929–933, Mar. 2005.

[14] H. Hasegawa, Y. Oikawa, and M. Nakazawa, "A 10-GHz optoelectronic oscillator at 850 nm using a single-mode VCSEL and a photonic crystal fiber," *IEEE Photon. Technol. Lett.*, vol. 19, no. 19, pp. 1451–1453, Oct. 2007.

[15] S. Bigo, E. Desurvire, S. Gauchard, and E. Brun, "Bit-rate enhancement through optical NRZ-to-RZ conversion and passive time-division multiplexing for soliton transmission systems," *Electron. Lett.*, vol. 30, no. 12, pp. 984–985, Jun. 1994.

[16] D. Norte and A. E. Willner, "Demonstration of an all-optical data format transparent WDM-to-TDM network node with extinction ratio enhancement for reconfigurable WDM networks," *IEEE Photon. Technol. Lett.*, vol. 8, no. 5, pp. 715–717, May 1996.

[17] Y. C. Keh and M. K. Park, "High speed TO-CAN based optical module," U.S. Patent 200401266A1, Jun. 6, 2006.

[18] P. P. Vasil'ev, *Ultrafast Diode Lasers: Fundamentals and Applications*. Norwood, MA: Artech House, 1995, ch. 3.

[19] M. Osinski and M. Adams, "Picosecond pulse analysis of gain-switched 1.55 μm InGaAsP laser," *IEEE J. Quantum Electron.*, vol. 21, no. 12, pp. 1929–1936, Dec. 1985.

[20] G. P. Agrawal, *Fiber-Optic Communication Systems*. New York: Wiley, 1992, ch. 3.

[21] K. K. Gupta, D. Novak, and H. F. Liu, "Noise characterization of a regeneratively mode-locked fiber ring laser," *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 70–78, Jan. 2000.

[22] P. A. Yazaki, K. Komori, S. Arai, A. Endo, and Y. Suematsu, "Chirping compensation using a two-section semiconductor laser amplifier," *J. Lightw. Technol.*, vol. 10, no. 9, pp. 1247–1255, Sep. 1992.

[23] C. C. Lin, H. C. Kuo, P. C. Peng, and G.-R. Lin, "Chirp and error rate analyses of an optical-injection gain-switching VCSEL based all-optical NRZ-to-PRZ converter," *Opt. Exp.*, vol. 16, no. 7, pp. 4838–4847, Mar. 2008.

[24] Y. C. Chang, Y. H. Lin, J. H. Chen, and G.-R. Lin, "All-optical NRZ-to-PRZ format transformer with an injection-locked Fabry-Perot laser diode at unlasing condition," *Opt. Exp.*, vol. 12, no. 19, pp. 4449–4456, Sep. 2004.

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