Direct Optical Injection Locking of InP/InGaAs HPT Oscillator ICs for Microwave Photonics and 40-Gbit/s-Class Optoelectronic Clock Recovery

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***Abstract*—This paper presents fully monolithically integrated 10- and 39-GHz-band InP/InGaAs heterojunction phototransistor (HPT) oscillators that can be optically injection locked by directly illuminating the HPT. When optical signals are modulated by fundamental frequencies around free-running oscillations, the 10-GHz-band HPT oscillator integrated circuit (IC) achieves an ultra-wide locking range of 1401 MHz (relative bandwidth of 13.6%), and the 39-GHz-band HPT oscillator IC achieves a wide locking range of 768 MHz, which are records among the indirect and/or direct optical injection-locked oscillators reported to date. The 10-GHz-band HPT oscillator IC also achieves very wide locking ranges of 618 and 160 MHz for third and fifth subharmonic modulated optical signal injection, respectively, which is very useful for microwave photonics applications. Optoelectronic clock recovery for optical transmission systems was tested by using the 39-GHz-band HPT oscillator IC and a planar lightwave circuit Mach–Zehnder interferometer. A 38.8-GHz electrical clock signal was successfully extracted from 38.8-Gbit/s nonreturn-to-zero optical data streams. To our knowledge, the 38.8-GHz clock frequency is the highest ever reported as a clock extraction by a fundamental oscillation spectrum for optical injection-locked oscillators.**

***Index Terms*—Clock recovery, heterojunction bipolar transistor (HBT), injection-locked oscillator, microwave photonics, optical-fiber communication, optoelectronic integrated circuit.**

I. Introduction

OPTICAL injection locking of an electrical oscillator [1]–[7], which allows us to synchronize the frequency and phase of a free-running oscillator to the modulated optical signal, is very attractive for components in both microwave photonics and optical transmission systems. In microwave photonics applications, the local oscillator (LO) embedded in the radio base station [8] could be significantly simplified. In optical transmission systems, the application of an optoelectronic clock-recovery circuit [4]–[6], which is much simpler and more suitable for higher bit-rate equipment than a fully electrical circuit, is expected.

There are two types of optical injection-locked oscillator (OILO): the direct type and indirect type. A direct optical injection-locked oscillator (D-OILO) [1]–[5], whose active oscillator device (heterojunction bipolar transistor (HBT), etc.) itself is directly illuminated for synchronization, is widely preferred. This is because this type is much simpler and more suitable for monolithically integration than an indirect one [6], [7], which needs an external photodetector.

One of the most important characteristics required for an OILO is a wide locking range. This is because the free-running oscillation frequency of a practical electrical oscillator, especially in a low-Q monolithic integration, varies widely due to the fabrication process and temperature fluctuations. Therefore, a locking range at least wider than the oscillation frequency fluctuation is required for practical use. The locking range for electrical ILOs, Δf, is expressed as [9]

$$\Delta f = \frac{f\mathrm{osc}}{Q\mathrm{ext}}\left(\frac{P\mathrm{inj}}{P\mathrm{osc}}\right)^{1/2} \quad (1)$$

where $f\mathrm{osc}$ is the oscillation frequency, $Q\mathrm{ext}$ is the external quality factor, $P\mathrm{inj}$ is the electrical injection power, and $P\mathrm{osc}$ is the oscillation power.

For a D-OILO, $P\mathrm{inj}$ corresponds to the generated RF power from the photodetection of the active oscillator device itself. Therefore, it is very difficult to achieve a microwave/millimeter-wave D-OILO with a wide locking range because both high maximum oscillation frequency ($f_{\max}$) and excellent photodetection characteristics (efficiency, bandwidth, etc.) are required for the active oscillator device. To solve this problem, we developed D-OILOs using heterojunction phototransistors (HPTs) [1], [4], [5]. The locking ranges of our D-OILOs approach the best results obtained by an indirect OILO [7]. We have also reported the first-ever clock extraction from nonreturn-to-zero (NRZ) optical data streams [4] and considerable widening of the locking range by combining a D-OILO with a planar lightwave circuit Mach–Zehnder interferometer (PLC–MZI) EX–OR [5]. In addition, error-free clock and data recovery (CDR) operation for a 10-Gbit/s NRZ $2^{31}-1$ pseudorandom bit sequence (PRBS) data signal has been achieved [10].

This paper presents 10- and 39-GHz-band D-OILO integrated circuits (ICs) utilizing an InP/InGaAs HPT [4], [5]. Firstly, photoresponses of an InP/InGaAs HPT are discussed from the D-OILO application point-of-view. Next, the performance of the 10-GHz-band D-OILO IC is discussed for a

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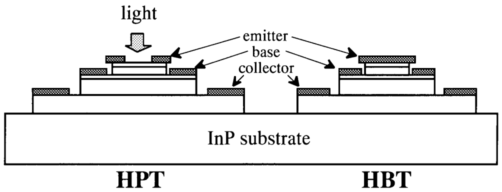

Fig. 1. Cross-sectional view of a top-illuminated HPT and HBT.

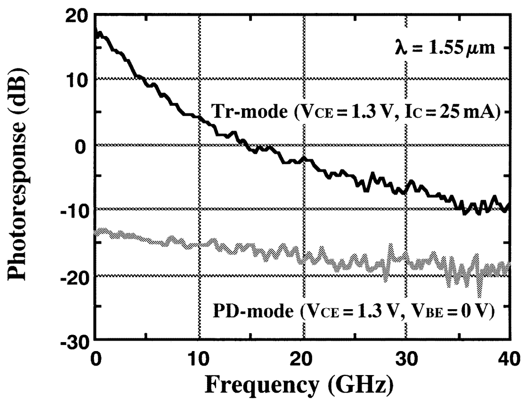

Fig. 2. Measured photoresponses of the HPT. Photoresponse $= 20 * \log[R]$, where R is in unit of A/W.

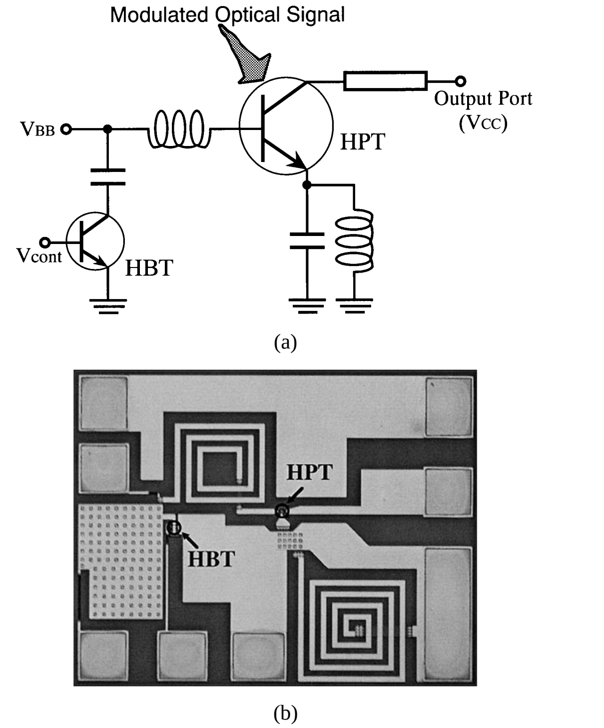

Fig. 3. Circuit diagram and microphotograph of the 10-GHz-band HPT D-OILO IC. (a) Circuit diagram. (b) Microphotograph. Chip size: 0.7 mm × 0.54 mm.

microwave photonics application. In such an application, a subharmonic injection-locking ability is important because the transmission frequency in a fiber-optic microwave link can be decreased as the subharmonic factor increases. Therefore, the costly high-speed laser diode (LD) or external optical modulator can be eliminated in an optical transmitter. Finally, application of the 39-GHz-band D-OILO IC to optoelectronic clock extraction is presented to demonstrate 40-Gbit/s-class optoelectronic clock recovery. The configuration for and principle of the optoelectronic clock recovery is described in detail. A 38.8-GHz electrical clock signal was successfully extracted from 38.8-Gbit/s NRZ optical data streams by using the 39-GHz-band D-OILO IC and a PLC–MZI.

II. InP/InGaAs HPT PERFORMANCE

Fig. 1 is a cross-sectional view of the top-illuminated HPT, which is fully compatible with the high-performance InP/InGaAs HBT [11]. Such layer compatibility enables us to achieve an HPT with both high $f_{\max}$ and an excellent photodetection characteristic [4]. Fig. 2 shows the measured photoresponses of the fabricated HPT, whose emitter and photo-coupling window are 34 μm^2 and 5 μmϕ in size. Photoresponses were measured by using a Cascade Microtech lightwave probe and an HP83467C lightwave component analyzer ($\lambda = 1.55$ μm). The two curves (PD and Tr modes) were obtained from the same HPT when the base was 50 Ω terminated using different bias conditions. The collector load resistor was 50 Ω. The PD mode was measured in which the base and emitter were shorted, and $V_{\rm CE}$ $(V_{\rm CB})$ $=$ 1.3 V and the photocurrent was 60 μA. Therefore, it corresponds to the photoresponse for base/collector-junction photodiode operation. The dc responsivity of the PD mode is 0.22 A/W. The bias condition of the Tr mode was $V_{\rm CE} = 1.3$ V and $I_C = 25$ mA. The difference between the Tr and PD modes represents internal gain. The internal gains are approximately as high as 20 dB (at 10 GHz) and 10 dB (at 40 GHz), respectively. This is due to the HPT's excellent RF characteristics (f_T: 153 GHz, $f_{\max}$: 94 GHz). This extremely high internal gain is very effective for widening the locking range of the D-OILO through the increase in Pinj in (1). Although Pinj could be increased by increasing optical input power, the large internal gain greatly reduces the optical input power required. This optical power reduction ability is effective in keeping Pinj high without dc saturation of the HPT. Therefore, we can achieve millimeter-wave D-OILOs with a wide locking range by using the HPT. Another excellent feature of the HPT is that it is quite easy to monolithically integrate it with ultrahigh-speed digital/analog circuits that use the HBT [4].

III. OPTICAL INJECTION-LOCKING PERFORMANCE OF HPT D-OILO IC

A. 10-GHz-Band HPT D-OILO IC

A 10-GHz-band D-OILO IC utilizing the HPT described above was designed and fabricated. Fig. 3(a) and (b) shows a circuit diagram and microphotograph of the IC, respectively. The chip size is only 0.7 mm × 0.54 mm. This circuit is based on the common-emitter series feedback configuration. The HBT in the feedback circuit is utilized as a variable resistor to control the free-running oscillation frequency and quality factor of the oscillator circuit [1], [5]. Passive components consist of spiral inductors and metal–insulator–metal (MIM) capacitors. A collector bias for the HPT (Vcc) was supplied through an external bias tee attached at the RF output port. The

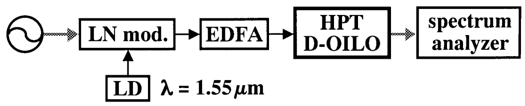

Fig. 4. Optical injection-locking measurement setup.

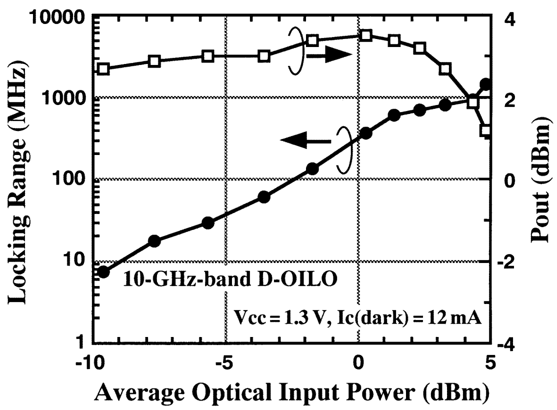

Fig. 5. Measured locking range and $Pout$ versus $Popt$ at fundamental (around 10 GHz) signal injection.

bias voltage for the HBT ($V\mathrm{cont}$) was kept constant throughout the measurements.

Optical injection locking was measured using the experimental setup shown in Fig. 4. The fundamental (around 10 GHz) or subharmonic signals from the signal source modulated the 1.55-μm optical output from the LD at the $LiNbO_3$ (LN) Mach–Zehnder optical intensity modulator ($V\pi = 4.1$ V @ 1 kHz, optical 3-dB bandwidth $= 19.3$ GHz). The modulated optical signal then directly illuminated the HPT in the D-OILO IC on a wafer after the intensity was adjusted by the Erbium-doped fiber amplifier (EDFA). The RF power input to the LN modulator was kept constant at $+18$ dBm. LN modulator bias was adjusted at around $0.5 \times V\pi$ by using a monitor photodetector so as to maximize the detected power at the input modulation frequency. The output signal was observed with a spectrum analyzer.

Fig. 5 shows the measured locking range and output power as a function of average optical input power ($P\mathrm{opt}$) when a fundamental (around 10 GHz) optical modulation signal was input at $Vcc = 1.3$ V. An extremely wide locking range of 1401 MHz (relative bandwidth of 13.6%) is achieved at the $P\mathrm{opt}$ of $+4.8$ dBm. This locking range is state-of-the-art for indirect and/or direct OILOs reported to date [7]. Even when the $P\mathrm{opt}$ is reduced to -3.6 dBm, the locking range is still as wide as 61 MHz. The output power of over $+1.2$ dBm was obtained for all the $P\mathrm{opt}$ values. The output power increased to approximately $+9$ dBm when $Vcc = 2$ V. Fig. 6 shows the spectrum for the locking condition observed with the maximum hold function of the spectrum analyzer. The spectra for two unlocking cases when an out-of-locking frequency was injected are also shown. The D-OILO output is nearly flat across the locking bandwidth without notable spurious signals.

Fig. 7 shows the measured locking range when subharmonically modulated optical signals were input at the $P\mathrm{opt}$ of $+4.8$ dBm. Data from even-order subharmonic injection are omitted here because these were very sensitive to the bias voltage change of the LN modulator. Extremely wide locking ranges of 618 and 160 MHz are achieved at 10-GHz-band frequencies for third subharmonic (around 3.5-GHz input) and fifth subharomonic (around 2.1-GHz input) injection, respectively. These subharmonic injection-locking abilities enable us to greatly reduce the modulation frequency of the optical transmitter for microwave photonics systems. Therefore, we can achieve a cost-effective and simple fiber-optic microwave link component to implement a remote LO in a radio base station [8].

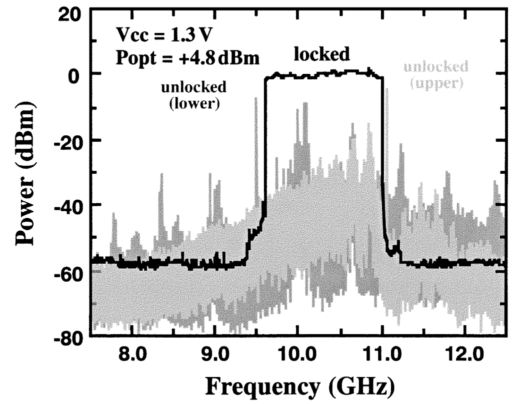

Fig. 6. Spectra under locking and unlocking conditions at fundamental (around 10 GHz) signal injection.

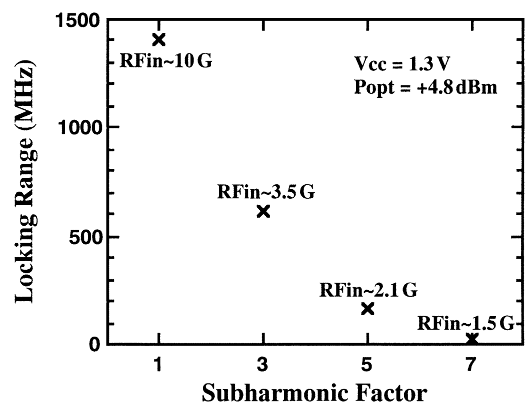

Fig. 7. Locking range versus the subharmonic factor.

B. 39-GHz-Band HPT D-OILO IC

A 39-GHz-band D-OILO IC utilizing the HPT described above was designed and fabricated. Fig. 8(a) and (b) shows a circuit diagram and microphotograph of the IC, respectively. The chip size is only 0.6 mm $\times$ 0.5 mm. This circuit is also based on the common-emitter series feedback configuration, but without a variable resistor HBT. Passive components are coplanar waveguides and MIM capacitors.

Fig. 9 shows the measured locking frequency edge (lower and upper) versus $P\mathrm{opt}$ when a fundamental (around 39 GHz) optical modulation signal was input at $Vcc = 1.3$ V. The wide locking range of 768 MHz is achieved at the $P\mathrm{opt}$ of $+5.8$ dBm. This is 54 times wider than that obtained by a 38-GHz-band InP HEMT D-OILO [3]. The output power was $+0.5$ dBm at $Vcc = 1.3$ V.

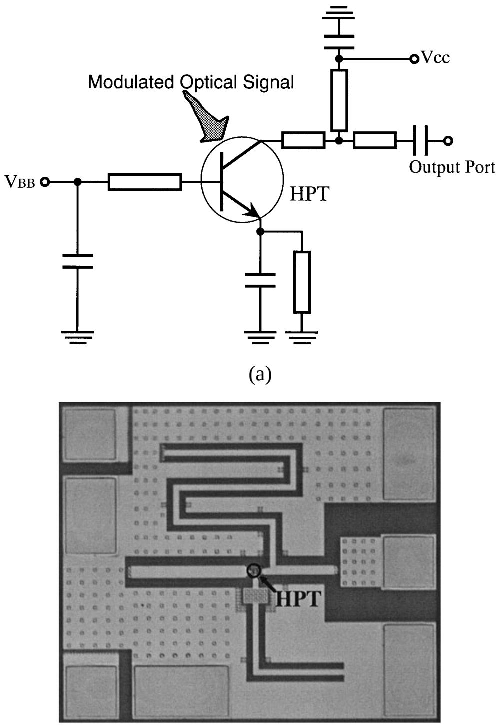

Fig. 8. Circuit diagram and microphotograph of the 39-GHz-band HPT D-OILO IC. (a) Circuit diagram. (b) Microphotograph. Chip size: 0.6 mm × 0.5 mm.

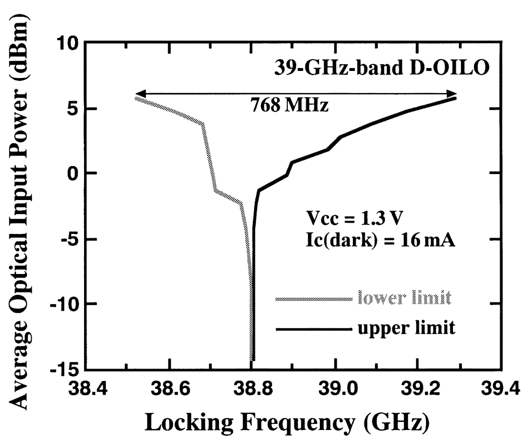

Fig. 9. Measured locking frequency edge versus $P\mathrm{opt}$.

Fig. 10 shows measured phase noises at 10-, 50- and 100-kHz off-carrier versus $P\mathrm{opt}$ when an optically modulated 38.8-GHz signal was input. Those of the signal source utilized in the measurements are also shown. Phase noise degradation from the signal source is less than 1.4 dB in the $P\mathrm{opt}$ range of over -6.4 dBm. Therefore, we can expect a low-jitter performance for clock-recovery application.

IV. Clock-Recovery Application

A. Configuration and Principle of the Optoelectronic Clock-Recovery Circuit

Direct clock extraction from NRZ signal at the data-rate frequency is quite difficult because there is no power spectrum at

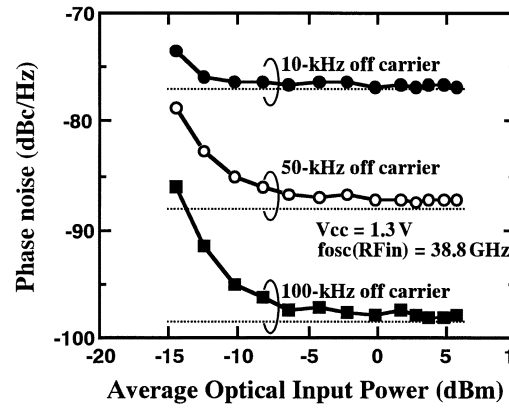

Fig. 10. Phase noise characteristics versus $P\mathrm{opt}$. Dashed lines represent phase noises of the signal source utilized in the measurements.

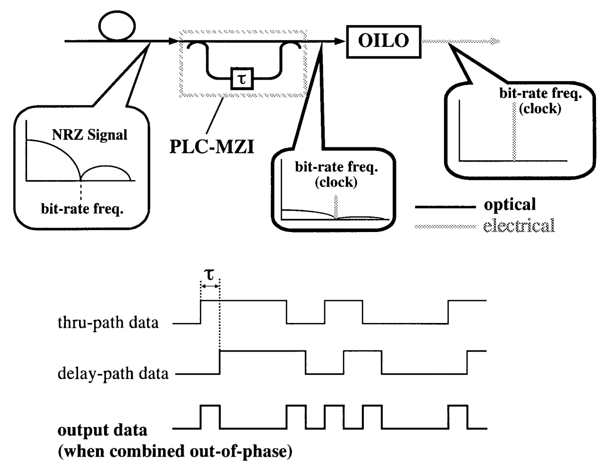

Fig. 11. Optoelectronic clock-recovery circuit combining PLC–MZI and OILO for NRZ-format optical transmission systems.

that frequency. Fig. 11 shows our optoelectronic clock-recovery circuit [5], [10]. When half-bit delayed data is combined with thru-path data out-of-phase in an optical carrier, the PLC–MZI works as an edge detector due to the subtraction function, as shown in the time chart. Therefore, the clock signal component can be generated from the NRZ optical data stream. When the clock frequency is within the locking range of the OILO, the electrical clock signal can be successfully extracted.

We have already reported successful extraction of 10-GHz-band electrical clock signals from 10-Gbit/s-class NRZ PRBS optical data streams by combining the 10-GHz-band D-OILO IC and a PLC–MZI with delay time $\tau = 50$ ps [10], and extremely low jitter and high output voltage swing characteristics with error-free CDR operation for the $2^{31} - 1$ PRBS data signal were achieved. Here, the experimental results for the 39-GHz-band D-OILO IC and a PLC–MZI with delay time $\tau = 12.5$ ps, which is suitable for clock extraction from the 40-Gbit/s-class NRZ signal, are presented to demonstrate 40-Gbit/s-class optoelectronic clock recovery.

Fig. 12 shows the experimental setup. NRZ PRBS data streams of approximately 39 Gbit/s are generated from a pulse pattern generator (PPG), then the data signal is amplified by a 40-Gbit/s driver amplifier (SHF 806P). The 1.55-μm-band optical carrier from a wavelength variable LD is modulated

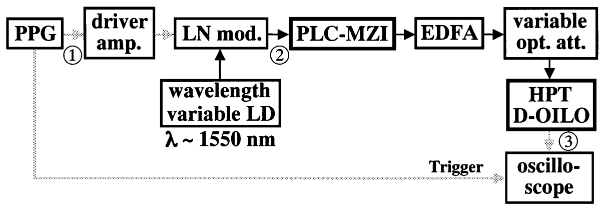

Fig. 12. Experimental setup for clock extraction.

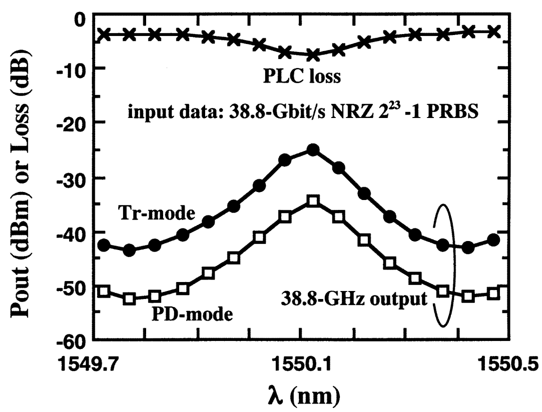

Fig. 13. PLC insertion loss and photodetected output from discrete HPT as a function of wavelength. Input optical signal is 38.8-Gbit/s NRZ $2^{23}-1$ PRBS.

by the data signal at the same LN optical modulator described in Section III. The modulated optical signal is input to the PLC–MZI, and the output optical signal is then amplified by an EDFA. After its intensity is adjusted with a variable optical attenuator, the HPT in the D-OILO IC is illuminated directly. The output electrical signal is observed with a digitizing sampling oscilloscope triggered by the PPG.

Firstly, the PLC–MZI EX–OR effect was evaluated. Fig. 13 shows the measured optical insertion loss of the PLC–MZI as a function of wavelength. The input optical signal was modulated by a 38.8-Gbit/s NRZ $2^{23}-1$ PRBS data. The temperature of the PLC–MZI module was kept constant (49.5 °C) during measurements. The maximum insertion loss is observed at the wavelength of 1550.12 nm. This means that delay- and thru-path optical carriers are out-of-phase at 1550.12 nm. Therefore, we can expect a maximum EX–OR effect at 1550.12 nm when the module temperature is 49.5 °C. The optimal optical wavelength is not limited to this particular one. It can be changed by adjusting the Peltier heater embedded in the PLC–MZI module.

Next, the output optical signal from the PLC–MZI was photodetected by the discrete HPT described above. An input optical signal was modulated by a 38.8-Gbit/s NRZ $2^{23}-1$ PRBS data. The temperature of the PLC–MZI module was kept constant (49.5 °C) during measurements. Fig. 13 also shows the photodetected 38.8-GHz output power from the discrete HPT under both Tr- and PD-mode bias conditions as a function of wavelength. The illuminated average optical input power was kept constant at +3.6 dBm for all wavelengths by adjusting the variable optical attenuator. As expected, a maximum photodetected output power was achieved at the wavelength of 1550.12 nm. This confirmed that a clock frequency signal component was successfully generated and its power enhanced by the PLC–MZI. The difference between the Tr and PD modes

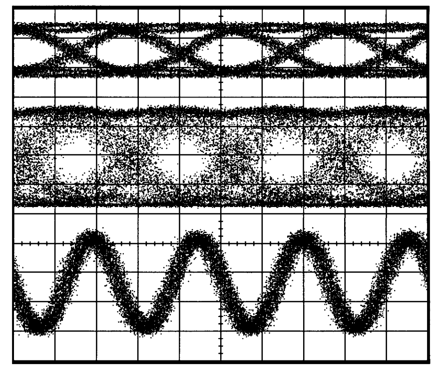

Fig. 14. Input and output waveforms. Upper: input ① (38.8-Gbit/s NRZ $2^{23}-1$ PRBS data signal) 500 mV/div., 10 ps/div. Middle: input ② (photodetected data signal) 100 mV/div., 10 ps/div. Lower: output ③ (38.8-GHz extracted clock signal) 200 mV/div., 10 ps/div.

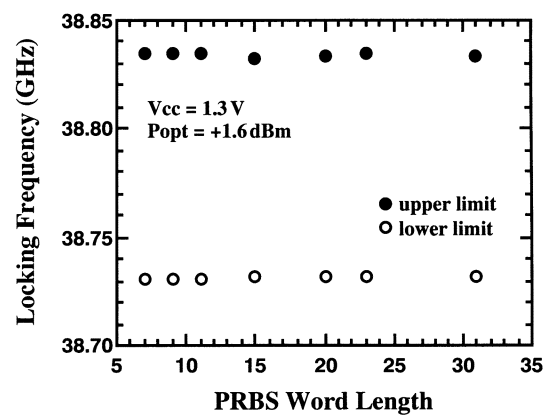

Fig. 15. Locking frequency edge versus PRBS word length (from 2^7-1 to $2^{31}-1$).

is internal gain, which corresponds to the difference shown in Fig. 2.

B. Clock Extraction From 40-Gbit/s-Class NRZ Optical Data Stream

Clock extraction was evaluated by combining the PLC–MZI with delay time $\tau = 12.5$ ps (described above) and the 39-GHz-band HPT D-OILO IC in the experimental setup shown in Fig. 12. The optical wavelength was set to 1550.12 nm, where the maximum EX–OR effect was obtained at the module temperature of 49.5 °C.

Fig. 14 shows the input and output waveforms when a clock signal is extracted from a 38.8-Gbit/s NRZ $2^{23}-1$ PRBS optical data stream. The upper waveform represents the 38.8-Gbit/s data signal from the PPG at ① in Fig. 12. The middle waveform represents the photodetected 38.8-Gbit/s data signal at ② in Fig. 12 by a unitraveling-carrier photodiode module with a 3-dB bandwidth of over 50 GHz. The eye opening is not very large because performances of the driver amplifier and the LN modulator are insufficient for 40-Gbit/s-class optical modulation. The lower waveform represents the electrical clock signal extracted by the 39-GHz-band HPT D-OILO IC at ③ in Fig. 12 when $P\mathrm{opt} = +1.6$ dBm. A 38.8-GHz clock signal synchronized to the input data signal was successfully obtained with a high-output voltage swing of 714 mVp-p at $Vcc = 1.3$ V.

This output swing is high enough to drive digital circuits directly. These characteristics are applicable to 40-Gbit/s-class CDR equipment that operates with a data-rate clock signal. Jitter was not measured. However, the oscillator has low phase-noise characteristics, as already shown in Fig. 10.

Fig. 15 shows the measured locking range as a function of PRBS word length at a $P\mathrm{opt}$ of $+1.6$ dBm. Nearly constant locking range is achieved up to $2^{31}-1$ PRBS. Locking ranges are slightly smaller than those for the optical sinusoidal input shown in Fig. 9. This is most likely due to the insufficient performance of the optical transmitter (driver amplifier and LN modulator) for 40-Gbit/s-class optical modulation utilized in the measurements.

V. Conclusion

This paper has presented fully monolithically integrated 10- and 39-GHz-band InP/InGaAs HPT D-OILOs with an extremely wide locking range. Subharmonic optical injection locking ability enables us to implement a compact and cost-effective LO in a radio base station and a fiber-optic subharmonic signal transmission link for synchronization of the LO. A 38.8-GHz clock extraction from 38.8-Gbit/s NRZ optical data stream has been achieved by combining a PLC–MZI and the 39-GHz-band HPT D-OILO IC. To our knowledge, this is the highest frequency ever reported as a clock extraction by the fundamental oscillation spectrum for OILOs. The HPT D-OILO IC promises to lead to 40-Gbit/s-class CDR OEICs that operate with an optoelectronically extracted data-rate clock signal owing to its ability to monolithically integrate an over-40-Gbit/s digital circuit [12] and its extremely wide locking range, low power consumption, high output power, small chip size, and excellent handling ability for consecutive identical digits.

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