10- and 39-GHz-Band InP/InGaAs HPT Direct Optical Injection-Locked Oscillator ICs for Optoelectronic Clock Recovery Circuits

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Abstract - **This paper presents two kinds of direct optical injection-locked oscillator (DOILO) ICs, which utilize an InP/InGaAs HPT that is fully compatible with the high-performance InP/InGaAs HBT fabrication process. A 10-GHz-band DOILO achieves an ultra-wide locking range of 1401 MHz (bandwidth of 13.6 %), which is state-of-the-art for indirect and/or direct OILOs reported to date. A 39-GHz-band DOILO achieves a wide locking range of 768 MHz. Clock extraction from 10-Gbit/s NRZ optical data streams is achieved by combining a DOILO and a planar lightwave circuit Mach-Zehnder interferometer. Error-free performance is confirmed for 2^{31}-1 PRBS data signal for clock and data recovery application.**

I. Introduction

Direct optical injection-locked oscillators (DOILOs) [1]-[5], which allow us to synchronize the frequency and phase of a free-running electrical oscillator to the optical sinusoidal signal by directly illuminating the active oscillator device itself, are expected to be key components in both microwave photonics and optical transmission systems. In the former, the local oscillator embedded in the radio base station [6] could be significantly simplified. In the latter, the application for an optoelectronic clock recovery circuit [4], [5], which is much simpler and consumes less power in comparison with a fully electrical circuit, is expected.

One of the most important characteristics required for DOILOs 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, at least, a locking range wider than the oscillation frequency fluctuation is required for practical use. The locking range for electrical ILOs, Δf, is expressed as [7]

$$\Delta f = \frac{fosc}{Qext}\left(\frac{Pinj}{Posc}\right)^{\frac{1}{2}}, \qquad (1)$$

where Pinj is the electrical injection power. For a DOILO, Pinj corresponds to the photodetected power from the built-in transistor itself. Therefore, it is very difficult to achieve a microwave/millimeter-wave DOILO with wide locking range because both high f_{max} and excellent photodetection characteristics are required for the built-in transistor. To solve this problem, we developed excellent DOILOs using heterojunction phototransistors (HPTs) [1], [4], [5] whose locking range approaches the best results obtained by an indirect OILO [8]. 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 DOILO with a planar lightwave circuit Mach-Zehnder interferometer (PLC-MZI) EX-OR [5]. However, their oscillation frequencies are below 16 GHz and evaluation for clock and data recovery (CDR) application have not been reported to date.

This paper presents 10- and 39-GHz-band DOILO ICs utilizing an InP/InGaAs HPT [4], [5] with extremely wide locking range. Error-free performance for optoelectronic CDR operation is confirmed for the first time.

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 [9]. 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 μm² and 5 μmϕ in size. The PD-mode represents the photoresponse for base/collector junction photodiode operation. Its dc responsivity is 0.22 A/W. The difference between the Tr-mode and PD-mode represents internal gain. The internal gains are

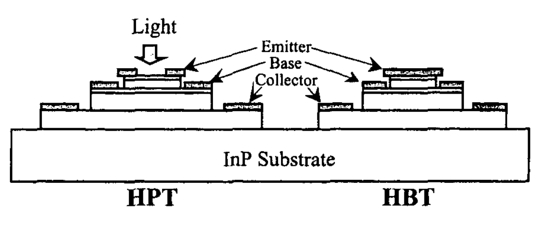

Fig. 1. Cross-sectional view of HPT and HBT.

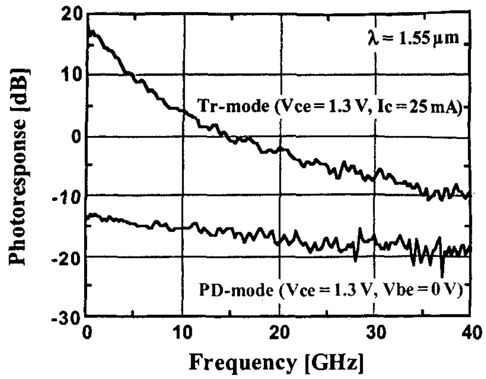

Fig. 2. Measured photoresponse of HPT. Photoresponse=20log[R], where R is in unit of A/W.

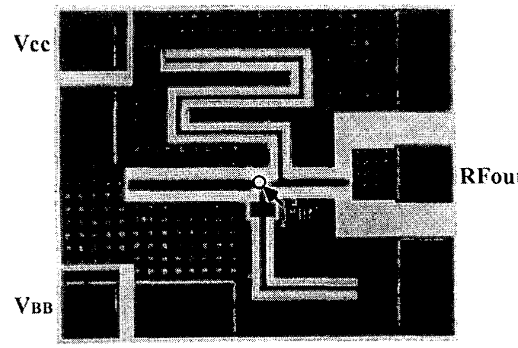

Fig. 3. Microphotograph of 39-GHz-band HPT DOILO IC.

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 DOILO 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 DOILOs 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 by using the HBT [4].

III. Optical Injection Locking Performance of HPT DOILO IC

The 10- and 39-GHz-band DOILO ICs utilizing the HPT described above were designed and fabricated. These circuits are based on the common-emitter series feedback configuration [1], [4]. A microphotograph of the 39-GHz-band DOILO is shown in Fig. 3. Chip size is only 0.6 mm x 0.5 mm.

Optical injection locking was measured using the experimental setup shown in Fig. 4. The 10- or 39-GHz-band signals from the synthesizer modulated the 1.55-μm optical signal from the LD, then the modulated optical signal directly illuminated the HPT in the DOILO IC on a wafer after the intensity was adjusted by the EDFA. 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 (Popt) for the 10-GHz-band IC. An extremely wide locking range of 1401 MHz (bandwidth of 13.6 %) is achieved at the Popt of +4.8 dBm. This locking range is state-of-the-art for indirect and/or direct OILOs reported to date [8]. The output power of over +1.2 dBm was obtained for all the Popt. The output power increased to approximately +9 dBm when Vcc = 2 V. Fig. 6 shows the spectrum for the locking condition observed with a maximum hold function. The spectra for two unlocking cases when an out-of-locking frequency was injected are also shown. The DOILO output is nearly flat across the locking bandwidth without notable spurious signals.

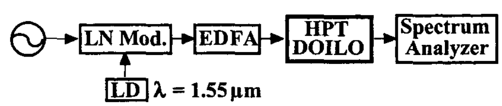

Fig. 4. Optical injection locking measurement setup.

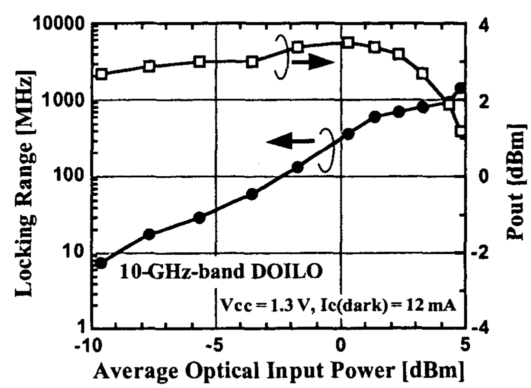

Fig. 5. Measured locking range and Pout versus Popt.

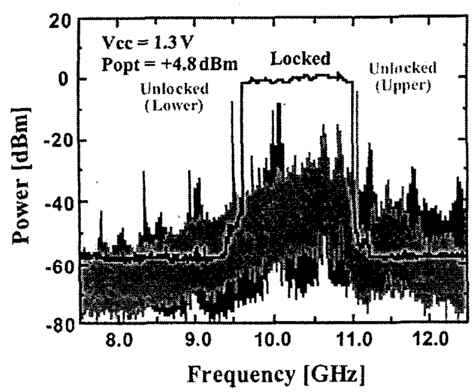

Fig. 6. Spectra for locking and unlocking conditions.

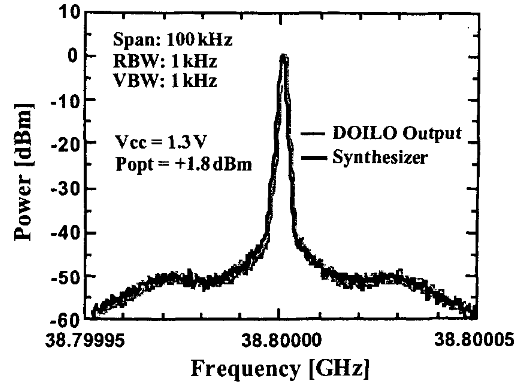

Fig. 8. Spectra of DOILO output and synthesizer.

Fig. 7 shows the measured locking frequency edge (lower and upper) versus Popt for the 39-GHz-band IC. The wide locking range of 768 MHz is achieved at the Popt of +5.8 dBm. This is 54 times wider than that obtained by a 38-GHz-band InP HEMT DOILO [3]. Fig. 8 compares the spectrum of the DOILO output and that for the reference synthesizer directly input to the spectrum analyzer. No notable phase noise degradation is observed. The output power is +0.5 dBm at Vcc = 1.3 V.

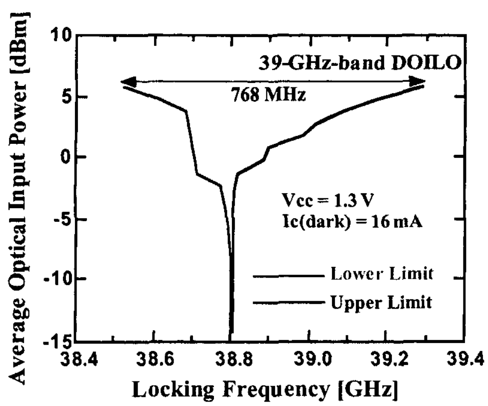

Fig. 7. Measured locking frequency edge versus Popt.

IV. Clock Recovery Application

Fig. 9 shows the optoelectronic clock recovery circuit that can extract electrical clock signal from NRZ optical data streams [5]. If 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 by 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.

Clock extraction was evaluated by combining the PLC-MZI with delay time $\tau = 50$ ps and the 10-GHz-band DOILO IC. Fig. 10 shows the experimental setup. The optical wavelength was set to 1549.95 nm, where a maximum EX-OR effect was obtained [5]. Of course, we can adjust the optimal operating optical wavelength by controlling a peltier heater embedded in the PLC-MZI module.

Fig. 11 shows the input and output waveforms when a 10.664228-Gbit/s NRZ pseudorandom bit sequence (PRBS) optical data signal was input. A 10.664228-GHz clock signal synchronized to the input data signal was successfully obtained with a high output voltage swing of 1.9 $V_{p\text{-}p}$ at Vcc = 2 V. This output swing is high enough to drive digital circuits directly. The measured rms jitter was

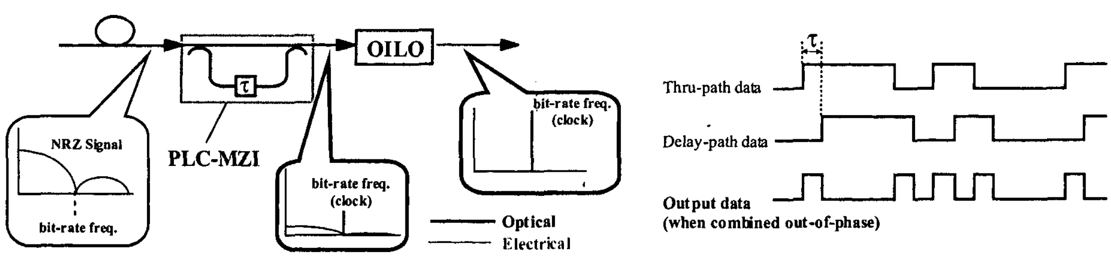

Fig. 9. Optoelectronic clock recovery circuit combining a PLC-MZI and OILO for NRZ-format optical transmission systems.

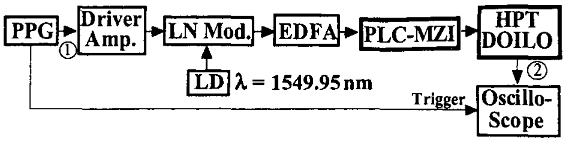

Fig. 10. Experimental setup for clock extraction.

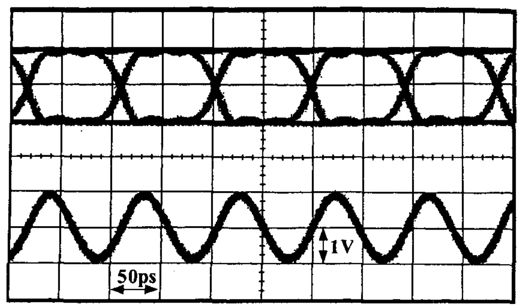

Fig. 11. Input and output waveforms.
Upper: Input ① (10.664228-Gbit/s 2^7-1 NRZ PRBS)
Lower: Output ② (10.664228-GHz extracted clock)

as low as 0.003 UIrms. This is well below the ITU-T standard (0.01 UIrms) for SONET/SDH transmission systems.

CDR operation was evaluated by replacing the oscilloscope with an error detector. $\overline{\text{DATA}}$ from the pulse pattern generator (PPG) was directly input to the error detector for use in the retimed data. A phase shifter was inserted between the PPG and the error detector. Error-free operation (BER<10^{-10}) with sufficient phase margin of over 200 degrees was confirmed for 2^{31}-1 PRBS data signal. For 2^{23}-1 PRBS data signal, error-free operation from 10.0- to 10.95-Gbit/s data signal was also confirmed.

V. Conclusion

Fig. 12 compares our results with the reported data on DOILO ICs. Our results are notable for the wide locking range and higher oscillation frequency. Error-free CDR operation for 10-Gbit/s 2^{31}-1 NRZ PRBS data signal has also been confirmed. To our knowledge, this is the first error-free optoelectronic CDR operation utilizing an OILO clock recovery circuit.

The HPT DOILO ICs promise to realize 40-Gbit/s-class CDR OEICs owing to their ability to monolithically integrate an over-40-Gbit/s digital circuit [10] and their extremely wide locking range, low power consumption, high output power, small chip size, and excellent handling ability for consecutive identical digits.

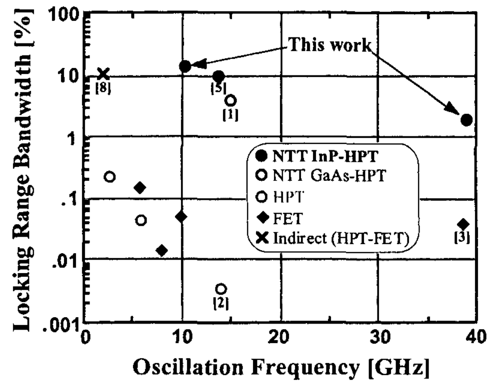

Fig. 12. Locking range bandwidth vs. fosc for DOILO ICs.

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