Direct Optical Injection Locking of InP/InGaAs HPT Oscillator Circuits for Millimeter-Wave Photonics and Optoelectronic Clock Recovery

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Abstract – Features and characteristics of InP/InGaAs HPTs and their application to up to 100-GHz oscillator circuits are presented. The circuits can be optically injection-locked and applied as a clock recovery circuit in a 43-Gbit/s HPT/HBT CDR OEIC.

I. Introduction

Optical injection locking of an electrical oscillator, which allows us to synchronize the frequency and phase of a free-running oscillator to a modulated optical signal, is very attractive for components in both microwave photonics and optical transmission systems. In microwave photonics applications, a remote local oscillator (LO) for radio-on-fiber systems could be significantly simplified. In optical transmission systems, the application of an optoelectronic clock recovery circuit [1], [2] is expected because it is more efficient in terms of power consumption, and more suitable for high-bit-rate equipment than a fully electrical circuit. In particular, a direct optical injection-locking type [1]-[5], whose active oscillator device (a heterojunction phototransistor (HPT)) itself is directly illuminated for synchronization, is widely preferred due to its quite simple configuration and suitability for monolithic integration.

This paper overviews our recent results for optically injection-locked oscillator (OILO) ICs. The ICs use an opto-microwave compatible InP/InGaAs HPT whose layer and fabrication process are fully compatible with an ultrahigh-speed heterojunction bipolar transistor (HBT) [6]. Firstly, the features and characteristics of the high-speed back-illuminated HPT are described. Then, up-to-about 100-GHz HPT oscillator circuits, which can be optically injection-locked and applied for a clock recovery circuit in a 43-Gbit/s HPT/HBT clock and data recovery (CDR) OEIC, are presented.

II. Back-Illuminated InP/InGaAs HPT

For OILO applications, sufficient electrical gain at the oscillation frequency, i.e., a much higher maximum oscillation frequency (f_{max}) than the oscillation frequency, is required for transistors. Good photoresponses (i.e., photodetection plus amplification) at the oscillation frequency are also required in order to increase the locking range through the increase in the photodetected injection power. From these points of view, the opto-microwave-compatible InP/InGaAs HPT [1] is one of the most promising devices. To achieve high f_{max} and fast photoresponse, HPTs must be made smaller while maintaining good photocoupling. The back-illuminated HPT [3]-[5] shown in Fig. 1 can meet these requirements. Owing to the "transparent" InP subcollector, we can effectively guide a 1.3- or 1.55-μm optical signal to the photoabsorption layer (base/collector) through the InP substrate. Therefore, the base/collector beneath the whole emitter area can be effectively illuminated, which enables us to create a smaller HPT with good photocoupling. The photoexcited carrier generation in the base/collector just beneath the emitter is essential for high-speed operation.

We fabricated a back-illuminated HPT that is fully compatible with the high-performance InP/InGaAs HBT fabrication process [6]. The epitaxial layers were grown on 3-inch wafer by metalorganic vapor phase epitaxy. The HPT/HBT has a 70-nm-thick undoped InP emitter, a 50-nm-thick carbon-doped InGaAs base, and a 300-nm-thick InGaAs

![Fig. 1. Cross-sectional view of back-illuminated HPT and HBT.](image-url)
collector. The fabricated back-illuminated HPT has an emitter area (= photocoupling area) of 4 µm φ. For comparison, we fabricated a conventional “top-illuminated” HPT with an emitter area of 34 µm² and photocoupling window of 5 µm φ [1], [2].

After polishing the back of the substrate, the photoresponses were measured on-wafer using an HP83467C lightwave component analyzer (λ = 1.55 µm). Fig. 2 shows the measured photoresponse of the HPTs when they were back-illuminated through the substrate with a spot diameter of 3.6 µm φ. Measurements were performed using two bias conditions when the base was 50-Ω terminated and the collector load resistor was 50 Ω. The PD mode was measured, for which the base and emitter were shorted and VCE (VCB) = 1.3 V. Therefore, the measured photoresponse corresponded to that for base/collector junction photodiode operation. Although both HPTs had exactly the same dc responsivity of 0.25 A/W, the photoresponse at millimeter-wave frequencies was better in the smaller back-illuminated HPT, as expected. The bias condition of the Tr mode was VCE = 1.3 V and IC = 14, 20 mA, respectively, for the back-illuminated and “top-illuminated” HPTs. At frequencies above 15 GHz, the back-illuminated HPT exhibited a higher Tr-mode photoresponse than the conventional “top-illuminated” HPT. The higher photoresponse of the “top-illuminated” HPT in the low-frequency region below 15 GHz is due to the emitter size effect. The measured fmax of the back-illuminated HPT was 144 GHz, while that of the “top-illuminated” HPT was 106 GHz [5]. This indicated that we could achieve OILOs with a higher oscillation frequency and a wider locking range by adopting the back-illuminated HPT.

III. 10-GHz-Band OILO with Wide Locking Range

One of the most important requirements 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. For microwave photonics applications, a subharmonic injection locking ability is also important because it allows to decrease the transmission frequency in a fiber-optic microwave link as the subharmonic factor increases, which results in reducing the cost of the optical transmitter greatly.

We designed and fabricated a 10-GHz-band OILO IC [1] using the top-illuminated HPT (emitter area = 34 µm²; diameter of photocoupling window = 5 µm φ; fmax = 94 GHz). The photodetection internal gain of the HPT is approximately as high as 20 dB at 10 GHz (Fig. 2), thus enabling us to increase the locking range of the 10-GHz-band OILO through the increase in photodetected injection power.

Fig. 3 shows the spectrum in the locking condition observed using the maximum hold function of the spectrum analyzer when the input optical modulation frequency was changed at around 10 GHz. Spectra for two unlocking cases when an out-of-locking frequency was injected are also shown. An extremely wide locking range of 1401 MHz (relative bandwidth of 13.6 %) was achieved, which is a record for indirect and/or direct OILOs reported to date.

The HPT OILO also achieved very wide locking ranges of 618 and 160 MHz for third- and fifth-subharmonic modulated optical signal injection, respectively [1], which should lead to a cost-effective

![Fig. 2. Measured photoresponses of back- and top-illuminated HPTs when photocoupled through the substrate.](image)

![Fig. 3. Spectra under locking and unlocking conditions from the 10-GHz-band OILO at around 10-GHz signal injection.](image)
and simple fiber-optic microwave link component for a remote LO.

IV. 43-Gbit/s HPT/HBT CDR OEIC

One of the prime benefits of our HPT OILO is that it can be quite easily monolithically integrated with state-of-the-art ultrahigh-speed HBT circuits. To demonstrate this, we designed and fabricated a 43-Gbit/s CDR OEIC [2] that integrates a 43-GHz OILO using the top-illuminated HPT and a 43-Gbit/s HBT decision circuit [7]. Fig. 4 is a microphotograph of the fabricated OEIC. For OEIC evaluation, a PLC-MZI with delay time of 12.5 ps was used for the EX-OR operation in the optical domain [1] for optoelectronic clock recovery from nonreturn-to-zero (NRZ) optical data streams as shown in Fig. 5. Fig. 6 shows the output waveforms of recovered data (upper) and recovered clock (lower) when the input data was a 43-Gbit/s NRZ 2^31-1 PRBS and the average optical input power (P_{opt}) was 0.2 dBm. Clear eye opening of the recovered data was observed. The measured rms jitter was 0.930 and 0.624 ps, respectively, for the data and clock. Error-free operation was confirmed in the wide bit-rate range from 42.8 to 43.1 Gbit/s for 2^{31}-1 PRBS data signal, which demonstrates that the clock signal optoelectronically recovered by the HPT OILO is good enough quality.

The power dissipation of the OEIC was 0.79 W, which is less than half that of a PLL-based fully electrical CDR IC. To our knowledge, this is the first successful demonstration of CDR OEICs using OILOs as optoelectronic clock recovery circuits, and the 43-GHz clock frequency is the highest ever reported for clock extraction using a fundamental oscillation spectrum for OILOs.

V. 100-GHz-Class HPT OILO

By using a back-illuminated HPT with 4-μm φ emitter area, a 100-GHz-class oscillator IC [4], [5] was designed and fabricated. Fig. 7 shows a microphotograph of the chip. This circuit is based on the common-emitter series feedback configuration. Fig. 8(a) shows the measured free-running oscillation spectrum when V_{cc} = 1.3 V and I_{c} = 9.7 mA. The oscillation frequency of 96.43127 GHz and the output power of -6.30 dBm, which includes the insertion loss of the probe head (~1 dB), were measured. Utilizing a modulation signal of around 96 GHz, which was generated by using an LN Mach-Zehnder modulator biased at the transmission null point and a 48-GHz signal source, we measured optical-injection-locking performance. Fig. 8(b) shows an example of the measured optically injection-locked spectrum at an injection frequency of 96.43 GHz and

Fig. 4. 43-Gbit/s HPT/HBT CDR OEIC Chip (2 mm x 2mm).

Fig. 6. Output waveforms of data (upper) and clock (lower).

Fig. 5. Optoelectronic clock recovery circuit combining a PLC-MZI and OILO for NRZ-format optical transmission systems.
a Popt of +3 dBm. One can see that the phase noise is greatly reduced in the locked state compared with the free-running state shown in Fig. 8(a). To our knowledge, this is the highest optically injection-locked frequency ever reported for electrical oscillators. The output power of the locked state (−4.30 dBm) slightly increased from that of the free-running state. In addition, a wide locking range of 113 MHz was measured at the Popt of +5.0 dBm [4]. An even wider locking range could be obtained if a higher-speed optical modulator were used.

The IC also could be optically injection-locked by heterodyne optical signal with a beat frequency of around 192 GHz [5], which corresponds to the second harmonic of the oscillator. To our knowledge, 192 GHz is the highest input-modulation frequency ever reported for electrical oscillators.

From these experiments, we can say that 100-GHz-class electrical clock extraction from 100-Gbit/s-class optical data streams and half-rate clock extraction from 200-Gbit/s-class optical data streams are possible.

VI. Conclusion

The HPT OILOs promise simple, low-power-consumption equipment for up-to-100-GHz LOs for microwave and millimeter-wave photonics and 100-Gbit/s-class optoelectronic clock recovery applications.

Acknowledgment

The authors thank K. Ishii for helpful advice in digital circuit design. They also thank M. Muraguchi, H. Toba, M. Tokumitsu, and T. Enoki for their continuous support and encouragement.

References