Optical Injection Locking of a 38-GHz-Band InP-Based HEMT Oscillator Using a 1.55-μm DSB-SC Modulated Lightwave

Hiroyuki Furuta, Mikio Maeda, Toshihiro Nomoto, *Member, IEEE*, Jun Kobayashi, and Shegeo Kawasaki, *Member, IEEE*

***Abstract*—Optical injection locking was experimentally performed using a 38-GHz-band InP-based HEMT MMIC oscillator and a 1.55-μm lightwave. Two optical modulation schemes were compared for optical injection locking, and no difference was found except for the optical modulation frequency. With suppressed carrier modulation of the lightwave, phase noise of less than −73.2 dBc/Hz at a 10-kHz frequency offset and a 14-MHz locking range were achieved.**

***Index Terms*—InP HEMT oscillator, millimeter-wave, optical-injection locking, optical suppressed-carrier modulation.**

I. Introduction

THE MERGING of microwave and optical technologies will affect the development of fiber-optical distribution of microwave and millimeter-wave (mm-wave) signals, optical interfacing, and isolating control of RF signals in radio-on-fiber, array antenna systems, and so on. The development of high-speed, highly efficient photo-responsive devices for these systems is expected. An optically injection-locked microwave or mm-wave oscillator is an attractive candidate for such devices.

Several research groups have been working on optical injection locking technologies using microwave and mm-wave oscillators made with IMPATT, FET, and HBT devices [1]–[5]. Indirect subharmonic optical injection locking of an IMPATT oscillator has been demonstrated up to 39 GHz [1]. Direct optical injection locking was reported at 14 GHz using an InAlAs/InGaAs HBT-based MMIC oscillator and a 1.55-μm light source [5]. Since most investigations concerning optical fiber communications have concentrated on the 1.55-μm wavelength, where the transmission loss of fiber is lowest, it is important to investigate InP-based heterostructure devices illuminated by 1.55-μm light sources.

A mm-wave signal is degraded or lost when the signal is transmitted on a 1.55-μm optical carrier with double-sideband (DSB) modulation and photodetected after passing through some length of single-mode optical fiber. This is explained by the interference effect of sidebands with fiber chromatic dispersion [6]. To cope with the problem, single-sideband with carrier (SSB) and double-sideband with suppressed-carrier (DSB-SC) optical modulation, which is achieved by using a Mach–Zehnder modulator (MZM), have been proposed [7], [8].

The DSB-SC modulation signal is frequency-doubled at photodetection, while that of SSB is the same as the original signal. Thus the DSB-SC modulation frequency can be half the frequency necessary at detection. This enables high-speed optical modulators. Injection locking more efficient than subharmonic injection locking can be expected when using DSB-SC, because the deepest modulation depth can be obtained as long as the magnitude of the illuminated power is fixed. Moreover, the mm-wave signal transmission characteristics of a DSB-SC lightwave are more stable against fiber chromatic dispersion than those of an SSB lightwave [9].

In this paper, the first trial results of direct optical injection locking using a 38-GHz-band InP-based HEMT MMIC oscillator and a 1.55-μm DFB laser diode (LD) with DSB-SC modulation are presented.

II. Theory

A. Optical Modulation and Detection

An optically modulated sinusoidal signal creates optical sidebands depending on the optical modulation, as illustrated in Fig. 1, and is photodetected as cross terms of the carrier and the sideband in optic-to-electric conversion (O/E).

In the usual DSB modulation, i.e., with intensity modulation or amplitude modulation, the photocurrent I_r after O/E is expressed as

$$I_r \propto P_{opt}\left[1 + m_O \sin(2\pi f t)\right] \tag{1}$$

where
- f frequency of the signal modulating lightwave;
- t time;
- P_{opt} optical power illuminating the photodetector;
- m_O optical modulation depth [8].

The original modulating signal appears in the second term of the right-hand side. The photocurrent for the SSB modulation can also be expressed as (1)

In the case of DSB-SC modulation, since the signal is transmitted only on the sidebands, the photocurrent I_r after O/E is expressed as

$$I_r \propto P_{opt}\left\{1 - \cos[2\pi(2f')t]\right\} \tag{2}$$

Manuscript received August 31, 2000; revised December 13, 2000. This work was supported in part by Tokai University Rainbow 21 Project and the Asahi Glass Foundation.

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Publisher Item Identifier S 1531-1309(01)01965-1.

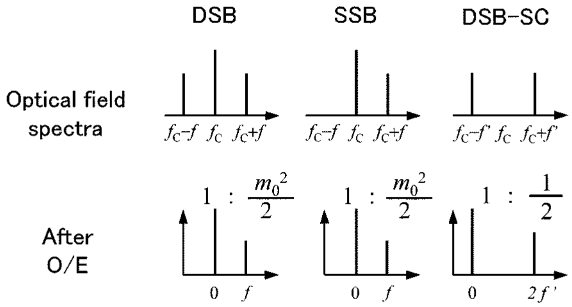

Fig. 1. Optical modulation.

where f_0 is the frequency of the modulating signal [8]. The frequency is doubled through optical transmission. When $2f'$ equals to f, the DSB-SC signal after O/E is same as that of DSB, m_O of which is 1, i.e., 100% (see Fig. 1).

B. Optical Injection-Locking Range

The modulated optical signals can be either directly illuminated onto the active device of the oscillator or received by a photodiode and then injected electrically to the oscillator circuit. The locking range Δf_m for small signal injection is derived using Adler's equation [10], and expressed as

$$\Delta f_m = \frac{f_{osc}}{Q_{ext}} \cdot \sqrt{\frac{P_{inj}}{P_{osc}}} \tag{3}$$

where

- f_{osc} frequency of the illuminated oscillator;
- Q_{ext} external quality factor of the oscillator;
- P_{inj} and P_{osc} power of the injected signal and oscillator output, respectively [2].

Then, considering the second term of (1), (3) can be rewritten as

$$\frac{\sqrt{P_{osc}} \cdot \Delta f_m}{m_O \cdot P_{opt}} = C_{opt} \cdot \frac{f_{osc}}{Q_{ext}} \tag{4}$$

where C_{opt} is a parameter that includes coupling efficiency and photo-responsivity. Since f_{osc} and Q_{ext} can be taken as constant values, the right-hand side of (4) becomes constant. Thus, Δf_m is proportional to the illuminated power P_{opt}. For DSB-SC modulation, m_O of 100% was used in (4)

Equation (4) was used to compare optical modulation schemes in terms of optical injection locking.

III. Experiments

A. Setup

Fig. 2 shows our experimental setup to evaluate the phase noise and locking range of an optically injection locked oscillator.

The oscillator used in this experiment was a 38-GHz-band InP-based HEMT MMIC oscillator with a coplanar waveguide (CPW) [11]. The HEMT in the oscillator had an InAlAs/InGaAs pseudomorphic structure. The 1.55-μm lightwave was absorbed in the 20-nm thick $In_{0.80}Ga_{0.20}As$ channel layers of the HEMT and the additional 20-nm thick $In_{0.53}Ga_{0.47}As$ layers, but not in the InAlAs Schottky barrier or donor layers. The oscillator signal was output through a 10-dB buffer amplifier in the MMIC and monitored with a spectrum analyzer. The drain bias voltage for the HEMT was set at 2 V, and that for the gate varied from -0.4 to -0.6 V; in this range the self-oscillating frequency and the output power of the oscillator ranged from 38.6 to 39.2 GHz and around -3 dBm, respectively, without illumination.

Optical illumination was applied from a 1.55-μm DFB LD. The observed frequency shift and the power degradation were -200 MHz and less than 1 dB, respectively, at the gate bias of -0.6 V when the oscillator HEMT was illuminated with a 1.55-μm light at about 7 dBm and without mm-wave modulation. The frequency shift decreased, while the power degradation increased by a few dB, as the bias increased. These were related to the virtual gate bias change of the HEMT caused by the internal photovoltaic effect [12].

The lightwave from the LD was DSB-SC modulated externally by a 19.4-GHz mm-wave sinusoidal signal through an optical MZM so that the injected signal frequency was close to the self-oscillating frequency of the illuminated oscillator; i.e., 38.8 GHz.

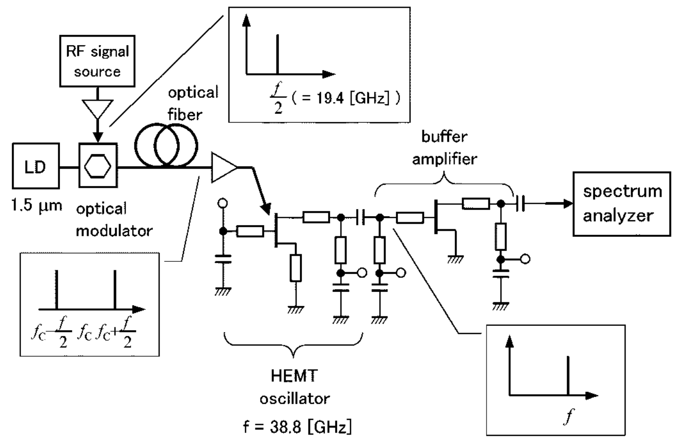

Fig. 2. Experimental setup.

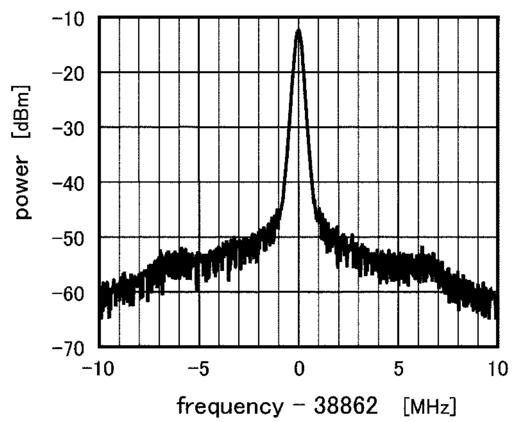

Fig. 3. Example of the injection-locked condition.

B. Results and Discussion

1) Phase noise: Fig. 3 is an example of the spectrum at the optical injection locking of the oscillator.

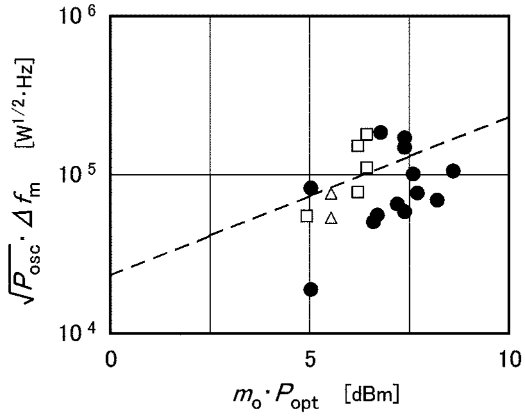

Fig. 4. Locking range versus illuminated power.

Less than -73.2 dBc/Hz of phase noise was observed at a 10-kHz frequency offset in the spectrum under optical illumination of more than 6.6 dBm. This phase noise is as low as that of a commercial synthesizer in 38-GHz range [13]. The phase noise of the signal source was −83.5 dBc/Hz at 10-kHz frequency offset of 19.9 GHz; larger by 10 dB. The phase noise might increase by 6 dB because the signal is frequency-doubled in DSB-SC transmission, so the difference in phase noise could be about 4 dB. This degradation could be caused primarily by the frequency detuning between the injection signal frequency and the free-running oscillator frequency [14]. The free-running frequency of oscillator illuminated might change easily when the optical power fluctuated with vibration of optical probe.

2) Locking Range: While changing the illuminating power P_{opt}, we measured the locking range Δf_m. A maximum Δf_m of 14 MHz was obtained at oscillator output P_{osc} of −8 dBm and P_{opt} of 6.8 dBm. Fig. 4 shows Δf_m as a function of P_{opt}. To compensate the fluctuations of the oscillator power, the values of Δf_m were multiplied by the values of $\sqrt{P_{osc}}$. To allow comparison of optical modulation schemes, DSB results are also plotted as squares (□) for $m_O = 0.7$ and triangles (△) for $m_O = 0.6$. Theoretical values calculated from (4), the left-hand side of which was assumed to be constant, are shown as a dashed line in Fig. 4.

The results imply that there is no significant difference in the modulation schemes for illumination, i.e., DSB-SC and DSB, at the modulation depth of 100%.

The values of Δf_m were small despite the magnitude of the illuminated optical power. Applying 200 for Q_{ext}, which was obtained experimentally [15], the injection power estimated from (3) was −30 dB lower than that from (2). This is because the frequency response of photodetection was restricted by a longer minority carrier lifetime in the HEMT, which affected the internal photovoltaic effect [12], which in turn affected the large optical gain obtained near the dc region.

IV. Conclusions

Optical injection locking was experimentally performed using a 38-GHz-band InP-based HEMT MMIC oscillator and a DSB-SC modulated 1.55-μm lightwave.

Phase noise of less than −73.2 dBc/Hz at a 10-kHz frequency offset and a 14-MHz locking range were achieved. Two optical modulation schemes for optical injection were compared, and the difference in the optical modulation was found not to affect the phase-locking performance.

Acknowledgment

The authors would like to acknowledge the suggestions and encouragement of J. Kumada, Dr. H. Matsumura, and K. Murakami at NHK. They would like to thank F. Suginoshita and their other colleagues at NHK for their valuable discussions. They would also like to thank T. Morimoto, S. Yasumatsu, and T. Kuwayama at Tokai University for their support in the experiments.

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