Characteristics of InP–InGaAs HPT-Based Optically Injection-Locked Self-Oscillating Optoelectronic Mixers and Their Influence on Radio-Over-Fiber System Performance

Jae-Young Kim, Chang-Soon Choi, Woo-Young Choi, Hideki Kamitsuna, Minoru Ida, and Kenji Kurishima

***Abstract*—A 30-GHz optically injection-locked self-oscillating optoelectronic mixer (OIL-SOM) is implemented with a high-performance InP–InGaAs heterojunction phototransistor. The subharmonic conversion efficiency and phase noise characteristics of OIL-SOM are investigated and used for analyzing OIL-SOM-based 60-GHz radio-over-fiber downlink data transmission performance. The OIL-SOM characteristics provide lower and upper boundaries for the input optical local oscillation (LO) power range within which the link performance does not significantly depend on input optical LO power.**

***Index Terms*—60 GHz, conversion efficiency, heterojunction phototransistor (HPT), optical local oscillation (LO) power, optically injection-locked self-oscillating optoelectronic mixer (OIL-SOM), phase noise, radio-over-fiber (RoF) system.**

I. Introduction

THERE is a growing need for millimeter-wave wireless data transmission systems having very wide bandwidth. Millimeter-wave wireless networks should have small cell sizes since millimeter-waves have high transmission loss in air. While the small cell size can offer effective frequency reusability and low power consumption, it requires a large number of base stations. Radio-over-fiber (RoF) systems are and attractive candidate for millimeter-wave wireless networks, because they can connect a large number of base stations to one central station having centralized functions through fiber, which can support low loss and wide bandwidth transmission.

Among several approaches for realizing RoF systems, the remote up-conversion scheme with optical local oscillation (LO) distribution is attracting much attention [1], [2]. In this scheme, data are transmitted from the central station to base stations in the optical immediate frequency (IF) and frequency up-converted to the desired radio frequency (RF) with the optically distributed LO signal, thus eliminating the need for phase-locked oscillators in base stations. Furthermore, the optical LO signal provided by the central station can be shared among many base stations. InP-based heterojunction phototransistors (HPTs) can be used as optoelectronic mixers in this scheme because they can simultaneously perform photodetection of optical LO and data signals, and frequency mixing of them [2], [3]. HPTs are fully compatible to monolithic microwave integrated circuit (MMIC) technology [4], [5], allowing the possibility of the system-on-chip solution for the entire base station including power amplifier and bandpass filter (BPF) except the antenna.

Although the remote up-conversion scheme with optical LO and HPT optoelectronic mixer has the potential to simplify base-station architecture, the required optical LO power for efficient frequency up-conversion can be very high, and the variation of delivered optical LO power due to differences in the distance between central and base stations can seriously affect system performance. The HPT-based optically injection-locked self-oscillating optoelectronic mixer (OIL-SOM) [6], [7] can be a solution for these problems because the output power of the optically injection locked oscillator [8], [9] does not directly depend on the injected optical LO power. Using the OIL-SOM as a harmonic optoelectronic mixer, we have successfully demonstrated 30- and 60-GHz RoF downlink transmission of 20-Mb/s 16 QAM data [6], [7]. In the 60-GHz RoF downlink demonstration, we observed that the link performance does not significantly change with the optical LO power when the input optical LO power is in a range from -11 to 0 dBm [7]. In this letter, we report the characteristics of phase noises and optoelectronic mixing efficiencies for the HPT-based 60-GHz harmonic OIL-SOM at various optical LO power levels. Then, we analyze the influence of these characteristics on the link performance of OIL-SOM-based RoF downlink transmission.

II. Operation Principle and Characteristics

Using a high-performance InP–InGaAs HPT having 70-nm-thick undoped InP emitter, 50-nm carbon-doped InGaAs base, and 300-nm-thick InGaAs collector, we implemented a hybrid-type HPT oscillator operating in 30 GHz. The HPT has a responsivity of 0.2 A/W at photodiode (PD)-mode when the base-emitter terminal is shorted. The electrical current gain cutoff frequency and the maximum oscillation frequency of this HPT are

Manuscript received May 18, 2006; revised October, 27 2006. The work of J.-Y. Kim, C.-S. Choi, and W.-Y. Choi was supported by the Basic Research Program of the Korea Science and Engineering Foundation.

J.-Y. Kim and W.-Y. Choi are with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: wchoi@yonsei.ac.kr).

C.-S. Choi is with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea, and also with the National Institute of Information and Communications Technology (NiCT), Yokosuka, Kanagawa 239-09847, Japan (e-mail: cschoi@ieee.org).

H. Kamitsuna, M. Ida, and K. Kurishima are with NTT Photonics Laboratories, NTT Corporation, Atsugi-shi, Kanagawa 243-0198, Japan (e-mail: kamituna@aecl.ntt.co.jp).

Digital Object Identifier 10.1109/LPT.2006.889989

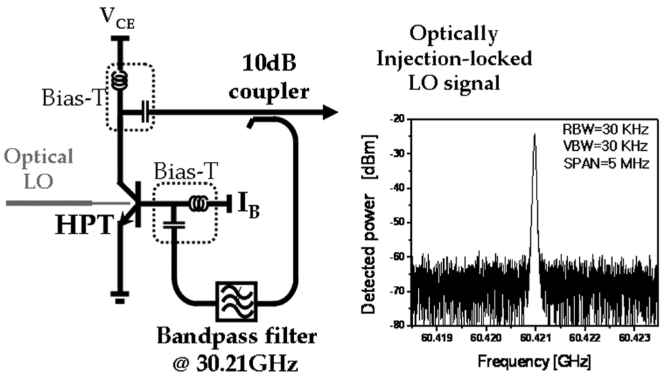

Fig. 1. Schematic diagram of HPT-based OIL-SOM.

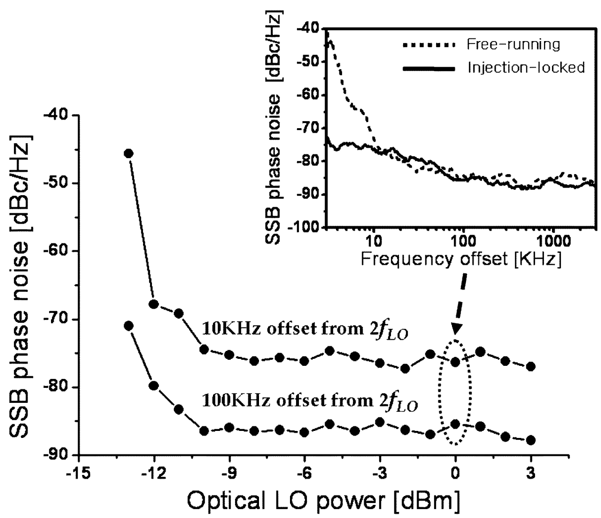

Fig. 2. Single-sideband phase noise of optically injection-locked oscillator as a function of optical LO power.

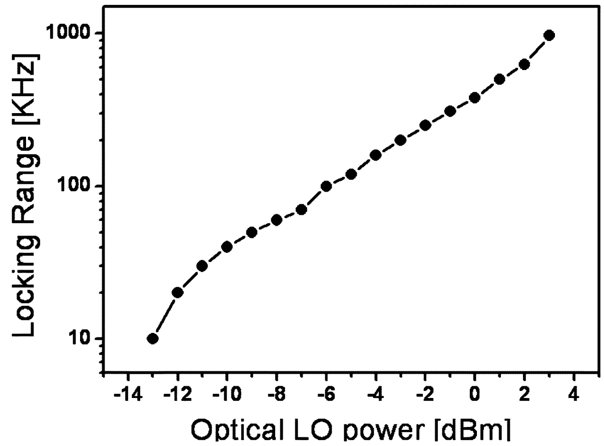

Fig. 3. Locking range of optically injection-locked oscillator as a function of optical LO power.

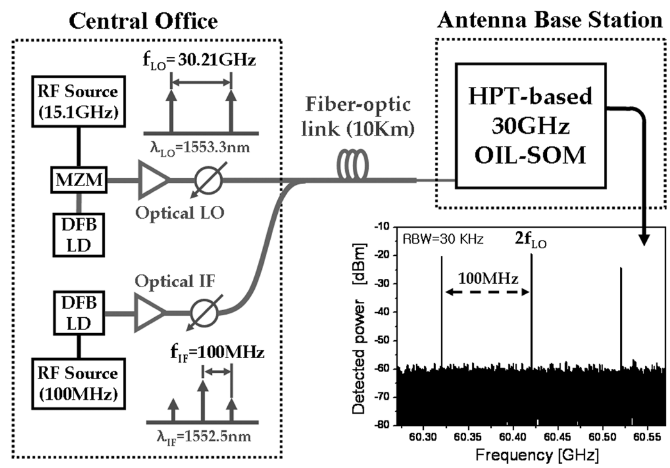

Fig. 4. Base station architecture using HPT-based OIL-SOM.

153 and 94 GHz, respectively [10]. Because the HPT has sufficient gain of 14 dB at 30 GHz, a free-running HPT oscillator can be implemented with a simple feedback loop connecting the collector and base ports through a 30-GHz bandpass filter having quality factor of 100, as shown in Fig. 1. The oscillator also produces harmonic signals at the 60-GHz band and our investigation is focused on 60-GHz signals as we are interested in using the OIL-SOM for 60-GHz applications.

When 30-GHz optical LO generated in central station is injected into the HPT, it can injection-lock the free-running oscillator and significantly improve the phase noise characteristics. The resulting spectrum of optically injection-locked 60-GHz LO signal with 0-dBm optical LO is shown in Fig. 1. The inset in Fig. 2 shows the single-sideband phase noise characteristics of 60-GHz LO. Significant reduction in phase noises due to injection-locking can be observed especially in the low frequency offset range. Fig. 2 also shows the phase noise at 10- and 100-KHz offset frequencies measured at various optical LO powers. When the optical LO power is higher than -10 dBm, low phase-noise characteristics are maintained. However, when the optical LO power is lower than -10 dBm, the HPT oscillator becomes unlocked and the phase noise increases rapidly. In addition, the injection-locking range of HPT oscillator depends on the injected optical LO power. The locking range is defined as a frequency range within which the oscillator is synchronized to the optical LO. Fig. 3 shows the increase in the locking range with the incident optical LO power. The small locking range is due to the high Q-factor (about 100) of BPF used in our experiment. A reduced Q-factor BPF or an MMIC oscillator can produce a much larger locking range.

Fig. 4 shows the experimental setup used for characterizing harmonic mixing characteristics of OIL-SOM. Optical IF signals are generated by direct modulation of a distributed-feedback laser diode with 100-MHz IF signals. Then, the optical IF signals are combined with optical LO generated by the double sideband suppressed carrier method [11] and, after 10-km transmission in single-mode fiber, injected into the HPT inside OIL-SOM. Injected optical IF signals are first photodetected and then mixed with LO signals. As a result, we can obtain harmonically frequency up-converted RF signals in the 60-GHz band whose spectrum is shown in the inset of Fig. 4. Fig. 5 shows the internal conversion gain of OIL-SOM as a function of delivered optical LO power when the input optical IF power is -6 dBm. The internal conversion gain is defined as the power ratio of the frequency up-converted RF signals to the photodetected IF signal power measured in PD-mode, as schematically shown in Fig. 5. Measured conversion gain is independent of optical LO

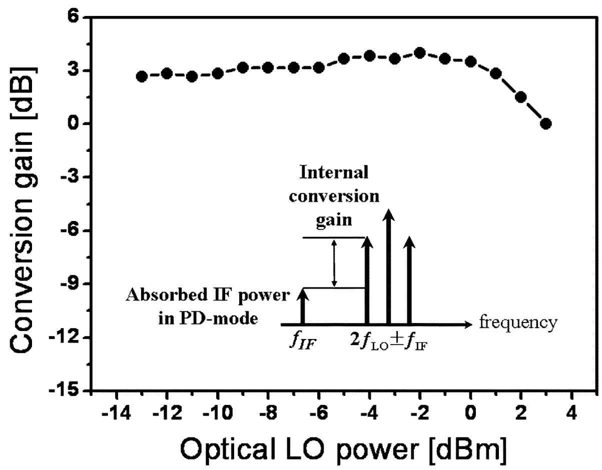

Fig. 5. Internal conversion gain of OIL-SOM as a function of optical LO power.

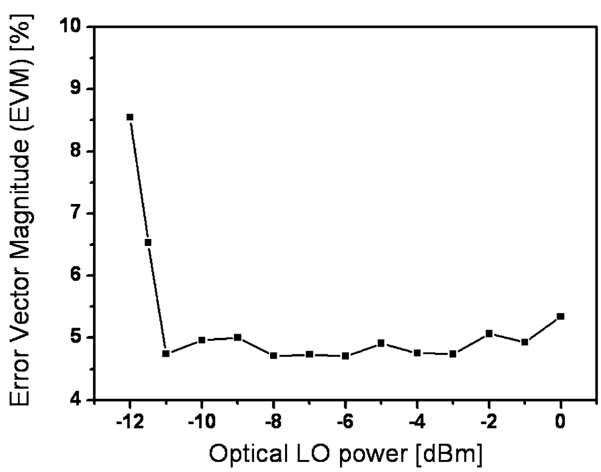

Fig. 6. EVM as a function of optical LO power.

power, because the output power of OIL-SOM does not directly depend on the injected optical LO power. When the optical LO power becomes larger than 1 dBm, however, the conversion efficiency decreases. This is because the saturation effect of HPT under high-power optical illumination lowers oscillation power of the HPT oscillator and degrades the conversion efficiency.

The performance of OIL-SOM as an optoelectronic mixer was investigated by injecting 20-Mb/s 16 QAM optical data into the mixer along with optical LO, up-converting them into the 60 GHz, and then evaluating the resulting error vector magnitudes (EVMs) of down-converted baseband signals. The details of down-conversion and demodulation methods can be found in our pervious work [7]. The EVMs were measured as a function of input optical LO power when the optical IF power was fixed at -6 dBm. As shown in Fig. 6, as long as injected optical LO power to OIL-SOM is in the range from -11 to 0 dBm, the EVMs do not significantly change with the optical LO power. This is because the phase noise characteristics and conversion efficiencies of OIL-SOM do not change much with the incident optical LO power in this range. Reducing optical LO power below -11 dBm causes a rapid increase in EVM since the phase noise degrades due to unlocking of OIL-SOM. When the optical LO power increases over 0 dBm, the EVM slowly increases because the conversion efficiency of OIL-SOM decreases due to high-power optical illumination. Overall, OIL-SOM provides uniform link performance over the larger than 10-dB optical LO power range, which corresponds to substantial margin in system design to accommodate fiber length and other variations.

III. Conclusion

We implemented a 30-GHz hybrid-type OIL-SOM based on a high-performance InP–InGaAs HPT. It has low phase-noise characteristics and provides efficient optoelectronic frequency up-conversion at 60 GHz. Once the input optical LO power is larger than -11 dBm, the phase noise of OIL-SOM is maintained below -85 dBc/Hz at 100-kHz offset independent of optical LO power. The conversion efficiency of OIL-SOM does not depend on optical LO power as long as the optical power is lower than 0 dBm. These phase noise and conversion characteristics provide the lower and upper boundaries of optical LO power within which the OIL-SOM-employed RoF downlink transmission system can have uniform link performance.

Acknowledgment

H. Kamitsuna, M. Ida, and K. Kurishima would like to thank Dr. Y. Itaya, Dr. T. Enoki, and Dr. K. Murata in NTT Photonics Laboratories for their support and encouragement.

References

[1] J.-H. Seo, C.-S. Choi, Y.-S. Kang, Y.-D. Chung, J. Kim, and W.-Y. Choi, "SOA-EAM frequency up/down-converters for 60-GHz bi-directional radio-on-fiber systems," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pt. 2, pp. 959–966, Feb. 2006.

[2] C.-S. Choi, J.-H. Seo, W.-Y. Choi, H. Kamitsuna, M. Ida, and K. Kurishima, "60 GHz bidirectional radio-on-fiber links based on InP-InGaAs HPT optoelectronic mixers," *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2721–2723, Dec. 2005.

[3] C. P. Liu, A. J. Seeds, and D. Wake, "Two-terminal edge-coupled InP/InGaAs heterojunction phototransistor optoelectronic mixer," *IEEE Microw. Guided Wave Lett.*, vol. 7, no. 3, pp. 72–74, Mar. 1997.

[4] J.-L. Polleux, L. Paszkiewicz, A.-L. Billabert, J. Salset, and C. Rumelhard, "Optimization of InP-InGaAs HPT gain: Design of an opto-microwave monolithic amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 3, pp. 871–881, Mar. 2004.

[5] H. Kamitsuna, Y. Matsuoka, S. Yamahata, and N. Shigekawa, "Ultrahigh-speed InP/InGaAs DHPTs for OEMMICs," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 10, pp. 1921–1925, Oct. 2001.

[6] C.-S. Choi, J.-H. Seo, W.-Y. Choi, H. Kamitsuna, M. Ida, and K. Kurishima, "Radio-on-fiber downlink transmission systems based on optically controlled InP/InGaAs HPT oscillator," in *IEEE MTT-S Int.*, Long Beach, CA, Jun. 2005, pp. 11–14.

[7] J.-Y. Kim, J.-H. Seo, W.-Y. Choi, H. Kamitsuna, M. Ida, and K. Kurishima, "60 GHz radio-on-fiber downlink systems using optically injection-locked self-oscillating optoelectronic mixers based in InP/InGaAs HPTs," in *OFC/NFOEC*, Anaheim, CA, Mar. 2006.

[8] H. W. Yen and M. K. Barnoski, "Optical injection locking of transistor oscillators," *IEEE Trans. Electron Devices*, vol. 24, no. 9, pp. 1211–1211, Sep. 1977.

[9] A. Bangert and T. Lauterbach, "Initial observations of optical injection locking of oscillators using heterojunction bipolar transistors," *Electron. Lett.*, vol. 28, no. 7, pp. 621–623, Mar. 1992.

[10] H. Kamitsuna, T. Shibata, K. Kurishima, and M. Ida, "Direct optical injection locking of InP/InGaAs HPT oscillator ICs for microwave photonics and 40-Gbit/s-class optoelectronic clock recovery," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 12, pp. 3002–3008, Dec. 2002.

[11] R. Montgomery and R. DeSalvo, "A novel technique for double sideband suppressed carrier modulation of optical fields," *IEEE Photon. Technol. Lett.*, vol. 7, no. 4, pp. 434–436, Apr. 1995.