Integrated Heterojunction Bipolar Transistor Optically Injection-Locked Self-Oscillating Opto-Electronic Mixers for Bi-Directional Fiber-Fed Wireless Applications

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***Abstract*—A 30-GHz-band third harmonic optically injection-locked self-oscillating opto-electronic mixer is implemented with a 10-GHz InP heterojunction bipolar transistor monolithic microwave integrated circuit oscillator. The monolithic self-oscillating mixer can be optically injection locked in wide operating conditions and can perform efficient frequency up- and down-conversion with low-power optical local-oscillator signals. Using the mixer, bi-directional transmission of 32 quadrature amplitude modulation data in a 30-GHz fiber-fed wireless link is successfully demonstrated.**

***Index Terms*—Fiber-fed wireless link, InP heterojunction bipolar transistor (HBT), monolithic microwave integrated circuit (MMIC), optical injection locking, self-oscillating opto-electronic (O/E) mixer.**

I. Introduction

WIRELESS communication systems have shown tremendous progress in recent years and the interest for short-range high-speed wireless systems such as wireless local area network (LAN) and personal area network (PAN) are rapidly growing. The millimeter-wave band is very attractive for these applications because it can offer wide bandwidth up to several gigahertz. However, due to high transmission loss of millimeter waves in the air, the millimeter-wave wireless systems are expected to use picocell network topology, which requires a large number of antenna base stations. Consequently, there is a need for careful network design that can provide simple antenna base-station architecture for overall cost reduction.

The fiber-fed millimeter-wave wireless system based on the optical local oscillator (LO) distribution scheme [1]–[3] has been reported as an attractive method to simplify the antenna base station by replacing the millimeter-wave phase-locked oscillator with optically distributed LO from the central station. For this scheme, the opto-electronic (O/E) mixer installed in the antenna base station is an important component. Several types of O/E mixers have been investigated based on InP high-electron mobility transistors [4], InP heterojunction bipolar transistors (HBTs) [5], [6], and HBT oscillators [7]–[9]. Among them, optically injection-locked self-oscillating O/E mixers have many advantages such as wide photo-detection bandwidth, high conversion efficiency, and less dependence on injected optical LO power [7]–[9].

Previously, we demonstrated 30-GHz harmonic O/E frequency up-conversion based on a 10-GHz optically injection-locked HBT oscillator in a hybrid configuration and reported its downlink data transmission [8]. We also reported a 60-GHz sub-harmonic frequency up-converter based on a 30-GHz HBT oscillator, as well as 60-GHz downlink data transmission [9].

In this paper, we report on a 30-GHz harmonic O/E frequency up/down converter realized with an optically injection-locked 10-GHz HBT monolithic microwave integrated circuit (MMIC) oscillator and demonstrate 30-GHz bi-directional data transmission. The HBT MMIC self-oscillating mixer can perform simultaneous frequency up/down conversion for bi-directional data transmission and provides a wider optical injection-locking range. Initial results of our investigation have been presented in [10], but this paper includes additional results regarding frequency up/down conversion characteristics and locking stability of the self-oscillating mixer.

This paper is organized as follows. Section II describes optical injection-locking and frequency up/down conversion characteristics of the MMIC self-oscillating O/E mixer. Section III reports demonstration of bi-directional 32 quadrature amplitude modulation (QAM) data transmission in a 30-GHz fiber-fed wireless system using the mixer.

II. Characteristics of MMIC Self-Oscillating Mixer

A. Configuration and Basic Performance

In our scheme for bi-directional fiber-fed wireless systems, a 10-GHz MMIC HBT oscillator in the antenna base station performs harmonic frequency up/down conversion of downlink IF and uplink RF signals to and from the 30-GHz band, respectively. We first investigate optical injection-locking and harmonic frequency conversion characteristics of the mixer. Fig. 1 shows the experimental setup used for characterization.

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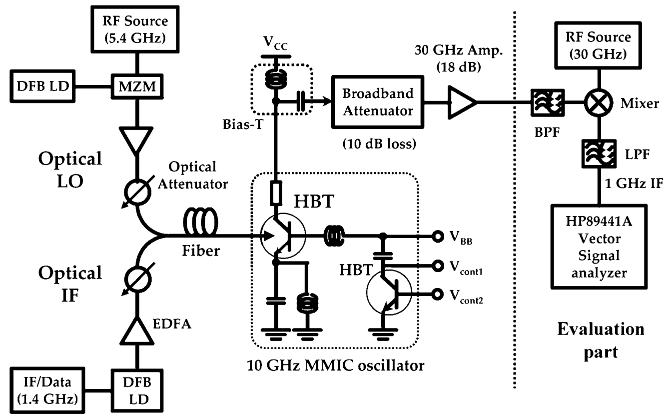


Fig. 1. Experimental setup for 30-GHz downlink data transmission using InP HBT-based MMIC optically injection-locked self-oscillating O/E mixer and characterization of the self-oscillating O/E mixer. Evaluation part is only for downlink data transmission. DFB LD: distributed feedback laser diode, MZM: Mach–Zehnder modulator, EDFA: Er-doped fiber amplifier, BPF: bandpass filter, LPF: low-pass filter. From [10].

A detailed description for the MMIC oscillator used in our investigation can be found in [11]. The HBT device inside the oscillator exhibits large phototransistor gain of 18 dB at 10-GHz optical modulation frequency. The oscillator was realized in a common emitter feedback configuration using a spiral inductor, a metal–insulator–metal (MIM) capacitor, and another HBT acting as a variable resistor. External bias-tees were used for base and collector biasing of the oscillation HBT. 10.8-GHz optical LO was generated with the double-sideband suppressed-carrier method [12] in which two optical modes separated by 10.8 GHz were generated with a Mach–Zehnder modulator biased at V_π and modulated with a 5.4-GHz RF signal.

When the 10.8-GHz optical LO was injected into the free-running oscillator, it was injection-locked by the optical LO and generated the third harmonic phase-locked LO signals at 32.4 GHz. These were measured with a spectrum analyzer after passing through a broadband attenuator and a 30-GHz amplifier. A broadband attenuator with 10-dB loss was used because without it, the 30-GHz amplifier was not impedance-matched to 50 Ω in the 10-GHz band, resulting in unstable oscillation. Fig. 2(a) and (b) shows the spectrum of free-running and optically injection-locked 32.4-GHz LO signals when injected optical LO power was 0 dBm. The reduction of phase noise by optical injection locking is clearly shown from single-sideband phase-noise measurement results shown in Fig. 2(c).

Optical IF signals were generated by direct modulation of a distributed-feedback laser diode with 1.4-GHz IF signals and injected into the MMIC oscillator through fiber, as shown in Fig. 1. The optical IF signals were photo-detected, amplified, and harmonically frequency up-converted to the 30-GHz band with the help of the injection-locked LO signal all within the self-oscillating O/E mixer, as shown in Fig. 3. Fig. 4 shows the power of frequency up-converted RF signals as a function of delivered optical LO power when the input optical IF power was 0 dBm. The photo-detected IF power was −40 dBm when the oscillator HBT was biased at the photodiode mode (base voltage = 0 V) in which the HBT operates as a p-n junction photodiode without any internal phototransistor gain. The harmonic frequency up-conversion loss of the self-oscillating O/E mixer was approximately 8 dB with conversion gain defined as the power ratio of frequency up-converted RF to photo-detected IF power measured in the photodiode mode [4]. The measured conversion efficiency was nearly independent of optical LO power because output power of the self-oscillating O/E mixer does not directly depend on the injected optical LO

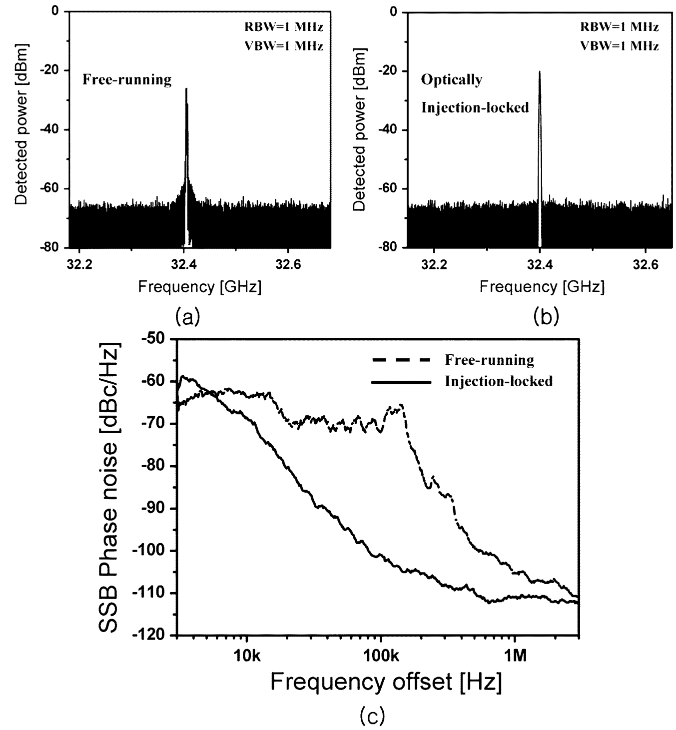
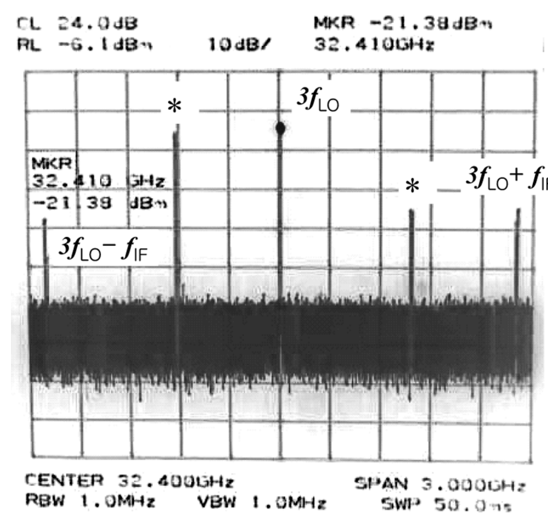


Fig. 2. Spectrum of: (a) free-running third harmonic LO signals, (b) optically injection-locked third harmonic LO signals when injected optical LO is 0 dBm, and (c) single-sideband phase noise of third harmonic free-running and optically injection-locked LO signals. (c) is from [10].



* : Image signals due to the harmonic mixer (HP 11970A) used for spectrum analyzer.

Fig. 3. Spectrum of harmonically frequency up-converted RF and LO signals when both of optical LO and IF powers are 0 dBm. The up-converted RF signals appear in both sides of 32.4-GHz LO separated by IF of 1.4 GHz.

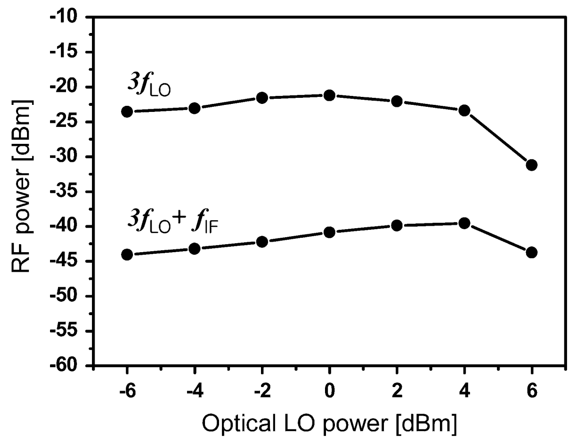


Fig. 4. Powers of frequency up-converted RF (33.8 GHz, upper sideband) and LO (32.4 GHz) signals as a function of injected optical LO power when optical IF power is 0 dBm.

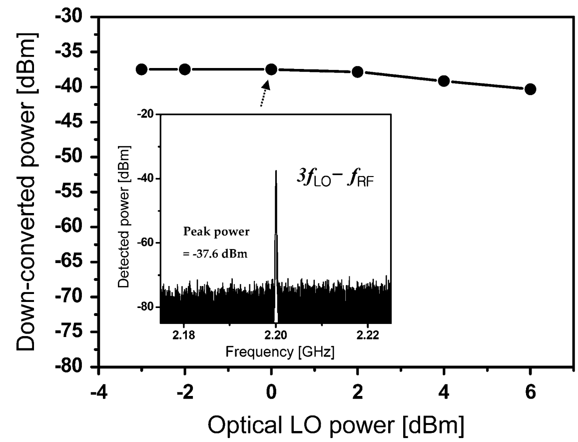


Fig. 6. Powers of frequency down-converted IF (2.2 GHz) signals as a function of injected optical LO power when injected RF power is -2 dBm. Inset is spectrum of down-converted IF signals when optical LO power is 0 dBm.

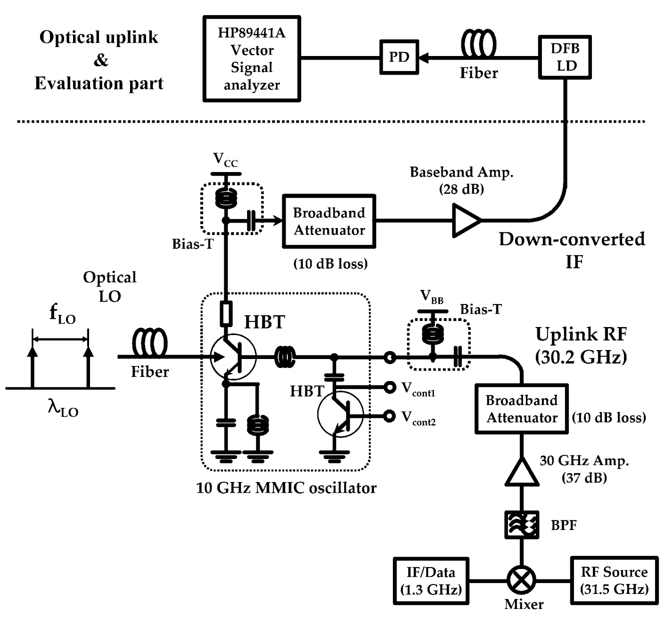


Fig. 5. Experimental setup for 30-GHz uplink data transmission using InP HBT-based MMIC optically injection-locked self-oscillating O/E mixer as a frequency down-converter and characterization of the down-converter. Optical uplink and evaluation part is only for uplink data transmission. DFB LD: distributed feedback laser diode, BPF: bandpass filter, PD: photodetector. From [10].

power. When the optical LO power was larger than 4 dBm, however, the conversion efficiency decreased. This is because the saturation effect of the HBT oscillator under high optical illumination lowered oscillation power and degraded the conversion efficiency, as reported in [9].

The harmonic frequency down conversion in the optically injection-locked self-oscillating O/E mixer was also investigated in the experimental setup shown in Fig. 5. The 30-GHz RF signals were injected to the base terminal of the oscillation HBT and harmonically frequency down-converted to 2.2-GHz IF. These were measured with a spectrum analyzer after a broadband attenuator and a baseband amplifier, as shown in the inset of Fig. 6. The broadband attenuator was connected between the HBT collector and base terminals for impedance matching at 10 GHz. Fig. 6 shows the power of down-converted IF signals as a function of injected optical LO power when the input RF power at the base terminal was -2 dBm. The measured down-conversion efficiency is nearly independent of optical LO power, similar to the case of frequency up-conversion.

B. Comparison With Simple O/E Mixer

The major advantage of the self-oscillating O/E mixer is higher conversion efficiency provided by higher LO power. To validate this, we directly compared conversion efficiency of the self-oscillating mixer with that of a simple HBT O/E mixer. Fig. 7(a) and (b) shows the spectrum of 10.8-GHz LO signals at the output of the self-oscillating mixer and HBT O/E mixer when the same power of 0-dBm optical LO signals were applied. The output LO power of the self-oscillating mixer was approximately 20 dB higher than HBT O/E mixer, whereas the phase noises were almost the same. Fig. 7(c) and (d) shows the measured power of frequency up/down-converted signals as a function of optical LO powers. These results show that the self-oscillating mixer has higher conversion efficiency and less dependence on optical LO power than the HBT O/E mixer.

C. Locking Stability

In applications of optically injection-locked self-oscillating O/E mixers, many factors can induce oscillation frequency variations, and it is possible that the HBT oscillator cannot be locked by the injected optical LO if their frequency difference is too large. Consequently, obtaining a large locking range is very important. In our case, the measured locking range was approximately 1.5 GHz with a 6-dBm optical LO, as shown in Fig. 8. We also investigated changes in free-running oscillation frequency with temperature and the results are shown in Fig. 9. The frequency change was approximately 18 MHz with a 94° change in temperature. Since the locking range is much larger than the frequency drift with temperature change, we can be sure that our

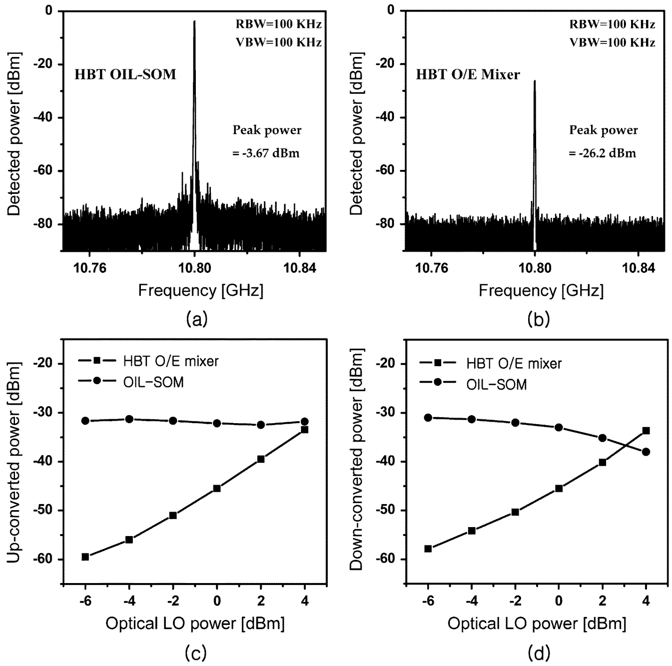


Fig. 7. Spectrum of: (a) optically injection-locked LO signals of MMIC oscillator and (b) photo-detected LO signals of HBT O/E mixer biased at $I_B = 400\,\mu$A, $V_C = 1$ V when injected optical LO power is 0 dBm. (c) Powers of frequency up-converted RF signals (10 GHz, lower sideband) at the output of optically injection-locked self-oscillating O/E mixer (OIL-SOM) and HBT O/E mixer as a function of optical LO power when optical IF (0.8 GHz) power is 0 dBm. (d) Powers of frequency down-converted IF (0.8 GHz) signals as a function of optical LO power when supplied RF (10 GHz) power is -10 dBm.

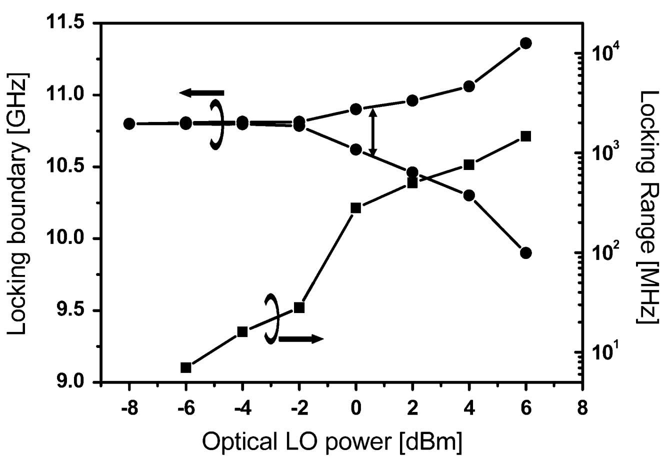


Fig. 8. Locking range and its lower/upper locking boundary of the MMIC HBT oscillator as a function of optical LO power. When the frequency of the optical LO is between the lower and upper locking boundary, the free-running oscillator is synchronized with the optical LO. The locking range is the difference of the two boundaries.

optically injection-locked self-oscillating O/E mixer has high locking-stability against temperature variation.

III. Gigahertz Bi-Directional Link Demonstration

To investigate the feasibility of the optically injection-locked self-oscillating O/E mixer for the fiber-fed wireless system, we demonstrated bi-directional transmission of 32-QAM data in the

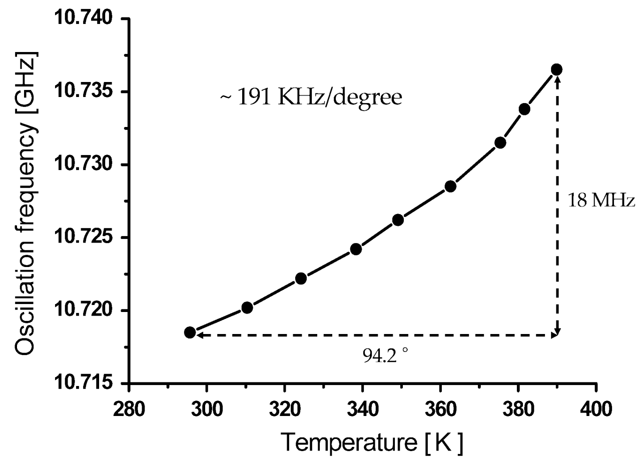


Fig. 9. Free-running oscillation frequency of the MMIC HBT oscillator without optical illumination as a function of the operating temperature. The temperature was controlled with a hot plate and a thermometer.

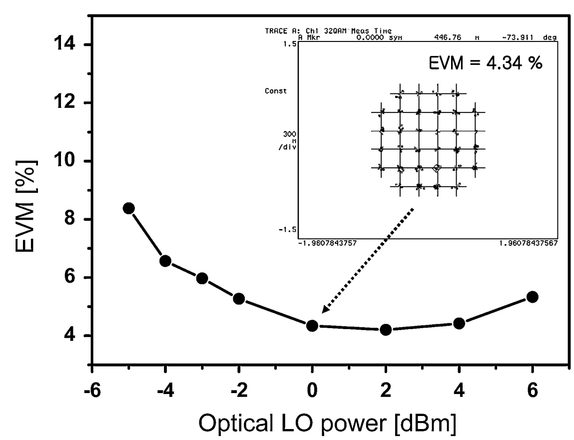


Fig. 10. EVMs measured with VSA as a function of optical LO power when the optical IF power is 0 dBm. Inset is constellation of 32 QAM data demodulated by VSA when both of optical IF and LO are 0 dBm. From [10].

30-GHz band. For downlink data transmission, optical IF signals were generated by direct modulation of a distributed-feedback laser diode with 25-Mb/s 32-QAM signals at 1.4-GHz IF and injected into the self-oscillating O/E mixer through fiber, as shown in Fig. 1. These signals were frequency up-converted to the 30-GHz band. In practical systems, they would radiate to mobile terminals through an antenna. However, we left out the wireless link transmission for simplicity.

For evaluation, up-converted 30-GHz RF signals were down-converted to 1-GHz IF band using an electrical mixer and a bandpass filter, and demodulated by a vector signal analyzer (VSA). When both optical LO and IF powers were 0 dBm, the measured error vector magnitude (EVM) of the demodulated signal was 4.34%, which is sufficient for many wireless applications. For example, the IEEE 802.15.3 standard specifies the transmitter EVM to be less than 4.8% for 32 QAM [13]. The inset of Fig. 10 shows the constellation of the demodulated 32-QAM signal. The EVMs were measured as a function of incident optical LO powers and the results are shown in Fig. 10. They show that there is an optimum range of optical LO power from 0 to 4 dBm. When the optical LO power is less than 0 dBm,

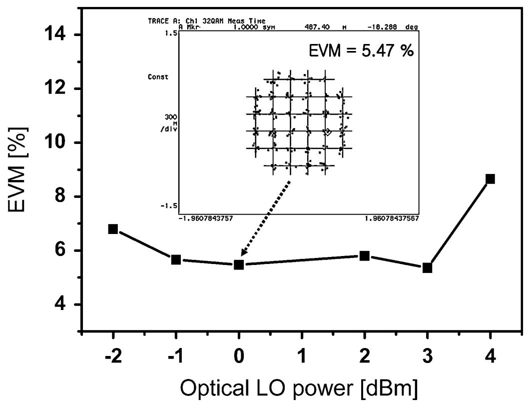


Fig. 11. EVMs measured with VSA as a function of optical LO power when the uplink RF power is −2 dBm. Inset is constellation of 32-QAM data demodulated by the VSA after optical uplink transmission when optical LO and uplink RF powers are 0 and −2 dBm, separately. From [10].

the EVM increases due to phase error increase. On the other hand, when the optical LO power is larger than 4 dBm, the EVM increases due to degradation of conversion efficiency caused by the saturation effect of the oscillator under high power optical illumination.

The experimental setup for uplink data transmission is shown in Fig. 5. For generation of 30-GHz-band uplink RF signals, 25-Mb/s 32 QAM signals with 1.3-GHz IF were frequency up-converted to 30.2-GHz band using an electrical mixer and 31.5-GHz electrical LO signal. After passing through a bandpass filter, an amplifier, and a broadband attenuator, 30.2-GHz RF signals were injected into the self-oscillating mixer and harmonically frequency down-converted to 2.2-GHz IF band. The spectrum of down-converted signals can be found in our previous publication [10]. For optical uplink transmission from antenna base station to central station, frequency down-converted signals directly modulated a distributed-feedback laser diode and the resulting optical uplink signal was detected by a photodetector. The link loss of the optical uplink transmission was about 10 dB.

After optical uplink transmission, IF signals were demodulated by a VSA for evaluation. Fig. 11 shows the measured EVMs as a function of optical LO power, illustrating that there is an optimum range of optical LO power from −1 to 3 dBm. The inset of Fig. 11 shows the constellation of the demodulated 32-QAM signal when injected optical LO and electrical RF powers were 0 and −2 dBm, respectively, in which the EVM was 5.47%. The resulting EVM values for uplink transmission are relatively larger than those for downlink due to lower signal-to-noise ratio. This may be because down-conversion efficiency of our self-oscillating O/E mixer is lower than up-conversion efficiency.

IV. Conclusion

We have implemented a 30-GHz-band optically injection-locked self-oscillating O/E mixer using a 10-GHz InP HBT MMIC oscillator. The self-oscillating O/E mixer performs efficient frequency up/down conversion with little dependence on LO power. The wide locking range of the MMIC oscillator offers a high degree of locking stability over operating temperature variation. Using this optically injection-locked self-oscillating O/E mixer, we realized a 30-GHz bi-directional fiber-fed wireless link and successfully demonstrated bi-directional transmission of 32-QAM data.

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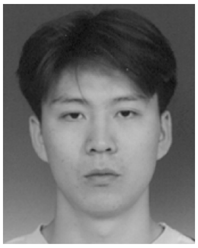

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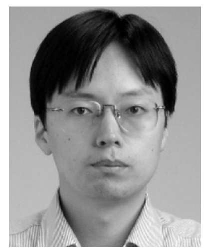

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