Optically Injection-Locked Self-Oscillating Optoelectronic Mixers Based on InP–InGaAs HPTs for Radio-on-Fiber Applications

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

***Abstract*—We demonstrate an optically injection-locked self-oscillating optoelectronic mixer (OIL-SOM) for radio-on-fiber downlink applications. OIL-SOM is based on a monolithic oscillator containing an InP–InGaAs heterojunction phototransistor (HPT). The oscillator is OIL by remotely delivered optical local oscillator (LO) signals, and provides low phase-noise and high-power electrical LO signals. In addition, the HPT in this oscillator can simultaneously perform optoelectronic mixing, in which optically transmitted intermediate frequency signals are up-converted to the desired radio-frequency band with high conversion efficiency. With these, OIL-SOM can make base station architecture simple in radio-on-fiber downlink systems.**

***Index Terms*—Heterojunction phototransistor (HPT), heterojunction bipolar transistor, optically injection-locked (OIL) oscillator, optoelectronic mixer, phase-locked oscillator, radio-on-fiber system.**

I. Introduction

RADIO-ON-FIBER systems are expected to play an important role in broad-band wireline/wireless convergence networks because they offer an efficient way to merge fiber-optic networks with broad-band wireless communication systems [1], [2]. With optical fiber having low loss and wide bandwidth transmission characteristics, it is possible to distribute broad-band data and/or high frequency signals to many wireline or wireless subscribers.

Among several approaches for realizing radio-on-fiber systems, a remote up-conversion scheme has received much attention because it provides immunity to dispersion-induced carrier suppression problems and compatibility with wavelength-division-multiplexing fiber-optic networks [3], [4]. However, complex base station architecture is inevitable because many components are required in the base station such as photodetector, frequency mixer, local oscillator (LO), and amplifier. Phototransistors based on indium phosphide (InP) materials are useful for simplifying base station architecture because they can simultaneously perform several functions such as photodetection and optoelectronic mixing. Furthermore, they are fully compatible to monolithic microwave integrated circuit (MMIC) technology, making one-chip solution for the entire base station excluding antenna a possibility [5]–[7].

However, the realization of low-cost and miniaturized phase-locked oscillator is a challenging task especially for millimeter-wave applications. One attractive solution for this problem is to optically distribute LO signals from the central office to many base stations [8], [9]. In such a scheme, data can be delivered from central office to base station in optical intermediate frequency (IF) signals and frequency up-converted to the desired radio-frequency (RF) band at the base station through mixing with optical LO signals. Although this scheme has the potential to eliminate phase-locked oscillators in many base stations, the total amount of required optical LO power can be very high in order to support efficient frequency up-conversion process and the optical LO power delivered to each base station can vary depending on the fiber transmission distance, causing difficulties in system design.

In this letter, we propose new base station architecture based on optically injection-locked self-oscillating optoelectronic mixer (OIL-SOM) which can solve the above-mentioned problems. It simultaneously performs photodetection to 1.55-μm lightwave, frequency mixing, and phase-locked oscillation. Because it can be realized with a monolithic oscillator integrated circuit (IC), a very simplified base station is possible for remote up-conversion radio-on-fiber systems.

II. Proposed Scheme

Fig. 1 schematically shows the proposed base station architecture based on OIL-SOM. A simple free-running oscillator based on three-terminal phototransistor can be used for realizing OIL-SOM. The free-running oscillator is injection-locked by optically delivered LO signals from the central office. At the same time, optical IF signals at different wavelengths from optical LO are illuminated to the phototransistor inside the oscillator and frequency up-conversion can be achieved by optoelectronic mixing. For example, RF spectrum for OIL-SOM based on InP–InGaAs heterojunction phototransistor (HPT) oscillator IC is shown in the inset of Fig. 1 when optical LO frequency and IF are 10.94 GHz and 200 MHz, respectively.

Using this OIL-SOM, base station architecture for remote up-conversion scheme can be significantly simplified because a single oscillator plays the roles of photodetector, frequency

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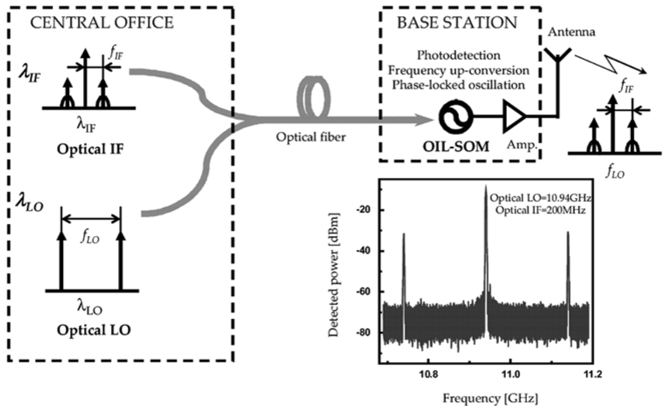

Fig. 1. Proposed antenna base station architecture based on OIL-SOM and example of its output spectrum.

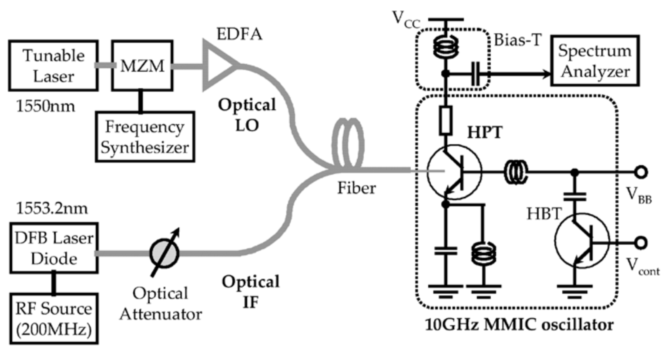

Fig. 2. Experimental setup for OIL-SOM and the schematic diagram for InP–InGaAs HPT oscillator IC. MZM: Mach–Zehnder modulator.

mixer, and high-power phase-locked LO. Because the output power of OIL oscillator depends not on incident optical LO power but on the free-running oscillator itself [5], OIL-SOM allows both high LO power and efficient frequency up-conversion independent of optical transmission distance.

III. Experimental Results

The detailed description of InP–InGaAs HPT oscillator used in our investigation can be found in [5]. The device structure of HPT is identical to that of InP–InGaAs heterojunction bipolar transistor (HBT) with the exception that the optical window with 5-μm diameter is located on top of emitter. The HPT is fully compatible to InP HBT-based MMIC process, and a monolithic OIL-SOM can be easily realized. The electrical current gain cutoff frequency (f_T) and maximum frequency of oscillation $(f_{\max})$ for the HPT are 153 and 94 GHz, respectively. The fabricated HPT exhibits large phototransistor internal gain of 18 dB at 10-GHz optical modulation frequency, which is expected to provide a wide locking range of optical injection-locked oscillator [5].

Fig. 2 shows the circuit diagram for 10-GHz band oscillator IC used in our investigation. The chip size is only 0.7×0.54 mm. The common emitter feedback was realized by using spiral inductors, MIM capacitors, and an HBT acting as a variable resistor. Free-running oscillation frequency and quality factor of the oscillator can be controlled by adjusting bias voltage for the HBT $(V_{\rm cont})$. An external bias-tee was used for collector biasing of the HPT $(V_{\rm CC})$. The experimental setup for characterizing OIL-SOM is also shown in Fig. 2. Optical LO signals at 1550 nm were generated by a Mach–Zehnder modulator and amplified by an erbium-doped fiber amplifier. For optical IF signals, a distributed feedback laser diode having lasing wavelength of 1552 nm was directly modulated with 200-MHz IF signals. For simplicity, no data were applied to IF signal. Optical LO and optical IF signals were combined and illuminated onto the HPT in the oscillator through single-mode lensed fiber. During these measurements, optical IF power injected to the HPT was set to be -3 dBm.

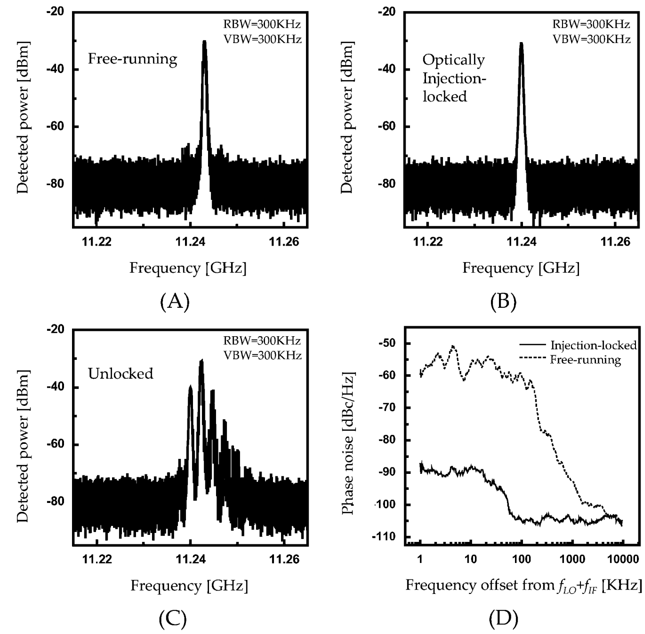

Fig. 3. Output RF spectra for frequency up-converted signal $(f_{\rm LO}+f_{\rm IF})$ when InP–InGaAs oscillator is under (A) free-running (B) OIL ($P_{\rm opt} = -1$ dBm), and (C) unlocked ($P_{\rm opt} = -10$ dBm) conditions. The phase-noise characteristics for $f_{\rm LO} + f_{\rm IF}$ when the oscillator is under free-running and injection-locked conditions are compared in (D).

To investigate the influence of optical injection-locking on the quality of frequency up-converted signals, $f_{\rm LO}+f_{\rm IF}$ signals were observed at the output port of InP–InGaAs HPT oscillator. Fig. 3 shows the output RF spectra at $f_{\rm LO}+f_{\rm IF}$ when the oscillator is under (A) free-running, (B) OIL, and (C) unlocked conditions when $V_{\rm CC} = 1$ V. The oscillator was judged injection-locked when its output spectrum has the same optical modulation frequency with low phase-noise. When OIL, the frequency up-converted signals exhibit very stable spectrum and suppressed phase-noise characteristics. We obtained a very wide locking range of about 1.4 GHz under the injection of 2-dBm optical LO signals. Fig. 3(D) shows the phase-noise characteristics of frequency up-converted signals when the oscillator is free-running and OIL. Phase noises of frequency up-converted signals are significantly reduced by optical injection-locking, resulting in phase-noise values of -88.5 and -104 dBc/Hz at 10- and 100-KHz frequency offsets from $f_{\rm LO}+f_{\rm IF}$, respectively. Such phase-noise characteristics should be sufficient for many wireless applications employing phase-modulated data schemes. When incident optical LO power is lower than -10 dBm, the oscillator goes into unlocked

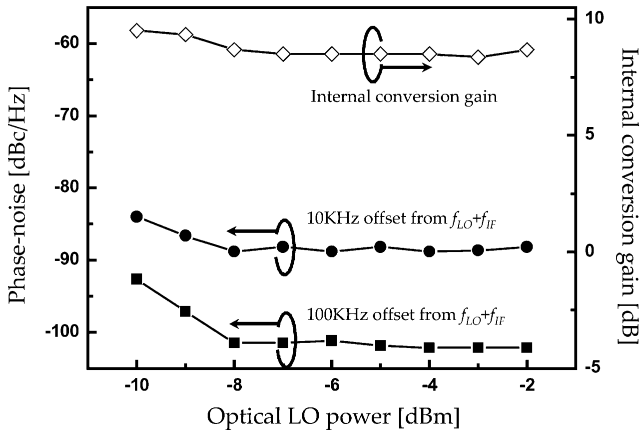

Fig. 4. Measured phase-noises and internal conversion gains as a function of input optical LO powers.

condition and frequency up-converted signals have many spurious sidebands originating from frequency mixing of optically injected signals and free-running oscillation signals.

The phase-noise characteristics of frequency up-converted signals were measured as a function of input optical LO power, and the results are shown in Fig. 4. On the condition that optical LO power is higher than -8 dBm, phase-noise characteristics are independent of optical LO power. Reducing optical LO power below -8 dBm makes the phase-noise characteristics deteriorated even under OIL condition. The internal conversion gain of OIL-SOM is also shown in Fig. 4 as a function of input optical LO power. The internal conversion gain is defined as the power ratio of the optoelectronic mixing signal at $f_{\rm LO}+f_{\rm IF}$ to the primary photodetected signal at $f_{\rm IF}$ that can be measured when HPT is at cutoff. As can be seen in Fig. 4, high internal conversion gain of about 9 dB can be achieved regardless of input optical LO power. These features are very attractive for radio-on-fiber systems that employ optical LO distribution scheme because frequency up-conversion performance is not significantly influenced by the amount of optical LO power, which may vary among base stations, as long as the locking condition is achieved with relatively small optical LO power of -8 dBm.

IV. Conclusion

We investigated OIL-SOM that can be used for simplifying base station architecture in remote up-conversion radio-on-fiber downlink systems. It provides low phase noise and high output power LO signals and simultaneously perform optoelectronic frequency up-conversion of incoming optical IF signal with high conversion gain. Furthermore, its device performance is uniform over the wide power range of optical LO, which promises high performance independent of optical transmission distance. Because this approach is based on a single InP–InGaAs HPT oscillator, it can greatly reduce the complexity of base station architecture in radio-on-fiber systems.

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