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Frequency Up-Conversion Technique for Radio Over Fiber (RoF) Remote Antenna Unit Configuration

N. Mohamed[1,*], S. M. Idrus[2], A. B. Mohammad[2], H. Harun[2], R. Mohamad[3] and S. Yaakob[3]

[1]*Universiti Teknologi Malaysia, Razak School of Engineering and Advanced Technology, Kuala Lumpur, Malaysia*

[2]*Universiti Teknologi Malaysia, Photonic Research Laboratory, Johor, Malaysia*

[3]*Telekom Research and Development Sdn. Bhd., Photonics Program, Cyberjaya, Selangor, Malaysia*

Abstract: This work involves in transmitting of intermediate frequency (IF) signal over fiber utilizing photonics frequency conversion, which, the main focus is the development of optical front-end receiver. The system uses photodiode and heterojunction bipolar transistor (HBT) to detect and up-convert the received IF modulated optical signal. The photodiode (PD) and HBT are very useful devices for photonics frequency conversion technique with high internal gain and frequency up conversion of optical signal. Through simulation, the optimum device parameters and characteristics were determined. The system was implemented to detect a 0.4 GHz of IF carriers signal and up-converted to 3.4 GHz of radio frequency (RF) signal. The optimum conversion gain that has been obtained from the measurement and simulation were about -11 dB and -8 dB, respectively, at V_{BE} = 0.7 V, P_{LO} = 4 dBm, and -25 dBm of IF optical input power. The system has been practically demonstrated and shown to agree reasonably well with both the theory and simulation. This article also refers to some recent patents on frequency conversion techniques.

Keywords: Radio over fiber (RoF), frequency up-conversion, heterojunction bipolar transistor (HBT).

1. INTRODUCTION

Due to a great promising key factor of radio over fiber (RoF) technology, it has caught the attention of many researchers to investigate the millimeter-wave (mm-wave) generation techniques for high transmission performance. As has been reported, mm-wave can be generated in many ways such as direct modulation detection for low frequency of RoF system [1], external modulation either based on single sideband (SSB) or double sideband (DSB) [2-5], optical heterodyning detection [6], and etc. Due to the many options we have, thus, many works have been conducted to realize this mm-wave transmission system for various applications. Wireless networks based on RoF technologies have been proposed as a promising cost-effective solution to meet an increasing user bandwidth and wireless demands. Since it was first demonstrated for cordless or mobile telephone service in 1990 [7], a lot of researches have been carried out to investigate its limitation and develop new and high performance of RoF technologies. In this network, a central station (CS) is connected to numerous functionally simple remote antenna units (RAUs) via an optical fiber as shown in Fig. (**1**). The main function of RAU is to convert optical signal to wireless one and vice versa. Almost all processing including the modulation, demodulation, coding, and routing are performed at the CS. Therefore, RoF networks use highly linear optic fiber link to distribute RF signal between the CS and RAUs.

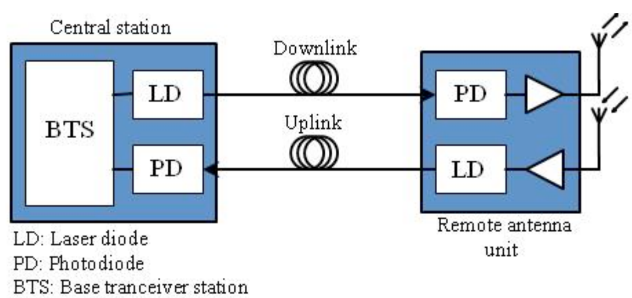

Fig. (1). Block diagram of RoF system.

RoF is unlike conventional optical networks where digital signal is mainly transmitted. RoF is fundamentally an analog transmission system because it distributes the radio waveform, directly at the radio carrier frequency, from a CS to a RAU. Actually, the analog signal that is transmitted over the optical fiber can either be RF signal, or IF signal. For an ideal case, the output signal from the optical link will be the same as of the input signal. However, there are some limitations because of non-linearity and frequency response limitation in the laser and modulation device as well as dispersion in the fiber [8-9]. The transmission of analog signals puts certain requirements on the linearity, and dynamic range of the optical link. These demands are different and more exact than requirements on digital transmission systems [10].

Up- and down-conversion is the technique where the IF signals is transmitted over optical fiber instead of RF signal.

*Address correspondence to this author at Razak School of Engineering and Advanced Technology, Universiti Teknologi Malaysia, International Campus, Jalan Semarak, 54100 Kuala Lumpur, Malaysia; Tel: +603-26154502; Fax: +603-26934844; E-mail: norliza_mohamed@yahoo.com, mnorliza@ic.utm.my.

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The transmitted IF-band optical signal is almost free from the fiber dispersion effect. There are two techniques either in electrical conversion or optical conversion domain. The electrical technique uses RF mixer. There are many reported works in up-converting frequency implementing the external modulation [11], optical heterodyne [12], optical transceiver [13], or mixing element like *p-i-n* PD [14], high electron mobility transistor (HEMT) [15] and HBT [16-17]. In addition, there are also some patented design in frequency up-conversion that have been published utilizing a translational phase locked loop (PLL) as the up-conversion module [18] and using a semiconductor optical amplifier (SOA) that mixes the IF with optical LO through four wave mixing [19]. Recently, [20] reported the receiver that configured selectively receive an RF signal from an operating band having a plurality of RF channels.

In this paper, we demonstrate a simulation of a photonic frequency up-conversion system by employing nonlinear harmonic balance model performed by single stage three-terminal SiGe HBT. By taking advantages of the nonlinearities of the HBT, we obtained the up-conversion frequency of a modulated optical signal and compared to the experimental from the device development. In this work, the development of the design is protected under the Malaysian Patents PI20084484 [21] and PI2010001880 [22].

2. UP-CONVERSION MODEL

A very limited amount of work has been published on the modeling of HBT optoelectronic mixer (OEM). Betser *et al.,* [23] reported modeling a three-terminal HBT electrically pumped OEM using SPICE (Simulation Program with Integrated Circuit Emphasis-Orcad 9.2) software. The equivalent circuit used was a standard SPICE bipolar transistor (BJT) model with a current source connected between the base and the collector to account for the primary photocurrent generation. This model suffers from a number of weaknesses. First, the use of a standard SPICE BJT model implicitly assumes that the base current is dominated by the back-injection hole current from the base to the emitter, which has the same ideality factor as the injection current from the emitter to the base, and hence the collector current. As has been explained, this is not accurate because of the use of the heterojunction and the base current in the present InP/InGaAs HBT is dominated by the base-emitter junction recombination current, having a different ideality factor from the collector current. The difference in the ideality factors of the base and collector currents contributes a significant mixing mechanism because the transistor current gain becomes a function of V_{BE} (or I_C) which in turn is modulated by the local oscillator (LO). If the base current has the same ideality factor as the collector current, as is assumed in the SPICE BJT model in [23], current gain variation with V_{BE} can only occur when the frequency is higher than the inverse of the time constant of the base-emitter capacitance and dynamic resistance. In other words, the assumption of equal ideality factor implies that at low frequencies when the impedance of the base-emitter capacitance is high compared to the base-emitter dynamic resistance, mixing becomes less efficient because the transistor current gain does not vary much with V_{BE}. Harmonic balance techniques have been popular in large-signal microwave circuit analysis [24-25] and ever since have been employed in modeling laser dynamics [26-27]. However in this work, harmonic balance technique was applied to modeled and simulate the optoelectronic mixing in single-stage three terminal HBT.

Table 1. SiGe HBT Mixer Circuit Parameters

Symbol	Value
R1	20 Ω
R2	20 kΩ
R3	50 Ω
C1	20 fF
C2	12 fF
C3	20 fF
L1	100 nH
L2	150 nH

The mechanism of the HBT is highly non-linear; therefore it is necessary to obtain simulation results prior to practical implementation. The circuit was initially simulated in time-domain utilizing SPICE. Then, by transforming the output waveform using Fourier transforms, it will give the frequency spectrum from which the conversion gain of the mixer is determined. The results have been published in [28] and [29] presenting the performance of the OEM. However, there are a few difficulties in such a time-domain approaches. Firstly, the circuit might contain an input and output impedance matching network, signal filters and frequency-dependent transistor parameters such as the base transport factor. These linear elements can be easily described in the frequency-domain but it would be rather complicated to do so in the time-domain. Secondly, since only the steady-state solution of the mixing is of interest in the current investigation, the number of LO cycles the simulator takes to reach a steady state can be very high. One usually has to examine manually the waveforms and decide when a steady-state solution has been reached. Finally and most importantly, mixing involves not only the LO frequency but also the IF and other up- and down-converted and image frequencies.

A non-linear harmonic balance model was employed to simulate the mixing performance of the single stage three-terminal SiGe HBT electrically pumped optoelectronic mixer. The simulations were implemented in a commercial non-linear harmonic balance simulator to perform a multi-tone harmonic balance small-signal analysis of the generation and amplification of the detected signal from a 1550nm wavelength and 0.001 – 10mW of laser source. Table **1** lists the parameters that have been used in the HBT electrically pumped optoelectronic mixer while the schematic circuit diagram of the HBT optoelectronic mixer using the harmonic balance simulator is shown in Fig. (**2**). The voltage source, V_{LO}, represents the electrically pumped LO and the base terminal of the HBT served as an input terminal for the LO signal. The frequency of the LO signal used for simulation was 3.0 GHz and the frequency of the IF optically modulated input signal was 0.4 GHz.

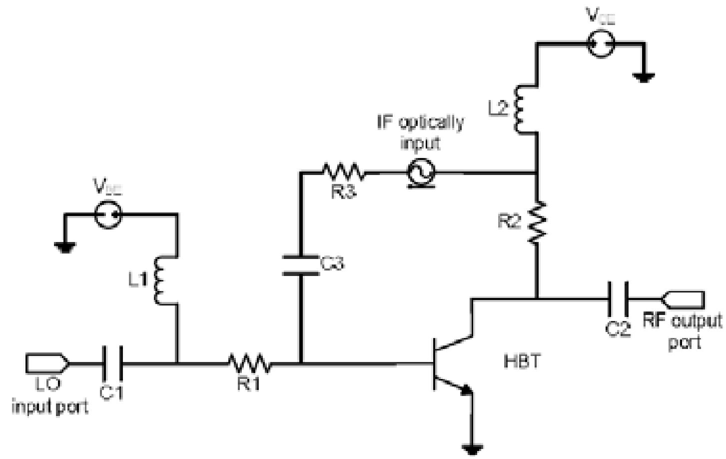


Fig. (2). HBT up-converter circuit mixer for harmonic balance simulation.

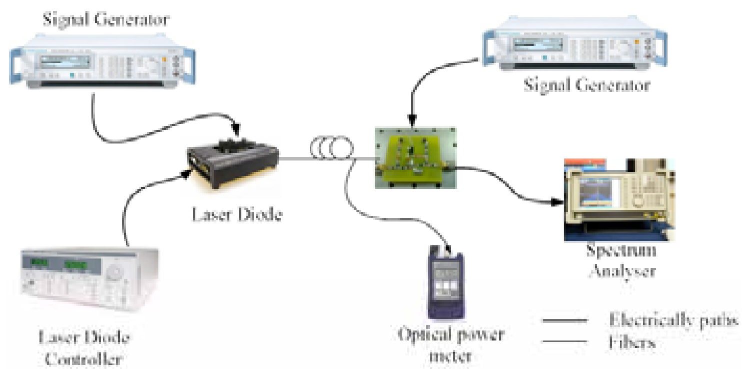


Fig. (3). Experimental arrangement of the 3.4 GHz optical front-end receiver using RoF setup.

A 50-Ω load resistor represented the input impedance of the spectrum analyzer, and the inductance of the bonding wires was includes as well. The simulation was carried out for different LO power and the result will be discussed in the results section. A mixing model was carried out by taking advantages of the nonlinearities of the HBT to achieve up-conversion of a modulated optical signal. The intensity of the optical signal was modulated by an IF signal ranging from 0.1 GHz to 0.4 GHz. The 100 – 400 MHz modulated optical input power was -16 dBm. The local oscillation frequency injected into the base terminal was 3 GHz with input power levels that have been varied from -5 dBm until 5 dBm.

3. EXPERIMENTAL SETUP

This section is concerning on the development and experimental of the three-terminal normal incidence HBT mixer. The mixer was developed by means as the front-end optical receiver to perform photonics frequency conversion up to 3.4 GHz for RoF. The circuit and system parameters for practical arrangement were based on the system simulation parameters that have been discussed in previous section. The optically modulated IF signal were transmitted through a single mode fiber by the laser diode mount from ILX Lightwave. The laser diode mount current and temperature were controlled and supplied by the laser diode controller, also from ILX Lightwave. The current at the laser diode controller was set to 22 mA in order to obtain the 1mW optical output power at end of the fiber. The length of the employed fiber was 500 meters. An optical power meter was used to measure the optical power at the end of fiber optic.

400 MHz optically modulated IF at 1550 nm wavelength was absorbed in the base and collector of the HBT. The primary photocurrent serves as the base bias in a normal bipolar transistor. The HBT was biasing using the direct current (DC) power supply. The DC biasing at the base and collector terminals of HBT are important to get the optimum gain of the up-conversion. The 3 GHz LO signal from signal generator was pumped at the HBT base terminal and the LO power was varied from -30 dBm to 4 dBm. While at the collector terminal, the spectrum analyzer was connected to measure the output signal power of the up-converted RF signal. The lower and upper side bands at the output terminal were also measured.

Both HBT base and collector terminals were biased via ZFBT-6G-FT Bias Tees having a frequency range of 10 MHz to 6 GHz for external bias and alternating current (AC) signal coupling. Fig. (**3**) shows the experimental arrangement of 3.4 GHz front-end optical receiver for radio over fiber system. The base terminal of the HBT that was in electrically pumped mixing mode was driven by the LO while the output signal was separately obtained from the collector terminal. The emitter terminal was set to the ground. The broadband photodiode and SiGe HBT were mounted on FR4 board with 1.6 mm thickness. SMA connectors were then attached to both ends of the mount so that the HBT mixer could be electrically accessed using conventional microwave cables. The circuit for the measurement of the 3.4 GHz optical front-end receiver for the RoF system is shown in

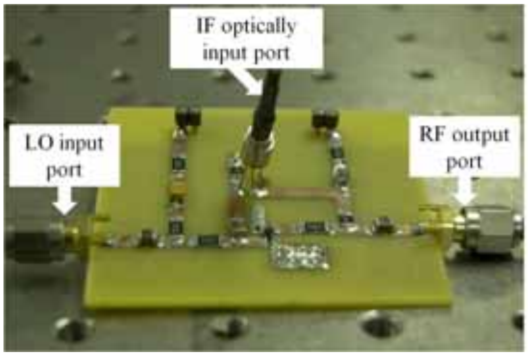
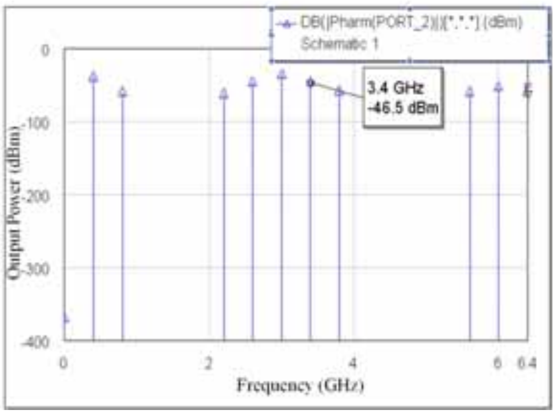
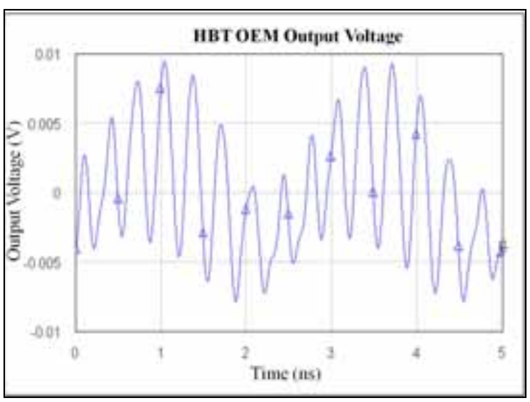


Fig. (4). HBT mixer board circuit for up-conversion 400 MHz to 3.4 GHz.



(**a**)



(**b**)

Fig. (5). The output product in **(a)** time domain, **(b)** frequency domain.

Fig. (**4**). It was designed to detect a 400 MHz IF optically modulated signal, up-converted to 3.4 GHz electrically RF signals.

4. RESULTS AND DISCUSSION

The simulation was carried out as a function of the base-emitter voltage and collector-emitter voltage for different LO power levels. The RF output power levels were considered in the range of 3.1-3.4 GHz as the HBT was operating for up conversion mode. In the up conversion mode, the baseband was translated to a higher frequency, which is equal to the sum of baseband (f_{IF}) plus pumped signal (f_{LO}). Harmonic balance simulator was able to produce the output either in the time domain or in the frequency domain as can be found

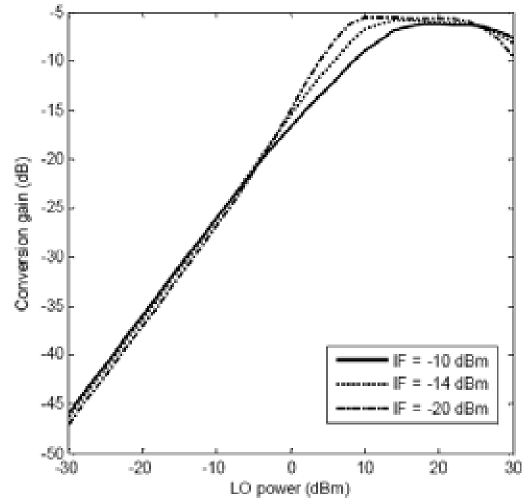


Fig. (6). System conversion gain as a function of LO input power, V_{BE} = 0.74 V and V_{CE} = 15 V.

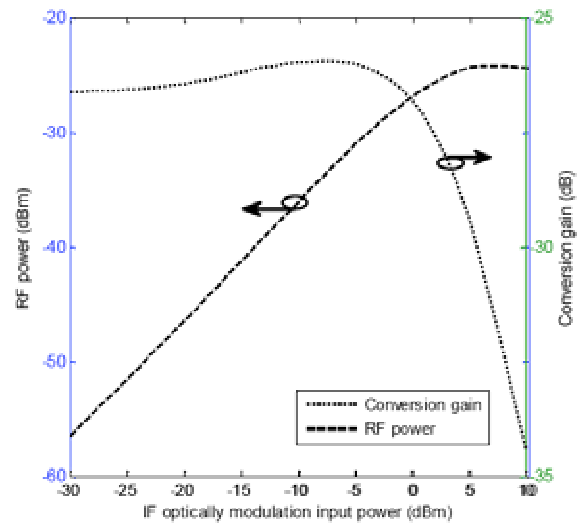


Fig. (7). The conversion gain and RF output power of the BFP640 simulated mixer as a function of IF optical modulated input power at V_{BE} = 0.74 V, V_{CE} = 15 V, and P_{LO} = -10 dBm.

in Fig. (**5a**) and (**5b**). Fig. (**5b**) demonstrates the harmonic spectrum for mixer product in frequency domain at V_{BE} = 0.74 V and P_{LO} = -10 dBm.

Initially, the conversion gain was steadily increased as the LO power increased. However, when the device was penetrated the saturation region which about 10 dBm of LO power, the conversion gain was started to maintain at almost a constant value. The behavior of the conversion gain can be seen in Fig. (**6**). It was found that by using the BFP640 model, the simulation has shown that the IF optical modulated input power did not effect the conversion gain when the LO power that is less than -5 dBm. At -20 dBm of IF optical modulated input power, the conversion gain was at its maximum point i.e at about -5 dB with LO drive power of 10 dBm. The peak conversion gain for IF optical modulated input power of -14 dBm and -20 dBm were reached at LO power of 14 dBm and 18 dBm respectively.

Both conversion gain and RF output power versus the IF optical modulated input power level are shown in Fig. (**7**).

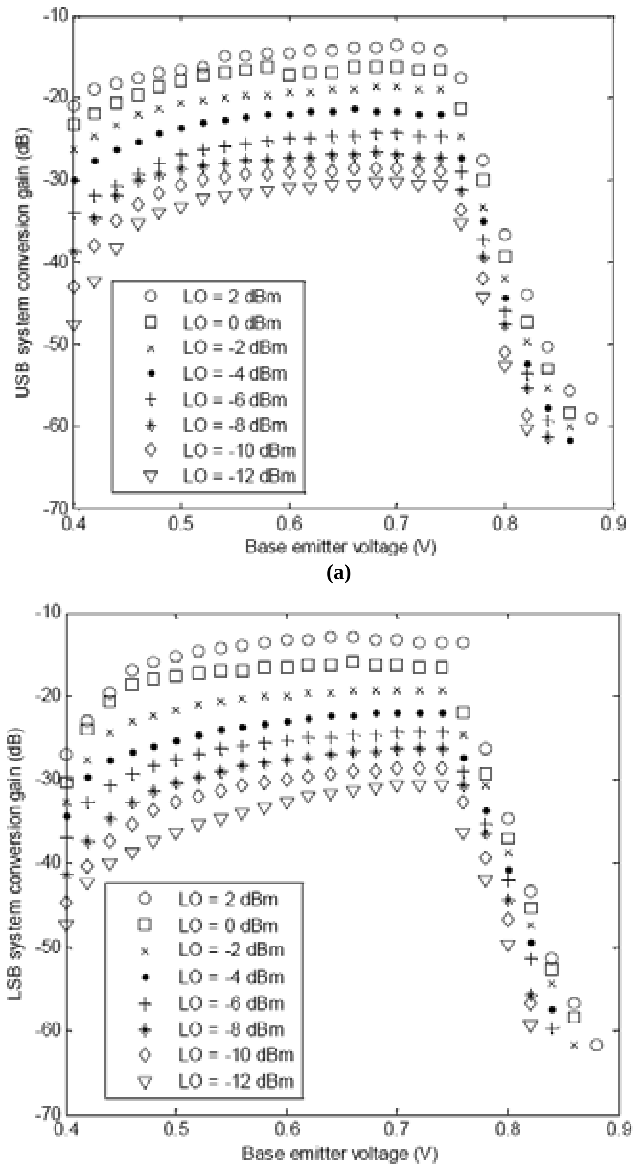


Fig. (8). Measured system conversion gain for **(a)** upper side band, **(b)** lower side band versus base emitter voltage as a function of LO powers at P_{IF} = -30 dBm, V_{CE} = 15 V, f_{IF} = 0.4 GHz and f_{LO} = 3.0 GHz.

The conversion gain remained constant until the device dropped abruptly at around -5 dBm of IF optical modulated input power. The optimum conversion gain that was obtained at LO power of -10 dBm was approximately -27 dB.

Fig. (**8a**) and (**8b**) portray the measured conversion gain for upper side band (USB) and lower side band (LSB) of the device. The measured system conversion gain at different LO power levels in the function of the base-emitter voltages were about -14.3 dB and -14 dB for the USB and LSB respectively. The measurement was based on the setting where 400 MHz of intensity modulated light with the power of -30 dBm and 2 dBm of LO signal at V_{BE} = 0.7 V and V_{BE} = 0.66 V correspondingly. The results indicated that the dynamic emitter resistance, r_e, limited the conversion gain, which determined the current gain of the HBT.

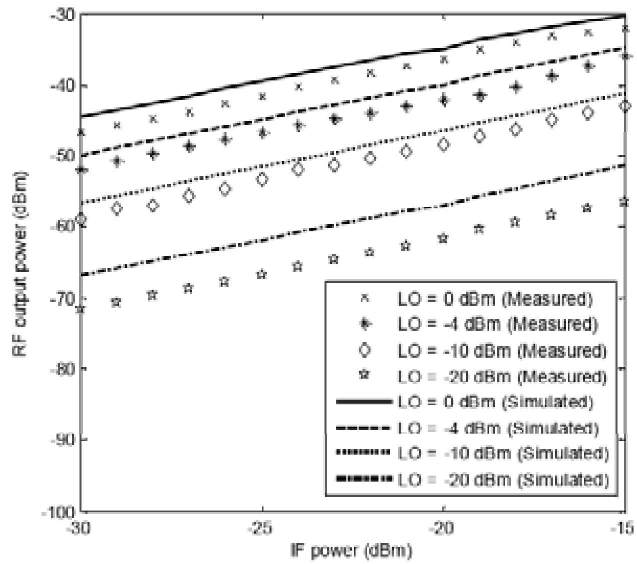


Fig. (9). Comparison of measured and simulated of RF output power versus IF optical modulated power level as a function of LO power.

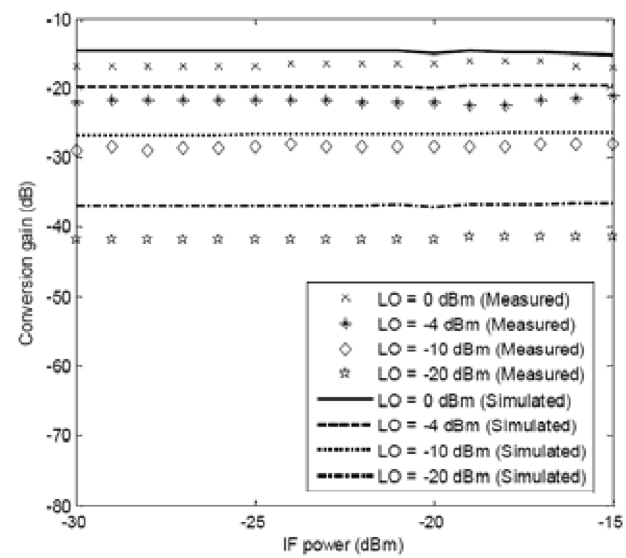


Fig. (10). Comparison of measured and simulated of system up-conversion gain versus IF optical modulated power level as a function of LO power.

HBT frequency mixing is conventionally carried out by first converting an IF modulated optical signal into an electrical signal, and the IF signal will then be mixed with an LO signal to produce mixed product at both upper and lower side bands. In this arrangement, the power of IF modulated signal was varied from -30 dBm to -15 dBm. The up converted RF signal at 3.4 GHz was obtained by selecting the USB at the emitter port of SiGe HBT. The base emitter voltage, V_{BE} was fixed at 0.7 V to achieve the maximum output power for the USB condition.

The simulated and measured RF output power and conversion gain characteristic can be found in Fig. (**9**) and Fig. (**10**) respectively. The results show that the RF power raised linearly when the optically modulated IF power increased. On the other hand, the conversion gain almost remained at the same value as the optically modulated IF power increased. From Fig. (**10**), it shows that the highest conversion gain that has been obtained was about -17dB at LO power level of 0 dBm. The difference was about 3 dB as compared to the simulation results. The mean optical power of the photodetector and HBT was 1 mW. Urey *et al.*, [30] demonstrated the conversion gain using HBT electrically pumped mixing at -21 dB with mean optical power around 18 mW. From this observation, we concluded that the the conversion gain was not affected by the changes of the optically modulated IF power. It was found that the results that have been obtained from the practical measurement showed good qualitative agreement with the simulation results.

CONCLUSION

Based on the biasing voltage with LO input power and IF optically input power that have been used, this front-end optical receiver has achieved a good conversion gain at different frequencies. The measured system gain characteristics have been compared with the simulation results of the harmonic-balance model. The simulation results have shown good qualitative agreement with the experimental results. The inconsistency between the simulation and measurement results are attributed to the high-level assumption that the mixing mechanism of the HBT mixer was the terminal voltage dependence of small-signal photocurrent gain, and the quasi-static nature of the model. Nevertheless, the model has provided a simple way of predicting the conversion characteristics of the HBT electrically pumped mixer.

CONFLICT OF INTEREST

None declared.

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CURRENT AND FUTURE DEVELOPMENT

Presently, we are developing an up-conversion design for frequency of up to 42.4 GHz. The design is also based on simulation and hardware implementation. As for now, we have achieved an up-conversion frequency of millimeter-wave band and will demonstrate this configuration for millimeter-wave radio over fiber system as for future practical system development.

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