Optoelectronic Mixing, Modulation, and Injection Locking in Millimeter-Wave Self-Oscillating InP/InGaAs Heterojunction Bipolar Photo Transistors—Single and Dual Transistor Configurations

Jacob Lasri, *Student Member, IEEE*, Alberto Bilenca, *Student Member, IEEE*, Gadi Eisenstein, *Fellow, IEEE*, and Dan Ritter

***Abstract*—We describe an experimental investigation of two millimeter-wave oscillators one employing a single and the other using two InGaAs/InP heterojunction bipolar photo-transistors (photo-HBTs). The single HBT oscillator can be optically injection locked to improve its spectral purity. Alternatively, it can be modulated by analog or digital data carried by an optical signal. In the two photo-transistors case, one HBT oscillates and is optically injection locked while the second serves as a modulator. The two-transistor case proved to be superior in terms of carrier spectral purity, analog modulation efficiency and linearity as well as for digital modulation. Its advantages stem from the better isolation between the local oscillator and modulating signals and from the ability to separate the injection-locking and modulation functions.**

***Index Terms*—Heterojunction bipolar transistor, injection-locked oscillator, modulation, optoelectronic mixing, self-oscillator.**

I. Introduction

The future use of broad-band wireless communication services will require massive integration between the network distributing microwave and millimeter-wave radio signals and the optical fiber network which will carry broad-band data and control signals. Several possible approaches to obtain analog or digitally modulated high frequency signals at a remote base station (BS) have been investigated [1]–[3]. One of those relies on the generation of a microwave or millimeter-wave local oscillator signal at the BS. Data originating from a distant central station are distributed over an optical fiber to the BS where it modulates the carrier prior to transmission by the antenna. Data received at the BS antenna are down converted using the available local oscillator signal and the recovered data modulates an optical signal which transmits the data down stream from the base station. The incorporation of such a local oscillator at the BS implies the availability of a compact, efficient and reliable source which can be modulated.

An attractive possibility, which has been recently demonstrated in several experiments [4]–[7] is the use of optoelectronic devices such as MESFETs, high electron-mobility transistors (HEMTs), and heterojunction bipolar transistors (HBTs) for these kind of compact sources. Optoelectronic devices allow to combine the functions of microwave oscillation, photodetection, and frequency up-conversion and also offer intrinsic gain and high responsivities. The photo-HBT has the highest optical coupling efficiency [8] and lowest low frequency noise among the three transistors [9], making it attractive for various types of fiber-optic/microwave links.

In this paper, we present an experimental investigation of milimeter-wave sources based on self-oscillating InGaAs/InP photo-HBTs. Two configurations have been studied, one employs a single photo-HBT and the other uses two. Both configurations unify the functions of photodetection, oscillation, and frequency up-conversion. The devices we employed have been described in detail before [6], [10]. The optical window at their base has an area of 30 μm^2, the quantum efficiency (defined in [10]) is ~30% and typically, $f_T = 70$ GHz.

The following three aspects of the self-oscillators were investigated. 1) Optical injection locking to improve the spectral purity of the oscillator. A phase noise lower than -100 dBc/Hz at a 10-kHz offset from the carrier was demonstrated in a 10-GHz oscillator. 2) Analog and digital modulation obtained by coupling an information carrying signal to the optical port thereby imprinting the data via the optoelectronic mixing process. Efficient analog modulation was demonstrated for 10- and 30-GHz oscillators and the modulation linearity was examined. Wide band digital modulation with error free capabilities was also demonstrated. 3) The use of two photo-HBTs, where one transistor self-oscillates, is optically injection locked and feeds the base of a second HBT (via a stub-tuner) which in turn serves as an optoelectronic mixer/modulator. Analog and digital modulation were demonstrated and the characteristics were found to be superior to the corresponding ones in the single HBT case.

II. Photo–HBT Self-Oscillator

A. Experimental Setup—Single Transistor Configuration

The single photo HBT oscillator is described in Fig. 1(a). The collector electrode is fed back to the base via a narrow bandpass

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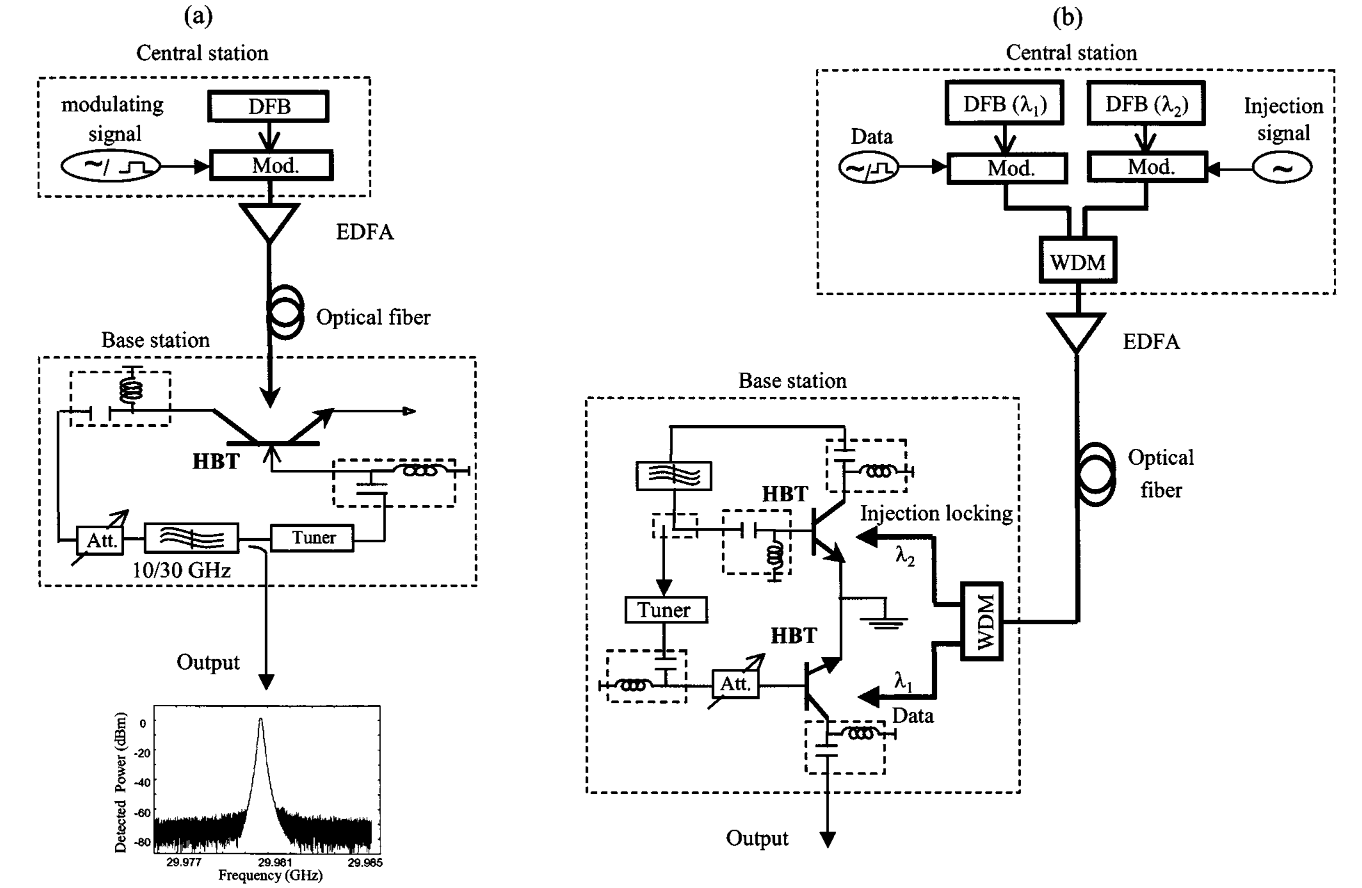

Fig. 1. Experimental setup for the self-oscillating photo-HBT optoelectronic mixer. (a) Single HBT configuration. (b) Dual HBT configuration. The insert describes a nonmodulated 30-GHz carrier.

filter centered at 10 or 30 GHz, an attenuator and a microwave tuner to form the oscillator. The output signal is extracted via a broad-band directional coupler at the collector. A modulated optical carrier is coupled to the optical window at the base region of the photo-HBT and the modulation is imprinted on the carrier. For injection locking, the optical input signal is modulated using a highly pure microwave source operating at the self-oscillating frequency. The insert of Fig. 1(a) shows an oscillating spectrum at 30 GHz with the optical signal being turned off. The operating conditions of the transistor were $V_{BE} = 0.7\,\text{V}$ and $V_{CE} = 1.5\,\text{V}$.

B. Experimental Setup—Dual Transistor Configuration

The two HBT configuration is illustrated in Fig. 1(b). The first photo-HBT self-oscillates at 30 GHz with the base dc bias setting an optimum operating point. An attenuator and a microwave tuner are used to adjust the RF signal level fed to the base of the second (modulating) transistor. The dc bias is adjusted so as to keep the second (modulator) transistor in the active mode.

The optical port of the oscillating transistor is used for injection locking and the second photo-HBT receives the optical modulating signal. The two optical carriers can be transmitted from a distant base station on separate wavelengths and demultiplexed by standard WDM techniques.

C. Injection Locking

The phase noise of the free-running oscillator is determined by the Q value of the microwave filter and the loop losses. For the 10-GHz oscillator, the free-running phase noise measured at a 10-kHz offset was -81 dBc/Hz. For the 30-GHz oscillator, the loop losses were larger resulting in an increased phase noise of -68 dBc/Hz. These phase noise values, while rather low, may cause detection difficulties for phase sensitive modulation schemes. With optical injection locking under optimum conditions, the phase noise of the 10-GHz oscillator was reduced to below -100 dBc/Hz and, in the corresponding 30-GHz case, it was -80 dBc/Hz. The minimum obtainable phase noise depends on the locking range and the measurement offset frequency [11], [12]. The near-carrier noise is approximately that of the injected signal over most of the locking range, but approaches that of the free-running oscillator at the band edges. In the present case, the range is $\sim$100 kHz (at -10-dBm optical power) and we measured at 10-kHz offset so we actually obtained the phase noise of the injected signal (<-100 dBc/Hz).

In Fig. 2(a) we display the phase noise dependence on the detuning between the free-running 10-GHz oscillator and the injection-locking input frequency. The injection level was measured using the HBT as a photodetector (namely, with zero bias to the base) and was found to be rather low (less than -10 dBm, as compared to a few milliwatts of the free-running oscillator). The low injection level results in a narrow locking range however, operation with a low optical power is important for practical applications since it enables multicasting an optical locking signal between many base stations. In Fig. 3 below we demonstrate an increased locking range using higher optical powers.

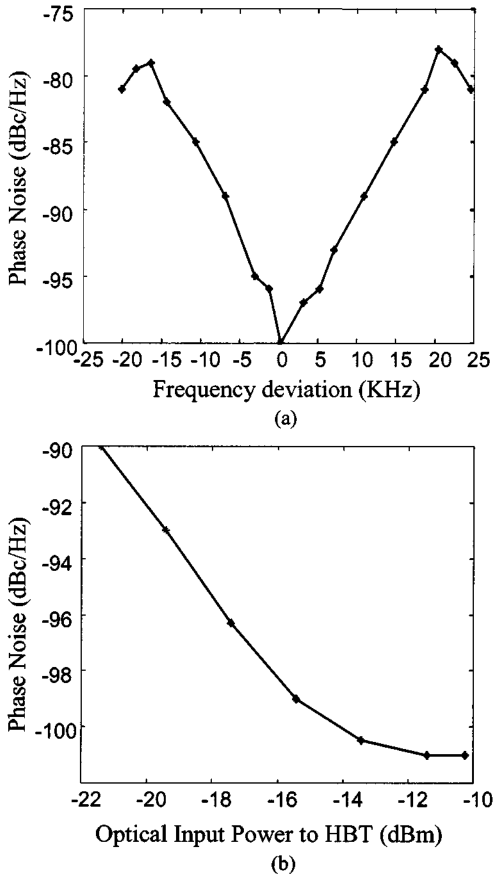

Fig. 2. Measured phase noise at 10-kHz offset in the 10-GHz source. (a) As a function of the frequency detuning between the free-running oscillator and the injection-locking input frequency (using an average optical input power of -10 dBm). (b) As a function of the average optical power to the HBT.

The significant effect of the injection-locking process is clearly seen in the figure with the phase noise reaching a minimum below -100 dBc/Hz. Fig. 2(b) shows the phase noise as a function of the average optical power under optimum detuning and modulation depth conditions. We note that at injected powers above -13 dBm the phase noise saturates at the low level of ~ -100 dBc/Hz.

Fig. 3 validates the square root dependence of the locking range on the injection power (given by the Adler equation, [13], [16]). Fig. 3 also demonstrates that by increasing the optical power, the narrow range over which the phase noise is low [see Fig. 2(a)] can be increased as dictated by specific applications. From the experimental data we obtained a cold cavity bandwidth of $\sim$1 MHz, implying that the Q factor of the suggested oscillator is on the order of 10 000. We note that the bandwidth of the bandpass filter was 10 MHz.

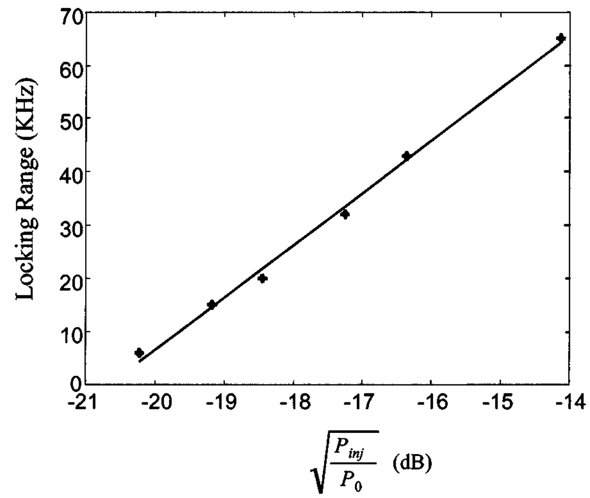

Fig. 3. Injection-locking range as a function of the square root of the ratio of injected input power to free-running output power.

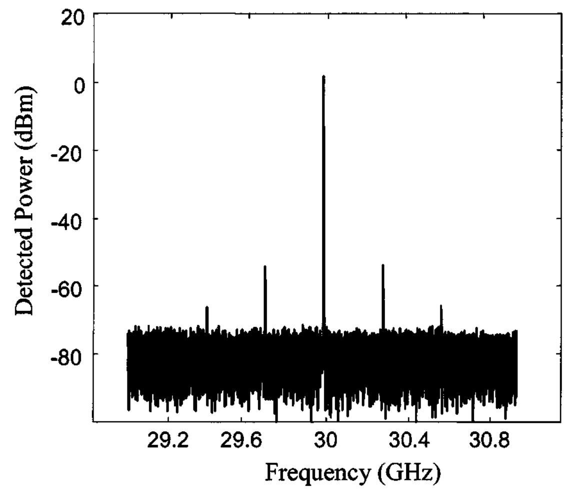

Fig. 4. Measured spectrum of a 30-GHz carrier modulated at 300 MHz.

III. Modulation

A. Analog Modulation

Fig. 4 shows a measured spectrum of the single HBT oscillating at 30 GHz, without injection locking. The two sidebands due to a 300-MHz optical modulation and the harmonics at 600 MHz are also seen in this figure. A similar spectrum was obtained with the two-transistor configuration. The detected power at the upper sideband is shown for the two configurations in Fig. 5 as a function of the modulating input power. The modulating input power is that of the 300-MHz component measured by the HBT operating as a photo detector with zero base–emitter voltage. The use of the detected modulation signal as the input parameter ensures that the self-oscillator characterization is independent of the particular transmitter used in the central station.

For both configurations, the average optical input power was -3 dBm and the power of the 30-GHz carrier was -10 dBm. In the single self-oscillator configuration the power was measured using a coupler placed at the base electrode and monitoring the exact carrier power that was fed to the base. For the two-HBT configuration, we measured the 30-GHz carrier power coupled to the modulating HBT directly. We note that the modulation efficiency of the two-transistor configuration is approximately 3 dB higher than that of the single HBT.

In a single self-oscillating photo-HBT, the RF current generated in response to the modulated optical signal is not isolated well from the local oscillator current (at the oscillating frequency). This coupling occurring mainly at the base degrades the modulation efficiency. It was eliminated in the two-HBT configuration by adding the broad-band stub-tuner between the

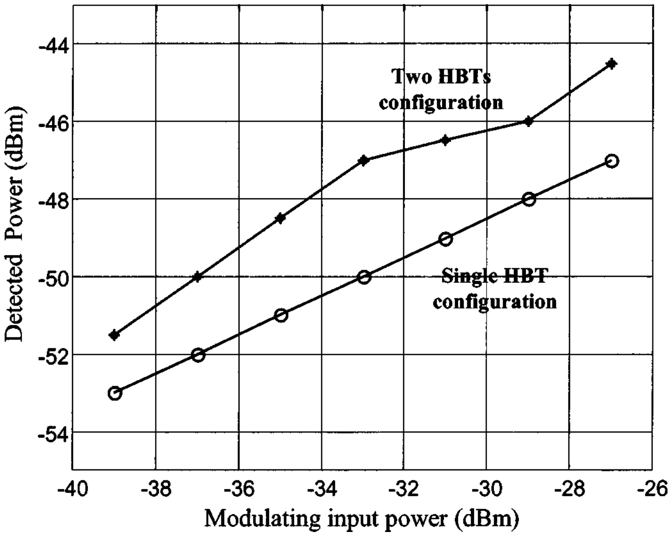

Fig. 5. Detected power of the upper sideband as a function of the modulating input power for the two configurations (the average optical input power was −3 dBm and the 30-GHz carrier power was −10 dBm for the two configurations, that means a modulation depth of 20%).

oscillator output (at the collector) and the input port of the modulating HBT (at the base). The stub-tuner did not simply improve the impedance match between the two transistors as the measured local oscillator power did not change. Rather, proper adjustment of the tuner increased the isolation which in turn improved the modulation efficiency [14].

The modulation linearity of the two cases is described in Figs. 6 and 7. The dependence on the modulation input power of the first and second modulation sidebands (at 30 GHz + 300 MHz and 30 GHz + 600 MHz) are shown in Fig. 6(a) and (b) for the single and dual HBT configurations, respectively. The results are summarized in Fig. 7 which compares the harmonic suppression (the ratio between the first and second modulation sidebands) in the two configurations for different modulating input powers. For this experiment we used (in both configurations) an average optical input power of −3 dBm and the 30-GHz carrier power was −10 dBm. We note that the linearity of the two HBT configuration is better by several decibels.

The nonlinear modulation characteristics have a component due to the nonlinearity of the (nominally linear) HBT gain. This nonlinearity was recently characterized for a similar HBT operating as a mixer using the two-tone technique with two laser sources [15]. In the two-HBT configuration, the modulating transistor operates in the active mode and this particular nonlinear contribution is significant. In the single HBT case, the gain is heavily saturated due to the oscillation conditions and the saturation dominates the nonlinearity, which is higher.

B. Digital Modulation

Digital modulation was characterized in both the frequency and time domains. Fig. 8 shows the spectrum of a 10-GHz single HBT oscillator modulated at 500 Mb/s. The typical sinc^2 functional shape with no spectral distortions is observed. The insert show detected eye pattern which is open and relatively noise free. We do note that the noise in the "1" state is larger than the corresponding noise in the "0" state. The difference stems from

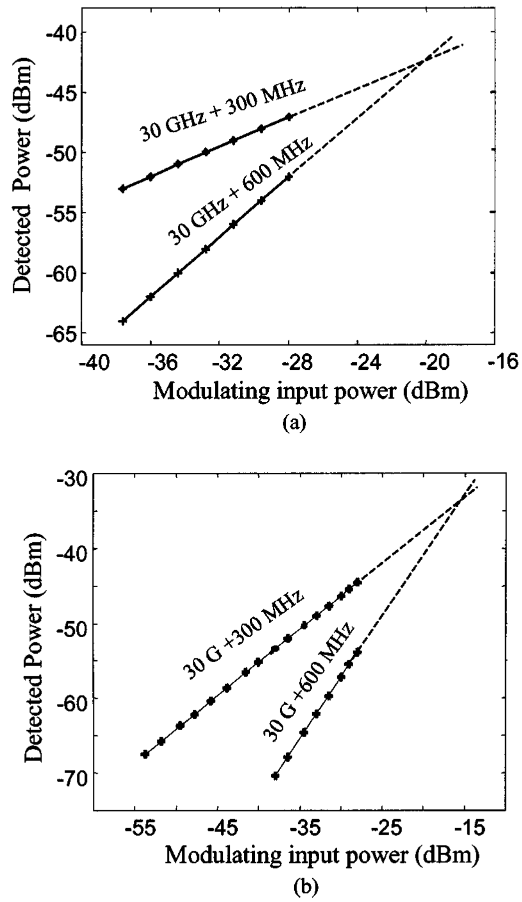

Fig. 6. Modulation sidebands as a function of the modulating input power. (a) Single HBT configuration. (b) Dual HBT configuration (the average optical input power was −3 dBm and the 30-GHz carrier power was −10 dBm for the two configurations, that means a modulation depth of 20%).

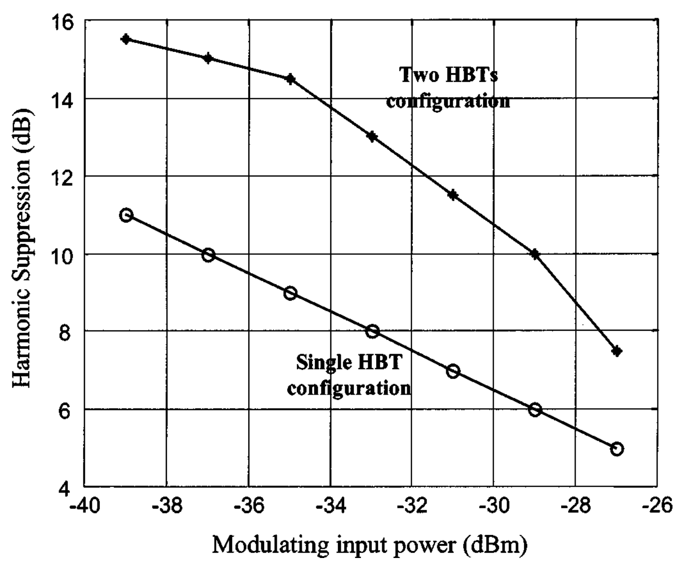

Fig. 7. Harmonic suppression (the ratio between the first and second modulation sidebands) as a function of the modulating input power for the two configurations.

the different shot noise levels experienced by the photo-HBT in the detection process of the two states. For the two photo-HBT case we obtained identical qualitative results in both the frequency and time domains.

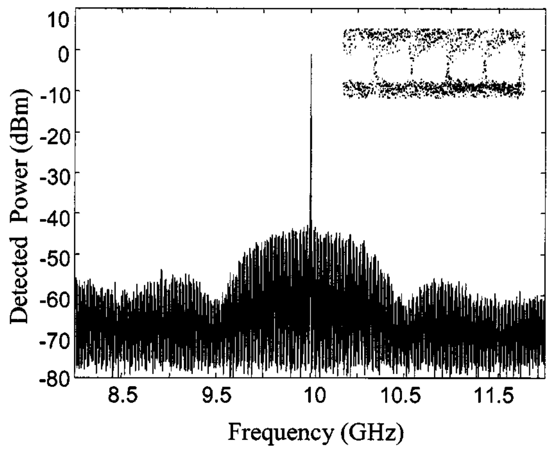

Fig. 8. Measured spectrum of a 10-GHz single photo-HBT oscillator digitally modulated at 500 Mb/s. The insert show detected eye pattern.

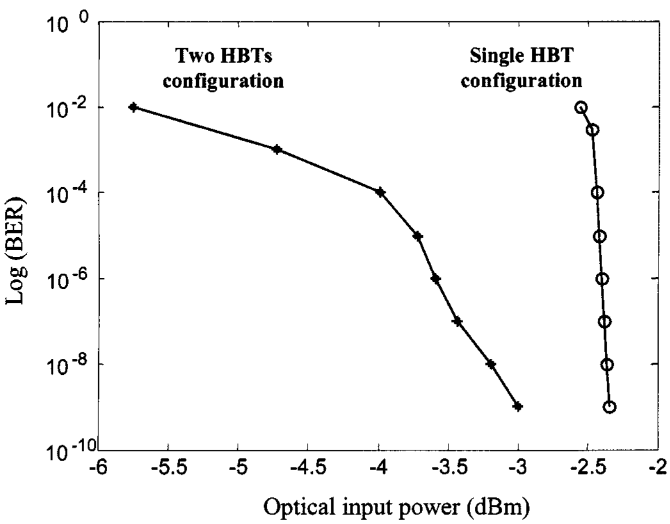

Fig. 9. Bit error rate as a function of input optical power of the two oscillator configurations operating at 10 GHz with 500-Mb/s modulation.

A coherent homodyne receiver detected the digitally modulated signal. The base band signal was amplified and fed to the bit error rate receiver. Bit error rate measurements as a function of average optical power are shown in Fig. 9 for the two configurations. The results demonstrate the ability to generate a high quality digitally modulated signal for error free transmission in both cases. Comparing the two BER curves shown in Fig. 9 we first note that the single HBT case is less sensitive by $\sim$1 dB. Moreover, there is a difference in the curves slope which means that the dual HBT case is better immune to fluctuations in the optical power level.

IV. Conclusion

Two self-oscillators, one based on single InP/InGaAs photo-HBT and the second using two such photo transistors, have been demonstrated. Optical injection locking to reduce the phase noise and optoelectronic mixing for modulation were demonstrated. Analog modulation measurements yield a linear up-conversion behavior and digital modulation with no errors was demonstrated exhibiting the ability to operate in the large signal regime.

The two-transistor configuration was shown to be advantageous because of the good isolation between the carrier generation and the modulation signal. This results in larger conversion efficiency for analog modulation and a smoother BER curve, which means an increase in the power tolerance, for digital modulation. Furthermore, the two photo-HBTs configuration separates the optical injection-locking and modulation processes thereby allowing the optimization of both.

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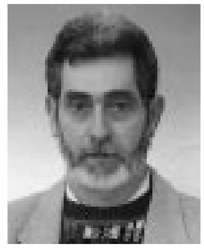

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