MODELING AND PERFORMANCE OF A ONE STAGE InP/GaInAs OPTOELECTRONIC HBT 3-TERMINAL MIXER

Y. Betser and D. Ritter
Department of Electrical Engineering, Technion, Haifa, Israel.

C.P. Liu and A.J. Seeds

A. Madjar
RAFAEL, P.O. Box 2250 (Code 87), Haifa, Israel.

Abstract

A high conversion gain 3-terminal heterojunction photo transistor optoelectronic mixer was demonstrated. The maximum obtained internal mixing efficiency was 11.3dB. The mixing performance was measured as a function of the DC bias of the device and local oscillator power level. A SPICE based large signal model was employed to simulate the device. The main non-linear effects which contribute to the mixing process were the bias dependence of the dynamic emitter resistance, and the transition from the active to the saturation mode.

I. Introduction.

In optical subcarrier multiplexing (SCM) systems (1,2) the modulated laser beam is detected, down-converted, and amplified, to recover the original baseband information. The heterojunction photo transistors (HPT) is a natural candidate to carry out all three tasks simultaneously. The inherent non-linearity of 3-terminal InP/GaInAs HPTs, and their excellent high frequency performance as front end components (3), are very attractive for SCM systems.

In this publication, we report on the performance of a one stage InP/GaInAs HPT optoelectronic mixer (OEM). The obtained mixing performance at different bias conditions and local oscillator power levels is compared to a SPICE based large signal model. We believe this is the first report on modeling of an HPT-OEM. An intrinsic conversion gain (i.e., the ratio between the output IF power and the primary photogenerated RF input power) of 11.3dB was obtained. Due to a light coupling efficiency of only 15%, the extrinsic conversion gain is -5.1dB, which still compares favorably with previously reported results of -21.1dB, -26dB and -29dB for 3-terminal HBT, HEMT and JFET, OEMs (4). The origin of the various non-linear effects in HPTs is discussed as well.

II. HBT fabrication.

The epitaxial layers were grown on semi insulating InP substrates by a compact metalorganic molecular beam epitaxy system (5). Conventional wet etching and a self aligned Pt/Ti/Pt/Au one step metalization process were employed to fabricate the devices. Polyimide passivation and Ti/Au pads completed the fabrication process.

A schematic diagram of the device is shown in Fig.1. The optical window was located on the base mesa in order to minimize device dimensions. Current crowding effects (6) are also avoided because the light is absorbed in the extrinsic base collector junction. This configuration is basically similar to a separate PIN diode connected to the base terminal, except that the reverse bias of the PIN diode cannot be separately set.

Figure 1 - Schematic diagram of layer structure and mesa structure of the HPT. Emitter and base dimensions are 3.3x11μm² and 8.5x22.5μm², respectively. Optical window (on the base mesa) size is 5x6μm².
III. Large signal modeling

A large signal SPICE model was employed to simulate the mixing performance of the HPT. The model parameters were extracted from DC measurements and small signal on wafer RF measurements up to 40GHz (7). Fc and Fmax of 65GHz and 35GHz, respectively, were measured at Ic = 20mA, Vce = 2V. Table 1 lists the parameters used in the simulations.

Table 1. Large signal SPICE model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>REE</td>
<td>8Ω</td>
</tr>
<tr>
<td>RCC</td>
<td>3Ω</td>
</tr>
<tr>
<td>Rb</td>
<td>15Ω</td>
</tr>
<tr>
<td>Cbc(v=0)</td>
<td>120fF</td>
</tr>
<tr>
<td>Cbe(v=0)</td>
<td>32fF</td>
</tr>
<tr>
<td>Nf</td>
<td>1.1</td>
</tr>
<tr>
<td>Nr</td>
<td>1.2</td>
</tr>
<tr>
<td>Is</td>
<td>1fA</td>
</tr>
<tr>
<td>Ics</td>
<td>6nA</td>
</tr>
<tr>
<td>Beta</td>
<td>80</td>
</tr>
<tr>
<td>tr</td>
<td>0.85ns</td>
</tr>
<tr>
<td>tv</td>
<td>1ns</td>
</tr>
</tbody>
</table>

The schematic circuit diagram of the packaged HPT is shown in Fig. 2. The voltage source, Vle, represented the local oscillator. The current source, Iph, represented the modulated primary photocurrent (RF signal). The input impedance of the spectrum analyzer was represented by a 50Ω load resistor, and the inductance of the bonding wires was included as well. The simulations were carried out using SPICE transient analysis and a subsequent Fourier transform. The results are presented in section V.

Figure 2 - A SPICE based large signal model of the HPT optoelectronic mixer.

IV. Electrooptical Mixing Experiment

The experimental setup is shown in Fig. 3. The HPT was mounted onto 50Ω transmission lines. A current modulated distributed feedback laser generated the RF optical signal. The wavelength of the light was 1.55μm and the modulation frequency 3GHz. The laser average optical power was 0.37mW and the modulation index was 24%.

The base terminal of the HPT served as an input terminal for the local oscillator (LO) signal. The frequency of the (LO) signal was 3.1GHz. The 100MHz intermediate frequency (IF) output power at the collector was measured using a spectrum analyzer. Measurements were carried out as a function of the base-emitter voltage and collector-emitter voltage for different LO power levels.

Figure 3. - Experimental setup.

V. Results and discussion

In Fig. 4 the measured and calculated IF power is plotted as a function of base emitter voltage for different LO power levels. The mixing efficiency exhibits a clear maximum at \( V_{BE} = 0.8V \). The physical reason for the shape of the curve is the following. The HPT serves as a mixer and current amplifier simultaneously. The main non-linear effect in this bias range is the bias dependence of the dynamic emitter resistance, \( r_e \), which determines the current gain of the HPT at high frequencies. At low values of \( V_{BE} \), \( r_e \) is large and the amplification level of the IF signal is low. For high values of \( V_{BE} \), \( r_e \) is small, and therefore the modulation of \( r_e \) modulates the current gain to a small extent only. The mixing efficiency is thus maximized at intermediate values of \( V_{BE} \).

As evident by inspecting Fig.4 the simulations agree very well with the experimental results for low to moderate base emitter voltages. However, at high \( V_{BE} \), and for moderate \( V_{BE} \) with large LO power, the simulations do not agree well with the measured data. We believe this discrepancy is due to high current density effects (8), such as the Kirk effect, which were not included in our model.

381
Figure 4 - Calculated and measured IF (100MHz) power as a function of base emitter voltage.
Incident optical RF (3GHz) peak power is -10.5dBm. \( V_{CE} = 1.5V \)

An additional non linear effect in HBTs is the transition from the linear mode to the saturation mode. This effect is important at low values of the emitter to collector voltage. In Fig. 5 the measured and calculated IF power is plotted as a function of base emitter voltage with an emitter to collector voltage of 0.8V. Since \( V_{CE} \) is constant in this experiment, at low \( V_{BE} \) the base collector junction is reverse biased, and the HPT is in the active mode. At high values of \( V_{BE} \) the base collector junction is forward biased, and the HPT is in the saturation mode. A clear minimum in the measured and calculated IF power can be observed in the transition region between the linear and saturation modes. We believe this minimum is due to an opposite phase of the two non-linear effects resulting in a mutual cancellation of the IF signal.

Figure 5 - Calculated and measure IF (100MHz) power as a function of base emitter voltage.
Incident optical RF (3GHz) peak power is -10.5dBm. \( V_{CE} = 0.8V \)

In the saturation mode a severe degradation of the IF current gain of the HPT takes place. However, the results presented in Fig. 5 demonstrate that reasonable IF power levels were obtained in the saturation mode as well. The strong non-linearity caused by the transition between the active and saturation modes generates the IF power levels obtained. The discrepancy between the simulations and experimental results in the saturation mode is an indication that our modeling in this range must still be improved.

In Fig. 6 the measured IF power is shown as a function of emitter to collector voltage with \( V_{BE} = 0.8V \) and LO power of -6dBm. The best mixing results are achieved when the HBT is biased in the active mode. For \( V_{CE} > 15V \) the IF power saturates because the high frequency response of the HBT and the non-linear effects depend weakly on \( V_{CE} \).

Figure 6 - IF (100MHz) power as a function of collector to emitter voltage. \( V_{BE} = 0.8V \) and LO (3.1GHz) power is -6dBm. Incident RF (3GHz) power is -10.5dBm.

VI. Mixing performance

The quantum efficiency \( \eta \) of the HPT was found to be 15%. It was obtained by measuring the DC primary photocurrent (base shorted to the emitter). This relatively low quantum efficiency is due to the total thickness of the base and collector layers which is about 3 times shorter than the absorption depth of the light.

We define the intrinsic conversion gain, \( G_{int} \), as the ratio between the IF power delivered to the 50\( \Omega \) load and the power delivered by the primary photocurrent RF power into a 50\( \Omega \) load. The primary photo generated RF power was \( P_{prim} = \text{\textless}2.3dBm \) in our experiments. The extrinsic (or system) conversion gain, \( G_{ext} \), is defined as

\[
G_{ext} = \eta G_{int}
\]

The highest intrinsic conversion gain obtained in our experiments was 6.1dB. Since the base is connected to the LO source via a 50\( \Omega \) line some of the primary photocurrent leaks
through the LO source to the ground. To rectify this, a 3-stub tuner was inserted between the LO source and the base and was adjusted to obtain maximum IF power. The intrinsic conversion gain improved in this manner by 5.2dB to 11.3dB. The insertion of the 3-stub tuner increased the RF output power by 4.1dB and the LO output power by only 0.4dB, indicating that the improvement of the conversion gain is due to a more efficient collection of the primary photocurrent into the base, and not due to a better matching of the LO network.

The obtained extrinsic conversion gain was -5.2dB using the 3-stub tuner. This result compares favorably with previously reported results of -21.1dB, -26dB and -29dB for 3-terminal HBT, HEMT and JFET, OEMs (4).


8. Y. Betser and D. Ritter, “Measurement of high current density phenomena and velocity overshoot in InP/GaInAs HBTs”, this conference proceedings.

**VII. Conclusion**

The performance and modeling of a high conversion gain 3-terminal HPT OEM is reported as a function of the bias level and LO power level. The highest mixing efficiency is achieved when the HPT operates in the active mode. The largest non-linear effect which is responsible for the mixing process is the bias dependence of the dynamic emitter resistance. Further improvement of the mixing efficiency can be achieved by increasing the quantum efficiency (increasing the collector thickness), RF isolation of the base terminal, and reducing the collector load impedance.

**References**


