OPTOELECTRONIC MIXING IN THREE-TERMINAL InP/InGaAs HETEROJUNCTION BIPOLAR TRANSISTORS

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Abstract

A three-terminal InP/InGaAs heterojunction bipolar transistor (HBT) with optical access has been fabricated and used in an optoelectronic mixer (OEM) configuration. Leakage of the photogenerated RF signal from the HBT base was identified as a cause of reduced mixed IF output power. By using a 3-stub tuner to present a high impedance to the base at signal frequency, over 5dB improvement in the IF power was obtained resulting in a -4.7dB system conversion gain. This result is the highest yet reported for a three-terminal HBT OEM and over 16dB better than for a high quality photodiode/double-balanced mixer combination.

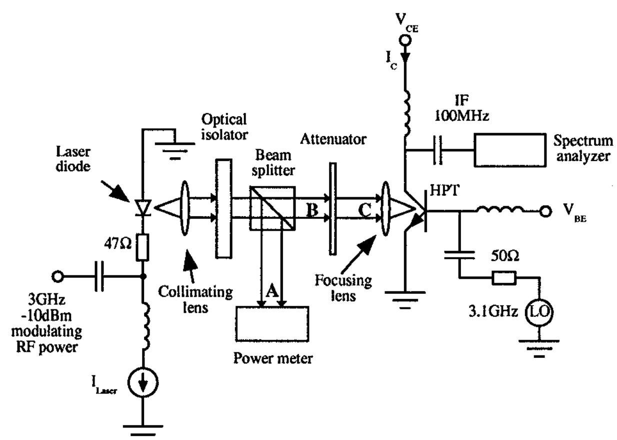

Figure 1: Experimental arrangement.

Introduction

Heterojunction bipolar transistors (HBTs) are important in modern optical communication systems because of their high gain and speed. Heterojunction phototransistors with a base terminal have also been shown to have better performance in direct photodetection [1] than their two-terminal counterparts. In optical subcarrier multiplexing (SCM) systems [2,3], the incoming optical signal needs to be detected, down-converted and amplified in order to recover the original baseband information. As a result, HBTs have been investigated as optoelectronic mixers (OEMs) [4] for such applications. In photodetection, the base of the HBT is made ac open by the bias network and the detected signal is taken from the collector. When the HBT is operated as a mixer, the base is connected to and electrically pumped by a local oscillator (LO) source which has a 50Ω source impedance. Consequently the photogenerated current in the base sees a parallel combination of 50Ω and the base-emitter resistance and thus tends to leak out of the base resulting in reduced gain in the mixing process.

In this paper, we report measurements of optoelectronic mixing in 3-terminal InP/InGaAs HBTs having windowed base access. We also demonstrate an improvement of over 5dB in the conversion gain by inserting a 3-stub tuner between the base and the local oscillator (LO) to block the signal leak mentioned above. Comparisons with previously reported results are made. The system conversion gain is the highest ever reported for 3-terminal HBT optoelectronic mixers.

Mixing experiment

The 3-terminal InP/InGaAs npn HBT [5] had the following doping profiles, dimensions and layer thicknesses: contact layer: InGaAs, $1x10^{19}/cm^3$, n-type, $3.3x11\mu m^2$, 1000Å; emitter: InP, $1x10^{17}/cm^3$, n-type, $3.3x11\mu m^2$, 2000Å; base: InGaAs $5x10^{19}/cm^3$, p-type, $8.5x22.5\mu m^2$, 560Å; collector: InGaAs, $2x10^{16}/cm^3$, n-type, $8.5x22.5\mu m^2$, 4000Å; barrier layer: InP ,$1x10^{18}/cm^3$, n-type, $8.5x22.5\mu m^2$, 2000Å; sub-collector: InGaAs, $1x10^{19}/cm^3$, n-type, 4000Å. Bond wires and

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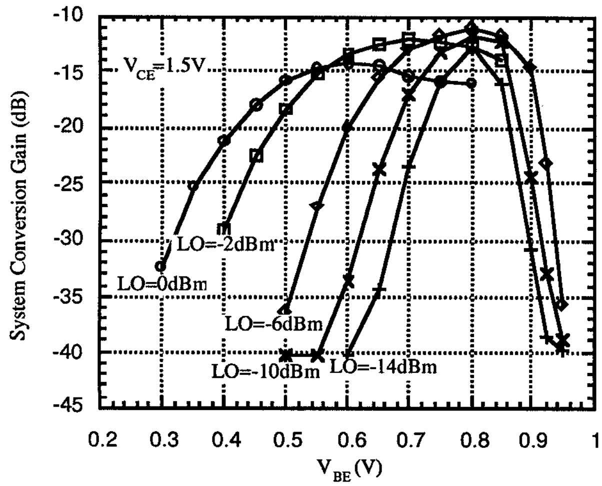

Figure 2: System conversion gain relative to a 100% quantum efficient photodetector operated at the optical modulation frequency vs. V_{BE}. V_{CE}=1.5V

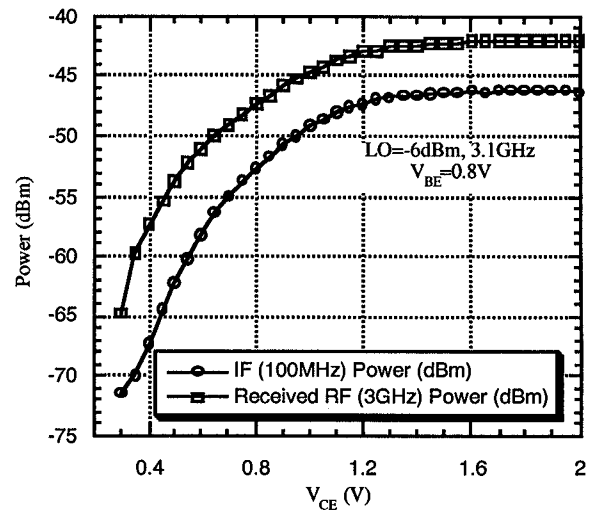

Figure 3: Mixed IF power and received RF power vs. V_{CE}

two 1cm long 50Ω characteristic impedance microstrip lines were used to connect the base and collector to SMA sockets for external connections. The emitter was connected to the common ground via a bond wire. The illumination of the device was normal to the epilayer via a 5x6μm^2 optical window above the base.

The experimental arrangement is shown in Figure 1 A DFB laser of 1.55μm wavelength was intensity modulated with a -10dBm RF signal at 3GHz. The average optical power, P_{opt}, incident on the focusing lens was measured to be 0.37mW. Since the lens used has very small loss, P_{opt} is taken as the incident optical power on the HBT. An optical power meter in position A monitored the laser output power. The modulation index of the laser beam was measured to be 0.24 or -6.2dB using an HP70810B lightwave signal analyzer, giving a peak modulated component, P_{mod}, of 0.24 x 0.37mW = 88μW. If P_{mod} was detected by a 100% quantum efficient photodetector terminated in a 50Ω load resistor, the electrical power generated in that load, P_r, would be -35.2dBm. In this paper the system conversion gain is defined as the ratio of the intermediate frequency (IF) output power measured at the HBT collector to the power P_r This definition enables one to evaluate how the optoelectronic mixer performs when incorporated in a complete microwave photonic system. To operate the HBT as a mixer, the base was electrically pumped by a 3.1GHz local oscillator signal and the 100MHz IF output of the HBT mixer was taken from the collector and measured with a spectrum analyzer.

Figure 2 shows the measured system conversion gain as a function of V_{BE}. For LO powers ≤ -6dBm, V_{BE}=0.8V gives the optimum gain. For larger LO powers, the optimum V_{BE} is lower. The maximum measured system conversion gain was -11dB.

Figure 3 shows how the IF and RF powers measured at the collector vary with V_{CE}. The difference between the received RF power and the IF power is rather constant for V_{CE}>1.2V, indicating that the mixing efficiency is not a strong function of V_{CE} when the HBT is operating well inside the active region.

Since the base is connected to the LO source via a 50Ω line and the LO also has a 50Ω output impedance, the alternating component of the photogenerated current in the base sees a parallel combination of 50Ω and the base-emitter resistance. Therefore part of the photogenerated current is lost to the LO source, thus reducing the gain of the OEM. To rectify this, a 3-stub tuner was inserted between the LO and the base and was adjusted to give maximum IF power. Table. 1 shows the measured powers at the collector port with and without the tuner.

Base tuning gives a 5.2dB increase in IF power and thus an equal increase in the system conversion gain. The reflection coefficients of the tuner from the base direction were measured to be 0.98 at 100MHz (IF), 0.85 at 3GHz (RF) and 0.25 at 3.1GHz (LO), showing that the tuner acts to reduce RF leakage from the base.

The maximum system conversion gain with tuning was -4.7dB. As a comparison, we have calculated the system conversion gains of the 3-terminal HBT, HEMT, and JFET OEMs in [4] to be -21dB, -26dB and -20dB, respectively.

	Without tuner (dBm)	With tuner (dBm)	Improvement (dB)
IF power	-45.9	-40.7	5.2
RF power	-42.7	-38.6	4.1
LO power	-6.2	-5.8	0.4

Table 1: Effect of tuned base operation. V_{BE}=0.8V, V_{CE}=1.3V, LO=-10dBm, Laser modulated by -10dBm RF signal.

The external quantum efficiency can be calculated by comparing the measured photogenerated current with V_{BE}=0V, when the HBT has no gain, with the equivalent current that would be generated by a 100% quantum efficient photodetector when illuminated by the same incident optical power. The ratio of the two currents gives a 16% external quantum efficiency. Therefore the intrinsic conversion gain of the HBT, defined in this paper as the ratio of the IF output power to the equivalent detected RF signal power, is calculated to be 4.8dB without the tuner and 10dB with the tuner. As a second comparison, Suematsu *et al* [6] estimated the intrinsic conversion gain of their 3-terminal HBT up-converting OEM to be -4dB. Ogawa *et al* [7] also reported an intrinsic conversion gain of -8.1dB using an InGaAs p-i-n photodiode as an up-converting OEM.

The authors have recently demonstrated a 2-terminal edge-coupled HPT optoelectronic mixer [8] and achieved a 7dB system conversion gain. The reason for the better system conversion gain with this device is that since the light was edge-coupled to the base, the length for optical absorption was equal to the lateral dimension of the transistor which was several microns long. In the present normal incidence illuminated HBT, the length for optical absorption is only the thickness of the base plus the collector depletion layer which is 0.5μm and hence less light is absorbed. The absorption coefficient for InGaAs is approximately 10,000/cm. Therefore only 37% of light is absorbed in the present HBT while over 99% of light is absorbed in the edge-coupled HPT if the entire optical spot can be focused onto the base.

Conclusion

We have reported a windowed 3-terminal HBT OEM and achieved a maximum system conversion gain of -4.7dB which is the highest ever reported for 3-terminal HBTs. We have also demonstrated that tuned base operation can improve the system conversion gain by over 5dB. As a further comparison the combination of a high quality commercial photodiode and a double-balanced diode mixer would give -21dB system conversion gain, 16.3dB lower than the present HBT OEM. Thus HBT OEMs are expected to have important applications in microwave optoelectronic systems.

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C. P. Liu graduated from University College London, England in 1994 with a first class honours B.Eng degree in the electronic and electrical engineering. In the same year, he was awarded the IEE prize by the Institution of Electrical Engineers. He is currently working towards a PhD degree at the same university under the supervision of Prof. A. J. Seeds where his thesis topic is the optical control of heterojunction bipolar transistors.

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