

Two-Terminal Edge-Coupled InP/InGaAs Heterojunction Phototransistor Optoelectronic Mixer

C. P. Liu, A. J. Seeds, *Fellow, IEEE*, and D. Wake

Abstract—We report the first experimental results for optoelectronic mixing using a two-terminal edge-coupled InP/InGaAs heterojunction phototransistor (HPT). The HPT optoelectronic mixer (OEM) exhibits a maximum of 7-dB conversion gain relative to a 100% quantum efficient photodetector operated at the optical modulation frequency. We give a qualitative explanation for the observed conversion gain variation with the HPT bias voltage.

Index Terms—Heterojunction phototransistor, microwave optoelectronics, optoelectronic mixing.

I. INTRODUCTION

OPTICAL control of microwave semiconductor devices [1], [2] has become an actively researched area due to the low loss, light weight, wide bandwidth, and RF isolation advantages offered by optical fibers over conventional copper microwave cables. In particular, optically controlled microwave oscillators (OCMO's) [1]–[10] and optoelectronic mixers (OEM's) [1], [2] have received most attention from researchers. OCMO's find their main applications in phased array systems [11] while OEM's, when configured as up-converters, have recently been shown to be useful in fiber radio links [12], especially in the millimeter-wave band [13], [14]. On the other hand, down-converting OEM's offer cost-effective, simple, and potentially high-performance alternatives in microwave subcarrier multiplexing (SCM) [15], [16] systems in which broadband signals are transmitted over single-mode optical fibers. A number of different semiconductor devices [17]–[20] have been investigated for use as OEM's. Urey *et al.* [21] were the first to demonstrate the improved signal-to-noise ratio of heterojunction bipolar transistor (HBT) OEM's relative to HEMT's and JFET's. Recently Van de Castele *et al.* [22] demonstrated using an edge-coupled heterojunction phototransistor to mix two laser beams, one modulated with a 2-kHz square wave and the other with a 2-GHz RF signal.

In this letter, we report the use of a two-terminal edge-coupled InP/InGaAs heterojunction phototransistor (HPT) [23] as a down-converting OEM and present the measured conversion gain as a function of the collector-emitter voltage and injected local oscillator (LO) power. A qualitative explanation for the variation in conversion gain with bias is also given. To

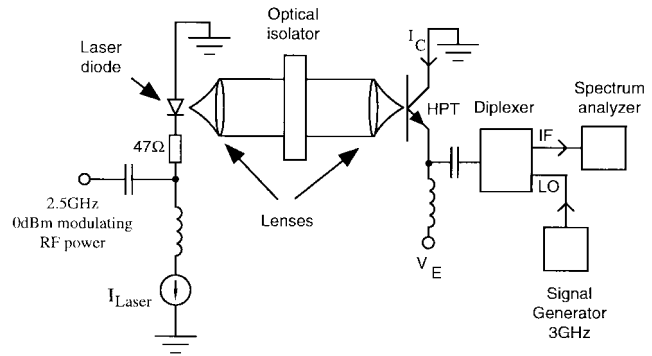


Fig. 1. Simplified schematic of the experimental arrangement.

the authors' knowledge, these are the first published results for a two-terminal HPT.

II. OPTOELECTRONIC MIXING EXPERIMENT AND RESULTS

Full details of the HPT used in the experiment are given in [23]. Growth was by MOVPE on an N^+ substrate and consisted of a collector (InGaAs, $n = 10^{16} \text{ cm}^{-3}$, $t = 0.4 \mu\text{m}$), an electrically floating base (InGaAs, $p = 10^{19} \text{ cm}^{-3}$, $t = 0.1 \mu\text{m}$) and an emitter (InP, $n = 5 \times 10^{17} \text{ cm}^{-3}$, $t = 0.15 \mu\text{m}$) where n and p are the n - and p -type doping concentrations, respectively, and t is the thickness. The p -type dopant was zinc and the n -type dopant was sulphur. A thin spacer layer (InGaAs, $n = 10^{16} \text{ cm}^{-3}$, $t = 0.02 \mu\text{m}$) between the base and emitter was used to reduce the effects of outdiffusion of the base dopant, and a highly doped emitter contact layer (InGaAs, $n = 10^{19} \text{ cm}^{-3}$, $t = 0.05 \mu\text{m}$) was also included. The finished device area was $5 \times 10 \mu\text{m}^2$ with the narrow dimension of the device illuminated.

Fig. 1 shows a simplified schematic of the experimental arrangement used. A DFB laser of 1550-nm wavelength was used as the light source. The collimating and focusing lenses used were Newport F-L40B and F-L10B, respectively. Light was edge-coupled to the HPT base. The HPT emitter was connected to an external SMA connector via a short 50- Ω microstrip transmission line. A microstrip coupled line diplexer was employed to separate the 500-MHz intermediate frequency (IF) and 3-GHz LO signals at the HPT emitter. The diplexer loss was 2.13 dB for the LO and 0.07 dB for the IF.

The static responsivity was first measured and is shown in Fig. 2. The increase in the responsivity, and hence the collector current, with V_{CE} is particularly nonlinear at $V_{CE} = 0 \text{ V}$ (switched off) and $0.2 \text{ V} < V_{CE} < 0.4 \text{ V}$. Also the responsivity is nonlinearly dependent on the incident optical

Manuscript received October 1, 1996.

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Publisher Item Identifier S 1051-8207(97)01771-6.

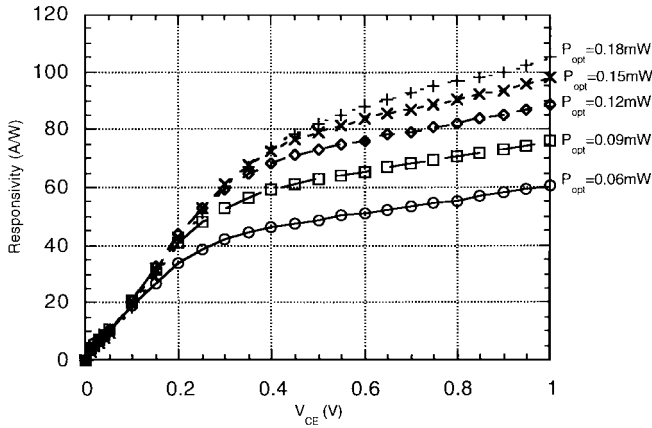


Fig. 2. DC responsivity of two terminal HPT.

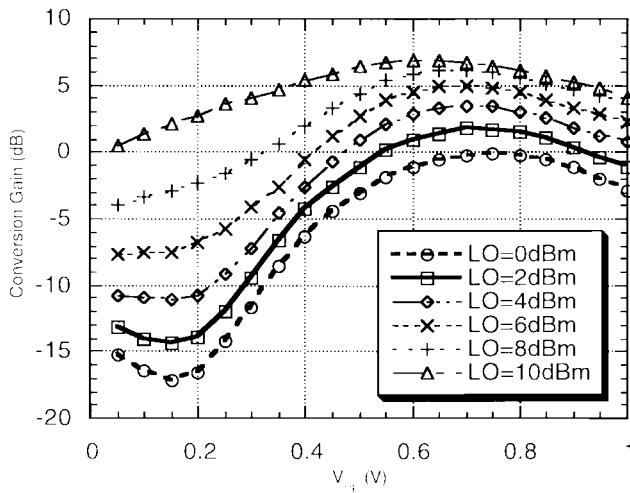


Fig. 3. Conversion gain compared to a 100% quantum efficient photodetector.

power P_{opt} . Such nonlinearity is favorable to the mixing process.

The laser was then intensity modulated by a 0-dBm power radio frequency (RF) signal at 2.5 GHz. The average optical power P_{avg} and modulated optical power P_{mod} incident on the HPT were measured, using an HP70810B lightwave signal analyzer, to be 0.14 mW and 0.072 mW (peak), respectively. If this P_{mod} is detected by a 100% quantum efficient photodetector in a 50- Ω system, the equivalent electrical RF power P_{RF} will be 0.20 μ W or -37 dBm. This -37 dBm electrical RF power will be used as a reference to calculate the HPT mixer conversion gain. The emitter voltage V_E was varied from -0.05 V to -1 V in steps of -0.05 V. The emitter was also injected with the LO signal at 3 GHz via the diplexer. For each V_{CE} and LO setting, the corresponding mixed IF power at 500 MHz was measured at the diplexer IF output by a spectrum analyzer. The conversion gain, which is defined as the ratio of the mixed IF output power to the equivalent electrical RF power defined above, is shown in Fig. 3.

The HPT showed a maximum of 7-dB conversion gain, 10 dB above the theoretical maximum for a perfect switching

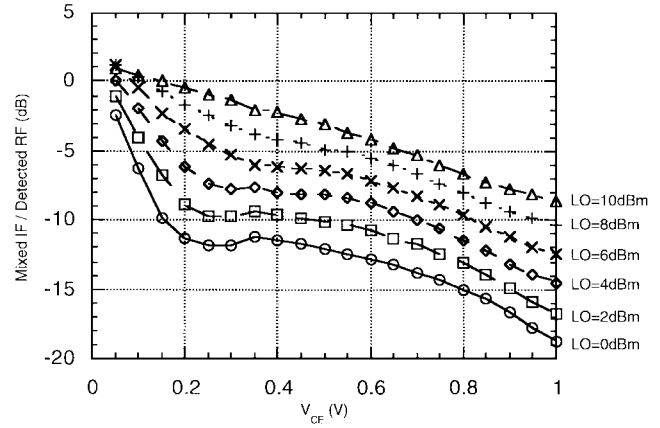


Fig. 4. Power ratio of the mixed IF to the detected RF measured at the diplexer IF port.

mixer. The optical coupling loss has not been corrected for in the results; thus the conversion gain of the HPT itself is much higher. As a comparison, we have calculated the conversion losses of the HBT, HEMT, and MBE JFET optoelectronic mixers in [21] to be 21.1, 26, and 29 dB, respectively, when the RF signal is 10 GHz. Ogawa *et al.* [24] used an InGaAs p-i-n photodiode as an optoelectronic up-converting mixer and achieved a conversion loss of 8.1 dB. The LO used was 4 GHz and the signal was 0.9 GHz. Suematsu *et al.* [14] also reported a three-terminal HBT optoelectronic up-converting mixer with a conversion loss of 4 dB when IF = 3.2 GHz, RF = 30 GHz, and LO = 26.8 GHz.

Three main factors determine the conversion gain of the HPT mixer. The first is the nonlinearity of the HPT, which depends on the bias voltage V_{CE} . For $V_{\text{CE}} > 0.4$ V, the HPT operates less nonlinearly and the mixing process becomes less efficient. However, the conversion gain increases with V_{CE} until a few tenths of a volt higher, then it begins to drop. This is due to the second factor, the increase of the responsivity with V_{CE} . The effect of the increase in the responsivity compensates for that of the reduction in the nonlinearity in the region $0.4 \text{ V} < V_{\text{CE}} < 0.7 \text{ V}$. Beyond this region, the conversion gain decreases due to the near constant responsivity coupled with reduced nonlinearity. The last factor is the power of the injected LO signal. The HPT characteristics become more nonlinear when pumped with larger LO powers. Also at very small LO powers, conversion gain minima are observed at around $V_{\text{CE}} = 0.15$ V. This is because the collector current increases more linearly with V_{CE} before the HPT is saturated.

Another method of evaluating HPT mixing performance is to investigate the power ratio of the mixed IF to the detected RF measured at the diplexer IF port. This is shown in Fig. 4. This power ratio has an overall downward trend because as V_{CE} increases, the HPT characteristics is more linear and thus the mixing is less efficient. Therefore, the mixing process is seen to be most efficient when V_{CE} is close to 0 V. However, it is not very useful to bias the HPT at these small voltages because the device responsivity is then very low, making the overall IF output also very small. Thus, an optimum balance between responsivity and nonlinearity must be found, as shown in Fig. 3.

The present HPT optoelectronic mixer has certain advantages as well as disadvantages over conventional discrete component counterparts, which normally consist of a photodetector, an electronic mixer, and an amplifier cascaded. Being a single device, the HPT optoelectronic mixer is simpler and incurs less parasitics due to the interconnection of separate components, leading to better high-frequency performance. Also, gain is applied to the mixed IF at the very first stage and a better overall system noise figure should be possible. For the discrete component counterparts, the mixer and the amplifier can be separately optimized so that high mixing efficiency and high gain can be obtained simultaneously and a smaller LO signal is required to achieve a similar IF output level.

III. CONCLUSION

We have reported the first optoelectronic mixing results for a two-terminal edge-coupled InP/InGaAs heterojunction phototransistor. The HPT optoelectronic mixer exhibits a maximum of 7-dB conversion gain relative to a 100% quantum efficient photodetector operated at the optical modulation frequency. Comparisons with other published results have been made and show that this two-terminal HPT offers the highest conversion gain for optoelectronic mixers yet reported. We are currently investigating the noise performance of the mixer.

REFERENCES

- [1] A. J. Seeds and A. A. de Salles, "Optical control of microwave semiconductor devices," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 577–585, May 1990.
- [2] A. J. Seeds, "Tutorial review: Microwave optoelectronics," *Optical and Quantum Electronics*, no. 25, pp. 219–229, 1993.
- [3] H. W. Yen and M. K. Barnoski, "Optical injection locking and switching of transistor oscillators," *Appl. Phys. Lett.*, vol. 32, no. 3, pp. 182–184, Feb. 1, 1978.
- [4] P. Freeman, X. Zhang, I. Vurgaftman, J. Singh, and P. Bhattacharya, "Optical control of 14 GHz MMIC oscillators based on InAlAs/InGaAs HBT's with monolithically integrated optical waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 373–379, Mar. 1996.
- [5] M. Karakucuk, W. Li, P. Freeman, J. East, G. I. Haddad, and P. Bhattacharya, "Transparent emitter contact HBT's for direct optical injection locking of oscillators," in *IEEE MTT-S Dig.*, 1994, pp. 1391–1394.
- [6] D. Sommer, N. J. Gomes, and D. Wake, "Optical injection locking of microstrip MESFET oscillator using heterojunction phototransistors," *Electron. Lett.*, vol. 30, no. 13, pp. 1097–1098, June 23, 1994.
- [7] T. P. Higgins, J. F. Harvey, D. J. Sturzebecher, A. C. Paoletta, and R. A. Lux, "Direct optical frequency modulation and injection locking of resonant tunnel diode oscillator," *Electron. Lett.*, vol. 28, no. 17, pp. 1574–1576, Aug. 13, 1992.
- [8] A. Bangert and Th. Lauterbach, "Initial observations of optical injection locking of oscillators using heterojunction bipolar transistors," *Electron. Lett.*, vol. 28, no. 7, pp. 621–623, Mar. 26, 1992.
- [9] I. D. Blanchflower and A. J. Seeds, "Optical control of frequency and phase of GaAs MESFET oscillator," *Electron. Lett.*, vol. 25, no. 5, pp. 359–360, Mar. 2, 1989.
- [10] A. J. Seeds and J. R. Forrest, "Initial observations of optical injection locking of an X-band IMPATT oscillator," *Electron. Lett.*, vol. 14, no. 25, pp. 829–830, Dec. 7, 1978.
- [11] A. J. Seeds, "Optical technologies for phased array antennas," *IEICE Trans. Electron.*, vol. E76-C, no. 2, pp. 198–206, Feb. 1993.
- [12] Q. Z. Liu, R. Davies, and R. I. MacDonald, "Experimental investigation of fiber optic microwave link with monolithic integrated optoelectronic mixing receiver," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2357–2360, Sept. 1995.
- [13] H. Kamitsuna and H. Ogawa, "Monolithic image-rejection optoelectronic up-converters that employ the MMIC process," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 2323–2329, Dec. 1993.
- [14] E. Suematsu and N. Imai, "A fiber optic/millimeter-wave radio transmission link using HBT as direct photodetector and an optoelectronic up-converter," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 133–143, Jan. 1996.
- [15] T. E. Darcie, "Subcarrier multiplexing for multiple-access lightwave networks," *J. Lightwave Technol.*, vol. LT-5, pp. 1103–1110, Aug. 1987.
- [16] R. Olshansky, V. A. Lanzisera, and P. M. Hill, "Subcarrier multiplexed lightwave systems for broad-band distribution," *J. Lightwave Technol.*, vol. 7, pp. 1329–1342, Sept. 1989.
- [17] T. Berceci, "Dynamic properties of optical-microwave mixing processes utilizing FET devices," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2330–2333, Sept. 1995.
- [18] T. Berceci, P. R. Herczfeld, and A. Paoletta, "A new high-efficiency optical-microwave mixing procedure," in *23rd Euro. Microwave Conf. Proc.*, Madrid, Spain, Sept. 1993, pp. 317–319.
- [19] N. J. Gomes and A. J. Seeds, "Tunnelling metal-semiconductor contact optically pumped mixer," *Proc. Inst. Elec. Eng.*, pt. J, vol. 136, no. 1, pp. 88–96, Feb. 1989.
- [20] N. J. Gomes and A. J. Seeds, "Novel optically pumped electronic mixer using a mott diode structure," *Electron. Lett.*, vol. 23, no. 20, pp. 1084–1085, Sept. 1987.
- [21] Z. Urey, D. Wake, D. J. Newson, and I. D. Henning, "Comparison of InGaAs transistors as optoelectronic mixers," *Electron. Lett.*, vol. 29, no. 20, pp. 1796–1797, Sept. 1993.
- [22] J. Van de Castele, J. P. Vilcot, J. P. Gouy, F. Mollot, and D. Decoster, "Electro-optical mixing in an edge-coupled GaInAs/InP heterojunction phototransistor," *Electron. Lett.*, vol. 32, no. 11, pp. 1030–1032, May 1996.
- [23] D. Wake, D. J. Newson, M. J. Harlow, and I. D. Henning, "Optically-biased, edge-coupled InP/InGaAs heterojunction phototransistors," *Electron. Lett.*, vol. 29, no. 25, pp. 2217–2219, Dec. 1993.
- [24] H. Ogawa and Y. Kamiya, "Fiber-optic microwave transmission using harmonic laser mixing, optoelectronic mixing, and optically pumped mixing," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 2045–2051, Dec. 1991.