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InP photodetectors for millimeter wave applications based on edge-coupled heterojunction phototransistors

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ABSTRACT

In this paper, we present first experimental results obtained on two and three terminal edge-coupled InP/InGaAs heterojunction phototransistors showing that these devices seem very promising for microwave and millimeter wave applications.

Keywords : phototransistor , heterojunction, edge-coupled, microwave, millimeter wave, GaInAs/InP, photodetector

1. INTRODUCTION

Future systems based on microwave and optics such as fiber optic radio communications will require very high speed InP photodetectors able to work in the microwave or millimeter wave frequency range. It is well-known that PIN photodetectors limitations are due to transit time and capacitance. To increase their cut-off frequency, it is necessary to reduce transit time, so thickness of absorbing layer, and capacitance. For top-illuminated PIN photodetectors, this will decrease dramatically the responsivity of the photodetector, and theses detectors are generally used up to around 20 GHz, as maximum bandwidth. For upper frequencies, the PIN waveguide photodetector is an attractive device, since it is possible to reduce transit time without decreasing responsivity, because of the absorbing core waveguide structure. Moreover, the optical signal is absorbed over a short length (5-10 µm), and the device , so the capacitance, can be very small. Recently, demonstrations with high responsivity up to 60 GHz at Thomson LCR[1] and even at higher millimeter wave frequencies[2] were performed with device grown on semi-insulating InP substrate. Microwave access is a coplanar line to reduce parasitics, and the waveguide is a multimode structure to improve the optical coupling with the optical fiber. Interdigitated Metal Semiconductor Metal (MSM) photodetectors on AlInAs/GaInAs/InP epilayers were also subject to attention because of their low capacitance. Commercially available MSM (New Focus) were developed with 40 GHz cut-off frequency. Nevertheless, as for PIN photodetectors, high speed MSM photodetectors require thin absorbing layers together with short electrode spacing, so reduced responsivity[3]. Solution would be waveguide devices, or MSM coupled with optical waveguide, but the technology is then more complicated, and the PIN waveguide photodetector remains the best solution.

PIN photodiode (or MSM photodetector) does not exhibit internal gain. It is the reason why heterojunction phototransistor (HPT) in the InP/InGaAs material system has been studied for several years. HPTs could be a good alternative to top illuminated or edge-coupled PIN photodiodes[4] since they exhibit an internal gain owing to transistor effect, without high bias voltage as required for avalanche photodiodes and without excess noise due to avalanching[5]. If we do not consider doping of epilayers, epitaxial structure of HPT is very similar to the one of PIN waveguide photodiode. It means that waveguide technique could also be interesting to apply to HPTs for microwave or millimeter wave applications.

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Following this way, recently Wake et al.[6] demonstrated very interesting potentialities of GaInAs/InP two terminal edge-coupled HPTs used as photodetectors, with internal gain up to 30 GHz.

In this paper, we give first experimental results obtained on two and three terminal (2T and 3T) edge-coupled InGaAs/InP HPTs fabricated in our laboratory. Electro-optical mixing were also performed in these devices. All our experiments show that these devices exhibit very promising properties for microwave and millimeter wave applications. It can be noticed that edge-coupled InP 3T HPT were fabricated for the first time. We will first present technology and experimental results on 2T HPTs, and then on 3T HPTs.

2. TWO TERMINAL EDGE-COUPLED GAINAS/INP HETEROJUNCTION BIPOLAR PHOTOTRANSISTOR

2.1. Technological process

Phototransistors were fabricated from epitaxial layers grown by gas source MBE on a n+ InP substrate. The structure is very similar to the one previously proposed by Wake[6]. The epilayers are the following, beginning from the substrate (Figure 1): a n+ InP subcollector (5000 Å, 2.10^{18} cm^{-3}), a n- GaInAs collector (4000 Å, 5.10^{15} cm^{-3}), a p+ GaInAs base (1000 Å, 10^{19} cm^{-3}), a n- GaInAs spacer (200 Å, 5.10^{15} cm^{-3}), a n+ InP emitter (1500 Å, 5.10^{17} cm^{-3}) and a n+ GaInAs emitter top contact layer (500 Å, 5.10^{18} cm^{-3}).

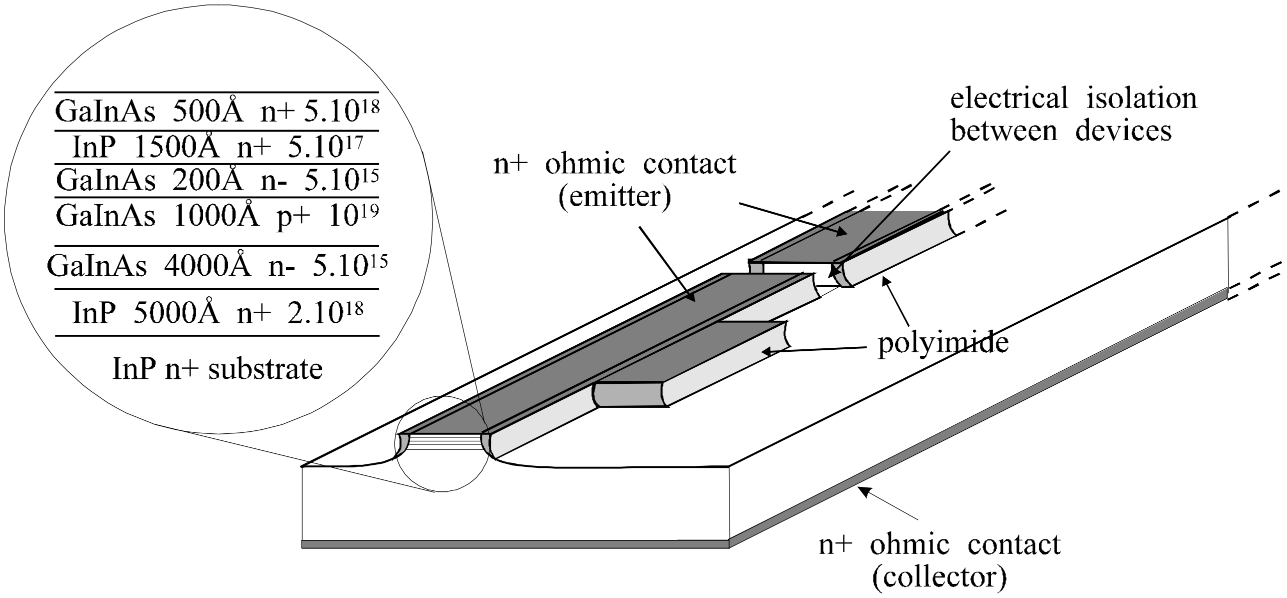

Figure 1 : Schematic view of the 2T HPT.

A very simple technological process was used including only two photolithographic steps. First, ridges of 6 µm width were formed by dry etching down to InP subcollector layer. This is obtained with the first optical mask. Secondly, a polyimide layer was deposited (~2 µm), followed by a resist layer (~3 µm), in order to planarize the structure. Etching of resist and polyimide layers by oxygen plasma was stopped right to the top of the ridges, to form the contact window. This did not need any mask but requires accurate control. The second photolithographic step, which defines the emitter top ohmic contact, is designed such as, each 300 µm, a gap (5 µm, 10 µm, or 20 µm) appears on the electrode metallization. This allows to isolate the HPTs from each other, thanks to a self-aligned dry etching process as next step. So, in order to improve the cleaving, polyimide which was not protected by emitter metallization was removed by oxygen plasma. At last, the wafer was thinned down to around 100 µm, the n+ collector ohmic contact was deposited on the back side, and components were cleaved. No anti-reflection coatings were used. Figure 1 shows a schematic view of the device.

2.2. Experimental results

Components of different length were cleaved; we report here results for a component which size is 6 µm × 115 µm. Typical static common-collector current-voltage characteristics as a function of optical bias were recorded at 1.3 µm wavelength (Figure 2).

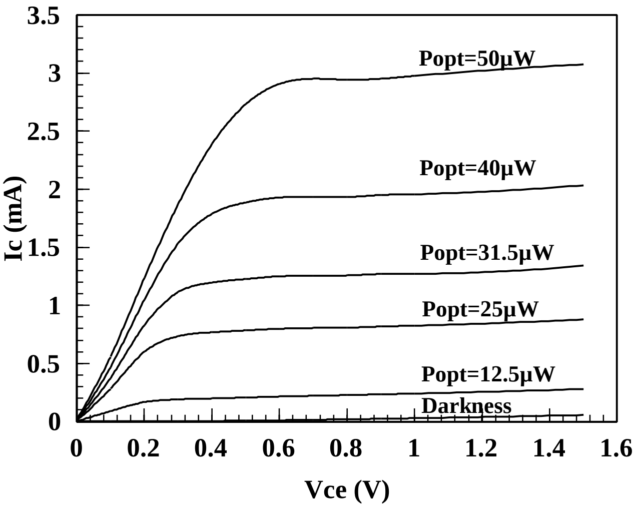

Figure 2: Static common-collector current-voltage characteristics as a function of absorbed optical power for a 2T HPT.

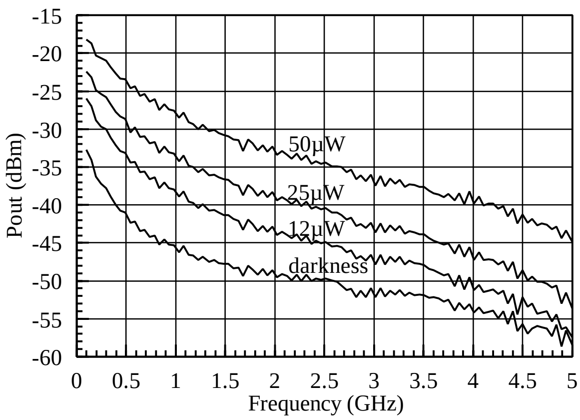

Figure 3: Microwave power at the output of the 2T HPT versus frequency for different CW absorbed optical powers.

Concerning the dynamic response, our 2T-HPT exhibits gain up to around 25 GHz frequency, accordingly to Wake experiments. But new results[7] were obtained by the experimental demonstration of the use of gain nonlinearities of HPTs at low input optical power to mix two demodulated signals stemming from separately modulated optical beams. For this experiment, two semiconductor laser output beams are coupled to the same single mode optical fiber via a 3 dB coupler. Laser 1 (λ=1.319 µm, Hewlett Packard 8153A) delivered a CW or a low frequency square modulated signal, and we applied a RF or microwave signal which frequency is tuned from 100 MHz to 5 GHz on laser 2 (Thomson, λ=1.33 µm, Fabry-Perot).

Figure 3 shows the microwave response of the HPT in the 100 MHz - 5 GHz frequency range; a 0 dBm microwave signal is applied on laser 2, and the corresponding average optical power absorbed into the HPT is 15 µW. Simultaneously, a CW optical signal delivered by the laser 1 is applied and the corresponding absorbed optical power is tuned from 0 to 50 µW. It can be seen that the intensity of the microwave power at the output of the HPT can be strongly increased by the injection of the CW optical power. The improvement can reach 18 dB at 1 GHz, 16 dB at 2 GHz, and 14 dB at 5 GHz for 50 µW of absorbed CW light power. This phenomenon is obviously related to the variation of internal phototransistor gain with average incident light power. Surimposing a low frequency modulated signal to laser 1 and applying simultaneously a microwave signal to laser 2, with power in the range of those used in previous experiment, would consequently lead to an amplitude modulation of the microwave signal by the low frequency signal at the output of the HPT. This experiment was successfully carried out with 2 kHz square wave and 2 GHz RF modulated optical signals (average absorbed optical power, respectively 50 µW, and 15 µW). Figure 4 shows the electrical spectrum of the resulting signal at the output of the HPT. Clearly, this spectrum exhibits the RF carrier at 2 GHz and the two first lateral sidebands at 2 kHz, demonstrating the amplitude modulation of the 2 GHz carrier by the 2 kHz square signal wave. Their relative amplitude to the carrier (-9.9 dB) exactly represents the one of the laser 1 modulating signal, i.e. whole modulation is reported on the RF carrier.

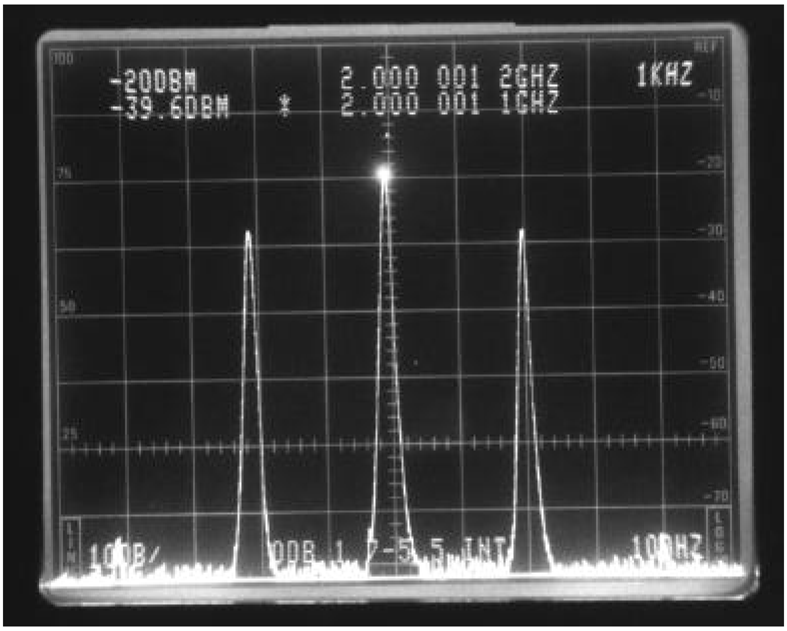

Figure 4: Output electrical signal showing the mixing into the 2T HPT of a 2 GHz modulated optical signal delivered by laser 2 (absorbed power=15 µW) and a 2 kHz modulated optical signal delivered by laser 1 (absorbed power=50 µW).

3. THREE TERMINAL EDGE-COUPLED GAINAS/INP HETEROJUNCTION BIPOLAR PHOTOTRANSISTOR

We fabricated for the first time an InGaAs/InP three terminal edge-coupled phototransistor (3T HPT).

3.1. Technological process

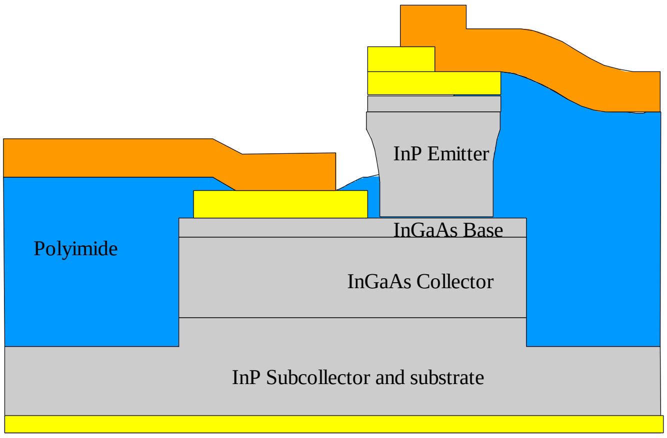

Figure 5 : Schematic view of the 3T HPT.

Phototransistors were fabricated from epitaxial layers grown by gas source MBE on a n+ InP substrate. The epilayers are the following, beginning from the substrate : a n+ InP subcollector (5000 Å, 2.10^{18} cm^{-3}), a n- InGaAs collector (4000 Å, 5.10^{15} cm^{-3}), a p+ InGaAs base (1000 Å, 10^{19} cm^{-3}), a n- InGaAs spacer (200 Å, 5.10^{15} cm^{-3}), a n+ InP emitter (1500 Å, 5.10^{17} cm^{-3} and 13500 Å, 5.10^{18} cm^{-3}), and a n+ InGaAs emitter top contact layer (500 Å, 5.10^{18} cm^{-3}). The technological process used is quite similar to a classical HBT, including five photolithographic steps. First, emitter ohmic contacts were deposited. Emitter mesa was formed by a combination of RIE and wet etching, self-aligned on metallization. Secondly, base ohmic contact was deposited, self-aligned on emitter mesa. Third, photolithographic step was used for base mesa etching. Polyimide and resist layers were then deposited in order to planarize the structure. Etching of resist and polyimide by oxygen plasma was stopped right to the top of emitter, and bounding pad was deposited. Same operation was realized to contact the base terminal. Finally, in order to improve the cleaving, polyimide which was not protected by metallization was removed by oxygen plasma. At last, the wafer was thinned down to around 100 µm, the n+ collector ohmic contact was deposited on the back side, and components were cleaved. Emitter width is 2 µm, 4 µm, and 6 µm. Its length is 20 µm before cleaving and it can be reduced down to 4 µm after cleaving. A schematic view of the device is given in Figure 5.

3.2. Experimental results

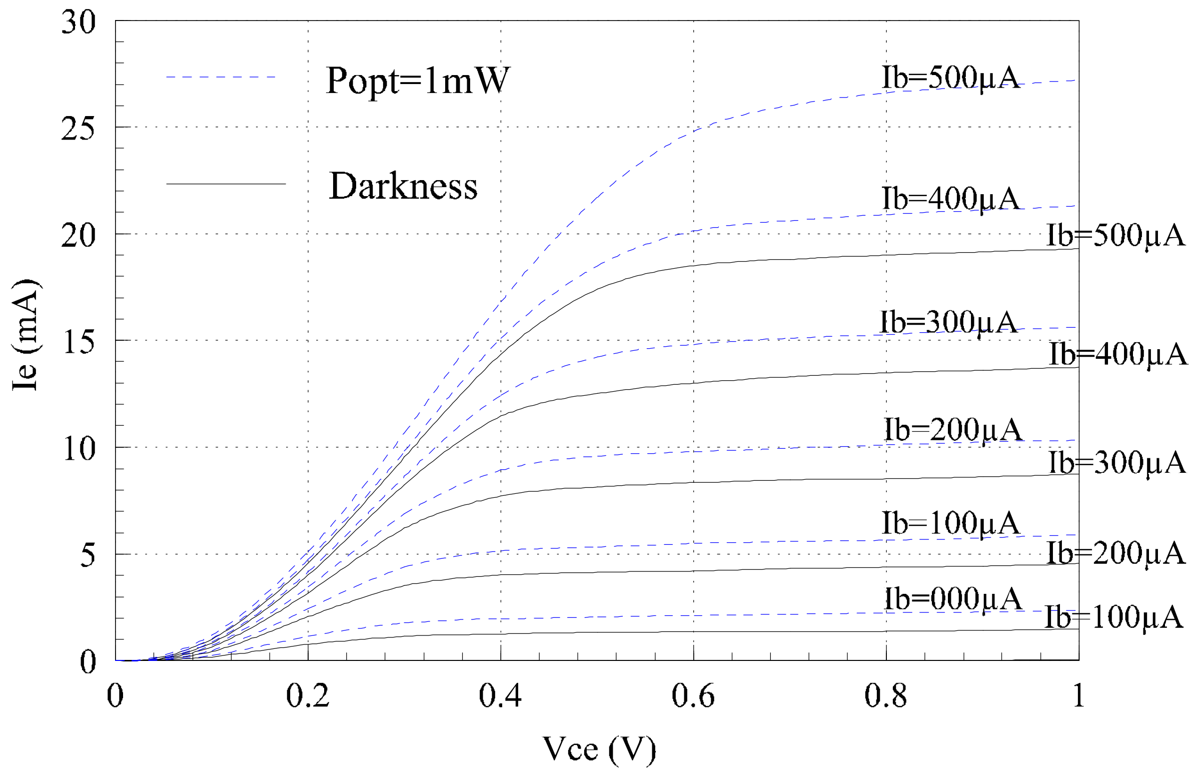

Figure 6: Static characteristics for a 3T HPT with and without optical power.

In this paper, we show experimental results obtained for a 4 × 8 µm² emitter device. An optical power (1.3 µm wavelength) of 1 mW, at the output of a monomode fiber, was impinging on the cleaved input facet. Base-collector junction used as PIN waveguide photodetector shows a responsivity of R=0.14 A/W. All experimental results reported here were obtained with a cleaved monomode fiber, but responsivity improvements up to 0.42 A/W can be obtained using lens-ended optical fibers. In Figure 6, we show the static common emitter current voltage characteristics under darkness and under optical power for different base currents. We define the internal optical gain by :

$$G = \frac{h\upsilon}{q} \cdot \frac{(I_e)_{opt}}{P_{abs}} = \frac{h\upsilon}{q} \cdot \frac{(I_e)_{opt}}{\eta . P_{opt}} \tag{1}$$

where $(I_e)_{opt}$ is the part of the emitter current due to the absorption of the optical power P_{abs}, and $P_{abs}=\eta.P_{opt}$ where P_{opt} is the optical power at the output of the optical fiber. This internal optical gain increases together with DC current bias applied on the base electrode and saturates to around 60. The use of an external base current allows to enhance the efficiency of the phototransistor.

Dynamic optical response measurements were also performed. We used a high speed Fabry-Perot laser diode (λ=1.3 µm) fabricated at Thomson LCR, which cut-off frequency is ranging between 7 and 18 GHz depending on biasing conditions used. Dynamic gain were deduced from comparison between microwave power measured at the output of 3T HPT and microwave power issued from the Base-Collector junction of the same device, which corresponds to the primary photocurrent, in the same electrical and optical conditions. Experiments were carried out up to 18 GHz. Results (bias conditions : V_{ce}=1.5 V and I_{base}=0.4 mA) are given in Figure 7. At low frequency, the dynamic gain is around 17 dB with a 3 dB cut-off frequency in the 3-4 GHz frequency range. At 10 GHz, the dynamic gain is more than 10 dB (≈12 dB) and is still around 7 dB at 18 GHz; 6 dB/octave extrapolation gives a 40 GHz unity gain frequency.

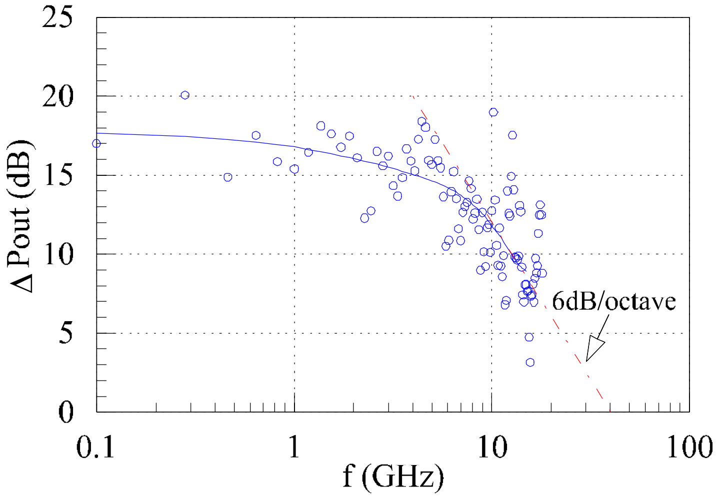

Figure 7: Dynamic characteristic of the 3T HPT.

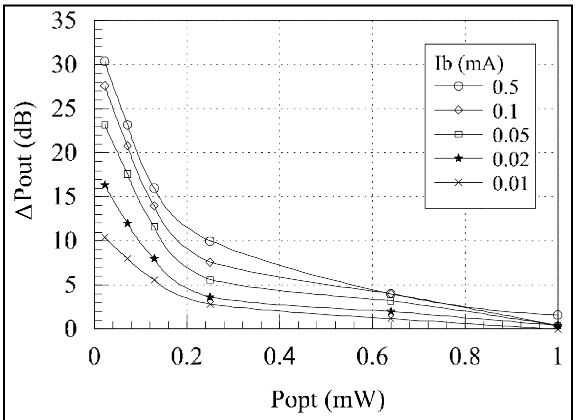

Figure 8: Improvement of the microwave output power versus optical power for different base currents (3T HPT).

Mixing experiments were also performed, as for 2T HPTs. But in this case, one electrical signal can be directly applied to the base of the phototransistor. In fact, the base current acts as the photocurrent in 2T HPT. It means that base current acts as a pump signal and allows to enhance the output device signal if we decrease the optical power at the output of the fiber. In Figure 8, results were carried out for an optical frequency signal at 1 GHz for different optical powers (from 0 to 1 mW at the output of the fiber, so from 0 to 140 µW of optical absorbed power) and electrical DC base currents. We can observe an improvement of more than 30 dB for very small optical powers which traduces the optical non-linearities of the device, and the complementarity of electrical and optical signals. Thanks to these non-linearities, we can hope to mix an optical signal with an electrical one applied on the base terminal. In Figure 9, we show an example of results of such an experiment were we mixed a 1 GHz optical signal with a 18 GHz electrical one used as a pump signal.

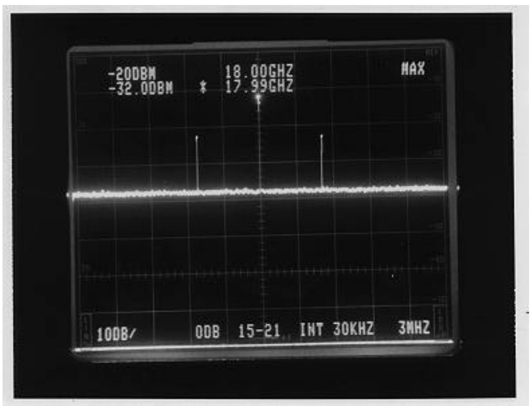

Figure 9: Mixing experiments with a 1 GHz optical signal and a 18 GHz electrical signal for the 3T HPT.

4. DISCUSSION AND CONCLUSION

These experiments show that 2T and 3T edge-coupled GaInAs/InP HPT are promising devices for microwave and millimeter wave applications, not only because of the high cutoff frequency gain, but because of nonlinearity gain effects, which can be used to very easily transmit a data signal on a microwave subcarrier on an AM scheme, the microwave subcarrier being transmitted through the fiber for 2T HPTs or delivered by a local oscillator (or fiber) for 3T HPTs.

This was demonstrated here in the microwave frequency range, for example at 2 GHz for 2T HPTs, for applications such as mobile communications, and further works are in progress to explore higher frequency ranges, particularly in the millimeter wave domain.

Improved results could be obtained with better designed devices. For example, high frequency limits are probably due to parasitics effects since bonding pads were not optimized for millimeter wave applications. Better responsivities are also possible to achieve: modeling predicts 63% external quantum efficiency (without antireflection coating) with a lens-ended fiber and a supplementary quaternary layer (InGaAsP) as part of the collector placed between GaInAs collector and InP subcollector.

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