High Conversion Gain Millimeter-wave Optoelectronic Mixer based on InAlAs/InGaAs Metamorphic HEMT

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Abstract

We experimentally investigate the InAlAs/InGaAs metamorphic HEMT (m-HEMT) on GaAs substrate as a millimeter-wave optoelectronic mixer. The maximum internal conversion gain of 18.17 dB is obtained with 0 dBm local oscillator (LO) power. The m-HEMT exhibits a wide LO frequency range which is well extended to the millimeter-wave band. We also measured the spurious free dynamic range of the m-HEMT as an optoelectronic mixer, whose value is about 96 dB · $Hz^{2/3}$.

Ⅰ. INTRODUCTION

As increasing demands for broadband wireless communication systems, radio-on-fiber systems are extensively studied because they provide the advantages of fiber-optic transmission including low loss, wide bandwidth and flexibility [1]. Since many antenna base stations are required in millimeter-wave radio-on-fiber systems, it is important to realize integration of photonic and RF components for low-cost antenna base station architecture.

InP-based high-electron-mobility transistor (HEMT) optoelectronic mixers have been received much attention because they simultaneously perform photodetection to 1.55 ㎛ lightwave and frequency up-conversion to millimeter-wave band [2]. In addition, InP-based HEMT as an optoelectronic mixer make it possible to realize monolithic millimeter-wave integrated circuits (MMIC) without increasing additional fabrication steps for photodetector. However, in spite of these merits, the InP-based HEMT has inherent disadvantages including low breakdown voltages, high cost and fragile InP substrates.

To overcome these problems, GaAs-based metamorphic HEMT (m-HEMT) has been regarded as an alternative to InP-based HEMT because it provides high breakdown voltages and compatibility to mature GaAs-based MMIC process [3]. Using the InAlAs graded buffer layer, the m-HEMT has shown high speed performance as well as high power capability [4].

In this work, we fabricate the InAlAs/InGaAs metamorphic HEMT on GaAs substrate and report the use of m-HEMT as a millimeter-wave optoelectronic up-converter. By investigating dependence of photodetection and optoelectronic mixing efficiency on the bias conditions, we determine the internal conversion gain for m-HEMT. We also measured the spurious free dynamic range of the m-HEMT as an optoelectronic up-converter.

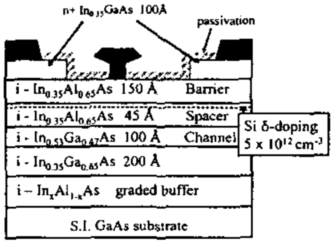

Fig. 1 The schematic diagram for the fabricated metamorphic HEMT with composite channel

Ⅱ. Device structure and experimental setup

Fig. 1 shows the epitaxial layer structure of the fabricated m-HEMT. The $In_xAl_{1-x}As$ graded buffer layer relaxes the strain caused by lattice mismatch between InGaAs channel layer and GaAs substrate [4]. The important feature of the m-HEMT is that it has $In_{0.53}Ga_{0.47}As$ / $In_{0.35}Ga_{0.65}As$ composite channel which make it possible to detect 1.55 μm lightwave as well as enhance intrinsic carrier transport. The m-HEMT used in this experiment has T-shaped gate whose gate length and width are 0.2 μm and 50 μm, respectively. The reverse breakdown voltage and the maximum transconductance of the m-HEMT are -13 V and 680 mS/mm, respectively. S-parameter measurements show that the current gain cutoff frequency (f_T) and the maximum oscillation frequency (f_{max}) are 95 GHz and 170 GHz, respectively, at V_G = 0.4 V and V_D = 1.0 V.

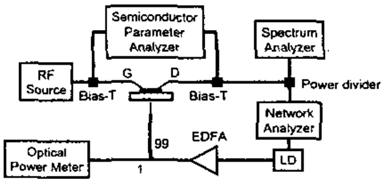

Fig. 2 Experimental setup

Fig. 2 shows the experimental setup for the m-HEMT as a photodetector and an optoelectronic mixer. For measuring the optical modulation response of m-HEMT, the DFB Laser Diode (LD) was directly modulated. The 1.55 μm lightwave generated by LD was illuminated to the back-side of the m-HEMT via single mode lensed-fiber. Because the optical coupling to the m-HEMT is not sufficient, the EDFA was used for optical amplification. For the accurate measurement, we first calibrated the modulation response of laser diode by using a calibrated photodiode whose 3 dB bandwidth is more than 20 GHz.

In the optoelectronic mixing experiment, we applied the RF source to the gate port and illuminated the modulated lightwave. The up-converted signals were measured at the drain port by using RF spectrum analyzer (HP8563E).

III. Photodetection characteristics of m-HEMT

In order to investigate photodetection characteristics to 1.55 μm lightwave, the device characteristics under DC lightwave illumination were measured. Fig. 3 shows the drain current as function of gate voltages under dark and illumination conditions. With the increasing incident optical powers, drain currents increase and the threshold voltages shift. This phenomenon can be explained by the photovoltaic effect in which photo-generated holes accumulated in the channel region cause effective forward gate bias [5].

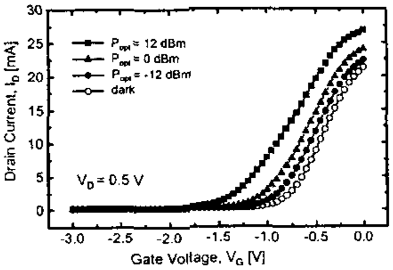

Fig. 3 Drain current as function of gate voltages under dark and optical illumination

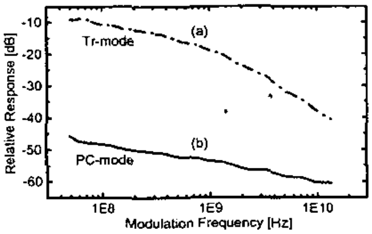

Fig. 4 Optical modulation response of the m-HEMT under back-side illumination at different bias conditions: (a) V_D = 2.5 V, V_G = -1.3 V (b) V_D = 2.5 V, V_G = -3.0 V

Fig 4 shows the optical modulation response for m-HEMT under different bias conditions. When the applied gate bias is higher than threshold voltage (V_G = -1.3 V), m-HEMT provides high optical gain but poor optical modulation response. It is because the photovoltaic effect which contributes the optical gain of m-HEMT is an inherently slow process. In this bias condition, the m-HEMT operates as a phototransistor which provides intrinsic optical gain (Tr-mode).

It should be noted that the photodetected signals appear under the turn-off state (V_G = -3.0 V) of m-HEMT. It is due to fast photoconductive effects dominated by photogenerated electrons, which results in large photonic bandwidth. In these bias conditions, m-HEMT operates as photoconductor and it has no optical gain (PC-mode)

Since the actually absorbed optical power in InGaAs channel layer cannot be measured, we can estimate the intrinsic gain defined as the ratio of the photodetected power at Tr mode to PC-mode where m-HEMT has no optical gain. From the results, the m-HEMT provides 34.5 dB gains at 1 GHz.

IV. The m-HEMT as an optoelectronic mixer

Fig. 5 shows the spectrum of up-converted signals when 30 GHz LO and 100 MHz modulated optical signals are applied. In Fig. 5, there are three components: an LO signal and two up-converted signals (upper and lower sideband). The asterisks (*) in Fig. 5 are image signals due to the external harmonic mixer (HP 11970A) used for the spectrum analyzer.

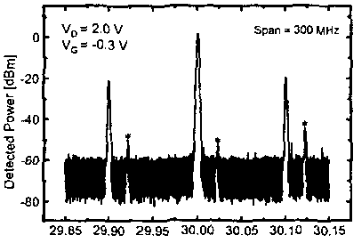

Fig. 5 Up-converted signal spectrum: LO frequency: 30 GHz, Optical IF: 100 MHz

In order to optimize the m-HEMT for high conversion gain, we investigate the mixing efficiency dependence on the bias voltages. Fig. 6 shows up-converted signal and photodetected signal powers as function of drain voltages. In Fig. 6, with the increasing drain bias, the up-converted signal power initially increases and begins to saturate. This result is similar to the transconductance curve versus drain voltage of the m-HEMT because the modulated lighwave effectively modulates the gate voltage. Fig. 7 shows the dependence of up-converted and detected signal power on the gate bias condition under 20 GHz, 0 dBm LO applied to the gate port. Internal conversion gain is defined as the ratio of the up-converted output power to the primary photodetected IF power under the condition that m-HEMT has no optical gain (PC-mode) [6]. In this experiment, the primary photodetected power was measured at V_G = -3.0 V. As the gate bias changes, the second order nonlinear coefficient also changes. The up-converted signal ($f_{LO}+f_{IF}$) power is related to the second order nonlinear coefficient thus the mixing efficiency of the m-HEMT can be affected by changing the V_G as shown in Fig. 7. In these experiments, we obtain maximum internal conversion gain of 18.17 dB with optimum bias conditions: high drain and gate voltages.

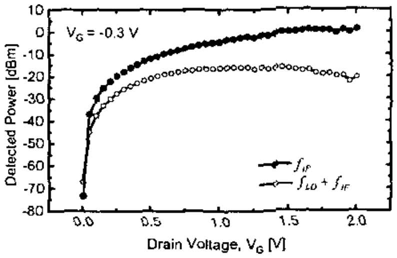

Fig. 6 Up-converted signal and photodetected signal as function of drain voltages at V_G = -0.3 V

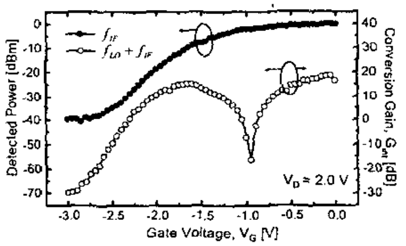

Fig. 7 Up-converted signal power and internal conversion gain and photodetected signal power as function of drain voltages at V_D = 2 V

Fig. 8 shows the up-converted signal power as a function of LO frequency. The up-converted power is nearly constant through the wide LO frequency range. Since the m-HEMT exhibits excellent microwave characteristics (f_T = 95 GHz), it has a wide LO frequency range up to millimeter-wave band for optoelectronic up-conversion.

The spurious free dynamic range (SFDR) is another important factor for the mixer performance, which limits the input power level of the device. We experimentally measured the SFDR of the m-HEMT as an optoelectronic mixer. In the experiment, two tone signals (f_1 = 495 MHz and f_2 = 505 MHz) were used to modulate LD and LO frequency of 20 GHz was applied to the gate port. Fig. 9 shows the up-converted signal spectrum. We observe two 3rd-order inter-modulation product signals (IMP3) in upper ($2f_2-f_1$, 20.515 GHz) and lower ($2f_1-f_2$, 20.485 GHz) side due to inherent

3rd order nonlinearity of the m-HEMT. Fig. 10 shows the fundamental signal power and IMP3 power as function of the input powers. In the experimental condition, the noise floor is about -151 dBm/Hz and we obtained the SFDR of 96 dB· $Hz^{2/3}$ at the bias conditions of V_G = -0.3 V and V_D = 2.0 V.

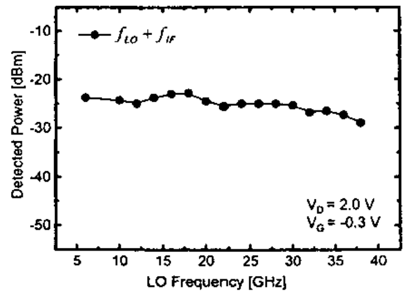

Fig. 8 Up-converted signal power as a function of LO frequency at V_D = 2 V, V_G = -0.3 V

V.Conclusion

We successfully demonstrated the optoelectronic up-conversion using InAlAs/InGaAs metamorphic HEMT on GaAs substrate. In order to maximize the mixing efficiency, we found the optimum bias conditions and obtained high internal conversion gain of more than 18 dB when 0 dBm LO power is applied. We also measured the SFDR of the m-HEMT as an optoelectronic mixer, whose value is about 96 dB· $Hz^{2/3}$. From these results, it is expected that an optoelectronic mixer based on m-HEMT can find useful application for radio-on-fiber system.

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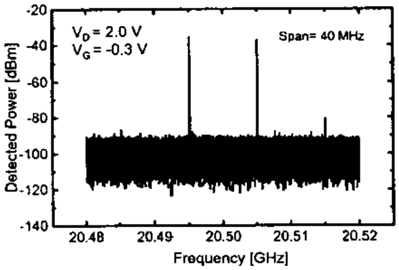

Fig. 9 Up-converted signal spectrum of two tone signal (f_1 = 495 MHz, f_2 = 505 MHz) at V_D = 2 V, V_G = -0.3 V

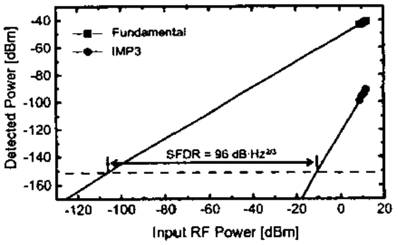

Fig. 10 Fundamental signal and IMP3 signal power as a function of input power at V_D = 2 V, V_G = -0.3 V