Millimeter-wave InP HEMT Optoelectronic Mixers

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***Abstract* — Device characteristics of millimeter-wave optoelectronic mixers based on InP HEMTs are investigated in detail. InP HEMT optoelectronic mixers simultaneously perform photodetection with high internal gain and frequency up-conversion of optical signals into the millimeter-wave band. We demonstrate 60GHz harmonic optoelectronic up-conversion by using a 30GHz local oscillator and, using this, 622Mbps data transmission in 60GHz radio-on-fiber system is demonstrated.**

***Index Terms* — millimeter-wave, radio-on-fiber system, InP HEMT, optoelectronic mixer, optoelectronic integration.**

I. INTRODUCTION

There has been much interest in employing indium-phosphide (InP) high-electron mobility transistors (HEMTs) for millimeter-wave radio-on-fiber systems [1]. They are very useful in simplifying antenna base station architecture because they can be utilized as optoelectronic mixers which accomplish the functions of photodetection to 1.55μm lightwave and frequency up-conversion in a single device. High conversion gain and perfect isolation are additional benefits for utilization of these devices as optoelectronic mixers [1-2].

In this paper, we present detailed characteristics of InP HEMT optoelectronic mixers. After clarifying photodetection mechanism in the InP HEMT, we describe its use as an optoelectronic mixer. In addition, it is experimentally demonstrated that the InP HEMT can be operated as a 60GHz harmonic optoelectronic mixer providing possibility of using a low frequency local oscillator (LO). Several mixer characteristics including internal conversion gain and spurious-free dynamic range (SFDR) are also investigated. In order to evaluate the feasibility for practical implementation to radio-on-fiber (RoF) systems, we construct a remote up-conversion 60GHz RoF system and demonstrate 622Mbps data transmission using the InP HEMT harmonic optoelectronic mixer.

II. PHOTODETECTION CHARACTERISTICS

Epitaxial layers for the InP HEMT used in this work are depicted in Fig. 1. It has a pseudomorphic $In_{0.65}Ga_{0.35}As$ channel in order to improve electrical device performance at the millimeter-wave operation. With 0.1μm gate-length, it exhibits maximum transconductance of 720mS/mm, current-gain cutoff frequency (f_T) of 170GHz and maximum oscillation frequency (f_{max}) of 215GHz at the gate bias of -0.4V and the drain bias of 1V.

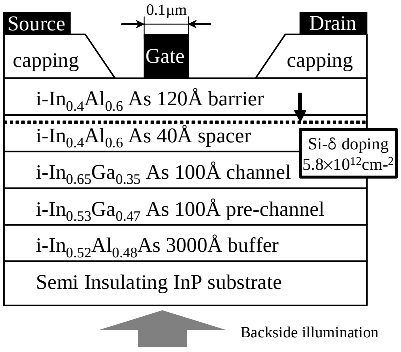


Fig. 1. Epitaxial layers of fabricated InP pseudomorphic HEMT.

We first investigate the photoresponses of InP HEMT in order to clarify physical origins for internal gain of the InP HEMT as a phototransistor. The 1.55μm photodetection characteristics were analyzed with semiconductor parameter analyzer (HP4145B), and network analyzer (HP8722D) with optical signals at 1552nm provided by a DFB laser. The lightwave was illuminated from the backside of the InP substrate using a single-mode lensed fiber which provides coupling efficiency of approximately 10%. Since InP substrate and InAlAs buffer layer are transparent to 1.55μm light, optical absorption occurs only at $In_{0.65}Ga_{0.35}As$ and $In_{0.53}Ga_{0.47}As$ channels.

Fig. 2 shows measured drain-currents (I_D) as a function of gate-voltages (V_G) under dark and illuminated conditions. The InP HEMT exhibits negative shifts in threshold voltages as well as increases in I_D with increasing incident optical powers. It has been reported that these threshold voltage shifts are due to the photovoltaic effect caused by photo-generated holes in the channel [2-3].

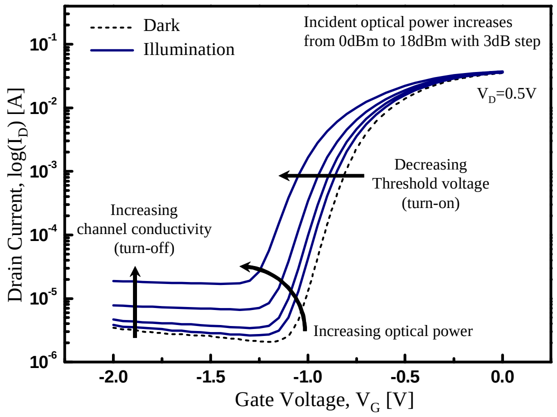


Fig. 2. I_D versus V_G under dark and illuminated conditions

Since the gate voltage is effectively modulated with the photovoltaic effect, internal gain is provided making the HEMT a phototransistor. Even when V_G is lower than the threshold voltage, or at turn-off condition, small increase in I_D is observed with illumination as can be seen in the figure. This is due to the photoconductive effect in which photo-generated electrons increase the channel conductivity and, thus, increase I_D. It should be noted that this does not provide any internal gain since the HEMT is off. These photodetection characteristics are affirmed by data shown in Fig. 3 where the InP HEMT optical modulation responses are shown for both turn-on and turn-off conditions. Because the photovoltaic effect is dominated by the long life-time of photo-generated holes, the photoresponse for turn-on condition has relatively small optical 3dB bandwidth of about 560MHz. On the other hand, for turn-off condition, the photoresponse has much larger 3dB bandwidth because photoconductive effect is dominated by photo-generated electrons having much short life-time. Since the HEMT does not operate as a transistor in turn-off condition, it performs only photodetection without any internal gain. By utilizing this dependence of photodetection characteristics on bias conditions, we can determine the internal gain provided by the HEMT as a phototransistor by measuring photodetected powers at both turn-off and turn-on conditions under the identical optical illumination condition, and taking their differences as shown in Fig. 3. In our experiments, 38dB internal gain is obtained at 100MHz optical modulation frequency. For its uses as a phototransistor and an optoelectronic mixer, InP HEMT should be at turn-on condition for providing internal gain. These optical modulation responses directly affect the photodetection bandwidth of optically transmitted intermediate frequency (IF) with data. It can be seen from the figure that IF up to the GHz range can have high internal gain, which should be sufficient for many applications.

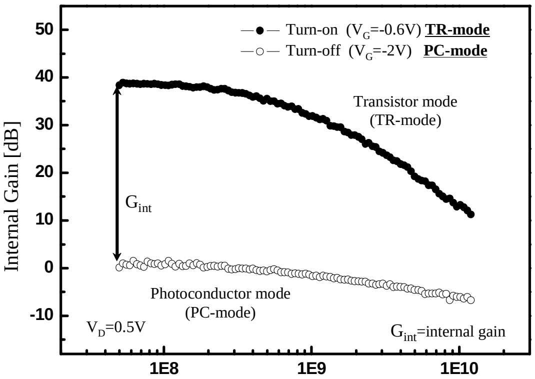


Fig. 3. Optical modulation responses of InP HEMT under turn-on condition (V_G=-0.6V) and turn-off condition (V_G=-2V)

III. HARMONIC OPTOELECTRONIC MIXING

The HEMT can be utilized as an optoelectronic mixer with its inherent nonlinearities [2]. For the frequency up-conversion to the millimeter-wave, the approach requires a phase-locked oscillator operating at desired millimeter-wave band, which increase cost for antenna base station. Therefore, we utilize InP HEMT as a harmonic optoelectronic mixer which provides the using of low frequency phase-locked LO [4].

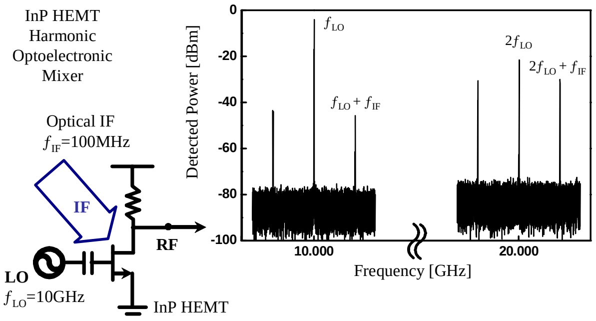


Fig. 4. InP HEMT harmonic optoelectronic mixer and its output spectrum under applying 10GHz LO and optical 100MHz IF.

Fig. 4 shows the schematic diagram for utilizing the InP HEMT as a harmonic optoelectronic mixer and its up-converted output spectrum by applying 10GHz LO to the gate port of InP HEMT. It can be seen that there are fundamental optoelectronic mixing products ($f_{LO} \pm f_{IF}$) and 2nd harmonic optoelectronic mixing products ($2f_{LO} \pm f_{IF}$) under applying 10GHz LO and optical 100MHz IF to the HEMT. Since mixing efficiencies strongly depend on the bias condition of the HEMT, we first investigate the optimum bias conditions in order to make the harmonic optoelectronic up-conversion efficiency to be maximized.

In order to evaluate the performance of InP HEMT optoelectronic mixer, we define internal conversion gain as the power ratio between the desired up-converted signal ($f_{LO}+f_{IF}$ for the fundamental and $2f_{LO}+f_{IF}$ for the 2nd harmonic) and the photodetected f_{IF} signal without internal gain measured at turn-off condition as mentioned earlier. Fig. 5 shows the internal conversion gain for $f_{LO}+f_{IF}$ and $2f_{LO}+f_{IF}$ components as a function of V_G. The photodetected f_{IF} signal power without internal gain is –49dBm measured at V_G=-2V. The non-monotonic curves for optoelectronic up-conversion efficiencies are attributed to the nonlinearity of HEMT transconductance [4]. It should be noted that the maximum 20dB internal conversion gain for harmonic optoelectronic up-conversion at $2f_{LO}+f_{IF}$ was obtained at V_G of -0.9V while suppressing undesired mixing component at $f_{LO}+f_{IF}$.

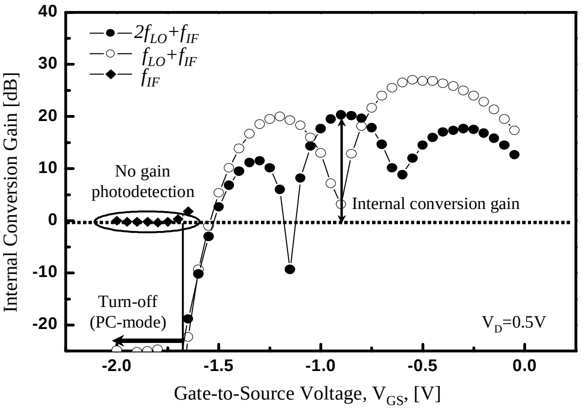


Fig. 5. Internal conversion gain for $f_{LO}+f_{IF}$ and $2f_{LO}+f_{IF}$ as a function of gate voltage

We also measured the internal conversion gain for $2f_{LO}+f_{IF}$ as a function of applied LO frequencies and the results are shown in Fig. 6. Measurement was not taken from 40GHz to 50GHz due to the lack of external harmonic mixer for these frequency bands. In our experiments, the InP HEMT as a harmonic optoelectronic mixer exhibits wide LO frequency ranges which are well extended to the millimeter-wave band. The origins for slightly decreased internal conversion gain as increasing LO frequency are due to the reduction in S_{21} indicating forward power gain and increased loss of RF components which are guaranteed below 50GHz. Nevertheless, the internal conversion gain of 18dB is obtained at 60GHz band. With its wide LO frequency range, we demonstrated the harmonic optoelectronic up-conversion of 100MHz optical signal to the 60GHz band by applying 30GHz LO with 0dBm, as shown in the inset of Fig. 6.

Another important parameter for evaluating the performance of a frequency mixer is the input dynamic range. For optoelectronic mixers, we characterized it by measuring spurious-free dynamic range (SFDR) which is defined as the input IF signal range in which third-order intermodulation products can be neglected. Two DFB laser diodes were directly modulated with 99MHz and 101MHz, independently. Fig. 7-(A) shows the harmonic optoelectronic up-converted upper sideband spectrum. We clearly observe the intermodulation products at 20.097GHz and 20.103GHz, which are generated during the harmonic optoelectronic up-conversion process. The SFDR measurements were performed by measuring these fundamental signals and third-order intermodulation products under different IF powers, which are indicated in Fig. 7-(B). We obtained the SFDR of 94.5dB·$Hz^{2/3}$, which is expected to be sufficient for many applications.

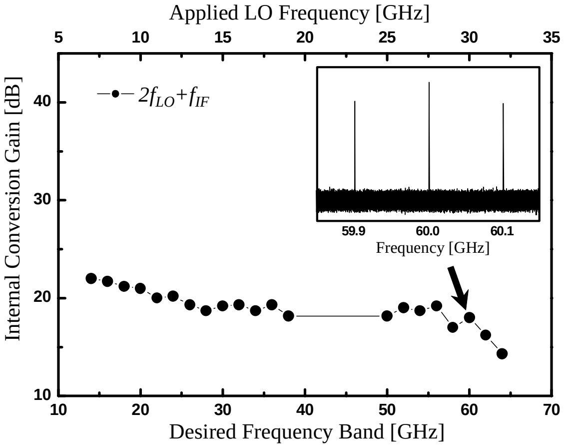
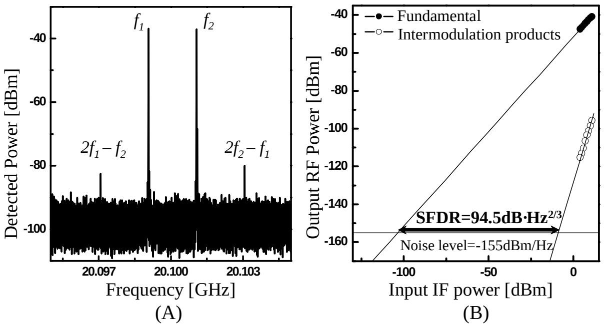


Fig. 6. Internal conversion gain for harmonic optoelectronic up-conversion at $2f_{LO}+f_{IF}$ as a function of applied LO frequencies. The inset shows 60GHz harmonic optoelectronic up-converted spectrum under applying 30GHz LO



(A) (B)

Fig. 7. (A) 20GHz harmonic optoelectronic up-converted signals including third-order intermodulation products under 99MHz and 101MHz IF signals (B) SFDR measurement.

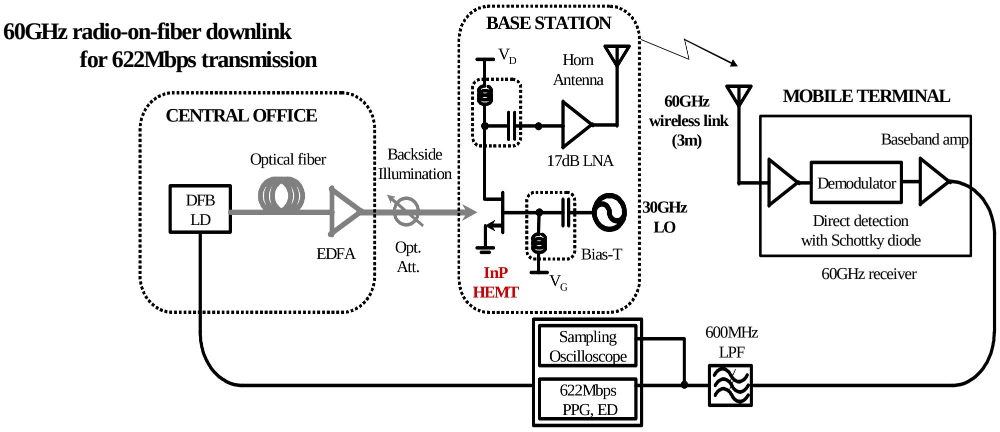


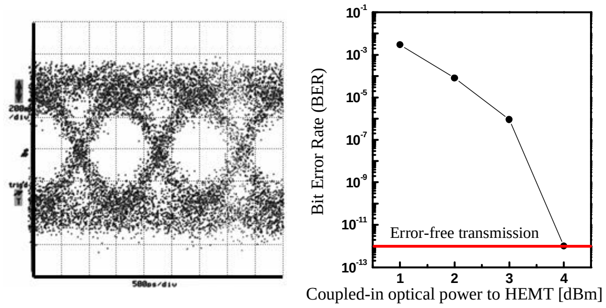
Fig. 8. 60GHz radio-on-fiber systems utilizing InP HEMT as a harmonic optoelectronic mixer

IV. 60GHZ RADIO-ON-FIBER SYSTEM

In order to investigate feasibility of using InP HEMT as a 60GHz harmonic optoelectronic mixer in a radio-on-fiber (RoF) system, a remote up-conversion 60GHz RoF downlink transmission system was constructed as shown in Fig. 8. Optical data channel produced by a DFB laser directly modulated with 622Mbs NRZ pseudo-random bit sequence (2^{15}-1) was transmitted from the central station to the base station. The optically transmitted data were then frequency up-converted to 60GHz band using the InP HEMT harmonic optoelectronic mixer with 30GHz LO with the power of -6dBm. The optimal bias condition of V_G=-0.9V was experimentally confirmed to be same as those determined at 20GHz. The output signal at drain port was amplified by 17dB LNA and radiated from the horn antenna with 20dB gain. After 3m wireless transmission, received signals were demodulated using the direct detection technique with a Schottky diode. Clear eye-opening was observed for the recovered data as shown in Fig. 9-(A). In addition, the link performance was evaluated by measuring the bit-error rate (BER) as a function of coupled-in powers to the InP HEMT, which are estimated to be 10% of incident optical power. Fig. 9-(B) shows the experimental results for BER performance of 60GHz radio-on-fiber links.

V. CONCLUSION

In this work, we investigated characteristics of a InP HEMT as an optoelectronic mixer. Based on the photodetection mechanism in the InP HEMT, we defined the internal conversion gain and investigated its dependence on V_G. By utilizing it as a harmonic optoelectronic mixer, we demonstrated 622Mbps data transmission in 60GHz radio-on-fiber system. It is expected that the InP HEMT optoelectronic mixer can be useful in simplifying antenna base station architecture in 60GHz radio-on-fiber systems.



(A)

(B)

Fig. 9. (A) Eye-diagram for recovered 622Mbps data (B) Bit-error rate as a function coupled-in optical power to HEMT

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