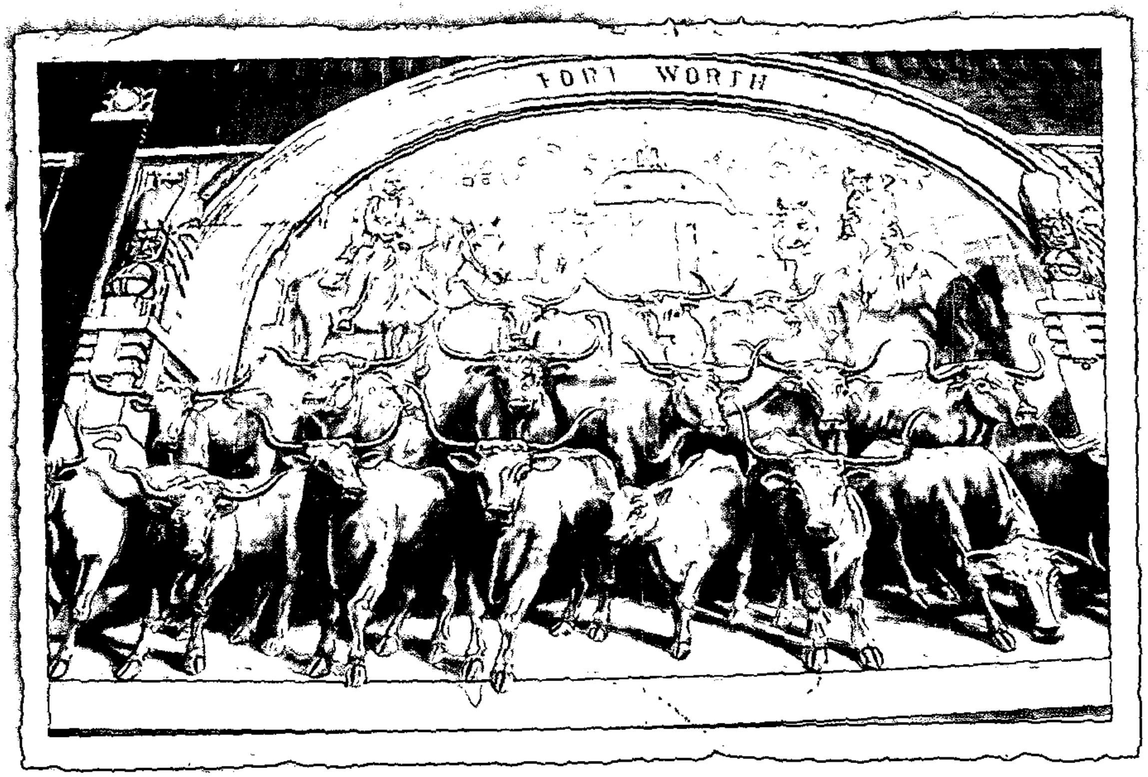
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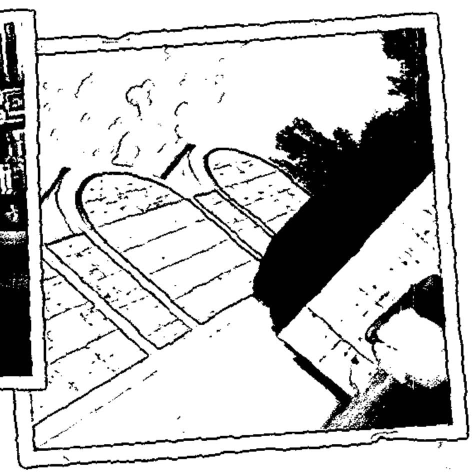

Characteristics of InP HEMT Harmonic Optoelectronic Mixers and Their Application to 60GHz Radio-on-Fiber Systems

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***Abstract* — We present device characteristics of InP HEMT as a harmonic optoelectronic mixer. A single InP HEMT device performs photodetection of optically transmitted data, and frequency up-conversion of them into 60GHz band. Several mixer performance characteristics are investigated and 622Mbps data transmission in 60GHz radio-on-fiber system is successfully demonstrated using InP HEMT harmonic optoelectronic mixer.**

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

I. INTRODUCTION

The needs for broadband wireless communication have grown much interest in millimeter-wave frequency bands, especially 60GHz, because of its wide transmission bandwidth and the possibility of efficient frequency reuse. However, their use is not yet widespread due to difficulties in millimeter-wave generation, transmission and processing. With development of fiber-optic technologies, radio-on-fiber systems which utilize optical fibers as low loss and highly flexible transmission medium have been investigated as a solution for these problems [1].

In millimeter-wave radio-on-fiber systems, a large number of antenna base stations are located within the coverage of a single central office in order to compensate high transmission loss of millimeter-waves. Consequently, it is important to come up with low cost and simple antenna base station architecture for practical implementation of these radio-on-fiber systems.

One attractive approach is the one-chip integration of a photodetector and other RF components that are required in antenna base station. Indium-phosphide high-electron mobility transistors (InP HEMTs) are very useful devices for this optoelectronic integration because they can perform photodetection to 1.55μm light with high internal gain while maintaining compatibility to conventional MMIC process [2]. In addition, they can provide additional functionalities such as optoelectronic mixing and optical injection-locked oscillation [2-3].

In this paper, we present detailed characteristics of a harmonic optoelectronic mixer based on a single InP HEMT and its application to 60GHz radio-on-fiber systems. The photodetection mechanism for the InP HEMT is first identified and it is experimentally demonstrated that the InP HEMT can be operated as a 60GHz harmonic optoelectronic mixer. Such opto-electronic mixer performance characteristics as internal conversion gain and local oscillator (LO) frequency ranges are investigated and 622Mbps data transmission in 60GHz radio-on-fiber system is demonstrated.

II. PHOTODETECTION CHARACTERISTICS

Epitaxial layers for the HEMT used for our investigation are schematically shown 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 the maximum transconductance of 720mS/mm, the current-gain cutoff frequency (f_T) of 165GHz and the maximum oscillation frequency (f_{max}) of 95GHz at the gate bias of -0.4V and the drain bias of 1V.

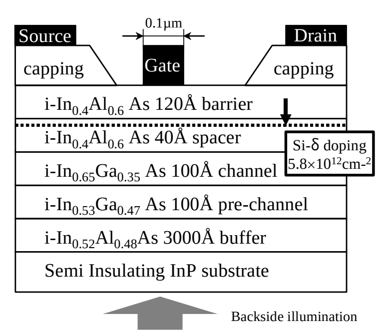

Fig. 1. Layer structure of InP pseudomorphic HEMT

1.55μm photodetection characteristics were analyzed with the semiconductor parameter analyzer (HP4145B), the network analyzer (HP8722D) with optical signals at 1552nm provided by a DFB laser. The light was illuminated from the backside of InP substrate with a

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single-mode lensed fiber which provides the 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.

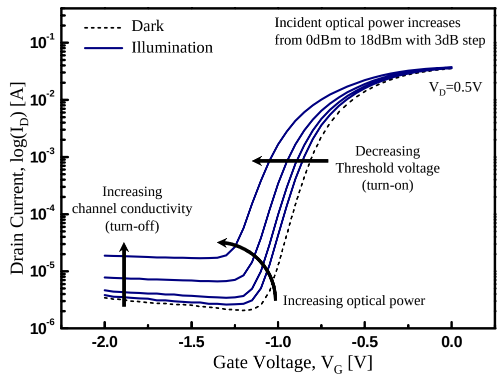


Fig. 2. I_D versus V_G under dark and illuminated conditions

Fig. 2 shows measured drain-currents (I_D) as a function of gate-voltages (V_G) under dark and illuminated conditions. The InP HEMT shows a negative shift in threshold voltages as well as increase 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 [3-5].

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, namely 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 it does not provide any internal gain since the HEMT is off. These photodetection characteristics are affirmed by Fig. 3 which shows the InP HEMT optical modulation responses for both turn-on and turn-off conditions. Because the photovoltaic effect is dominated by the 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 photoresponses 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.

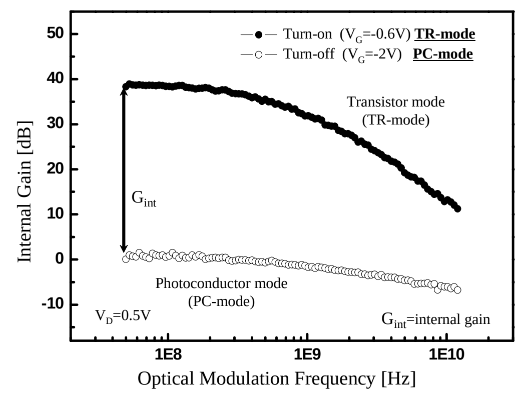


Fig. 3. Optical modulation responses of InP HEMT under turn-on condition (V_G=-0.6V) and turn-off condition (V_G=-2V)

III. Harmonic Optoelectronic Mixing

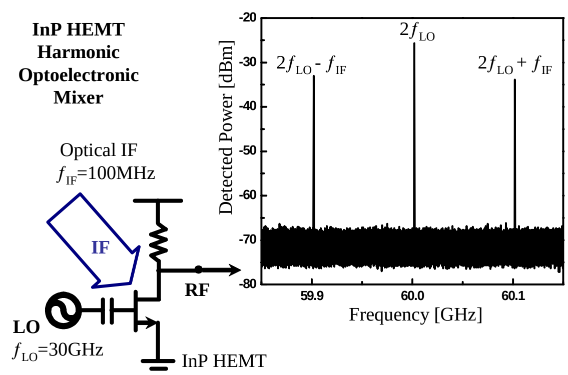


Fig. 4. InP HEMT harmonic optoelectronic mixer and its 60GHz frequency up-conversion spectrum under applying 30GHz LO and optical 100MHz IF.

With a single InP HEMT device, it is possible to realize photodetection and harmonic optoelectronic up-conversion simultaneously [5]. Fig. 4 shows the schematic diagram for utilizing the InP HEMT as a harmonic optoelectronic mixer and its up-converted output spectrum at 60GHz. It can be seen that there are harmonic optoelectronic mixing products at $2f_{LO}+f_{IF}$ (60.1GHz) and $2f_{LO}-f_{IF}$ (59.9GHz) and 2nd harmonic of LO at $2f_{LO}$ (60GHz) with 30GHz LO and optical 100MHz IF. With this harmonic up-conversion, lower frequency LO can be used making the implementation of base station easier.

Conversion gain is an important parameter for the performance of a frequency up-converter. In the case of an optoelectronic mixer, it is difficult to determine the conversion gain accurately since the actually absorbed optical IF power in HEMT is not accurately known. Instead, we define the internal conversion gain which is the power ratio of $2f_{LO}+f_{IF}$ and $2f_{LO}-f_{IF}$ optoelectronic up-converted signals to the photodetected f_{IF} signal without internal gain, which can be measured at turn-off condition as mentioned earlier.

Since the measurement sensitivity at 60GHz band is limited by high background noise level of the external V-band harmonic mixer (Agilent 11974V) used for our measurement, the experiments were first carried out in the 20GHz band with 10GHz LO having 0dBm power and 100MHz optical IF signals. 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 transconductance of the HEMT. 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 $f_{LO}+f_{IF}$. In this V_G condition, the output RF spectra at 10GHz and 20GHz bands are shown in Fig. 6. It can be seen that the output power of $2f_{LO}+f_{IF}$ is much larger than that of $f_{LO}+f_{IF}$.

For its use at millimeter-wave band, we measured the internal conversion gain for $2f_{LO}+f_{IF}$ as a function of applied LO frequencies and the results are shown in Fig. 7. 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 were guaranteed below 50GHz. Nevertheless, the internal conversion gain of 18dB is obtained at 60GHz band.

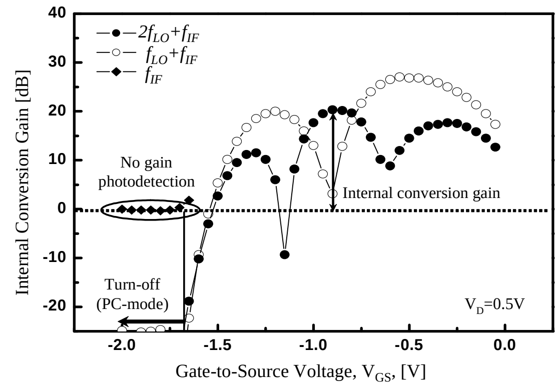


Fig. 5. Internal conversion gain for $f_{LO}+f_{IF}$ and $2f_{LO}+f_{IF}$ as a function of gate voltage

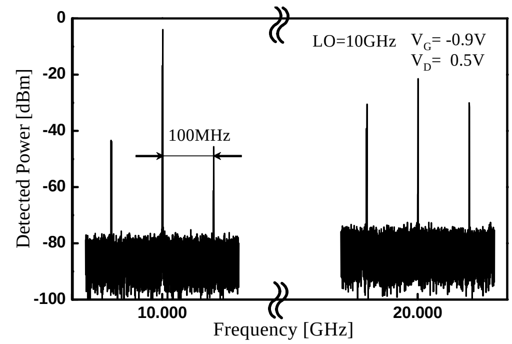


Fig. 6. Output RF spectrum of harmonic optoelectronic up-conversion by InP HEMT with optimum bias conditions, V_G=-0.9V and V_D=0.5V

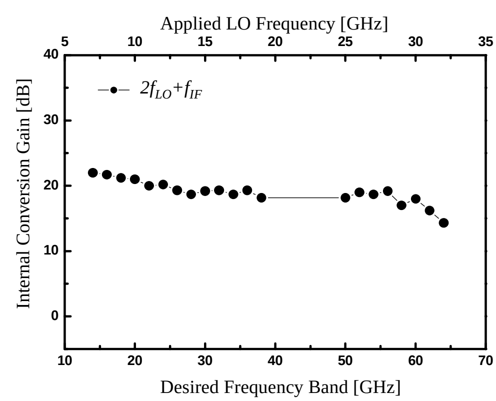


Fig. 7. Internal conversion gain for harmonic optoelectronic up-conversion at $2f_{LO}+f_{IF}$ as a function of applied LO frequencies.

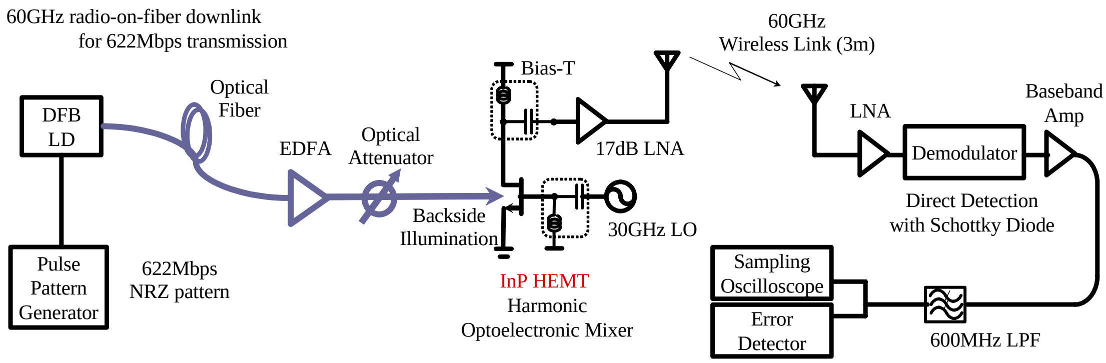


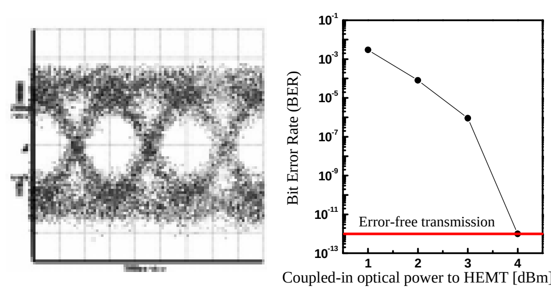
Fig. 8. 60GHz radio-on-fiber systems utilizing InP HEMT as a harmonic optoelectronic mixer

IV. 60GHz Radio-on-Fiber System

To investigate the 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 the optimal bias conditions and 30GHz, -6dBm LO. The optimal bias condition 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 the 20dB gain. After 3m wireless transmission, the 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. Error-free transmission was achieved at the coupled-in optical power of 4dBm.

V. Conclusion

In this work, we investigated characteristics of a InP HEMT as a millimeter-wave harmonic optoelectronic mixer and demonstrated 622Mbps data transmission in 60GHz radio-on-fiber system by utilizing it. Based on the photodetection mechanism in the InP HEMT, we defined internal conversion gain and investigated its dependence on V_G for the maximum harmonic optoelectronic mixing efficiency. At 60GHz band, internal conversion gain of 18dB was obtained. It is expected that InP HEMTs can be useful in simplifying antenna base station architecture in 60GHz radio-on-fiber system.



(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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