A Millimeter-wave Harmonic Optoelectronic Mixer based on InAlAs/InGaAs Metamorphic HEMT

Chang-Soon Choi[1], Woo-Young Choi[1], Dae-Hyun Kim[2], Kwang-Seok Seo[2]

[1]Department of Electrical and Electronic Engineering, Yonsei University, Seoul, 120-749, Korea

[2]School of Electrical Engineering, Seoul National University, Seoul, 151-742, Korea

***Abstract* — We investigate the InAlAs/InGaAs metamorphic HEMT on GaAs substrate as a harmonic optoelectronic mixer. The fabricated metamorphic HEMT simultaneously performs photodetection at 1.55µm lightwave and harmonic optoelectronic up-conversion into millimeter-wave band. By changing the bias conditions of the HEMT, the harmonic optoelectronic mixing efficiency can be selectively enhanced while suppressing undesired mixing components. The metamorphic HEMT as a harmonic optoelectronic mixer is a promising candidate that can simplify the base station architecture in fiber-optic millimeter-wave transmission systems.**

I. INTRODUCTION

Millimeter-wave wireless communication systems have been intensively developed for broadband wireless services including wireless local area networks and intelligent traffic systems. Since many base stations (BS) are required to compensate the large loss of millimeter-wave, fiber-optic technologies have been introduced which can provide flexible, wide bandwidth and low loss transmission systems [1].

There are two major approaches to construct these fiber-optic millimeter-wave transmission systems. In one configuration, millimeter-wave signals are optically generated and transmitted over the optical fiber, and converted back to millimeter-wave at the BS. In this system, several approaches for the optical generation of millimeter-wave have been proposed but it still remains as a challenging task [1-2]. In addition, the chromatic dispersion and the phase noise degradation of optical millimeter-wave signal are limiting factors for increasing transmission distance [3].

In the other configuration called IF feeder system, intermediate frequency (IF) modulated optical signals are transmitted over the fiber, and remotely up-converted to millimeter-wave at the BS. This IF feeder system mitigates the above-mentioned complexities and avoids high frequency photodetectors. However, it requires electrical mixers and phase-locked local oscillators (LO) operating at millimeter-wave, which can increase the BS cost.

For simplifying the BS architecture, optoelectronic mixers have been proposed for the mixing IF modulated lightwave with millimeter-wave LO signals [4-5]. InP-based HEMTs have received much attention for this application because they can detect modulated 1.55µm lightwave and have the compatibility with conventional MMIC fabrication process. However, low breakdown voltages and expensive InP substrates remain as obstacles for practical applications. In addition, the technologies for millimeter-wave phase-locked LO are not mature yet.

In this work, we experimentally demonstrate 60GHz up-conversion using an InAlAs/InGaAs metamorphic HEMT on GaAs substrate as a harmonic optoelectronic mixer. It has structural advantages including large optical responsivity to 1.55µm lightwave and possibility to use low frequency LO for the up-conversion to millimeter-wave. By investigating the mixing efficiency under various bias conditions, the optimization for harmonic optoelectronic up-converter is performed.

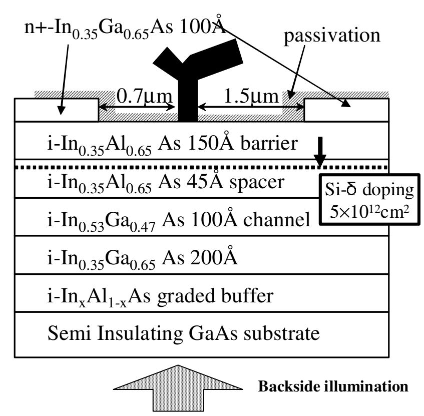

Fig. 1. The schematic cross-section of fabricated InAlAs/InGaAs metamorphic HEMT on GaAs substrate with composite channels

II. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

Fig. 1 shows the cross-section of the metamorphic InAlAs/InGaAs HEMT on GaAs substrate for harmonic optoelectronic mixer. It was fabricated on heterostructure epitaxial layers grown on semi-insulating GaAs substrate. The metamorphic HEMT has the $In_{0.53}Ga_{0.47}As$ /$In_{0.35}Ga_{0.65}As$ composite channels in order to improve carrier transport without sacrificing breakdown characteristics for high power performance [6]. In addition, the $In_{0.53}Ga_{0.47}As$ channel makes it possible for the metamorphic HEMT to detect 1.55μm lightwave. The fabricated metamorphic HEMT has the gate length of 0.25μm. The reverse breakdown voltage and the maximum transconductance of the HEMT are -13V and 680mS/mm, respectively. S-parameter measurements show that the current gain cutoff frequency (f_T) and the maximum frequency of oscillation (f_{max}) are 95GHz and 170GHz, respectively, at V_G=0.4V and V_D=1.0V.

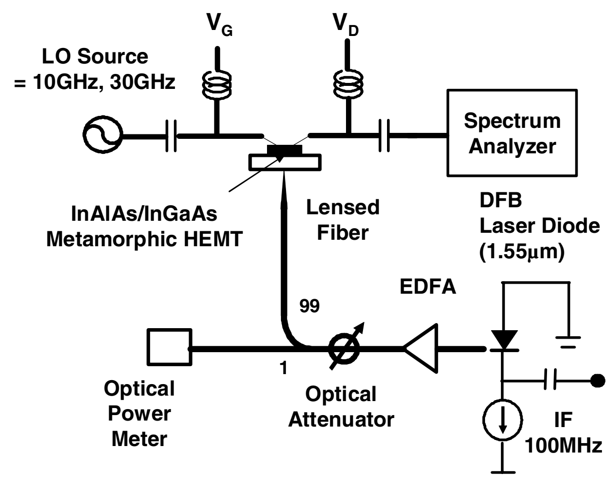

Fig. 2. Experimental configuration for the optoelectronic up-conversion

The experimental arrangement for the optoelectronic up-conversion using the HEMT is shown in Fig. 2. The 1552nm DFB laser diode was directly modulated by the 100MHz IF signal. The modulated lightwave was illuminated from the backside of the GaAs substrate using single mode lensed fiber in order to improve optical coupling efficiency and optical modulation response [7]. Because of large optical insertion loss due to diffraction and reflection of incident lightwave, EDFA was used for optical amplification. All measurements were performed in the common-source configuration by utilizing on-wafer GSG probes. A frequency synthesizer as an LO source and a DC voltage source were connected via bias-T to the gate port and the output from drain port was measured by spectrum analyzer (HP8563E) which has the frequency range up to 26.5GHz. At 60GHz band, an external V-band harmonic mixer (Agilent 11974V) was used.

II. RESULTS AND DISCUSSIONS

A. Optoelectronic Mixing Mechanism

Fig. 3 shows the dependence of drain-currents (I_D) on the gate-bias (V_G) under dark and illuminated conditions. During the measurements, the drain-bias (V_D) was set to 0.5V and the incident optical power was increased from -9dBm to 0dBm by 3dB step, which were measured at the end of lensed fiber. As can be seen in this figure, the metamorphic HEMT exhibits significant increase in I_D under illumination. As reported in several works [5,7], the major photodetection mechanism in HEMT is the photovoltaic effect which appears in threshold voltage shift of I_D-V_G curves.

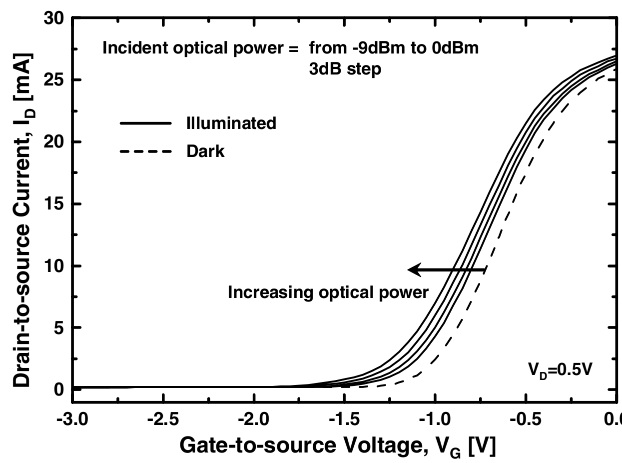

Fig. 3. Drain-currents (I_D) as a function of gate-bias (V_G) for the metamorphic HEMT under dark and optical illumination. The incident optical power increases from -9dBm to 0dBm with the step of 3dB. The drain bias is 0.5V

When low power optical illumination is applied to the HEMT, the photovoltage (V_{ph}) which is linearly proportional to the absorbed optical power (P) is given as

$$V_{ph} \approx a_1 P . \tag{1}$$

The optoelectronic mixing utilizes this photodetection characteristic along with the HEMT's non-linearity. The dominant origin for the optoelectronic mixing is considered to be the non-linear characteristics of I_D-V_G relationship [5]. The I_D of the HEMT can be written as

$$I_D = I_S + b_1 V_G + b_2 V_G^2 + b_3 V_G^3 + \cdots, \quad (2)$$

where $b_{1\cdots n}$ are the power-series coefficients and I_S is the static drain-current. The optical power of IF modulated lightwave is described by

$$P_{opt} = P_0[1 + m\cos(2\pi f_{IF} t)], \quad (3)$$

where P_0 is the average optical power, m is the modulation index. When LO signal is applied to the gate and the device is illuminated, V_G in (2) is modified as

$$V_G = V_{GB} + V_S \cos(2\pi f_{LO} t) + V_{ph} \cos(2\pi f_{IF} t), \quad (4)$$

where V_{GB} is the gate bias voltage and V_S and f_{LO} are the amplitude and frequency of LO, respectively. By substituting (3) and (4) into (2), the mixing products at $f_{LO} + f_{IF}$ and $2f_{LO} + f_{IF}$ are obtained as

$$I_D(f_{LO} + f_{IF}) \propto a_1 m P_0 \cdot b_2 V_S\ , \quad (5)$$

$$I_D(2f_{LO} + f_{IF}) \propto a_1 m P_0 \cdot b_3 V_S\ . \quad (6)$$

Since b_2 and b_3 are changed with V_G, the mixing efficiency of the desired frequency component can be controlled by changing V_G.

B. Dependence of Harmonic Optoelectronic Mixing Efficiency on the Bias conditions and LO Frequency

In order to optimize the bias conditions for harmonic optoelectronic mixing, experiments were first carried out in the 20GHz band with 10GHz LO, because the measurement sensitivity at 60GHz band is limited by high background noise level of the V-band external harmonic mixer. The incident optical power was 13dBm. 10GHz LO signal with 0dBm was applied to the gate port of the HEMT. Fig. 4 shows the dependence of optoelectronic up-converted signals at $f_{LO} + f_{IF}$ and $2f_{LO} + f_{IF}$ on V_G. It can be seen that up-converted powers strongly depend on V_G conditions. The non-monotonic curves for optoelectronic mixing are attributed to the dependence of the HEMT's nonlinearity on V_G. The mixing product at $2f_{LO} + f_{IF}$ can be selectively enhanced by setting optimum V_G condition, for example, V_G=-1.5V. This feature is advantageous in harmonic optoelectronic mixer where $2f_{LO} + f_{IF}$ component is utilized.

For further investigation of the bias conditions, we measured the dependence of optoelectronic up-converted signals on V_D as shown in Fig. 5. In the linear mode of the HEMT, the harmonic optoelectronic mixing efficiency at $2f_{LO} + f_{IF}$ is enhanced. However, in the saturation mode, it decreases as increasing V_D. The experimental results correspond to the characteristics of microwave electrical mixer in which harmonics of LO become strong under the linear mode of the HEMT [8]

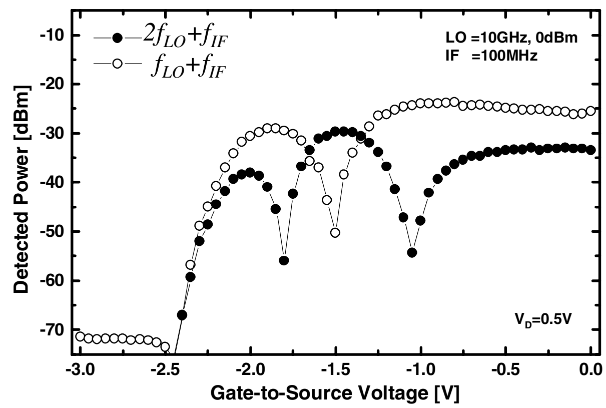

Fig. 4. Up-converted signals at $f_{LO}+f_{IF}$ and $2f_{LO}+f_{IF}$ as a function of V_G. The 10GHz LO power is 0dBm.

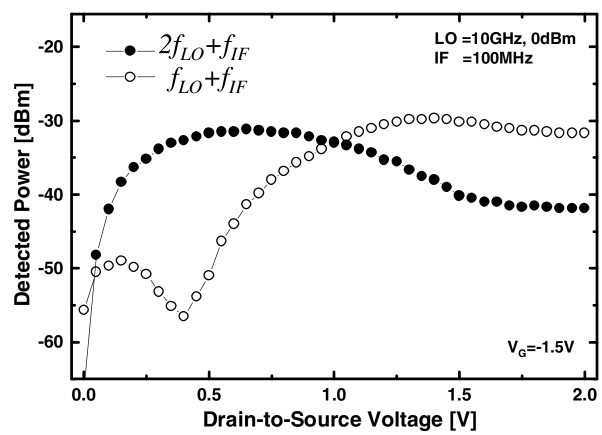

Fig. 5. Up-converted signals at $f_{LO}+f_{IF}$ and $2f_{LO}+f_{IF}$ as a function of V_D. The 10GHz LO power is 0dBm.

Fig. 6 shows the harmonic optoelectronic up-converted power at $2f_{LO} + f_{IF}$ as a function of LO frequency. Since the second harmonics of LO are utilized for the frequency up-conversion, applied LO frequency was set to be half of the desired frequency band. In the experimental results, the fairly flat optoelectronic response indicates that the metamorphic HEMT as a harmonic optoelectronic mixer has the wide LO frequency ranges which are well extended to 60GHz band.

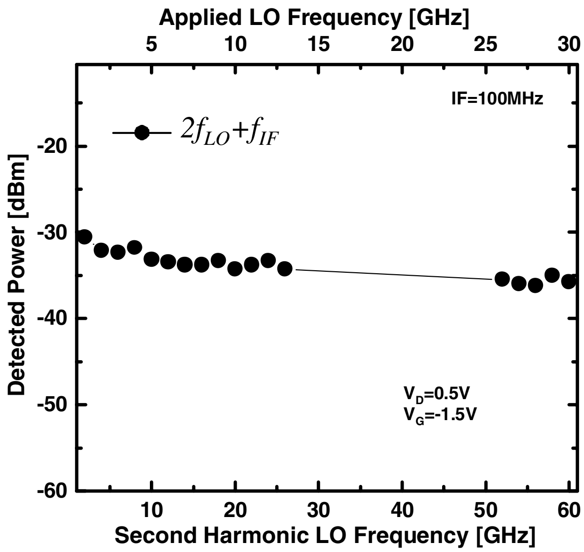

Fig. 6. Harmonic optoelectronic up-converted power at $2f_{LO}+f_{IF}$ as a function of LO frequency. The gate and drain bias conditions are -1.5V and 0.5V, respectively.

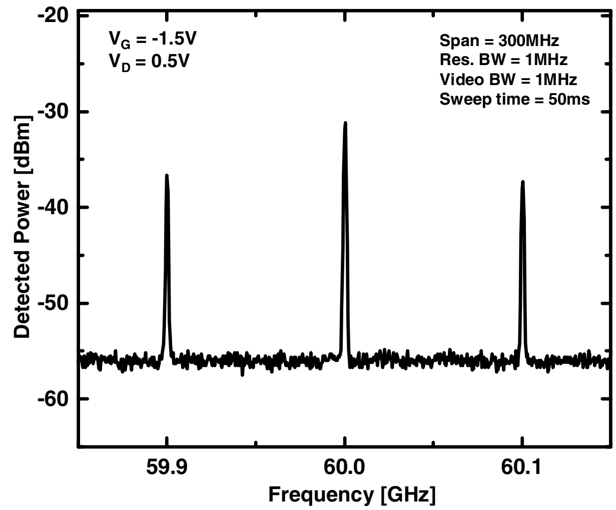

Fig. 7. 60GHz up-converted spectrum under the bias conditions of V_G=-1.5V and V_D=0.5V. The 30GHz LO and optical 100MHz IF signals are applied to the metamorphic HEMT.

C. 60GHz Up-conversion

By utilizing the metamorphic HEMT as a harmonic optoelectronic mixer, we successfully demonstrated the frequency up-conversion of optical 100MHz IF signal to the 60GHz band by applying 30GHz LO to the gate port. Fig. 7 shows the up-converted signals under the bias conditions of V_G=-1.5V and V_D=0.5V which were determined by the optimization process as described above. The dependence of 60GHz harmonic optoelectronic up-conversion on the bias conditions was similar to the 20GHz band experiments. When 10GHz LO was applied under same bias conditions, the detected power of up-converted signal was -45dBm.

IV. CONCLUSION

We demonstrate 60GHz harmonic optoelectronic up-conversion using the InAlAs/InGaAs metamorphic HEMT on GaAs substrate. Optimum bias conditions make it possible to enhance desired harmonic optoelectronic mixing components. It is also shown that the metamorphic HEMT has a wide LO frequency range up to the millimeter-wave band. We believe that this harmonic optoelectronic mixer based on metamorphic HEMT can be useful in fiber-optic millimeter-wave transmission systems.

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