Q-Band pHEMT and mHEMT Subharmonic Gilbert Upconversion Mixers

Jen-Yi Su, *Student Member, IEEE*, Chinchun Meng, *Member, IEEE*, and Po-Yi Wu

***Abstract*—This letter makes a comparison between Q-band 0.15 μm pseudomorphic high electron mobility transistor (pHEMT) and metamorphic high electron mobility transistor (mHEMT) stacked-LO subharmonic upconversion mixers in terms of gain, isolation and linearity. In general, a 0.15 μm mHEMT device has a higher transconductance and cutoff frequency than a 0.15 μm pHEMT does. Thus, the conversion gain of the mHEMT is higher than that of the pHEMT in the active Gilbert mixer design. The Q-band stacked-LO subharmonic upconversion mixers using the pHEMT and mHEMT technologies have conversion gain of -7.1 dB and -0.2 dB, respectively. The pHEMT upconversion mixer has an OIP_3 of -12 dBm and an $\mathrm{OP}_{1\,\mathrm{dB}}$ of -24 dBm, while the mHEMT one shows a 4 dB improvement on linearity for the difference between the OIP_3 and $\mathrm{OP}_{1\,\mathrm{dB}}$. Both the chip sizes are the same at 1.3 mm $\times$ 0.9 mm.**

***Index Terms*—Metamorphic high electron mobility transistor (mHEMT), pseudomorphic high electron mobility transistor (pHEMT), Q-band, stacked-LO, subharmonic, upconversion.**

I. Introduction

In the millimeter-wave or microwave regimes, a high electron mobility transistor (HEMT) with good high-frequency characteristics is popularly used [1], [2]. A metamorphic HEMT (mHEMT) on a GaAs substrate has a lower noise figure, a higher transconductance and a higher cutoff frequency $(\mathrm{f_T})$ as compared with a pseudomorphic HEMT (pHEMT). Fully integrated 60 GHz single-chip front-end MMICs show that the mHEMT, contrasted with the pHEMT, has higher gain, higher output power and lower power consumption [3]. The advantage of the technology appears obviously in the amplifiers, which is a conclusive outcome. At high frequencies, many mixers are widely designed to be passive mixers—diode mixers and FET resistive mixers [4]–[6]. However, the diode passive mixers, using the pHEMT and mHEMT technologies, show comparable performances because the potential barriers associated with pHEMT and mHEMT diodes are almost equivalent. Identical resistive mixers using the 0.15 μm mHEMT and pHEMT technologies nearly have the same conversion loss, even though the mHEMT technology has a higher $\mathrm{f_T}$ of 110 GHz, while the 0.15 μm pHEMT technology employed has an 85 GHz $\mathrm{f_T}$ [5].

An alternative for the mixer design is an active mixer based on the analog design approach, where a high $\mathrm{f_T}$ is important. The Gilbert mixer is a well-known topology for the active mixer [7]–[9]. The subharmonic Gilbert mixer is usually adopted for high-frequency applications since the LO is easily realized with half of the RF frequency [9]. The double balanced Gilbert mixer has the benefits of high gain and excellent port-to-port isolations in nature. The port-to-port isolations of the active mixer rely on the balanced structure and the device gate-to-drain reverse isolation while area-consuming $\lambda/4$ transmission lines and stubs are used for satisfying port-to-port isolations in the passive mixer. Therefore, the layout size of the active mixer is much smaller than that of the passive counterpart [4], [5].

In this letter, two Q-band subharmonic Gilbert upconverters are demonstrated for the first time, to the best of our knowledge, using the mHEMT and pHEMT processes. The experimental results show that the conversion gain of the mHEMT mixer is higher than that of the pHEMT mixer and the linearity of the mHEMT mixer is better. Both Gilbert mixers possess high port-to-port isolations. The performance comparison of the two mixers is established in this letter. Using the mHEMT technology in the millimeter-wave transceiver, the performance of the amplifier is improved and the active Gilbert mixer also works better. The outcomes offer another choice—the mHEMT analog circuit design approach in the fully integrated millimeter-wave regime.

II. Measured pHEMT and mHEMT DC Characteristics

The indium mole fraction of 15–30% and 40% is held for pHEMT and mHEMT devices provided by the standard foundry process [10]. Additionally, the process includes the metal-insulating-metal (MIM) capacitors ($\mathrm{C_{plate}} = 0.39\ \mathrm{fF}/\mu\mathrm{m}^2$), thin-film resistors (50 $\Omega/\square$), mesa resistors (150 $\Omega/\square$ for pHEMT and 180 $\Omega/\square$ for mHEMT), backside processing, via-hole etching, air-bridge and two metal layers.

In Fig. 1, the measured dc transconductance $(\mathrm{g_m})$ and drain current $(\mathrm{I_{ds}})$ are plotted as a function of gate voltage with $\mathrm{V_{ds}} = 1.5$ V for the 0.15 μm pHEMT and mHEMT, respectively. The $\mathrm{g_m}$ peaks around $\mathrm{V_{gs}} = -0.4$ V with a value of 467 mS/mm for the pHMET transistor and the mHEMT has a maximum $\mathrm{g_m}$ of 616 mS/mm at $\mathrm{V_{gs}} = -0.1$ V. At $\mathrm{V_{gs}} = 1.0$ V, the pHEMT and the mHEMT have a maximum drain current of 691 mA/mm and 660 mA/mm, respectively.

III. Circuit Design

The Q-band stacked-LO subharmonic Gilbert upconversion mixer structure is shown in Fig. 2. The stacked-LO subhar-

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The authors are with the Department of Communication Engineering, National Chiao Tung University, Hsinchu 300, Taiwan (e-mail: ccmeng@mail.nctu.edu.tw).

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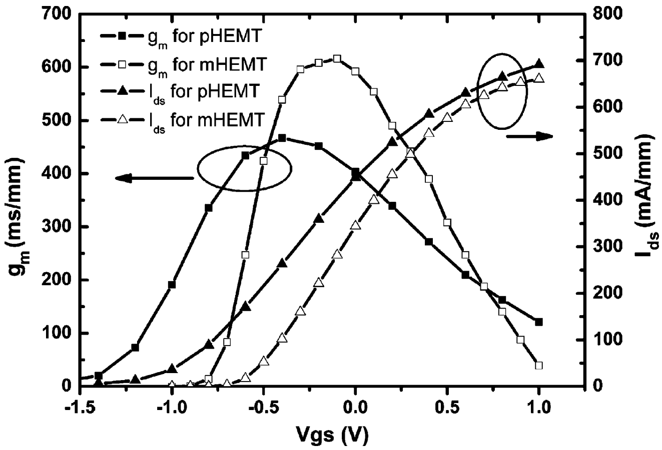

Fig. 1. Measured drain-to-source current (I_{ds}) and tranconductance (g_m) with respect to gate-to-source voltage for both pHEMT and mHEMT.

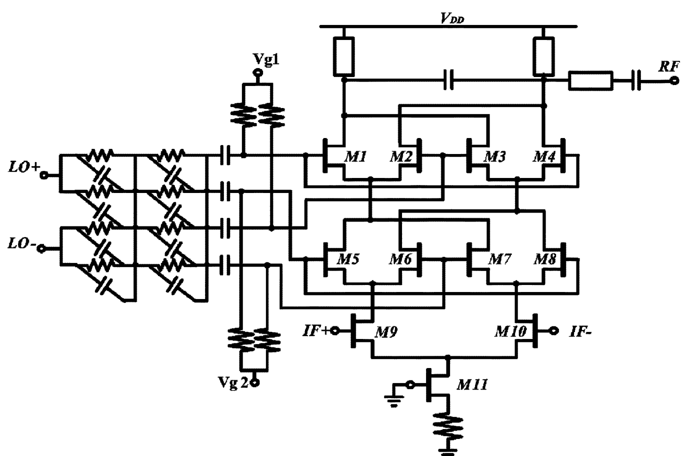

Fig. 2. Stacked-LO subharmonic Gilbert upconverter.

monic mixer is composed of the switching-pairs (M1–M2, ..., M7–M8), the transconductance-pair (M9–M10) and the current source (M11). The RF output port uses an LC current combiner with a matching network [11]. Short high impedance transmission lines are used as inductors at high frequencies in the LC current combiner. The LO input port adopts a two-section RC-CR polyphase filter. The quadrature LO generated by a polyphase filter for the subharmonic mixer is needed. The cascade stages of a polyphase filter can reduce phase and magnitude errors while accurate implementations of resistance and capacitance on semi-insulating GaAs substrate result in the highly precise quadrature outputs of the polyphase filter [9]. The output ports of the two-section polyphase filter connect with dc-blocking capacitors and large rf-choking resistors in order to isolate ac signals and dc biases. The device size of the current source (M11) is $2 \times 15\ \mu m$ and a resistor connects the M11 source port for the self-biasing technique.

For mHEMT and pHEMT mixers, the size of the transistors remains almost the same and the input transistors are biased at the maximum transconductance condition. Moreover, the two layouts of the pHEMT and mHEMT mixers remain nearly alike. The effect of complicated layout must be considered as a part

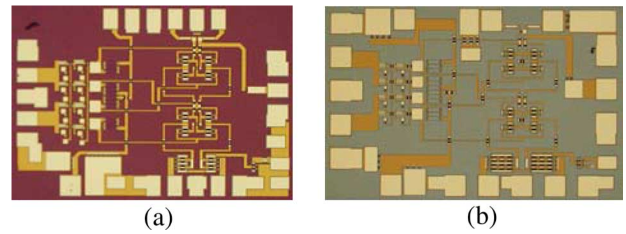

Fig. 3. Micrographs of (a) mHEMT and (b) pHEMT Gilbert upconverters.

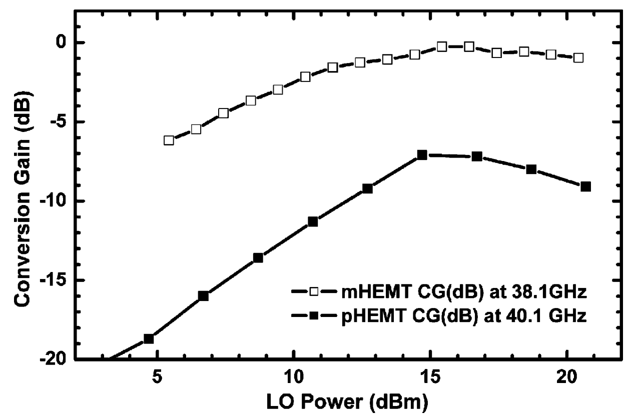

Fig. 4. Measured conversion gain of the pHEMT and mHEMT Gilbert upconverters when the LO frequency is fixed at 20/19 GHz, respectively.

of the mixer design and the line-to-line coupling effects have to be greatly alleviated.

IV. Measurement Results

Fig. 3 displays the fabricated chip micrographs with the same area of 1.3 mm $\times$ 0.9 mm including pads. Fig. 3(a) and (b) are mHEMT and pHEMT stacked-LO subharmonic Gilbert upconversion mixers, respectively. The left and bottom sides are LO and IF differential input ground-signal-ground-signal-ground (GSGSG) pads, respectively. The RF output GSG pad is on the right side. The supply voltage and current are 4.6 V and 7 mA for the mHEMT mixer, while the pHEMT mixer needs 5 V supply voltage and draws a 10 mA current.

The measured conversion gain with respect to LO power is shown in Fig. 4. When $\mathrm{LO} = 19/20$ GHz and $\mathrm{IF} = 0.1$ GHz, the mHEMT and pHEMT stacked-LO subharmonic Gilbert mixers have a peak gain of -0.2 dB and -7.1 dB, respectively. High LO driving power is needed to compensate for the loss of the two-section polyphase filter. The higher cut-off frequency of mHEMT devices renders a higher conversion gain for the active Gilbert mixer. The linearity of the mHEMT and pHEMT upconverters is displayed in Fig. 5. The pHEMT upconverter has a measured $\mathrm{OP}_{1\ \mathrm{dB}}$ of -24 dBm and OIP_3 of -12 dBm, while the mHEMT subharmonic mixer possesses -26 dBm $\mathrm{OP}_{1\ \mathrm{dB}}$ and -10 dBm OIP_3. The mHEMT mixer is better by 4 dB on linearity measured as the difference between the OIP_3 and $\mathrm{OP}_{1\ \mathrm{dB}}$. LO-to-RF and 2LO-to-RF [12] isolations are about 40 dB for the pHEMT mixer and 30 dB and 40 dB for the mHEMT mixer, respectively. The 45 dB and 50 dB IF-to-RF isolations are measured as $\mathrm{IF} = 100\ \mathrm{MHz} \sim 500\ \mathrm{MHz}$ for the mHEMT and pHEMT upconverters, respectively. The 3 dB

TABLE I
PERFORMANCE COMPARISONS OF UPCONVERSION MIXERS

Up-conversion mixer	Type	RF Freq. (GHz)	LO Power (dBm)	Conversion Gain(dB)	LO-RF Isolation(dB)	2LO-RF Isolation(dB)	OP_{1dB} (dBm)	OIP_3 (dBm)
0.18 μm pHEMT [4]	SH SB diode	43 ~ 46	+12	-11	NA	8 ~ 20	-16	NA
0.14 μm pHEMT [6]	FET resistive	30 ~ 50	+2	-6	>30	NA	NA	3
0.14 μm mHEMT [6]	FET resistive	30 ~ 50	+2	< -6	>30	NA	NA	< 6
0.18 μm SiGe BiCMOS [13]	DB Gilbert-cell	35 ~ 65	+5	-7	> 40	NA	-25	-16
0.13 μm CMOS [14]	DB Gilbert-cell	18 ~ 28	+3	-2 ~ 0.7	> 30	NA	-7 ~ -5.2	3 ~ 5.8
65 nm CMOS [15]	FET resistive	60	+8.7	-13.5	34	NA	-19	NA
This work (mHEMT)	SH Gilbert-cell	37.5 ~ 42.5	+15	-0.2	20 ~ 30	30 ~ 45	-26	-10
This work (pHEMT)	SH Gilbert-cell	35 ~ 42	+15	-7.1	33 ~ 40	> 40	-24	-12

$\mathrm{NA} = \mathrm{not\ available}, \mathrm{SH} = \mathrm{subharmonic}, \mathrm{SB} = \mathrm{Schottky\ barrier}, \mathrm{DB} = \mathrm{double-balanced}$

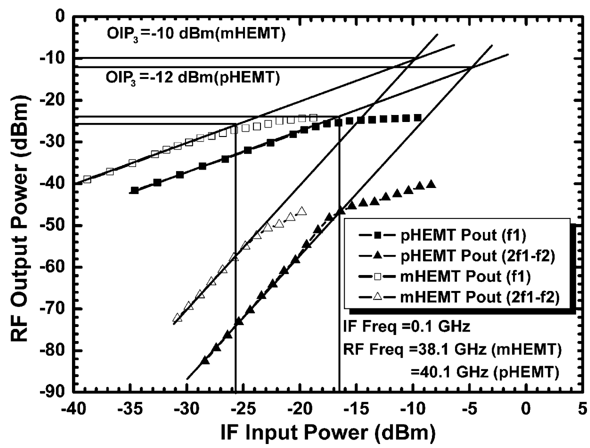

Fig. 5. Measured output performances of pHEMT and mHEMT upconverters. $\mathrm{RF} = 40.1\ \mathrm{GHz}$ and $\mathrm{IF} = 0.1\ \mathrm{GHz}$ for pHEMT while $\mathrm{RF} = 38.1\ \mathrm{GHz}$ and $\mathrm{IF} = 0.1\ \mathrm{GHz}$ for mHEMT.

RF bandwidth of pHEMT and mHEMT mixers are 5 GHz (37.5 $\sim$ 42.5 GHz) and 7 GHz (35 $\sim$ 42 GHz), respectively. The pHEMT mixer has an RF output return loss of 9.6 dB at 40 GHz and the best matching point of 11 dB at 39 GHz. The output return loss of the mHEMT mixer is 7 dB at 38 GHz and better than 10 dB from 42 to 47 GHz.

V. CONCLUSION

In this letter, the Q-band stacked-LO subharmonic upconversion mixers are designed and compared using both 0.15 μm mHEMT and pHEMT technologies. In the upconversion mixers, the performance comparisons of the previously published papers are shown in Table I at the similar frequency bands using pHEMT, mHEMT [4], [6], SiGe BiCMOS [13], and CMOS technologies [14], [15]. The mHEMT upconversion mixer has better conversion gain. The conversion gain of the mHEMT Gilbert mixer is improved by 7 dB in Q-band frequencies because the 0.15 μm mHEMT technology has higher $\mathrm{g_m}$ and $\mathrm{f_T}$ than the 0.15 μm pHEMT. A comparison of V-band mHEMT and pHEMT FET-based image reject mixers was published and their performances are almost the same [5]. It is of no use increasing the conversion gain in passive mixers by technological advances. In Table I, the experimental outcome shows that the active Gilbert mixer with good isolations can be implemented using HEMT in the millimeter-wave regime, and we can select the advanced mHEMT technology to improve conversion gain and linearity.

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