Design and Analysis of a Miniature W-Band MMIC Subharmonically Pumped Resistive Mixer

Ming-Fong Lei, Pei-Si Wu, Tian-Wei Huang, and Huei Wang

Department of Electrical Engineering and Graduate Institute of Communication Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

Abstract — A W-band monolithic sub-harmonically pumped (SHP) resistive mixer was designed and fabricated using a standard 0.15 μm PHEMT process. A nonlinear model featuring modified drain-current characteristics was developed and used in circuit simulation. A small chip size of $1.5 \times 1.0 \text{ mm}^2$ was achieved by using a transformer as a LO balun. Measured results of this circuit showed 14–18 dB conversion losses from 75 to 88 GHz, and agree well with simulation. Analysis on circuit imbalance shows that the phase imbalance of the balun is the dominant factor on LO isolation, and the conversion loss is quite robust to all circuit imbalances.

Index Terms—Millimeter wave mixers, MMICs

I. INTRODUCTION

Resistive mixers have lower LO power requirements, superior linearity and wider dynamic range compared with active FET mixers and diode mixers [1], therefore they are well suited for high linearity mixing operations. Sub-harmonically pumped (SHP) resistive mixers have the advantages of good LO-to-RF and LO-to-IF isolations due to the differential LO signal, and therefore are often used [2]–[5]. However, this architecture requires a LO balun, which may occupy up to one-third (approximately $780 \mu\text{m} \times 1100 \mu\text{m}$) of the entire chip area [5].

In this work, we designed a transformer balun using two intertwining spiral coils to reduce the size of the LO balun. The entire balun occupies a total area of $250 \mu\text{m}$ by $350 \mu\text{m}$ (including the two grounding via holes), which greatly reduced the size of the circuit. A study on balun imbalance can be used to predict the LO isolation performance. A resistive model was developed, with a modified drain-source conductance equation; measurement results of the final circuit agree well with simulation results, which validate our model. By using a compact transformer balun, the chip size is only $1.5 \times 1.0 \text{ mm}^2$, very small compared to other resistive mixers (see Table I and II), and requires no off-chip baluns.

II. CIRCUIT DESIGN

This circuit was fabricated using TRW's 0.15- μm standard high linearity GaAs PHEMT process. This process features a 100- μm substrate, MIM capacitors, air bridges, TFR resistors and spiral inductors. AWR's Microwave Office was used for circuit simulation, and a user-defined model was used for design. EM simulations (SONNET) was used to accurately simulate the LO balun, coupled lines, junctions, and other discontinuities.

A. Device Model

Most large signal models are designed to operate in class A and class AB region of the device but often neglect accurate description of the resistive region; therefore a resistive model was developed and is most useful in resistive mixer simulations [6]. In our model, we have adapted a more complex equation

$$G_{ds}(V_g) = g_{ds0} \tanh \left(k \cdot A \cdot \ln \left[1 + \exp \left(\frac{V_g - B}{A} \right) \right] \right) \quad (1)$$

in which

$$f(V_g) = k \cdot A \cdot \ln \left[1 + \exp \left(\frac{V_g - B}{A} \right) \right] \quad (2)$$

The function $f(V_g)$ is a two-segment line with a continuous transition: when $(V_g - B)$ is very negative, $f(V_g) \sim 0$; when $(V_g - B)$ is very positive, $f(V_g) \sim k(V_g - B)$. B is equivalent to V_{th} of the device, k defines the slope of the second line segment, and A defines the change rate of the transition. The inclusion of A and k into the equation allows us to adjust the channel conductance at near turn-on region of the device.

B. Design of Transformer Balun

In order to reduce the size of the balun, a compact transformer [7] is used to provide the differential LO signal. Full-wave EM simulator was used to simulate the entire structure and port reduction techniques were used to

measure the transformer on-wafer [8]. Figure 1 shows the simulated and measured results of the transformer. From the measured results we can see that the transformer is under-coupled, caused by the insufficient coupling between metals. The imbalance of the balun on circuit performance will be discussed in the next section. The layout of the balun occupies only a miniature area of 250 μm by 350 μm (including the two via holes).

Fig. 1. Insertion losses and phase difference of the transformer. Measured results are in bold, and simulated results in dotted lines; measured results at 36 GHz are 5.68 dB, 4.51 dB and phase difference of 163.5°.

Fig. 2. Schematic of the SHP resistive mixer.

C. SHP Resistive Mixer Design

The schematic of the SHP resistive mixer is shown in Fig. 2. Two four-finger devices with total gate width of 40 μm were used for mixing operations, and are connected together at the drains. Short stub matching circuits were used to match the input impedance of the devices to the LO balun, and to provide gate bias. Filters were applied at IF and RF ports for matching and isolation purposes. The

photograph of this circuit is shown in Fig. 3, chip size is 1.5 mm x 1.0 mm.

Fig. 3 Photograph of the SHP mixer chip

III. EFFECTS OF BALUN IMBALANCES ON CIRCUIT PERFORMANCE

The imbalances of the balun and transistors will affect both the isolation and the conversion loss of the circuit. A simple analysis can be performed on the imbalance of the differential signal paths to LO isolations. The LO signal at the connection of the two transistor drains (point P in Fig. 2) can be expressed in phasor notation as

$$S = A_1 L_1 e^{j\phi_1} + A_2 L_2 e^{j\phi_2} \quad (3)$$

Fig. 4. Graphical expression of equation (3)

A_1 , A_2 , L_1 , and L_2 are shown in Fig. 2, which represents the insertion losses of the LO balun, and the insertion losses of the matching circuits to the transistors, with the input LO signal normalized to unity. These four parameters are complex in nature, but are made to be real positive in (3), and their complex phase terms are absorbed into ϕ_1 and ϕ_2 , which usually differs by a value close to π . A graphical interpretation of (3) is shown in Fig. 4. From equation (3) it is easy to see, when the entire circuit is balanced, $A_1 = A_2$, $L_1 = L_2$ and $\phi_2 = \phi_1 + \pi$, then S

= 0, which means that the LO isolation at RF and IF is infinitely large. If the two are not balanced, by using the law of cosines (as shown in Fig. 4) and a second order Taylor expansion of the cosine function assuming the phase difference to be $180 \pm 20^\circ$, the amplitude of the LO signal will be

$$|S| = \sqrt{(L_1 A_1 - L_2 A_2)^2 + A_1 A_2 L_1 L_2 \Delta \phi^2}. \quad (4)$$

If $L_1 = L_2$, the equation may be simplified to

$$|S|/L = \sqrt{(A_1 - A_2)^2 + A_1 A_2 \Delta \phi^2}. \quad (5)$$

It is worth noting from (4) and more obvious from (5), the effects of phase imbalance have a more drastic effect on LO isolation than amplitude imbalance. For our balun, the measured insertion loss at the differential ports are 5.68 dB and 4.51 dB, and phase difference of 163.5° , the contribution of the balun to isolation is only 15 dB, which is 7.2 dB less than 22.2 dB if the phase difference is exactly 180° . The simulated LO isolation of the matching circuit and transistor is about 10 dB, and the LO isolation of the IF filter is 15 dB, therefore LO to IF isolation is about 40 dB.

The amplitude and phase imbalance of the balun also have an effect on conversion loss performance, but is less severe than isolation degradation. For example, a 3 dB amplitude difference in balun signals will degrade isolation up to 9.5 dB compared to a balun with 1 dB amplitude difference, but the total conversion loss is degraded by only 1.2 dB, and the degradation due to phase imbalance is almost negligible.

IV. MEASURED RESULTS AND DISCUSSIONS

This circuit was measured via on wafer probing. The measured conversion loss versus RF frequency is plotted in Fig. 5 against simulation results. The circuit has an average conversion loss of 17 dB from 75 to 88 GHz, and has a best conversion loss of 14 dB at 86 GHz. As it is shown in Fig. 5, the simulation predicted the performance of the circuit reasonably. Measured LO to IF isolation is 40 dB, which is consistent with the conclusion in the previous section. LO to RF isolation is not measured due to the cut-off nature of the WR-10 probe at the RF port.

The RF compression performance of this circuit has also been measured at 77 GHz, shown in Fig. 6. A RF amplifier module [9] was used to provide additional RF power. As the figure shows, the circuit showed about 1 dB conversion loss compression for an RF input power of 0 dBm. Compared with recent data on W-band diode mixers [13], the resistive mixer can handle 6 dB higher RF power than diode mixers.

Table I shows the comparisons of previously reported SHP resistive mixers and this work. In [5], a single device is divided into two gate manifolds, reducing the via-hole and drain line parasitic, greatly improving the conversion loss compared to standard transmission line connections, similar parasitic reducing techniques were also used in [4]; this technique may be applied to our circuit to improve the conversion loss. In Table II, we compared our circuit with reported fundamental resistive mixers. From both tables, it is observed that our circuit is the smallest fully monolithic resistive mixer. Although [11] has the smallest chip size of 0.87 mm^2 , it requires an off-chip IF balun.

Fig. 5. Measured conversion loss versus frequency. Bold line is measured performance, and dotted line is the simulation result. LO is set at 36 GHz, 5 dBm, and RF is set at -12 dBm.

Fig. 6. Measured RF compression performance of the circuit, relative to conversion loss at -15 dBm RF power.

V. CONCLUSION

A W-band sub-harmonic resistive mixer has been realized using standard 0.15 μm GaAs PHEMT process. A miniature transformer balun was designed to reduce the circuit size. A nonlinear model was developed to better fit the channel characteristics of the device. Due to the transformer balun, the chip size of this circuit is only 1.5 mm^2 . Measured results demonstrated a moderate 14-18 dB conversion loss from 75 to 88 GHz, which agrees well with simulation results, validating our model.

An analysis on the imbalance of the LO signals on circuit performance shows that phase imbalance is the dominating factor to isolation performance rather than amplitude imbalance, and the imbalances of either balun or transistors are insignificant to conversion loss.

ACKNOWLEDGEMENT

This work was supported in part by the National Science Council (NSC 91-2219-E-002-014, and NSC 91-2213-E-002-019), and the Research Excellence Program (ME 89-E-FA06-2-4) funded by the Ministry of Education, R. O. C. The chip is fabricated by TRW (now NGST) through the Chip Implementation Center of Taiwan. The authors would like to thank Hong-Yeh Chang for his assistance and suggestions on measurement setup.

REFERENCES

- [1] R. S. Virk, et al, "A comparison of W-Band MMIC mixers using InP HEMT technology," 1997 *IEEE MTT-S IMS Digest*, pp. 435-438, June 1997.
- [2] Herbert Zirath, "A subharmonically pumped resistive dual-HEMT-mixer," 1991 *IEEE MTT-S IMS Digest*, pp. 875-878, June 1991.
- [3] H. Zirath, et al, "A W-band subharmonically pumped resistive mixer based on pseudomorphic heterostructure field effect transistor technology," 1993 *IEEE MTT-S IMS Digest*, pp. 341-344, June 1993.
- [4] K. S. Ang, et al, "A millimeter-wave monolithic subharmonically pumped resistive mixer," 1999 *APMC Digest*, vol. 2, pp. 222-225, 30 Nov.-3 Dec. 1999.
- [5] A. R. Barnes, et al, "A comparison of W-band monolithic resistive mixer architectures," 2002 *IEEE MTT-S IMS Digest*, pp. 1867-1860, 2-7 June 2002.
- [6] Eric W. Lin and Walter, H. Ku, "Device considerations and modeling for the design of an InP-based MODFET millimeter-wave resistive mixer with superior conversion efficiency," *IEEE Trans. Microwave Theory & Tech.*, vol. 43, no. 8, pp. 1951-1959, Aug. 1995.
- [7] Pei-Si Wu, Chao-Hsiung Tseng, Tian-Wei Huang and Huei Wang, "A Singly balanced millimeter-wave mixer using a compact transformer," 2003 *APMC Digest*, vol. 3, pp. 649-652, Nov. 2003.
- [8] M. Davidovitz, "Reconstruction of the S-matrix for a 3-Port using measurements at only two ports," *IEEE MGWL*, vol. 5, no. 10, pp. 349-350, Oct. 1995.
- [9] Hong-Yeh Chang, Huei Wang, Michael Yu and Yonghui Shu, "A 77-GHz MMIC power amplifier for automotive radar applications," *IEEE MWCL*, vol. 13, no. 4, pp. 143-145, April 2003.
- [10] Masayuki Kimishima, Tsuyoshi Ataka, and Hideyuki Okabe, "A family of Q, V and W-Band monolithic resistive mixers," 2001 *IEEE MTT-S IMS Digest*, pp. 115-118, June 2001.
- [11] U. Schaper, et al, "70-90 GHz balanced resistive PHFET mixer MMIC," *Electronic Letters*, vol. 34, no. 14, pp. 1377-1379, 9 July 1998.
- [12] K. W. Chang, E. W. Lin, H. Wang, K. L. Tan and W. H. Ku, "A W-Band Monolithic, Singly Balanced Resistive Mixer With Low Conversion Loss," *IEEE MGWL*, vol. 4, no. 9, pp. 301-302, Sept. 1994.
- [13] K. Kanaya, et al, "A 94GHz high performance quadruple subharmonic mixer MMIC," 2002 *IEEE MTT-S IMS Digest*, pp. 1249-1252, June 2002.

TABLE I
COMPARISON OF REPORTED SHP RESISTIVE MIXERS

Reference	Technology	RF(GHz)	CL(dB)	LO-IF iso.	Chip size	Features
[2]	0.2 μm GaAs PHEMT	10-12	6.5	37 dB	-	MIC on 15mil alumina
[4]	0.25 μm GaAs PHEMT	36-40	10-13	32-47 dB	2.1mm x 1.1mm	MMIC, Marchand baluns
[3]	0.18 μm GaAs PHEMT	88-98	22	-	-	MMIC/hybrid, double δ -doping
[5]	0.1 μm InP HEMT	94	9.5	>35 dB	2.35mm x 1.1mm	MMIC, shared transistors
This work	0.15 μm GaAs PHEMT	75-88	14-18	40 dB	1.5mm x 1.0mm	Transformer balun

TABLE II
COMPARISON OF REPORTED W-BAND RESISTIVE MIXERS OF VARIOUS ARCHITECTURES*

Reference	Technology	RF(GHz)	CL(dB)	Chip size	Features
[1]	InP HEMT	95-104	9-11	1.5mm x 1.5mm	Single ended,
[10]	0.15 μm GaAs PHEMT	72-84	10-11.5	2.4mm x 1.8mm	Balanced structure
[11]	GaAs PHEMT	70-90	8-10	0.87mm ²	Balanced structure, off-chip IF balun required
[12]	0.1 μm GaAs PHEMT	93.2	12.8	>2mm x 1mm	Singly balanced
This work	0.15 μm GaAs PHEMT	75-88	14-18	1.5mm x 1.0mm	Transformer balun, fully monolithic

*The circuits in this table except for this work are fundamental mixers