A High Performance V-band Monolithic Quadruple Sub-harmonic Mixer

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Abstract — **In this paper, we present a high performance V-band quadruple sub-harmonic mixer monolithic circuit which is designed and fabricated for the millimeter wave down converter applications. While the typical sub-harmonic mixers use a half of fundamental frequency, we adopt a quarter of the fundamental frequency. The proposed circuit is based on sub-harmonic mixer with APDP (anti parallel diode pair). Upon the typical mixer design, additional stubs are placed with the modification of original stub length. And the 0.1 μm pseudomorphic high electron mobility transistors (PHEMTs) providing better gain are positioned to each port. Used lumped elements at IF port, it provides selectivity of IF frequency, and increases isolation. Maximum conversion gain of 0.8 dB at a LO frequency of 14.5 GHz and at a RF frequency of 60.4 GHz is measured. Both LO-to-RF and LO-to-IF isolations are higher than 40 dB. These conversion gain results and isolation characteristic are the best performances reported among the quadruple sub-harmonic mixers operating in the V-band millimeter wave frequency thus far.**

I. INTRODUCTION

Because of limited bandwidth and data capacity of the frequency in daily use, millimeter wave frequency, such as 60 GHz used in this study, has been an attractive solution providing several advantages in various future system applications. For this reason, many researchers made great effort on constructing the transceivers for wireless millimeter wave systems. However, there have been problems in obtaining the stable frequency sources for the up/down mixers because the fundamental frequency mixers are not suitable for generating LO signals at high frequency. Therefore, sub-harmonic mixers can be the effective components for millimeter wave systems by employing a halved LO frequency to avoid the problems of fundamental mixers. Especially, the sub-harmonic mixer topology with anti-parallel diode pair is the most widely used technique. A structure with anti-parallel diode pair has the extremely low even-order spurious components because of its anti-symmetric current-voltage characteristics. The even-order spurious components are suppressed in that they only flow within the diode loop [1]. For many years, this technique has been used for millimeter wave receivers [2]-[4].

We herein present a high performance V-band quadruple sub-harmonic mixer monolithic circuit for the millimeter wave down converter application based on superior features described in this paper. We employ a quarter of fundamental frequency and provide more stable frequency sources than conventional methods that use a half frequency. In addition, our proposed quadruple sub-harmonic mixer can be easily fabricated at low cost because it requires lower LO frequency than the conventional one. Upon the typical mixer design, additional stubs were placed with the modification of original stub length. The stubs, the pseudomorphic high electron mobility transistors (PHEMTs) and other components were appropriately positioned to each port for maximizing a quarter frequencies.

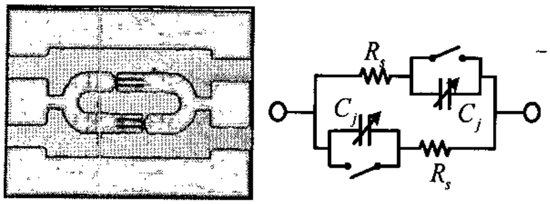
For the fabrication of the quadruple sub-harmonic mixers, our design library for the GaAs-based 0.1 μm gate length PHEMT diodes and the coplanar waveguide (CPW) is used [9]. The performance of fabricated sub-harmonic mixers was examined by using a 150 μm pitch Pico-probe. The fabricated circuits operate at RF frequencies of 58.4 ~ 62.4 GHz, an IF frequency of 2.4 GHz, and LO frequencies of 14 ~ 15 GHz.

II. CIRCUIT DESIGN

Both anti-parallel pair of diodes and the PHEMTs are the essential components in our sub-harmonic mixer design. The GaAs-based PHEMT diodes were employed as mixing elements by connecting the source to the drain. Most of these diodes under zero-bias require a comparably larger LO power than that of biased diodes. 70 μm x 2 PHEMTs with 0.1 μm gate length were used for this reason. This configuration of the diodes are advantageous

0-7803-7695-1/03/$17.00 © 2003 IEEE

because they use an adequate LO power level for the mixer operation and isolate three ports corresponding to the RF, the LO input and the IF output port.



(a) (b)

Fig. 1. (a) Anti-parallel diode pair and (b) an equivalent circuit for the diodes (C_j : junction capacitance, R_s : series resistance)

Figure 1 (a) shows a top-view photograph of an anti-parallel diode pair using PHEMT diodes. In Fig. 1 (b), a simple equivalent circuit for the anti-parallel diode pair is also shown. This diode has an anti-symmetric current-voltage characteristic; therefore the mixing components of even order, such as $n \cdot f_{RF} \pm m \cdot f_{LO}$ (n + m = even, m and n are integers), are fully suppressed, where f_{LO} and f_{RF} are frequencies of LO and RF, respectively. This is because they keep flowing only within the diode loop. Therefore, the mixing components of odd order, such as $n \cdot f_{RF} \pm m \cdot f_{LO}$ (n + m = odd), are obtained as outputs [1]. Typical sub-harmonic mixers for down-converters use the second harmonics of LO signals such that $f_{IF} = f_{RF} - 2 f_{LO}$ and m=2, where f_{LO} a frequency of LO [2]-[4]. On the other hand, our sub-harmonic mixers use fourth (m=4) harmonics of LO signals. Thus, the output IF frequency is described by equation (1).

$$f_{IF} = f_{RF} - 4 f_{LO} \qquad (1)$$

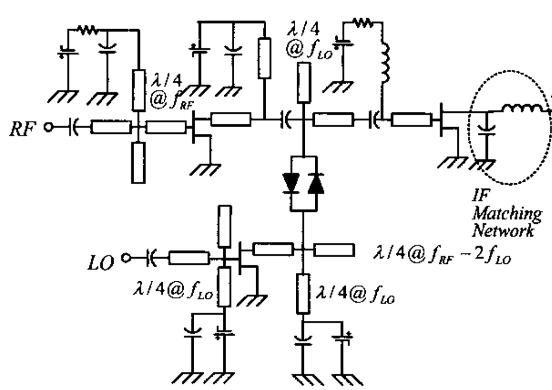


Fig. 2. A schematic of the quadruple sub-harmonic mixer circuit

In Fig. 2, the schematic of designed sub-harmonic mixer circuit is shown. It consists of an anti-parallel diode pair based on the GaAs Schottky diodes with 0.1 μm gate length. In order to provide ground paths to the RF and LO signals, the lengths of the open and short circuit stubs are designed to be equal to an electric length of λ/4 at a LO frequency, f_{LO}. A λ/4 at f_{LO} open circuit stub was placed at between the RF port and the diode pair, while the λ/4 at f_{LO} short circuit stub was positioned towards the LO port [1]-[8].

A λ/4 at f_{LO} short circuit stub acts as an open circuit at LO frequency, whereas as a short circuit at RF frequency. This is because RF frequency is nearly equal to 4 times LO frequency. Similarly, a λ/4 at f_{LO} open circuit stub acts as a short circuit at LO frequency, whereas as an open circuit at RF frequency. In this circuit, a λ/4 at f_{LO} short circuit stub is used to reject RF frequency as well as to drive a PHEMT at LO port as a drain bias line.

The anti-parallel diode pair as a mixing component produces not only the fifth component, such as $f_{RF} - 4 f_{LO}$, for quadruple sub-harmonic mixer but also the third component, such as $f_{RF} - 2 f_{LO}$. This is one of major causes to reduce the conversion gain. In order to compress the third component, λ/4 at $f_{RF} - 2 f_{LO}$, an open circuit stub was placed at the end of the anti-parallel diode pair [6].

At IF ports, we placed matching networks consisting of the lumped elements, such as capacitors and inductors. These matching networks behave as low pass filters. Thus, they adequately provide a selectivity for IF frequency and increase the isolations at both IF-to-LO port and IF-to-RF port.

III FABRICATION AND MEASUREMENT RESULTS

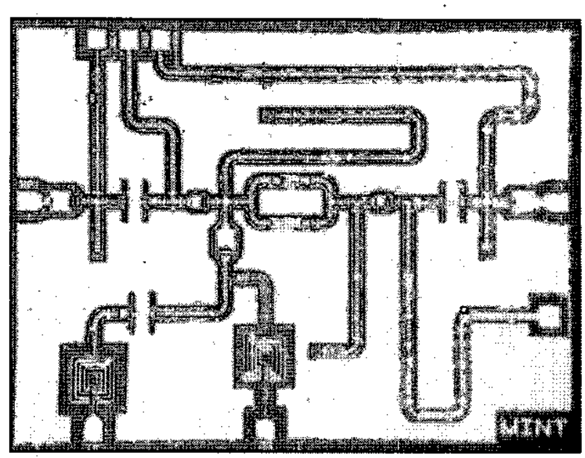


Fig. 3. Top-view photograph of the fabricated quadruple sub-harmonic mixer MIMIC (1.9mm x 2.6 mm)

Figure 3 shows a top-view photograph of the fabricated V-band quadruple sub-harmonic millimeter wave monolithic IC (MIMIC) mixer. The chip size is 1.9 mm x 2.6 mm. PHEMT diodes of the mixing structure were fabricated on a GaAs substrate employing 0.1 μm gate length PHEMT process technology [9]. The Schottky PHEMT diodes have a 70 μm gate width, 2 gate fingers, a series resistance of 9.9 Ω, and a zero bias junction capacitance of 0.093 pF. From these values, the cut off frequency was found to be 180 GHz.

The fabricated V-band monolithic quadruple sub-harmonic mixers employ the CPW as transmission structure. For this, we used a library including the CPW transmission lines of various characteristic of impedances (35, 50, and 70 ohm) as well as discontinuity patterns. This library also includes 900 Å Ti thin film resistors and MIM capacitors of 1000 Å Si_3N_4 which were used for DC block or bypass at RF inputs and outputs. 30.2~33.4 ohm/□ and 0.485~0.538 fF/μm^2 were measured from the thin film resistors and the MIM capacitors, respectively [9].

The fabricated MIMICs were measured using a on-wafer probing system. For the measurements, a RF input signal at 60.4 GHz was generated by connecting an Agilent 83623B signal generator and an Agilent 83557A mm-wave source module. And the LO signal at 14.5 GHz generated by Agilent 83630B signal generator. The output signal was detected by an Agilent E4407B spectrum analyzer.

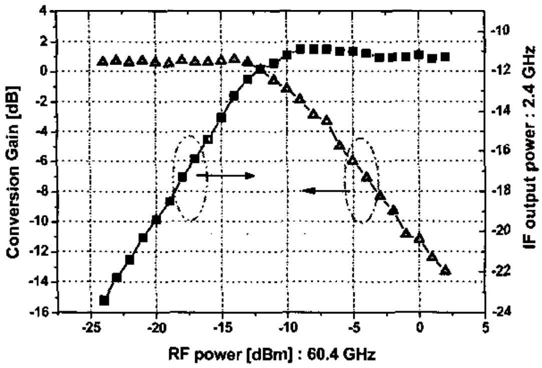


Fig. 4. Measured down conversion gain (G_c) and IF output power vs. RF input power

The measured results of down conversion gain and IF output power versus RF input power at operating point (RF frequency of 60.4 GHz and LO input power of 12 dBm) are shown in Fig. 4. A good conversion gain of 0.8 dB and a 1 dB compression point of -11 dBm are shown in the measurements.

The measurements were performed at a fixed RF input power of -14 dBm and a LO power of 12 dBm by varying input signal frequency. Figure 5 shows the measured results where the conversion gain was obtained in the range of 0.8 ~ -8.4 dB at an RF input power of -14 dBm and at 58.4 ~ 62.4 GHz

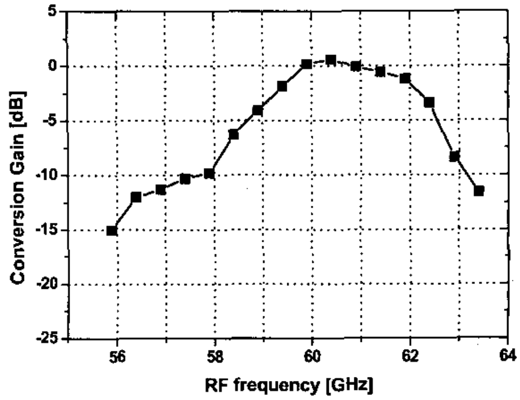


Fig. 5. Measured down conversion gain (G_c) vs. RF frequency.

We also measured the down conversion gain at various LO powers and at a LO frequency of 14.5 GHz. The measured results are shown in Figure 6. The conversion gain was nearly saturated at a LO input power level higher than 12 dBm.

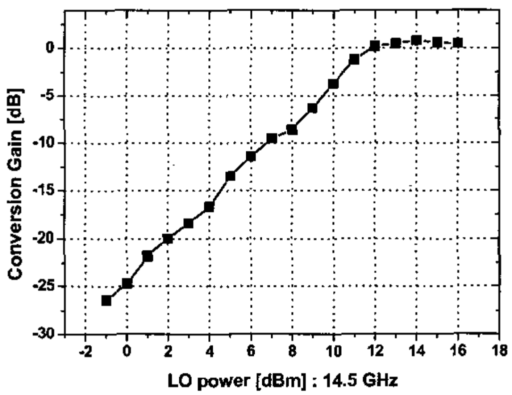


Fig. 6. Measured down conversion gain (G_c) vs. LO input power

Figure 7 shows the measured results of LO-to-IF and LO-to-RF isolations. As shown in the spectra, the measurement results exhibited a high degree of isolation characteristic. In the cases of the LO-to-IF and the LO-to-RF isolations, the best measured isolations were -61.7 and -52.1 dB, respectively, at 14.5 GHz. This superior isolation performance of the mixers is supposed to be due to an anti-symmetric characteristic of the anti-parallel diode pair and a quarter frequency of the fundamental frequency.

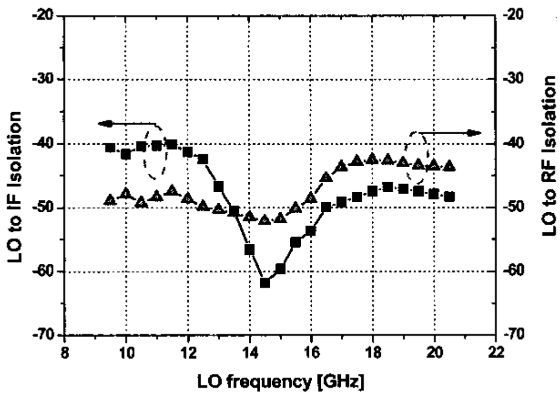


Fig.7. Measured isolation results of sub-harmonic mixer

IV. Conclusion

High performance V-band quadruple sub-harmonic MIMIC mixers are reported for the millimeter wave down converter applications. Due to superior features of the anti-parallel diode pair and the utilization of a quarter of fundamental frequency, which is more stable frequency sources than conventional methods, the proposed sub-harmonic mixers show a good conversion gain and isolation characteristic. The fabricated circuits operate in a RF frequency range of 58.4 ~ 62.4 GHz, at an IF frequency of 2.4 GHz, and in a LO frequency range of 14 ~ 15 GHz. An excellent conversion gain of 0.8 dB is obtained at a LO frequency of 14.5 GHz and a LO power of 12 dBm. In the operation range of the mixers, both LO-to-RF and LO-to-IF isolations are higher than 40 dB. These result in conversion gain and isolation characteristics are one of the best reports demonstrated from quadruple sub-harmonic MIMIC mixers operating at V-band frequency.

Acknowledgement

This work was supported by KOSEF (Korea Science and Engineering Foundation) under the ERC (Engineering Research Center) program through the MINT (Millimeter-wave Innovation Technology) research center at Dongguk University.

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