A 94GHz High Performance Quadruple Subharmonic Mixer MMIC

Ko Kanaya, Kenji Kawakami*, Takayuki Hisaka, Takahide Ishikawa, and Susumu Sakamoto

High Frequency and Optical Semiconductor Division, Mitsubishi Electric Corporation
4-1 Mizuhara, Itami, Hyogo, 664-8641, Japan
*Information Technology R&D Center, Mitsubishi Electric Corporation, Kamakura, Kanagawa, Japan
e-mail: kanaya.ko@lsi.melco.co.jp

Abstract — **A 94GHz high performance quadruple subharmonic mixer (4xSHM) MMIC has been designed and fabricated for a down converter. The required LO frequency is only a quarter of RF frequency which is a half LO frequency of conventional double subharmonic mixers (2xSHM). The conversion gain and noise power were experimentally compared with that of a conventional subharmonic mixer. The quadruple subharmonic mixer showed the maximum conversion gain of –11.4dB at an RF frequency of 94GHz and a LO frequency of 23.5GHz. The maximum noise power of –159dBm/Hz was obtained at an IF frequency of 100kHz. This noise measurement also suggests noise performance at low IF frequency depends not on the LO mixing frequency but on the 1/f noise of the Shottky barrier diode. The fabricated MMIC chip size is as small as 0.9mm x 1.4mm. To our knowledge, these results are the best performances demonstrated from a quadruple subharmonic mixer MMIC in the W-band millimeter-wave range.**

I. INTRODUCTION

In recent years, monolithic millimeter-wave integrated circuits have been studied for millimeter-wave systems such as automotive radars, radiometric sensors, wireless LANs, and so on. In particular, mixer MMICs for up/down converters are essential components in millimeter-wave systems. The millimeter-wave systems require low phase noise and stable frequency sources. The sources generally use fundamental frequency oscillators or lower frequency oscillators followed by multipliers to obtain a desired frequency. The source with a lower frequency oscillator is suited for low phase noise. Therefore, many subharmonic mixers with an anti-parallel diode pair (APDP) have been investigated and employed in millimeter-wave systems [1]-[10]. The subharmonic mixers with an APDP have advantages of no DC consumption and low LO frequency (f_{LO}) utilization. Furthermore, each diode needs no high reverse bias breakdown voltage. The LO frequency of the subharmonic mixer operating in W-band is higher than Ka-band. However, in the millimeter-wave range over Ka-band, it is generally difficult to obtain low phase noise sources and the device prices can be much expensive. Therefore, in W-band millimeter-wave systems, mixers operating at much lower LO frequency are required to employ a low phase noise oscillators.

In this paper, we present a 94GHz quadruple subharmonic mixer MMIC using an APDP for a down converter. The mixer MMIC operates in the 94GHz band, nevertheless, the required LO frequency is only a quarter of RF frequency (f_{RF}), which is a half of conventional subharmonic mixers. The mixing is performed between RF and the fourth harmonic of LO signals. The mixer plays a role of both a LO frequency quadrupler and a down converter, leading to size and cost reduction as well as topology simplification in millimeter-wave systems.

II. DEVICE STRUCTURE

A planar Schottky barrier diode (SBD) using 0.5um GaAs MESFET technology was employed as the mixing element. The 10um x2 planar MESFET diode was implemented by connecting the source to the drain. The noise performance of mixers at low IF frequency band depends strongly on the 1/f noise of SBD. To achieve low noise performance of the mixers, we developed a low 1/f noise SBD. Fig. 1 shows the schematic cross section of the planar SBD. The AlGaAs/GaAs superlattice buffer layer eliminates performance loss of the SBD induced by undesired current leakage and carrier traps. The thick n-GaAs layer on the buffer layer provides low series resistance. The thick active layer consisting of n-GaAs

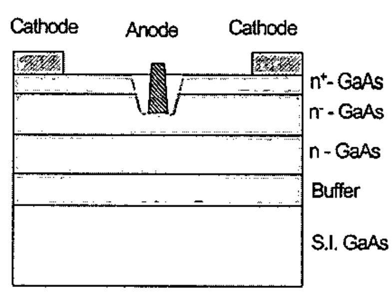

Fig. 1. Schematic cross section of the planar SBD.

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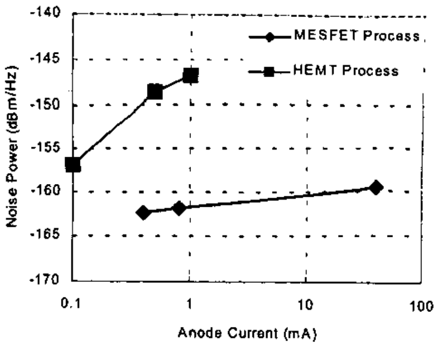

Fig. 2. 1/f noise characteristic of the SBDs at 100kHz. The anode width of both SBDs is 10um x2.

and n⁻-GaAs contributes to the reduction of the 1/f noise, because 1/f noise is inversely proportional to the thickness of the bulk layer [11]. An n^+-GaAs layer on the active layer offers low ohmic resistance. The Schottky electrode was formed on the recessed active n^--GaAs layer. The isolation of each SBD was realized by proton implantation.

The fabricated SBD with 10um x2 anode width has following parameters: a series resistance of 10.2Ω, zero bias junction capacitance of 0.019pF. From these values, the cut off frequency was found to be 0.82THz. Fig. 2 shows the 1/f noise characteristic of the developed MESFET processed SBD and 0.2um HEMT processed SBD. The noise power at 100kHz of MESFET process is much lower than that of the 0.2um HEMT processed SBD.

III. Circuit Design

In a subharmonic mixer using APDP, even mixing components, e.g. $2f_{LO}$, $4f_{LO}$ and $f_{RF}-f_{LO}$, flow within the diode loop. Only odd mixing components, e.g. $f_{RF}-2f_{LO}$ and $3f_{LO}$ are outputted [1]. Therefore, the IF frequency (f_{IF}) can be expressed as follows:

$$f_{IF} = |f_{RF}-2nf_{LO}| \quad \text{(n: integer)} \tag{1}$$

Conventional subharmonic mixers have used the second harmonic of LO signal as n=1 in the above expression [1]-[8]. The designed subharmonic mixer utilizes not second (n=1) but fourth (n=2) harmonic of LO signal as the mixing component. Thus, the resultant IF frequency can be expressed as:

$$f_{IF} = |f_{RF}-4f_{LO}| \tag{2}$$

The mixing of the developed subharmonic mixer is performed between RF signal and the fourth harmonic of LO signal, so that the required LO frequency is only a quarter of conventional fundamental wave mixers. Thus,

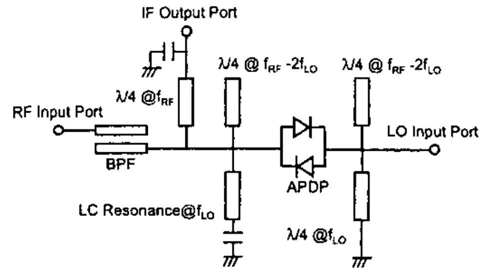

Fig. 3. Circuit schematic of the quadruple mixer MMIC.

the mixer works as both a LO frequency quadrupler and a down converter in millimeter-wave systems.

A high conversion gain needs large voltage amplitudes of RF and LO signal applied to the APDP. As shown in Fig. 3, two quarter-wavelength stubs and a quasi-lumped series L and C resonance circuit provide large voltage amplitudes of RF and LO signal. These circuits also offer sufficient LO-to-RF and RF-to-LO isolation. Because the IF frequency is much lower than RF frequency, the RF frequency can be nearly equal to 4 times the LO frequency ($f_{RF} \cong 4f_{LO}$). Thus, the quarter-wavelength shorted stub at LO frequency acts as both a shorted circuit for RF frequency and an opened circuit for LO frequency. The quarter-wavelength shorted stub at RF frequency acts as an opened circuit for RF frequency, which also functions a band pass filter that passes IF frequency and rejects RF frequency. The quasi-lumped series L and C resonance circuit acts as a shorted circuit for LO frequency. This resonance circuit facilitates the reduction of MMIC chip size, because the quarter-wavelength at LO frequency (f_{LO}=23.5GHz) of over 1200um occupies large chip area on a GaAs substrate. At the RF port, the band pass filter is placed to reject undesired mixing components.

The designed subharmonic mixer utilizes the fifth mixing component ($f_{RF}-4f_{LO}$). Along with this component, the third mixing component that consists of the RF signal and the second harmonic of LO signal ($f_{RF}-2f_{LO}$) is also produced. This component is one of the factors that reduce the conversion gain. To minimize the amplitude of this third mixing component, two quarter-wavelength opend stubs at the frequency of $f_{RF}-2f_{LO}$ are placed at both sides of the APDP. The conversion gains of subharmonic mixers with/without these stubs were compared in a harmonic balance simulator. The simulation suggested that the conversion gain of the subharmonic mixer with the stubs was about 4dB higher than that of the same mixer without stubs.

To compare the quadruple subharmonic mixer with a conventional one, we also designed a double subharmonic

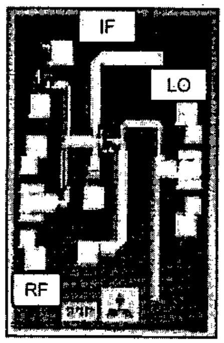

Fig. 4. Photograph of the quadruple subharmonic mixer MMIC. The chip size is 0.9mm x 1.4mm.

mixer (2xSHM) with the same topology as the quadruple subharmonic mixer (4xSHM). For the 2xSHM, RF frequency is 94GHz, and LO frequency is 47GHz, where the 2xSHM has no quarter-wavelength opened stubs for f_{RF}–$2f_{LO}$.

IV. MEASUREMENT

The SBDs for the subharmonic mixer with APDP must have identical characteristics to achieve high conversion gain. An MMIC has an advantage to obtain identical SBDs easily, so we realized the designed subharmonic mixers on a monolithic GaAs substrate. The thickness of the GaAs substrate is 100um. Fig. 4 is a photograph of a fabricated quadruple subharmonic mixer MMIC, where the chip size is as small as 0.9mm x 1.4mm.

The mixer MMICs were measured with on-wafer probing. For 4xSHM and 2xSHM, Fig. 5 shows the measured and simulated conversion gains as a function of LO power at an IF frequency of 100MHz. For the 4xSHM, the maximum conversion gain of −11.4dB was achieved at LO power of +10dBm. This conversion gain level is comparable with the best data of W-band 4xSHMs. For the 2xSHM, the maximum conversion gain of −9.2dB was obtained at LO power of +5dBm. These measurement results agree well with simulated ones. The conversion gain of 4xSHM is 2dB lower than that of 2xSHM and the LO power requirement of 4xSHM is 5dB larger than that of 2xSHM. However, these are acceptable level for W-band millimeter-wave systems. Fig. 6 shows the dependence of the noise power on the LO power at an IF frequency of 100kHz. Both maximum noise powers are about −160dBm/Hz, comparable to 1/f noise as shown Fig. 2. This result suggests that the noise performance of subharmonic mixers at low IF frequency depends not on LO mixing frequency but on 1/f noise characteristic of the SBD. Fig. 7 shows the dependence of the IF output power on the RF input power at the LO power of +10dBm for the 4xSHM. The IF power started saturating at −6dBm of the RF input power. Fig. 8 shows the dependence of the return loss on the LO power for the 4xSHM. The return loss decreases at the LO power of over +5dBm. The result corresponds with the conversion gain characteristic in Fig. 5. Because the return loss level is insufficient, the improvement of return loss would lead to better RF performance.

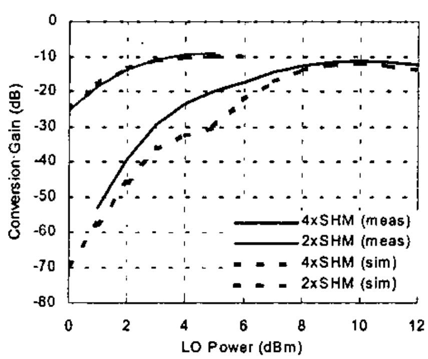

Fig. 5. Measured conversion gain as a function of LO power at an IF frequency of 100MHz.

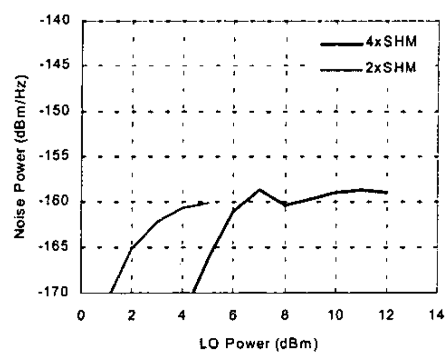

Fig. 6. Dependence of the noise power on the LO power at an IF frequency of 100kHz.

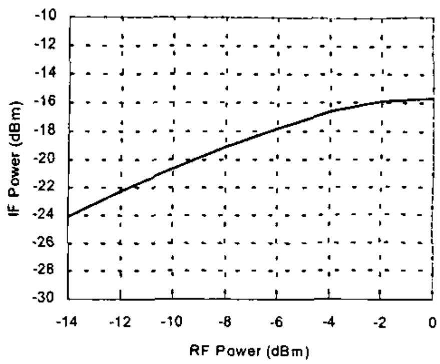

Fig. 7. Dependence of the IF output power on the RF input power.

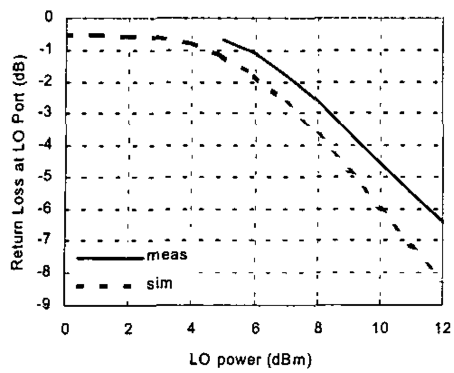

Fig. 8. The return loss at the LO port as a function of LO power.

V. CONCLUSION

We have designed and fabricated the quadruple subharmonic mixer MMIC which works as both a LO frequency quadrupler and a down converter. The developed subharmonic mixer showed the maximum conversion gain of −11.4dB. The maximum noise power of −159dBm/Hz was obtained at the IF frequency of 100kHz. This result suggests the noise performance at low IF frequency depends not on LO mixing frequency but on the 1/f noise of Shottky barrier diode. The fabricated MMIC chip size is as small as 0.9mm x 1.4mm. These performances allow millimeter-wave systems to employ a lower frequency oscillator, eliminating multipliers. The quadruple subharmonic mixer can be applied to such millimeter-wave systems as radiometric sensors, automotive radars and wireless LANs.

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