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A SINGLE-BALANCED QUADRUPLE SUBHARMONICAL MIXER WITH A COMPACT IF EXTRACTION

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Abstract—A novel 21–35 GHz single-balanced quadruple subharmonic monolithic passive mixer is fabricated using the 0.15 μm GaAs pHEMT process. This mixer consists of a local oscillation (LO) spiral balun and a radio frequency (RF) band pass filter which has an intermediate frequency (IF) extracted feature utilizing a pair of anti-parallel Schottky barrier diode to achieve quadruple subharmonic mixing mechanism. The RF band pass filter formed with an interdigital coupler and a low-pass network is used to reduce the chip dimension while operating at a low frequency band and to improve the isolation between the RF and IF ports with a broadband operation. From the measured results, the mixer exhibits 11.3–15.1 dB conversion loss, 28.8 dB-high RF-to-IF isolation, 40 dB-high LO-to-RF isolation, 60 dB-high 3LO-to-RF isolation over a 21–35 GHz RF bandwidth, and an input 1 dB compression power of 4 dBm. The compact IF extraction circuit supports an IF frequency ranging from DC to 3.1 GHz. The core chip size is only $0.67 \times 0.75\,\mathrm{mm}^2$.

1. INTRODUCTION

Emerging millimeter-wave communication systems demand broadband operation, compact size, low manufacturing cost, and low power consumption for high-performance transceiver solutions. One important component of these systems is the mixer which converts the signals from one frequency to another. The mixing mechanism of most mixers employs the fundamental local oscillation (LO) to achieve

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frequency conversion. However, as the operating frequency increases, the resonator quality used for the oscillator degrades, resulting in an increase in phase noise and degradation of output power. Moreover, fundamental mixers have LO self-mixing problems for direct-conversion transceivers, which is caused by LO leakage to the radio frequency (RF) port, generating a DC offset at the intermediate frequency (IF) port. Accordingly, the use of a frequency multiplier and a subharmonic mixer (SHM) is the most common approach that allows the use of an LO signal at a relatively low frequency. This makes LO sources more reliable and less expensive.

Previously, several quadruple SHMs using the anti-parallel diode pair (APDP) topology on the III-V process have been proposed [1–3]. The APDP topology can suppress any even-ordered spurious mixing component because of anti-symmetric current-voltage features. However, the operational bandwidth is limited by open/short stubs. Moreover, the required LO frequency is only a quarter of the RF frequency, and this causes quarter-wavelength open/short stubs at the LO frequency to occupy a large chip area. A miniature SHM with a directional coupler has been reported previously [4]. A directional coupler was employed to excite RF and LO signals into the APDP diodes. However, it is unsuitable for quadruple SHM design because the bandwidth of the directional coupler makes the combination of LO and RF signals difficult. The 10–40 GHz broadband CMOS SHM using two-stage Wilkinson power combiner with a broadband feature was reported [5]. However, the two-stage power combiner is limited the LO-to-RF isolation. A miniature quadruple SHM with lumped frequency diplexer can be found in [6]. The operation with overlapping frequency bands of RF and LO signals has been constrained by the frequency diplexer. Although the active quasi-circulator module (QCM) has been used to improve port-to-port isolations [7], it causes low power 1 dB compression and high power consumption. A reduced-size rat-race was used to achieve broadband distributed SHM [8]. The distributed double-balanced SHM can deliver a wide bandwidth, however, the reduced-size rat-race limits the operating bandwidth and requires high LO drive power.

In this work, a 21–35 GHz quadruple SHM with a compact chip size fabricated in a 0.15 μm GaAs pHEMT system is described. The proposed single-balanced quadruple SHM comprises a RF band-pass filter involved in the IF extraction circuit to accomplish a wider bandwidth operation and to maintain superior port-to-port isolations for down-converter applications.

2. CIRCUIT DESIGN AND IMPLEMENTATION

Due to the drawbacks of narrow operational bandwidth and large chip size of conventional quadruple SHMs using APDP technology [9], a broadband quadruple SHM with compact configuration and good port-to-port isolations for down-conversion applications is proposed. The architecture of the proposed quadruple SHM, which consists of an LO spiral balun and a RF band-pass filter, is demonstrated in Fig. 1. Mixing is performed between the RF signal and the fourth harmonic of the LO signal. This indicates that quadruple SHM requires a quarter of the LO frequency of a fundamental mixer. Consequently, combining the high-frequency RF signal with a relatively low-frequency LO signal by a hybrid is difficult. Accordingly, a single-balanced LO-pumped structure is used to overcome this problem and achieve high performance.

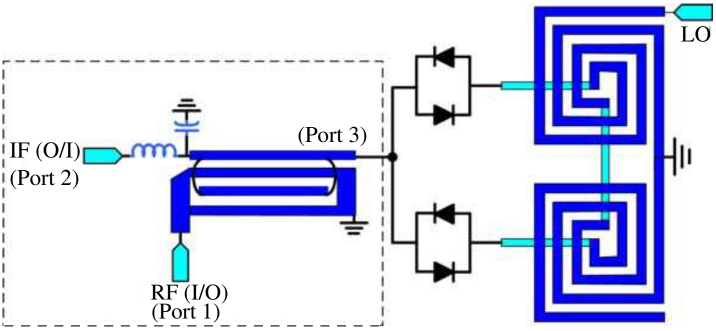


Figure 1. The proposed compact configuration of the quadruple SHM. The dashed-line box is the proposed RF band-pass filter involved in the IF extraction circuit.

The proposed RF band-pass filter involved in IF extraction circuit (dashed-line box shown in Fig. 1) is composed of a Lange coupler and a low pass filter. It can be analyzed as the circuit shown in Fig. 2(a). The scattering matrix can be derived as follows:

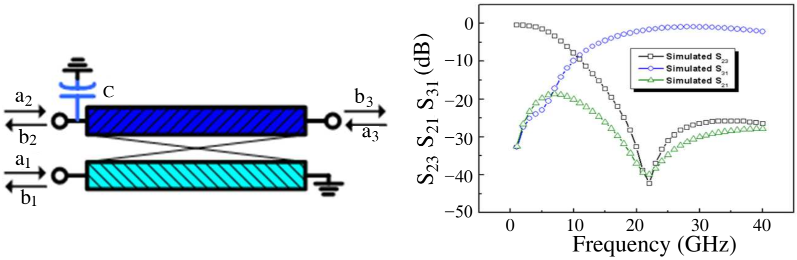
$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(1+\frac{-Y}{Y+2Y_0}\right) & \frac{\sqrt{2}Y_0}{Y+2Y_0} & \frac{j}{2}\left(1+\frac{Y}{Y+2Y_0}\right) \\ \frac{\sqrt{2}Y_0}{Y+2Y_0} & \frac{-Y}{Y+2Y_0} & \frac{-j\sqrt{2}Y_0}{Y+2Y_0} \\ \frac{j}{2}\left(1+\frac{Y}{Y+2Y_0}\right) & \frac{-j\sqrt{2}Y_0}{Y+2Y_0} & \frac{-1}{2}\left(1+\frac{-Y}{Y+2Y_0}\right) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \tag{1}$$

where $Y = j\omega C$ and $Y_o = 1/Z_o$ is the characteristic admittance between two ports. As $C \to \infty$, $Y \to \infty$, we have

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & j \\ 0 & -1 & 0 \\ j & 0 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \tag{2}$$

It can be seen that there are coupling between S_{31} and S_{13} with a 90° phase difference. RF signals can be fed into the APAD for subharmonic mixing. $S_{12} = S_{21} = 0$ means good isolation between RF-to-IF ports.

The purpose of the LO spiral balun is to excite an LO signal into APDP and to simultaneously improve isolation between the RF and LO ports with broadband operation. It is a three-port device used to pass LO signal operating at 5.25–8.75 GHz. Furthermore, it is used to improve the isolation between the RF and IF ports and thus attain good performance of the RF band-pass filter possessing IF extraction, the physical layout can be optimized by employing the full-wave electromagnetic (EM) simulator. The capacitance, C_1 is 0.45 pF ($0.45\,\mathrm{fF}/\mu\mathrm{m}^2 \times 32\,\mu\mathrm{m} \times 32\,\mu\mathrm{m}$), as shown in Fig. 3. The inductor value is also obtained as $L_1 = 1.8\,\mathrm{nH}$. The length and width of $\lambda/4$ microstrip line are 600 μm, and 7 μm, respectively. The spacing of Lange coupler is 5 μm to achieve good couple coefficient The simulated scattering parameters as a function of frequency for the proposed RF band-pass filter involved in IF extraction circuit (as the dash line box shown in Fig. 1) are shown in Fig. 2(b). The simulated isolation between port 2 and port 3 is better than 20 dB within the operation bandwidth. The S_{23} value varies from 0.43 to 43 dB over DC to the 40 GHz frequency range within the 3 dB IF bandwidth from DC to 3.1 GHz. This is more convenient in quadruple SHM design and more effective in extending the operational bandwidth with better impedance matching and chip area reduction. Furthermore, the designed quadruple SHM is well



(a) (b)

Figure 2. (a) The proposed RF band-pass filter involved in IF extraction circuit (dashed-line box shown in Fig. 1), (b) simulated scattering parameters as a function of frequency for the proposed RF band-pass filter involved in the IF extraction circuit.

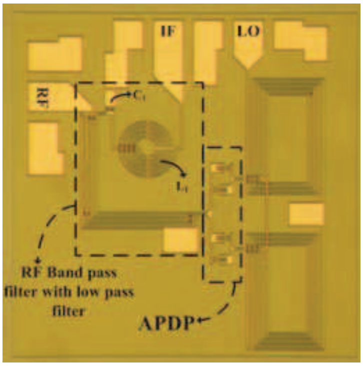


Figure 3. Microphotograph of the fabricated quadruple SHM. The overall chip dimension including the contact pad is $1 \times 1\,\mathrm{mm}^2$.

matched to the RF, LO, and IF ports and is not eminently affected by connecting the APDP.

In this design, the Marchand spiral balun is formed by a $\lambda/2$ and two $\lambda/4$ microstrip lines with one terminal grounded. Signal through $\lambda/2$ microstrip line is coupled to $\lambda/4$ microstrip line. The grounded terminal plays the role of low impedance device which can effectively reflect the high frequency with inverted phase. The microstrip length, width, and line spacing between two lines of Marchand spiral balun are 4177 µm, 7 µm and 5 µm respectively for the design at 6.25 GHz. The transistor with two fingers and a 10 µm gate width is optimized to achieve good impedance matching and to ensure minimum conversion loss implemented by the 0.15 µm pHEMT process developed by WIN Semiconductor Co. The substrate was thinned down to 100 µm with a relative permittivity of 12.9. A photograph of the fabricated quadruple SHM is shown in Fig. 3. The chip dimension is reduced to $1 \times 1\,\mathrm{mm}^2$. Moreover, the core chip area, excluding the contact GSG testing pads, is only $0.67 \times 0.75\,\mathrm{mm}^2$.

3. EXPERIMENTAL RESULTS

The fabricated MMIC quadruple SHMs were attached to carrier plates for testing. The measurement signals were provided by coplanar GSG and GSGSG on a wafer probe measurement system based on the Agilent E4446A spectrum analyzer calibrated with the E44198 power meter. The losses of the probes and cables were calibrated by the PNA E8364A network analyzer. Fig. 4 demonstrates the measured and simulated conversion loss of the quadruple SHM as a function of RF frequency for down-converter modes. The measurements were

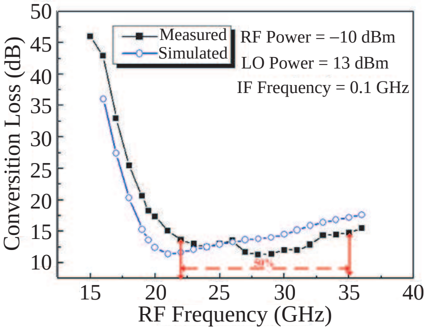


Figure 4. Measured and simulated conversion loss of the quadruple SHM as a function of RF frequency at a fixed LO power of 13 dBm and 0.1 GHz IF frequency.

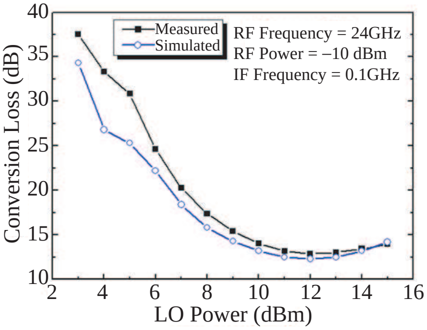


Figure 5. Measured and simulated conversion loss as a function of LO power at −10 dBm RF level and 0.1 GHz if frequency.

performed with an LO power level of 13 dBm and 0.1 GHz IF frequency. The obtained conversion loss is 11.3 to 15.1 dB within an RF bandwidth from 21 to 35 GHz. Due to high frequency parasitical effects, the operating bandwidth was slightly shifted from the design goal to a higher frequency band. A low conversion loss from 11.3 to 15.1 dB can be achieved at the high end of the band range from 21–35 GHz; however, a higher LO drive power of 13 dBm is necessary.

Figure 5 shows the measured and simulated conversion losses as a function of LO power level at 24 GHz RF frequency and an input power of −10 dBm for the down-converter mode. A significant mixing effect of an LO drive level of 10 dBm can be seen. The best conversion loss is 13 dB at a 12 dBm LO power level.

The measured and simulated LO-to-RF, LO-to-IF, and RF-to-IF isolations of the quadruple SHM for the down-converter mode are shown in Fig. 6. The RF-to-IF isolation is better than 28 dB over the operating band. The LO-to-IF isolation is higher than 27.5 dB at 14–35 GHz. This inherent LO/RF-to-IF isolation is due to the architecture of IF extraction. Furthermore, the LO-to-RF isolation benefited greatly from the single-balanced structure and exceeded 40 dB at 15–36 GHz. The 3LO-to-RF and 3LO-to-IF isolations as functions of RF frequency are shown in Fig. 7. The isolations of 3LO-to-IF and 3LO-to-RF were 57.3 to 71.3 dB and 33.8 to 60.2 dB, respectively, in the operation bandwidth of 15–36 GHz.

Due to APDP technology, the measured 4LO harmonics from the RF port in the required band falls into the noise floor. In addition, the

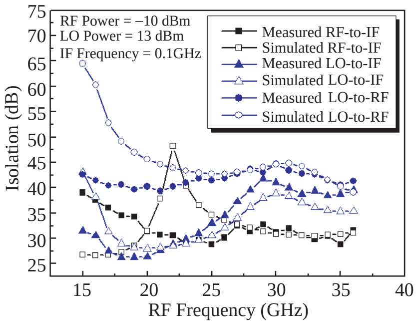


Figure 6. Measured and simulated LO-to-RF, LO-to-IF, and RF-to-IF isolations as a function of RF frequency at 13 dBm LO level and 0.1 GHz IF frequency.

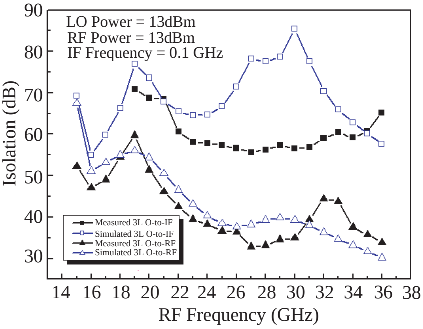


Figure 7. Measured and simulated 3LO-to-RF and 3LO-to-IF as a function of RF frequency at 13 dBm LO level and 0.1 GHz IF frequency.

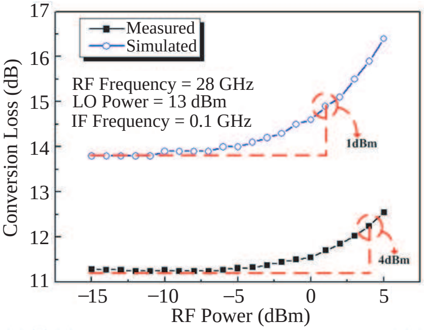


Figure 8. Measured and simulated conversion loss as a function of RF power at 13 dBm LO level and 28 GHz RF frequency.

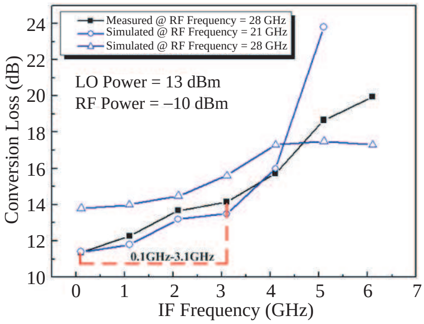


Figure 9. Measured and simulated conversion loss as a function of IF frequency.

measured input of 1 dB compression point as shown in Fig. 8 is 4 dBm with the RF fixed at 28 GHz.

Figure 9 shows the simulated and measured conversion loss as a function of IF frequency at an LO power of 13 dBm and RF power of −10 dBm. The bandwidth of IF is from DC to 3.1 GHz. Comparisons of the proposed structure with other published works [1–6] are summarized in Table 1. This work presents some significant advantages including an operating bandwidth of 14 GHz, an excellent port-to-port isolation, and a compact chip size.

Table 1. Comparison of the reported subharmonic mixers.

Ref.	Tech.	RF Freq. (GHz)	Die Size (mm^2)	LO/RF Iso. (dB)	P1dB (dBm)	LO Power (dBm)	CG* (dB)
[1]	GaAs	58.5-60.5	7	> 33	-	7	-11.3~-13.3
[2]	GaAs	94	1.26	-	-9	10	-11.4
[3]	GaAs	58.4-62.4	5	30	-11	12	-8.4~0.8
[4]	0.15 μm GaAs	23-37	0.72	> 20	6	13	-9.4~-12
[5]	0.18 μm CMOS	10-40	0.74	> 12	8	8	-15.6~-17.6
[6]	0.15 μm GaAs	16~31	0.35	> 14	-	12~14	-12.5~-16.5
[7]	0.18 μm CMOS	15~27	0.42$^+$	> 22	-6	11	-16.3~-19
[8]	0.13 μm CMOS	32~70	0.36	> 23	-4	13	-11~-13
This work	0.15 μm GaAs	21-35	0.5$^+$	> 40	4	13	-11.3~-15.1

CG*: CONVERSION GAIN; +CORE AREA EXCLUDING GSG PADS

4. CONCLUSION

A novel compact-sized 21–35 GHz quadruple SHM using the 0.15 μm GaAs pHEMT process is presented. The featured RF band-pass filter involved in the IF extraction circuit is utilized to excite the RF and LO signals into APDP while simultaneously extracting the IF signal and eliminating the use of short/open circuited stubs in conventional quadruple SHMs. This features the reduction of the chip dimension while operating at a low frequency band and to improve the isolation between the RF and IF ports with a broadband operation. Based on measured results show, this proposed quadruple SHM has significant advantages such as wider band performance, superior isolations, and small chip dimension which are relatively suitable for millimeter-wave front-end applications.

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