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V-BAND HIGH ISOLATION SUBHARMONIC MONOLITHIC MIXER WITH HAIRPIN DIPLEXER

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Abstract—A 54–66 GHz sub-harmonic monolithic passive mixer using the standard 0.15 µm pHEMT process is demonstrated. The proposed mixer is composed of a hairpin diplexer, an open stub, and a low-pass filter. The mixer also utilizes a pair of anti-parallel diodes to achieve a subharmonic mixing mechanism. The hairpin diplexer formed with two parallel-coupled line band-pass filters is used to improve the isolation between the radio frequency (RF) and local oscillation (LO) ports. The low-pass filter supports an intermediate frequency (IF) ranging from dc to 1 GHz. This proposed configuration leads to a die size of less than 1.5 mm^2. With a conversion loss of 15.2–18.3 dB, the 2LO-to-RF isolation is found to be better than 27.5 dB. A high LO-to-RF isolation of 23.5–45 dB over 54–66 GHz RF bandwidth, as well as 1 dB compression power of 8 dBm, can be achieved.

1. INTRODUCTION

Recently, millimeter-wave communication systems operating in the V-band have increased their focus on wider operational bandwidth, high-speed data transfer, low manufacturing cost, and low-power consumption. A mixer is an important component of millimeter-wave transceiver. Since subharmonic mixer (SHM) requires half-frequency local oscillator sources, it is considered as a good candidate over fundamental mixers for use of high frequency bands. This makes local oscillator sources more reliable and less expensive than its counterparts.

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Previous reports showed SHM using an anti-parallel diode pair (APDP) and fabricated in GaAs technologies [1,2]. APDP configuration has several advantages, such as being able to suppress any even harmonics of the local oscillator (LO), and the ability of not requiring dc power. However, the directional coupler is not suitable for SHM design because of its undesirable LO-to-RF isolation. CMOS has the advantage of low integration cost and high integration. Numerous SHM monolithic microwave integrated circuits (MMICs) have been demonstrated in CMOS process [3,4] (e.g., a 10–40 GHz broadband CMOS SHM using two-stage Wilkinson power combiner with a broadband feature) [3]. However, the LO-to-RF isolation is limited by a two-stage power combiner. Results from the subharmonic-pumped resistive mixer have demonstrated broadband operational performance and compact chip size [4]. Minimum LO-to-RF and 2LO-to-RF isolation is 17 and 27 dB, respectively. It is difficult to filter out the second harmonic of the LO signal at the RF port since the RF and 2LO frequency are too close to each other.

Hairpin diplexers realized by distributed circuit structures have attained low insertion loss and high isolation [5]. It is well known that planar hairpin diplexers have been used extensively in the microwave regime due to its several advantages, such as wider operational bandwidth and high isolation. In this paper, a novel 54–66 GHz SHM configuration utilizing APDP with a hairpin diplexer, an open stub, and a low-pass filter is established. The proposed V-band SHM with excellent LO-to-RF isolations for down-converter applications fabricated in a 0.15 µm GaAs pHEMT process is demonstrated.

2. CIRCUIT DESIGN AND IMPLEMENTATION

The schematic of the conventional SHM is shown in Figure 1 [6]. A $\lambda_{\mathrm{LO}}/4$ wavelength with short and open stubs was used to create ground paths for the RF and LO signals, respectively. In doing this, the RF port and LO port can be isolated. The IF signal was extracted using a low-pass filter to prevent leakage of LO/RF signals from the IF port. In order to avoid noise at the RF port, an RF band-pass filter is used. The two stubs and band-pass filter are key features in the operational bandwidth of conventional SHM.

Due to the drawback of narrow operational bandwidth in the conventional SHMs using APDP technology, a novel SHM with good port-to-port isolation and high dynamic range for down-conversion applications is proposed. The proposed configuration of the SHM is shown in Figure 2, which consists of a hairpin diplexer, an open stub, and a low-pass filter. Mixing is performed between the RF signal and

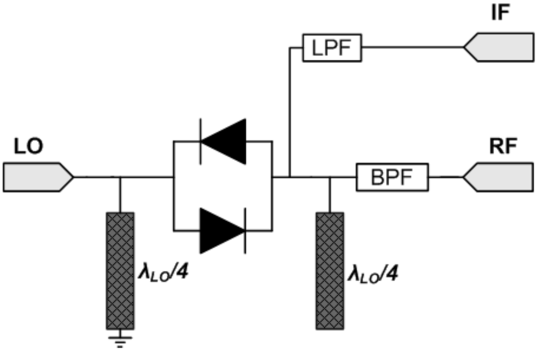

Figure 1. Conventional configuration of a subharmonic mixer.

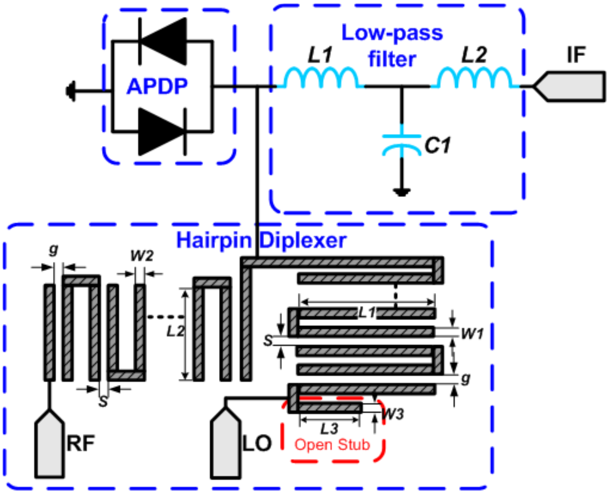

Figure 2. The proposed configuration of the subharmonic passive mixer.

the second harmonic of the LO signal, indicating that SHMs require half of the LO frequency of the fundamental mixer. Consequently, it is difficult to combine high-frequency RF signal with the relatively low frequency LO signal via hybrid. In this case, a hairpin diplexer is employed to overcome this issue and to achieve high performance of subharmonic mixer.

The purpose of the hairpin diplexer is to simultaneously excite an RF and LO signal into APDP and to improve isolation between RF and LO ports during operation bandwidth. This greatly benefits the enhancement of port-to-port isolation of the SHM. It is a three-port device passing an LO signal that operates at 26.5–32.5 GHz by the lower passband hairpin filter and an RF signal operating at 54–66 GHz by the higher passband hairpin filter. This leads to attain good performance of the hairpin diplexer and to improve isolation between the RF and LO ports. Furthermore, a thorough discussion of diplexer synthesis can be seen in [7]. An open stub is added in the LO input port of the lower passband hairpin filter into the decrease pole, and then to suppress the spurious response of lower passband filter appearing in the bandwidth of higher passband filter. Moreover, the hairpin diplexer can be further used to extend operational bandwidth with well impedance matching the SHM design. Therefore, the designed SHM well matches to the RF, LO, and IF ports and is not eminently affected by the APDP connection. Each passband hairpin filter consists of five identical resonator and two coupling I/O ports at the two sides.

The coupling coefficient as a function of the resonator spacing S is estimated by using complete full-wave electromagnetic (EM) simulator, Zealand IE3D. The normalized coupling coefficients in terms of low-pass prototype element values g_n and design frequency can be calculated as follows [8]:

$$K_{n,n+1} = \frac{BW}{f_0\sqrt{g_n \cdot g_{n+1}}} \tag{1}$$

where the $K_{n,n+1}$ is the theoretical coupling coefficient between the resonators n and $n+1$, BW is the equal-ripple bandwidth, and f_0 is the center frequency of the proposed filter. Moreover, it can be found that the theoretical coupling coefficient would affect the operating bandwidth of the diplexer [8].

In this case, a Chebyshev response with a ripple value of 0.2 dB is used to provide a much steeper stopband skirt. The factional bandwidth of lower passband hairpin filter and higher passband hairpin filter are both 20% at center frequency of 29.5 GHz and 60 GHz, respectively. The coupling coefficient parameters are determined to be $K_{12} = K_{45} = 0.1495$, $K_{23} = K_{34} = 0.1175$. In order to extend bandwidth, hence, the resonator spacing S should be placed tightly to assure the sufficient coupling coefficient. Consequently, the optimal resonator spacing S can be obtained as 5 µm, while the line width of W_1 and W_2 are 20 µm and 10 µm, respectively. Furthermore, the hairpin diplexer can be optimized further by employing the full-wave EM simulator. Line length values are also obtained, where L_1 is 800 µm and L_2 is 370 µm. The gap (g) between the I/O ports and the resonator can be obtained as 5 µm. The open stub line length of L_3 is 400 µm, line width of W_3 is 10 µm, and gap between the open stub and the input port of the lower passband hairpin filter can be obtained as 10 µm.

The simulation of the SHM was analyzed using Agilent ADS. Optimal design parameters were likewise obtained. In this design, the diode with one finger and 10 µm gate width was optimized to achieve a good impedance match. The substrate was thinned down to 100 µm with a relative permittivity of 12.9. A photograph of the fabricated SHM is shown in Figure 3. Chip dimension is $1.5 \times 1\,\text{mm}^2$.

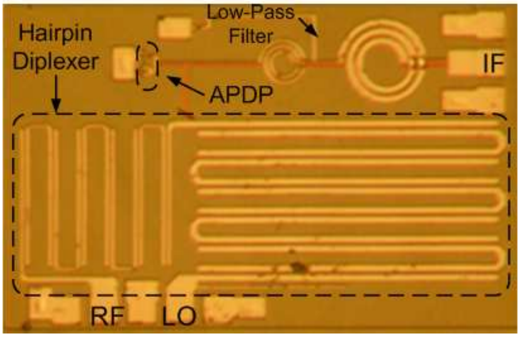

Figure 3. A photograph of the fabricated subharmonic passive mixer. The chip dimension including the contact pads is $1.5 \times 1\,\text{mm}^2$.

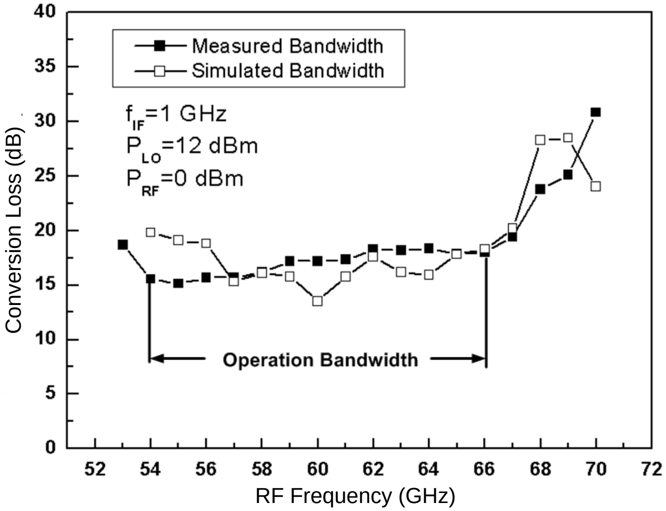

Figure 4. Conversion loss of the SHM as a function of RF frequency at a fixed LO power of 12 dBm and 1 GHz IF.

3. EXPERIMENTAL RESULTS

The fabricated MMIC SHMs were attached to the carrier plates for testing. Measurement signals were provided by the coplanar GSG and GSGSG on a wafer probe measurement system based on the Agilent E4440A spectrum analyzer and E8254 signal generator. Figure 4 illustrates the measured and simulated conversion loss of the SHM as a function of RF for the down-converter mode. Measurements were performed with an LO power level of 12 dBm and 1 GHz IF. The obtained conversion loss was 15.2 to 18.3 dB within the RF bandwidth of 54 to 66 GHz. Due to the larger hairpin diplexer insertion loss of 3.2 to 3.7 dB at operation bandwidth, the degraded conversion loss of the mixer is seen. The measured results show that the 13 GHz operation bandwidth of the proposed mixer is larger than 8 GHz of the simulated one at an LO drive power of 12 dBm.

The measured and simulated LO-to-RF, LO-to-IF, and RF-to-IF isolations as functions of frequency of the SHM for the down-converter mode are shown in Figure 5. LO-to-IF isolation is only between 16.5 and 22 dB at the high end of the band; however, it is greater than 20 dB at the low end of the band ranging from 54 to 60 GHz. It can be observed that the zero point of the low-pass filter has shifted away from the design goal, resulting in the degradation of LO-to-IF isolation. LO-to-RF isolation, which was limited by the proposed hairpin diplexer,

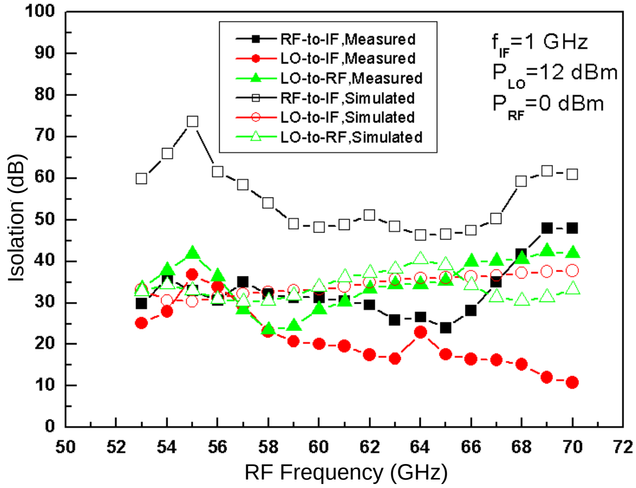

Figure 5. Isolation of the SHM at the 12 dBm LO level and 1 GHz IF.

is higher than 23.5 dB from 57 to 61 GHz; it is likewise better than 33 dB from 53 to 56 GHz and 62 to 64 GHz. Meanwhile, RF-to-IF isolation is higher than 25.8 dB for all the operation frequencies. The

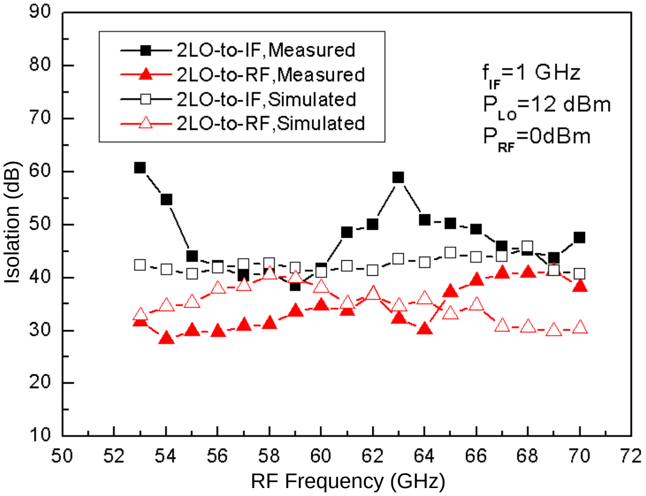

Figure 6. Measured 2LO-to-RF and 2LO-to-IF isolations at the 12 dBm LO level and 1 GHz IF.

Table 1. Comparison of the reported subharmonic Mixers.

Ref.	Technology	RF Freq. (GHz)	LO-to-RF isolation (dB)	Die Size (mm^2)	P1dB (dBm)	LO Power (dBm)	CG* (dB)
[1]	0.15 µm GaAs	23–37	22	0.72	6	12	$-9.4 \sim -12$
[3]	0.18 µm CMOS	10–40	12–20	0.837	8	8	$-15 \sim -17.6$
[4]	90 nm CMOS	9–31	19	1	N/A	9.7	$-8 \sim -11$
[9]	GaAs	40–50	N/A	2.24	−6	0.3	> 7
[10]	0.1 µm GaAs	40	35.9	3.8	−14	10	4.8
This Work	0.15 µm GaAs	54–66	23.5–45	1.5	8	12	$-15.2 \sim -18.3$

CG*: Conversion Gain

inherent LO/RF-to-IF isolation is caused by the low-pass filter. The 2LO-to-RF and 2LO-to-IF isolations, a function of RF frequency, are illustrated in Figure 6. The 2LO-to-IF isolation in the required band is 53 to 65 dB, while the 2LO-to-RF isolation is larger than 40 dB at the RF range of 53 to 70 GHz. In addition, the measured results exhibit a 1 dB compression point of 8 dBm when RF was fixed at 55 GHz, IF fixed at 1 GHz; and at LO power level of 12 dBm. Comparisons of the proposed structure with other published works are summarized in Table 1. This work presents some significant advantages, such as acquiring an operating bandwidth of 12 GHz and achieving excellent LO-to-RF isolation, as compared to previous works.

4. CONCLUSION

A 54–66 GHz SHM using the 0.15 μm GaAs pHEMT process has been demonstrated. The proposed hairpin diplexer has achieved a high-performance monolithic SHM with broad bandwidth. It not only eliminates the use of short/open circuited stubs in the conventional SHM, but also provides the RF and LO port with high isolation. As measured results show, the proposed architecture offers some significant advantages, such as a superior isolation, and higher dynamic range, which are relatively attractive for millimeter-wave applications.

ACKNOWLEDGMENT

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