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A 28–40 GHz DOUBLY BALANCED MONOLITHIC PASSIVE MIXER WITH A COMPACT IF EXTRACTION

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Abstract—A doubly balanced monolithic microwave passive mixer using novel configurations is designed and fabricated through a 0.15 μm GaAs pHEMT process. The configuration of the doubly balanced mixer (DBM) can eliminate the use of two dual baluns for application in the conventional star mixer, as well as make the mixer more compact and simplify IF extraction to obtain wider IF bandwidth up to 15 GHz. From the measured results, the fabricated DBM exhibits wideband performance, superior isolations and high dynamic range.

1. INTRODUCTION

Mixer is one of the important components of communication systems to convert signals from one frequency to another. Accordingly, it demands broadband operation, compact size, low cost, and low-power consumption for high performance transceiver solutions. Doubly balanced mixers (DBMs) are usually the choice because of their high dynamic range, even-order mixing product suppression, and inherent port-to-port isolation. The star configuration is commonly used for DBMs because of its low IF parasitic inductance, which enables wider IF bandwidth [1]. However, the star configuration in monolithic microwave integrated circuit (MMIC) design is difficult to implement because it uses two rather large half-wavelength Marchand dual baluns and also occupies a larger chip dimension. Moreover, the IF extraction of the MMIC based star DBM is more complicated. This leads to the increase of IF parasitic inductance and the degradation of IF bandwidth. Therefore, it is cost-effective if a star DBM could simplify IF extraction with small-chip-size requirements within the bandwidth.

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To overcome the difficulty of realizing non-planar structures as practical monolithic circuits, many configurations of star mixers have been developed [2–7]. However, the use of symmetrical dual baluns may still have large circuit dimensions. In order to overcome this problem, attention has been drawn to the design of miniature dual baluns. A number of spiral transformer baluns can provide an efficient method for shrinking chip area [8]. Subsequently, monolithic star DBMs using new miniature dual baluns have been proposed [9]. The DBM design still has a critical issue of IF extraction. For this reason, a new configuration of DBM is designed and fabricated in a 0.15 µm GaAs pHEMT with more compact in layout design and also more effective in improving the mixer's performance as compared to the conventional DBMs.

2. CIRCUIT DESIGN

The schematic diagram of a conventional MMIC star DBM is shown in Fig. 1(a). The architecture of the proposed DBM is illustrated in Fig. 1(b), which consists of two identical Marchand baluns and a new 180° hybrid. It utilizes a novel displacement of star quad diode to achieve a mixing mechanism. The first stage of the proposed DBM is the 180° hybrid that is employed to divide an incoming signal from the LO port or the RF port into two signals of equal amplitude with a phase difference of 0° or 180°, respectively. Hence, the phase relationships of the RF and LO signals at point E and F can be found in Fig. 1.

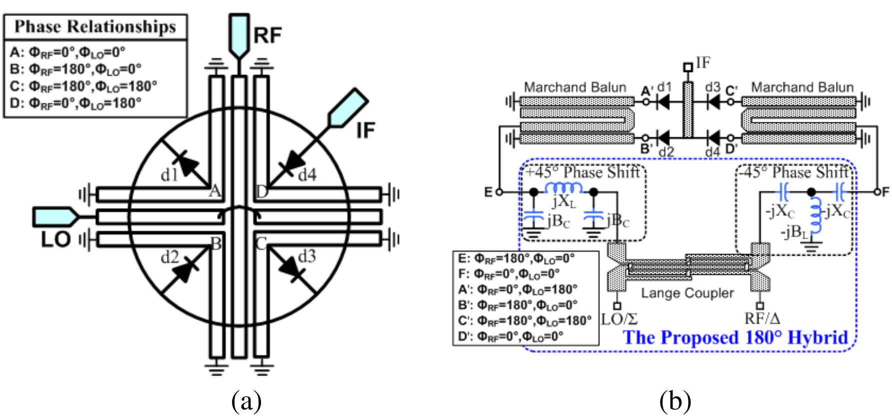

Figure 1. (a) Conventional configuration of a star DBM. (b) Schematic diagram of the proposed star DBM. The phase relationships at each point are also shown.

Subsequently, two identical Marchand baluns are connected to the outputs of the 180° hybrid. The RF and LO signals from point E and F fed into the Marchand baluns are then divided into two signals of equal amplitude with a phase difference of 180°. The phase relationships of the RF and LO signals at each diode are presented in Fig. 1. Compared to the conventional phase relationships shown in Fig. 1(a), the phase relationships of point A and D are different from point A' and D', respectively. Given that the IF port is a virtual ground, inverting the replacement of conventional star quad diode d_1 and d_4 is a way to achieve doubly balanced mixing mechanism. Finally, a new diode arrangement is used instead of the conventional star configuration. This proposed approach can not only simplify IF extraction to obtain wider IF bandwidth but also reduce chip dimension.

In this case, a 180° hybrid formed with an interdigital coupler, a +45° phase shifter, and a −45° phase shifter is proposed to improve the isolation between LO and RF ports. As shown in Fig. 1(b), a +45° phase shifter was added to the coupled port of the Lange coupler to generate a 45° and 135° phase shift of incoming signal from the LO port and RF port, respectively. Furthermore, a −45° phase shifter was added to the direct port to produce a +45° and a −45° phase shift of the incoming signal from the LO port and RF port. A comparison of the relative phase difference is made between point E and point F, as shown in Fig. 1. Likewise, the RF port and LO port are referred to as the difference port and the sum port, respectively. In particular, the new 180° hybrid eliminates the use of a crossover structure for application in the balanced mixer [10–12] and provides inherent isolation between the RF and LO ports. Indeed, this is very conducive to advancing the RF circuit design further. Design parameters based on the transmission matrix are developed as follows [13]. The +45° phase shifter is presented in Fig. 1, where the shunt element admittance $B_C = (\sqrt{2} - 1)Y_0$ and the series element impedance $X_L = (\sqrt{2}/2)Z_0$ are given. In addition, the −45° phase shifter is shown in Fig. 1, where the shunt element admittance $B_L = (\sqrt{2}/2)Y_0$ and the series element impedance $X_C = (\sqrt{2}-1)Z_0$ are also given. Finally, the proposed circuit is designed as a 180° hybrid covering the Ka-band applications in a $50\,\Omega$ system; the terminating impedance can be set to be $Z_0 = 1/Y_0 = 50\,\Omega$, and the center frequency can be set to $f = 30\,\text{GHz}$. To further improve the isolation between the RF and LO ports and obtain high performance of the 180° hybrid, the lumped elements of both phase shifters can be optimized by using the full-wave electromagnetic (EM) simulation. It should be noted that the capacitance of +45 phase shifter can be adjusted to ensure the impedance matching of RF and LO ports. The capacitance per unit area is $0.4\,\mathrm{fF}/\mu\mathrm{m}^2$, and the physical dimensions of C_1, C_2, and C_3, as shown in Fig. 2, are calculated as $12.5\,\mu\mathrm{m} \times 8\,\mu\mathrm{m}$, $25\,\mu\mathrm{m} \times 8\,\mu\mathrm{m}$, and $30\,\mu\mathrm{m} \times 23\,\mu\mathrm{m}$, respectively. The inductor values are also obtained, where $L_1 = 0.19\,\mathrm{nH}$ and $L_2 = 0.65\,\mathrm{nH}$.

3. CIRCUIT IMPLEMENTATION AND RESULTS

ADS momentum was used in the full-wave EM simulation to calculate the S-parameters of the passive circuits, reduce the dissipation losses, and improve the mixer's performance. An Agilent ADS corresponding to a WIN Semiconductor Corporation design kit was employed for circuit simulation. These individual components were combined in a harmonic balance simulator to optimize the mixer performance. The fabricated MMIC DBMs were then attached to the carrier plates for testing. The measurement signals were provided by the coplanar $150\,\mu\mathrm{m}$ pitch GSG and GSGSG on a wafer probes measurement system based on the Agilent E4446A spectrum analyzer, which was calibrated with the E44198 power meter. On the other hand, the losses of the probes and cables were measured separately and used to correct the measured results.

The proposed circuit was implemented by a $0.15\,\mu\mathrm{m}$ pHEMT technology offered by WIN Semiconductor Corporation. The substrate was thinned down to $100\,\mu\mathrm{m}$ with a relative permittivity of 12.9. The diodes of this DBM are all one-finger $10\,\mu\mathrm{m}$ devices. A microphotograph of the fabricated circuit is shown in Fig. 2. The chip dimension is as small as $1.8 \times 0.85\,\mathrm{mm}^2$. Moreover, the core

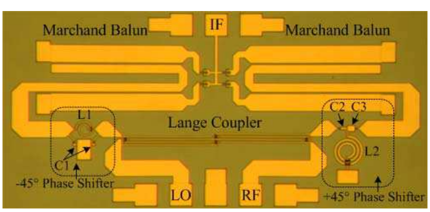

Figure 2. Microphotograph of the fabricated doubly balanced mixer. The overall chip dimension including the contact pads is $1.8\,\mathrm{mm} \times 0.85\,\mathrm{mm}$.

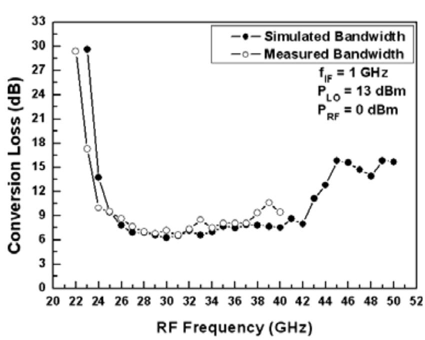

Figure 3. Measured and simulated conversion loss of the fabricated mixer as a function of frequency at a fixed LO power of 13 dBm and IF of 1 GHz.

chip dimension, excluding the contact GSG testing pads, is only $1.73 \times 0.63\,\text{mm}^2$.

Figure 3 represents the measured and simulated conversion loss as a function of RF frequency for the down-converter mode. The star DBM is driven by an LO power of 13 dBm. The measurements were performed with a RF power level of 0 dBm and a fixed IF frequency of 1 GHz. The conversion loss is 6.6 to 10.6 dB within an RF bandwidth from 24 to 40 GHz. The minimum conversion loss observed is 6.6 dB when the RF frequency is 31 GHz. This reveals that the simulated data are in close agreement with the measured result, signifying that the new configuration is workable. Fig. 4 illustrates the measured and simulated conversion loss versus the LO power level with a RF input power of 0 dBm. With the RF fixed at 31 GHz, conversion loss less than 10 dB at an LO drive level of 8 dBm can be seen. As the LO power increases from 11 to 14 dBm, the variation of the conversion loss is less than 0.5 dB. The lowest conversion loss is 6.6 dB at 13 dBm LO power.

The measured LO-to-RF, LO-to-IF, and RF-to-IF isolations as functions of the RF frequency from 22 to 40 GHz are plotted in Fig. 5. Under the measured conditions, LO-to-RF isolation is higher than 20 dB from 28 to 40 GHz. This indicates that the new 180° hybrid can provide superior isolation between the LO port and the RF port, as compared to the previous report [14]. The RF-to-IF isolation is higher than 22 dB from 22 to 40 GHz, and the LO-to-IF isolations also exceed 31 dB over the same RF/LO frequency range. As a result of the very good amplitude and phase balance in the passive circuits, this compact structure can provide both the inherent LO-to-IF and

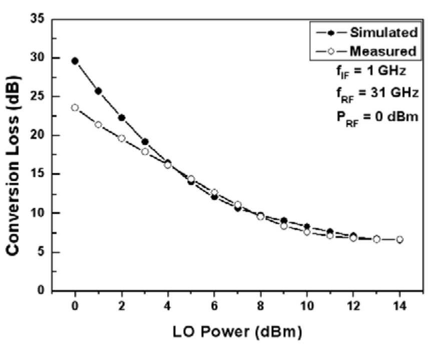

Figure 4. Measured and simulated conversion loss versus the LO power level with a RF input power of 0 dBm.

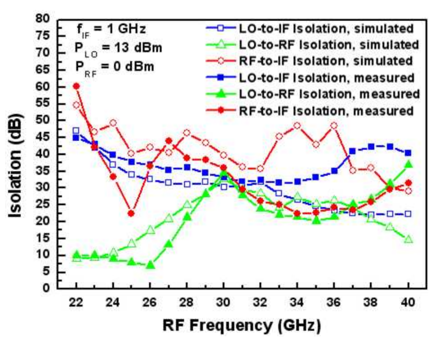

Figure 5. Measured and simulated LO-to-RF, LO-to-IF, and RF-to-IF isolations as a function of the RF frequency.

RF-to-IF isolations without additional low-pass filter.

Figure 6 shows the measured conversion loss for the IF bandwidth. The conversion loss is 6.5 to 9.5 dB within a 3-dB IF bandwidth from 1 to 15 GHz. Owing to compact IF extraction in the proposed configuration, the wider IF bandwidth ranging from 1 to 15 GHz can be achieved. The measured and simulated IF output power versus the RF power are shown in Fig. 7. The measured 1 dB compression point is 13 dBm, which is in close agreement with the simulation result.

The performance comparisons of the proposed structure with other reported DBMs are summarized in Table 1. The proposed configuration based on star DBM can simplify IF extraction to expand the IF bandwidth up to 15 GHz, because of the decrease in the IF inductance. The proposed work presents significant advantages such as a broadband operation, an excellent port-to-port isolation, and a compact configuration, as compared to previously reported works.

Table 1. Comparison of reported doubly balanced mixers.

Ref.	[3]	[4]	[5]	[7]	[9]	[10]	[11]	This work
Technology	0.15μm pHEMT	0.1μm pHEMT	0.15μm pHEMT	Package Diode	0.15μm pHEMT+	0.15μm pHEMT	0.25μm pHEMT	0.15μm pHEMT
RF (GHz)	52-68	50–75	28-36	1–35	25–55	26–38	29–40	28–40
IF BW (GHz)	DC–12	N/A	N/A	DC–1.8	N/A	DC–10	DC–8	DC–15
CL (dB)	8.6–12.5	13–18	11.9–16.2	6–18	7–12	5.4–10.7	10.3-14.7	6.6–10.6
LO power (dBm)	12	13	12	N/A	13	12	15	13
LO-to-RF Iso. (dB)	> 23	35	>46.5	15–30	> 20	> 13	28–39	> 20
LO-to-IF Iso. (dB)	> 18	N/A	>31	10–20	> 30	> 21	23.4–30..3	> 31
P1dB (dBm)	7.7	3	N/A	N/A	5	12	15	13
Chip size $(mm)^2$	0.68 × 0.59	1.5 × 1.5	1.7 ×1.7	N/A	1 × 1	2.5 × 1.0	0.8 × 1.75	1.8 × 0.85

+ Double spiral transformer

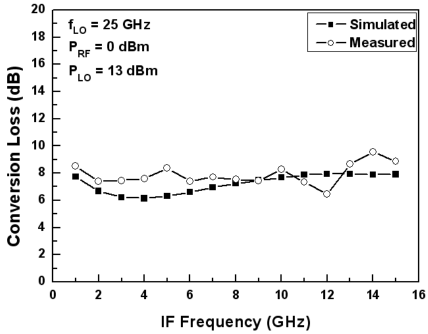

Figure 6. Measured and simulated IF bandwidth from 1 to 15 GHz.

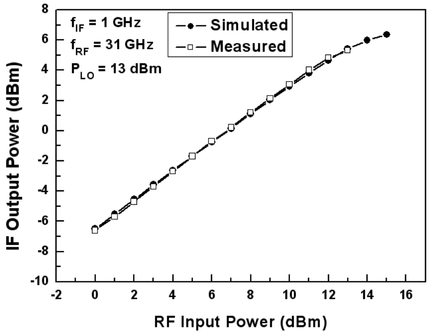

Figure 7. Measured and simulated IF output power versus RF power.

4. CONCLUSION

A novel configuration of the doubly balanced mixer has been utilized to simplify IF extractions and scale down overall chip dimensions on the GaAs pHEMT process. Performance enhancement and flexible layout design are possible with the proposed baluns as well, including IF extraction techniques. Owing to the utilization of the new 180° hybrid in the GaAs-based passive DBM, the LO-to-RF isolation can be improved significantly. The use of the180° hybrid can provide superior isolation between the LO port and the RF port, as compared to the previous report.

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