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A BROADBAND DOUBLY BALANCED MONOLITHIC RING MIXER WITH A COMPACT INTERMEDIATE FREQUENCY (IF) EXTRACTION

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Abstract—To meet the requirements for broadband operation, high port-to-port isolation, and miniature chip area, a doubly balanced monolithic microwave ring mixer with an advanced IF extraction fabricated using 0.15 µm GaAs pHEMT process is presented. A miniature Marchand-like spiral balun with low-pass filter is used to extract IF signals and maintain balun performance simultaneously. The low-pass filter can filter out both the RF and LO signals. This miniaturized mixer design can mitigate layout complexity, improve port-to-port isolations suitable for ultra-broadband Ku-, K-, and Ka-band applications. Subsequently, the LO/RF-to-IF isolations are greater than 43.2 and 32 dB from 11 to 40 GHz, respectively. The LO-to-RF isolation is between 26.9 and 50.7 dB within the same swept range. The conversion loss is 7.2–12.4 dB within the operating bandwidth.

1. INTRODUCTION

The mixer, which provides down-conversion for the receiver and up-conversion for the transmitter of baseband data, is an important component of communication systems. Doubly balanced mixers (DBMs) are the most attractive choice because of their superior suppression of spurious mixing products, wider dynamic range, excellent local oscillation (LO) noise rejection, and good port-to-port isolations [1]. Moreover, doubly balanced configurations allow the overlapping frequency bands of radio frequency (RF) and LO signal, subsequent to the efficient expansion of operating bandwidths.

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The resistive ring mixers with high 1 dB compression point output third-order intercept point (IP3) have been proposed [2–4]. However, the resistive ring mixers typically suffer from a larger chip dimension primarily because of the inclusion of the intermediate frequency (IF) balun. Although an active IF balun has been realized to further decrease chip area [4], the extra DC consumption cannot be avoided. Additionally, the challenge for a ring DBM design is IF signal extraction. Previous ring DBM designs require an additional extraction circuit for the IF port [5–7] to enhance RF-to-IF isolation. These methods may still cause layout complications, making the integration of the mixer in a low-cost and compact system more difficult. The dimension of passive circuits is also intensively increased at operating frequencies below 10 GHz. Active transformer technologies [8] with center tapped performance have been used to eliminate the IF extraction problem and to decrease chip area usage. However, the power consumption issue cannot be omitted yet. Another interesting solution is the design of miniature spiral baluns [9, 10]. However, it is difficult for the Marchand-like spiral balun to inherit center-tapped performance without degradation of amplitude and phase imbalances.

Previously, we have demonstrated new topologies [11–13] to realize a compact ring DBM even without an additional IF extraction circuit. However, because of the use of the 180° hybrid, conversion loss is increased when the ring DBM is operated in an up-converter mode. It is essential to design a compact, high-performance ring DBM without DC consumption. However, the narrow band performance of the L-C resonator degrades RF-to-IF isolation and spiral balun performance [13]. Indeed, the overall performance of the ring DBM is influenced by the narrow band L-C resonator. In this paper, a miniature Marchand-like spiral balun with low-pass filter is proposed to extract IF signals simply and to improve the port-to-port isolations for ultra-broadband mixer applications. A ring DBM is designed and fabricated using 0.15 μm GaAs pHEMT process. The proposed technique is more convenient in a circuit layout and is also more effective in improving the mixer's performance compared with conventional DBMs.

2. CIRCUIT DESIGN

The proposed configuration of the ring DBM as shown in Fig. 1 consists of Schottky diodes, an LO spiral balun, and an RF spiral balun with low-pass filter. In particular, the RF spiral balun and the low-pass filter using the L-C components were used to excite RF signals with a

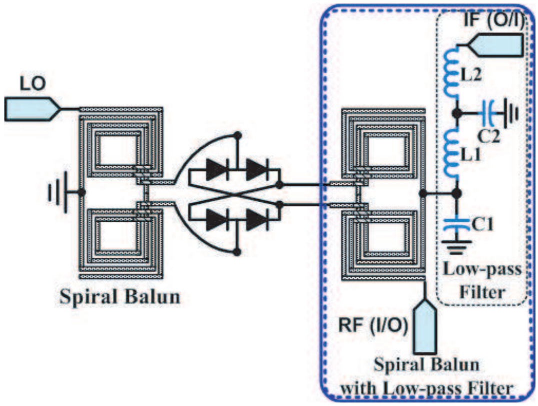

Figure 1. Schematic diagram of the proposed ring DBM.

180° relative phase difference into Schottky diode, as well as to provide an output port for IF signals. A 2nd order Chebyshev low pass filter is used to provide good stopband rejection. The capacitor and inductor values of low pass filter can be easily obtained. It is more suitable for the proposed approach, and it can be simultaneously employed to shorten RF/LO signals with a broad bandwidth and to lead out IF signals within the pass-band. This outcome implies that the RF spiral balun maintains its original performance; hence, the RF/LO-to-IF isolation can be improved with broadband operation.

In order to simplify the analysis, a simplified structure is shown in Fig. 2(a). The proposed balun is composed of two coupled sections, each of which is quarter- wavelength at the center frequency, and a grounded capacitor. It can be found the center draw out point at the via-holes of the Marchand balun short-circuited lines are replaced by the grounded capacitor to from I/O port. Consequently, it is a four-port device, ports 1 and 4 are the RF and IF ports, respectively, while ports 2 and 3 are the output ports of the RF spiral balun. In the proposed coupled-line balun, all port impedances are equal to characteristic impedance, Z_0, and the two identical couple lines are both of the TEM type, which scattering matrix for ideal coupled-line, as shown in Fig. 2(b), is given by

$$[S]_{coupler} = \begin{bmatrix} 0 & T & C & 0 \\ T & 0 & 0 & C \\ C & 0 & 0 & T \\ 0 & C & T & 0 \end{bmatrix} \tag{1}$$

where the scattering parameters of C and$T$ for the coupled and

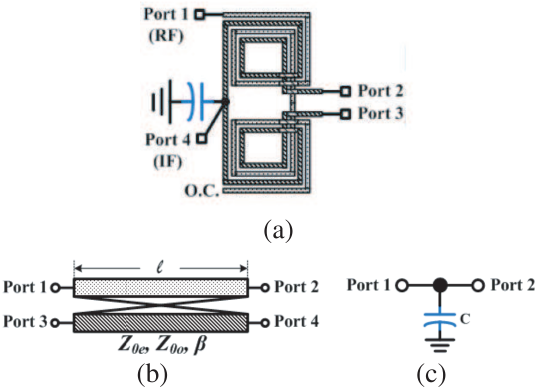

Figure 2. (a) Planar spiral balun with grounded capacitor. (b) Four-port network of coupled-line. (c) Two-port network of grounded capacitor.

transmitted ports, respectively, are

$$C = \frac{j\left(\frac{Z_{0e}}{Z_0} - \frac{Z_{0o}}{Z_0}\right)\sin(\beta\ell)}{2\cos(\beta\ell) + j\left(\frac{Z_{0e}}{Z_0} + \frac{Z_{0o}}{Z_0}\right)\sin(\beta\ell)} \tag{2}$$

$$T = \frac{2}{2\cos(\beta\ell) + j\left(\frac{Z_{0e}}{Z_0} + \frac{Z_{0o}}{Z_0}\right)\sin(\beta\ell)} \tag{3}$$

where Z_{0e} and Z_{0o} are the even- and odd-mode characteristic impedance, respectively. β is defined as the odd-mode and even-mode propagation constants, and ℓ is the length of the coupled line [14]. Furthermore, the scattering matrix of the two-port network of grounded capacitor, as shown in Fig. 2(c), can be expressed as

$$[S]_{Cap} = \frac{1}{Y + 2Y_0}\begin{bmatrix} -Y & 2Y_0 \\ 2Y_0 & -Y \end{bmatrix} \tag{4}$$

where $Y = j\omega C_g$ and $Y_0 = 1/Z_0$. C_g is the capacitance of grounded capacitor. While $Y \gg Y_0$, the return losses S_{11} and S_{22} of the two-port network present a short terminal characteristic, resulting in an anti-phase total reflection. This indicates that an appropriate capacitance should be considered cautiously to retain the performance of the proposed balun and to isolate RF signals from the IF port. Furthermore, IF signals can be excited through the grounded capacitor, and the coupled-line section into Schottky diodes, and vice versa. First, the IF frequency is assumed to be close to zero, which means that the two-port network of ground capacitor presents a lossless transmission circuit to pass the signal into the coupled-line section. The coupled-line length is designed to be a quarter wavelength at the center operation frequency, which is rather short for IF signals. Thus, $\ell = 0$ is substituted into Eqs. (2) and (3). The scattering parameters of C and T for IF signals are found to be $C = 0$ and $T = 1$. Consequently, IF signals can be directly transmitted to the transmission port without any losses. However, according to the foregoing discussion, a single grounded capacitor degrades the IF bandwidth. In our case, the grounded capacitor is superseded by the low-pass filter to extend the IF bandwidth. The high even-mode characteristic impedance is preferred for the proposed spiral balun to obtain wideband performance [14, 15]. Hence, this proposed configuration leads to a number of significant advantages, such as broadband operation, superior isolations, compact IF extraction, and flexible layout design. In addition, the Schottky diodes haven't any biases to optimize mixer performance. Therefore, to drive Schottky diode in the nonlinear characteristics of the mixer, the required LO power is high in general. This design purpose is to provide a simple IF extraction circuit to develop an ultra-broadband mixer suitable for Ku-, K-, and Ka-band applications. Additionally, this configuration is more compact in layout design and also more effective in improving the DBM performance as compared to the conventional doubly balanced ring mixers.

3. CIRCUIT IMPLEMENTATION AND RESULTS

In this mixer design, the lump-element model in electronic design automation software, including advanced design system (ADS) and microwave office (MWO), were utilized to synthesize the hybrid in the initial designs. A full-wave EM simulator, ADS Momentum, was used after the initial design to predict the performance more precisely. ADS Momentum was used to calculate the S-parameters of the passive structures for circuit simulations and then to optimize the geometry of the baluns to reduce insertion loss, reduce phase imbalance, and thus reduce the conversion loss of DBM. WIN Semiconductor corporation design kits for the GaAs pHEMT technologies have been used in ADS for circuit simulation. These individual components were combined in a harmonic balance simulator to optimize the mixer's performance.

To validate the proposed circuit, GaAs pHEMT technology (WIN Semiconductor Corporation) with a relative permittivity of 12.9 and a substrate thickness of 100 µm was used for the ring DBM. The capacitance per unit area was $0.4\,\mathrm{fF}/\mu\mathrm{m}^2$, and the physical dimensions of C_1 and C_2 were $32\,\mu\mathrm{m} \times 32\,\mu\mathrm{m}$ and $40\,\mu\mathrm{m} \times 38\,\mu\mathrm{m}$, respectively

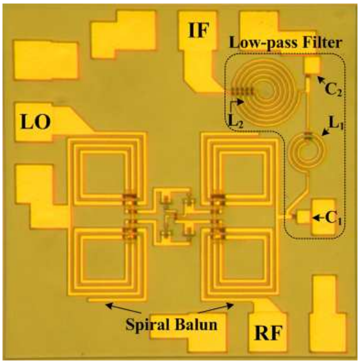

Figure 3. Microphotograph of the fabricated doubly balanced ring mixer. Overall chip dimension, including the contact pads, is $0.85 \times 0.85\,\mathrm{mm}^2$.

(Fig. 3). The inductor values were also obtained, where $L_1 = 0.5\,\mathrm{nH}$ and $L_2 = 2.8\,\mathrm{nH}$. The Schottky diodes were realized by connecting the drain and source pads of the pHEMT device to form the cathode. The gate width of the Schottky diodes in the ring DBM was 10 µm. The proposed balun dimension was $0.417 \times 0.194\,\mathrm{mm}^2$ The used line spacing was 5 µm, while the line width was 10 µm, line length was 1422 µm. Fig. 3 illustrates a microphotograph of the implemented circuit. The chip area is as small as $0.85 \times 0.85\,\mathrm{mm}^2$. The core chip dimension without contact GSG testing pads is only $0.6 \times 0.6\,\mathrm{mm}^2$.

Fabricated MMIC ring DBMs were then attached to the carrier plates for testing. Measurement signals were provided by the coplanar 100 µm pitch GSG probes on-wafer RF 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 were used to calibrate the measured results.

Figure 4 plots the conversion loss at a 13 dBm LO drive level for a swept response from 10 to 40 GHz and with an IF frequency of 1 GHz. The measured bandwidth for both down- and up-converter modes is wider than the design goal. The conversion loss is 7.2–12.4 dB within the operating bandwidth, ranging from 11 to 40 GHz. This broadband performance is due to the high even-mode impedance of the spiral baluns.

The measured conversion loss versus LO power (RF power of 0 dBm) for the down-converter mode is illustrated in Fig. 5. With the RF fixed at 32 GHz and 17 GHz, a significant mixing effect at a LO drive level of 9 dBm and 7 dBm can be respectively found. The

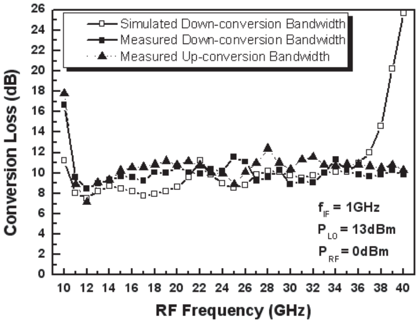

Figure 4. Measured and simulated conversion loss of the mixer as a function of frequency at a fixed LO power of 13 dBm and 1 GHz IF frequency.

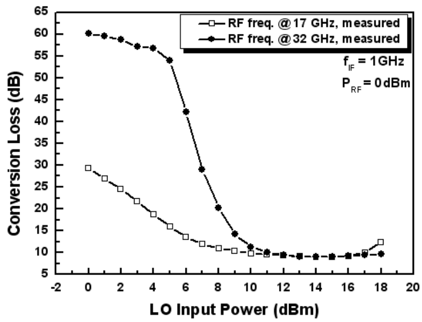

Figure 5. Measured conversion loss versus the LO power level with a RF input power of 0 dBm at 32 and 17 GHz, respectively.

higher LO power is adapted to Schottky diodes on the high frequency band. Furthermore, both conversion losses less than 10 dB in the LO power, ranging from 11 to 16 dBm, can also be achieved. Both the lowest conversion losses are around 9 dB at 13 dBm LO power.

Measured and simulated port-to-port isolations of the ring DBM for the down-converter mode are presented in Fig. 6. The low-pass filter can filter out both the RF and LO signals. Subsequently, the LO/RF-to-IF isolations are greater than 43.2 and 32 dB from 11 to 40 GHz, respectively. The LO-to-RF isolation is between 26.9 and 50.7 dB within the same swept range. This superior isolation is actualized by the Marchand-like spiral baluns with low-pass filter.

Figure 7 illustrates the measured and simulated IF output power versus the RF power at a fixed RF frequency of 12 GHz. Under the measured condition, the measured input of 1 dB compression point is approximately 12 dBm. Due to the pass-band of the low-pass filter, the measured 3-dB IF bandwidth ranges from DC to 2.5 GHz with the LO fixed at 11 GHz.

Table 1 summarizes the performances of the proposed ring DBMs and compares them with other reported DBMs. As compared to the previous report [12], the port-to-port isolations have been improved significantly. With the employment of the advanced IF extraction technique, the proposed ring DBM has the advantages in terms of operating bandwidth, port-to-port isolations, and chip dimension.

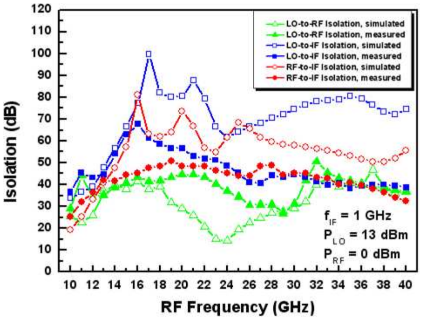

Figure 6. Measured and simulated LO-to-RF, LO-to-IF, and RF-to-IF isolations as a function of the RF frequency.

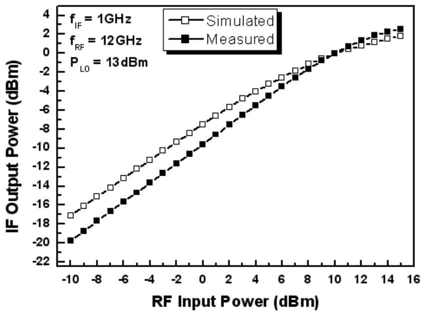

Figure 7. Measured and simulated IF output power versus RF power.

Table 1. Comparison of reported doubly balanced mixers.

Ref.	[4]*	[5]	[6]	[7]	[10]	[11]	[12]	This work
Technology	0.5 µm pHEMT	InP-based diode	0.18 µm CMOS	0.18 µm CMOS	0.15 µm pHEMT	0.15 µm pHEMT	0.15 µm pHEMT	0.15 µm pHEMT
RF (GHz)	8–20	30–45	16-46	15-50	16–40	16-44	12–40	11–40
CL (dB)	5–11	10–14	11.5-14.5	13-17	8-13	11-14	6.8–11.2	7.2–12.4
LO power (dBm)	16	4	11	10	14	15	13	13
IF (GHz)	1	N/A	0.4	DC-5	1-3	4.2-5.6	DC-8	DC-2.5
LO-to-RF Iso. (dB)	35	N/A	>20	>35	35-50	10-42	> 28	> 26.9
LO-to-IF Iso. (dB)	32	N/A	>37	> 35	27-44	27-50	> 24	> 43.2
RF-to-IF Iso. (dB)	20	N/A	>22	>30	13-35	>40	> 14	> 32
P1dB (dBm)	0–4	1.4	3	10	14	14	14	12
Chip size (mm^2)	1.7× 1.8	2 × 2	0.37×0.66	0.45×0.45	1 × 1	0.8 × 0.8	0.8×0.8	0.85×0.85

* Active circuit

4. CONCLUSION

An enhanced performance ring doubly balanced mixer with a simplified IF extraction realized by a 0.15 μm GaAs pHEMT technology has been realized. Utilizing the Marchand-like spiral baluns as well, including IF extraction technique, it is possible to achieve broadband mixing effect and improve port-to-port isolations. Furthermore, this design method enables the flexible circuit layout to further reduce chip dimension usage. Finally, the ring DBM is relatively suitable for high-level integration of the RF front end.

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