A millimeter-wave monolithic doubly balanced diode mixer

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Abstract: A broadband miniature doubly balanced diode mixer chip fabricated by Win's 0.15 μm pHEMT technology is presented. In order to save chip area, a four-fold modified Marchand balun is used. A coupled line U section improves the port to port isolation and provides the IF-output port. The mixer achieves a low conversion loss of 5.5 to 10.7 dB and high isolation of more than 26 dB over a 26–40 GHz RF/LO bandwidth and a DC–14 GHz IF bandwidth. The mixer's chip size is around 0.96 mm^2.

Key words: doubly balanced; Marchand balun; conversion loss
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1. Introduction

Recently, the increasing demand for high-speed data transfer and Internet access has become more prevalent in communication systems. The development of systems and components operating at the K- and Ka-bands thus makes millimeter-wave communication systems of great importance. One important component of these systems is the mixer, whose performance requires low conversion loss, high isolation, and, most importantly, small chip size. Because of their inherent isolation between signal ports without filters, doubly balanced mixers (DBM) are best suited for broadband operation. Further properties like LO noise and spurious signal rejection, as well as lower intermodulation, predestine doubly balanced mixers for test and measurement systems.

Marchand baluns or Lange coupler baluns[1] are often used to implement the doubly balanced topology. Maas *et al.* developed a good performance planar ring mixer by using a traditional Marchand balun[2, 3]. However, the chip area required for the quarter-wavelength matching stubs and baluns may still be too large. Trantanella demonstrated a model for a monolithic spiral transformer balun[4] and Lin designed a compact monolithic ring mixer consisting of two spiral baluns[5]. The spiral baluns can provide an efficient method for reducing chip area, but the conversion loss deteriorates severely. To decrease chip size, the traditional Marchand balun can also be modified by using multiple coupled lines and folded lines to decrease chip size[6].

This paper describes a ring mixer using modified Marchand baluns for the LO and RF port. The coupled lines of Marchand baluns at the RF and LO port were bent to minimize the length and reduce chip size. The RF balun, however, includes an extra coupled line U section that improves the performance of the balun. The measurement result showed that the designed DBM using two compensated four-fold Marchand baluns has a low conversion loss of 5.5 to 10.7 dB and good LO-RF isolation with a compact die size of 0.96 mm^2. Table 1 summarizes the comparisons of the proposed mixer with the reported doubly balanced mixers. The proposed mixer has the advantages of easier IF extraction, smaller chip size, and wider IF bandwidth.

2. Mixer principle

The schematic of a conventional ring mixer is shown in Fig. 1(a).The DBM consists of four parts: RF balun, LO balun, the ring quad diode and IF extraction circuit. The RF and LO single-ended signals are transformed into differential signals by using the RF balun and LO balun. The mixing generation mechanism is in general that the LO signal is used to switch the ring quad diode, and is then mixed with the RF signal. From Fig. 1(b), the equation of the intermediate frequency current[3] is given by:

$$\begin{aligned} i_{\mathrm{if}} &= i'_{\mathrm{if}} + i''_{\mathrm{if}} = (i_1 - i_2) + (i_3 - i_4) \\ &= \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \{ I_{n,m} \exp[j(n\omega_{\mathrm{L}} + m\omega_{\mathrm{s}})t] \\ &\quad \times (1 - \mathrm{e}^{jn\pi})(1 - \mathrm{e}^{jm\pi}) \}. \end{aligned} \tag{1}$$

When n and m are even integers, Equation (1) equals zero. So Equation (1) can be written as:

$$i(t) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} 4 I_{n,m} \exp[j(n\omega_{\mathrm{L}} + m\omega_{\mathrm{s}})t], \tag{2}$$

where n, m are odd integers. From Eq. (2), it can be seen that DBM can provide inherent port isolation, even-order mixing product suppression, and high dynamic range.

Figure 2 illustrates the basic structure of this work. Two Marchand baluns can replace the transformers in the MMIC circuit. An additional coupled-line section, which we shall call the U section, is used for IF extraction.

3. Marchand balun and U section design

The traditional Marchand balun, as shown in Fig. 3(a), consists of two coupled line sections connected in cascade, each having quarter-wavelength. A tight coupling factor K and high even-mode impedances $Z_{0\mathrm{E}}$ are required for both coupled line sections to obtain a well designed Marchand balun[7, 8]. For the edge-coupling structure, K can be increased by decreasing the spacing between the lines which is always limited by the

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Table 1. Performance summary of doubly balanced mixers.

Parameter	RF freq (GHz)	Die size (mm^2)	LO power (dBm)	Conversion loss (dB)	IF freq (GHz)	Technology
Ref. [1]	27–37	1.15	15	9–12	DC–3.5	Win 0.15 μm
Ref. [3]	18–40	6.5	17	6–9	DC–11	TRW 0.15 μm
Ref. [4]	18–32	0.48	11	7–9	DC–8	Hittite 0.5 μm
Ref. [5]	12–40	0.64	13	6–12	DC–8	Win 0.15 μm
Ref. [6]	16–40	1	14	8–13	DC–7	Win 0.15 μm
This work	26–40	0.96	13	5.5–10.7	DC–14	Win 0.15 μm

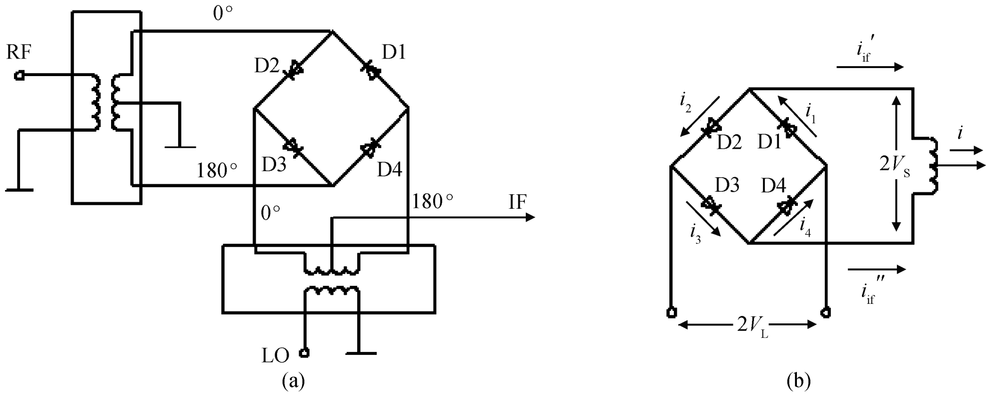

Fig. 1. (a) Basic configuration of ring mixer. (b) Equivalent AC circuit of ring mixer.

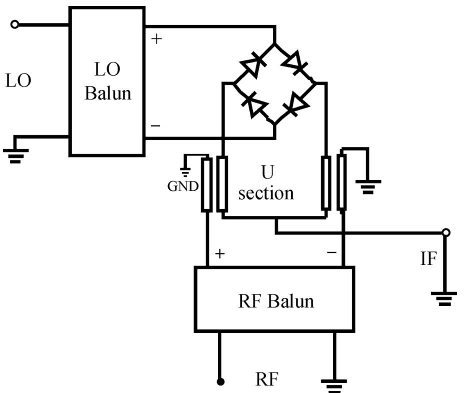

Fig. 2. Basic structure of this design.

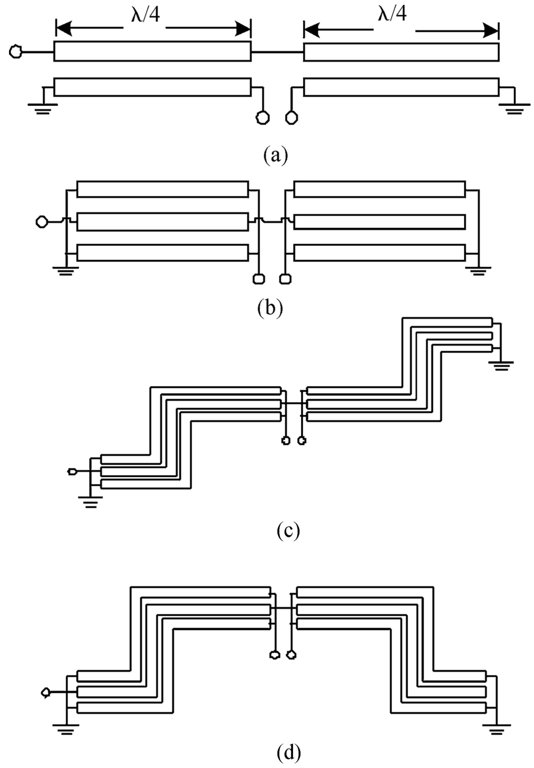

Fig. 3. (a) Structure of traditional Marchand balun. (b) Marchand balun using multiconductor coupled lines. (c) Four-fold Marchand balun. (d) Four-fold Marchand balun.

MMIC fabrication technology. To resolve the issue in planar transmission lines, multiconductor coupled lines, e.g., Lange couplers, can be used to achieve higher coupling with the same conductor spacing. Therefore, three-finger coupled lines were used in this work to replace the traditional Marchand balun, as shown in Fig. 3(b). In order to reduce chip area, the coupled lines of Marchand baluns at the RF and LO ports were bent to minimize the length. In this design, the four-fold coupled line was designed by modifying the Marchand balun as shown in Figs. 3(c) and 3(d). The Marchand balun shown in Fig. 3(c) is designed for the LO port and that shown in Fig. 3(d) is designed for the RF port.

Some other techniques are also available to equalize or compensate the imbalance of the magnitude and phase in microstrip baluns[9, 10]. Among them, the capacitive compensation technique has been widely adopted and analyzed by various researchers to achieve high performance directional couplers[11, 12]. Compensation can be implemented by employing capacitors at each end of the coupled lines as shown in Fig. 4. The capacitor will not affect the even-mode but effectively increases the odd-mode phase length. This will increase the directivity and thus provide broadband characteristics with good isolation. In this design, a microstrip stub is used as a capacitor.

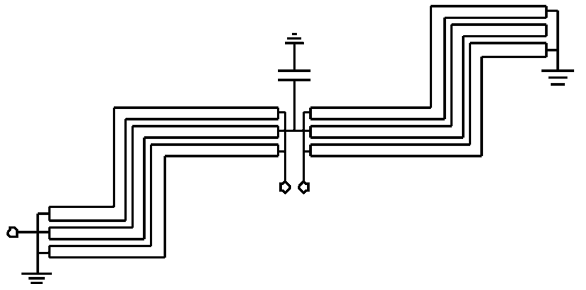

Fig. 4. Compensated Marchand balun.

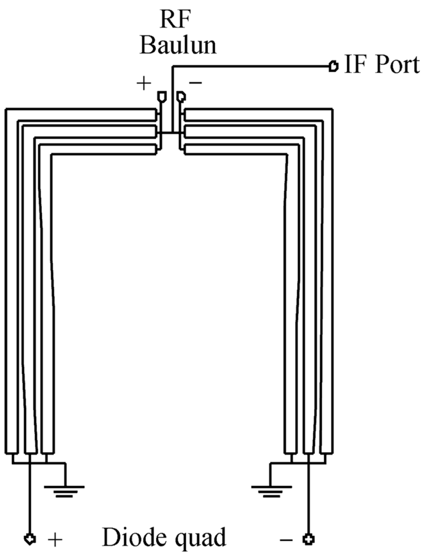

Fig. 5. IF extraction circuit, called the U section.

An IF extraction circuit, which we shall call the U section because of its shape, is used in the mixer. This section has several effects. First, it provides additional even-mode rejection. This improves the balance of the balun, and thus improves the port-to-port isolation and even-order spurious-response rejection of the mixer. Second, it provides an IF-output port. The coupled lines of the U section require a low even-mode impedance and a high odd-mode impedance. To meet this requirement we use multiple coupled lines, as shown in Fig. 5.

4. Mixer circuit simulation and fabrication

The simulation was done by using an Agilent ADS. EM models were first established for the two Marchand baluns. An Agilent EEHEMT model was used as the large-signal model for the Schottky diode. These individual components were combined in a harmonic balance simulator to optimize the performance of the mixer. Figure 6 shows the simulated conversion loss and isolations of the mixer as a function of RF frequency. The power level of LO is 13 dBm and the conversion loss is less than 8.3 dB from 26 to 40 GHz with the IF varying from 0.1 to 14 GHz. The LO to RF isolation is higher than 40 dB from 26 to 40 GHz. The LO to IF isolation and RF to IF isolation are also higher than 30 dB over the same frequency.

To design the doubly balanced mixer, the layout was verified using Agilent ADS Momentum and Cadence Virtuoso design environment software. WIN Semiconductors' standard 0.15-μm high-power InGaAs/AlGaAs/GaAs pseudomorphic

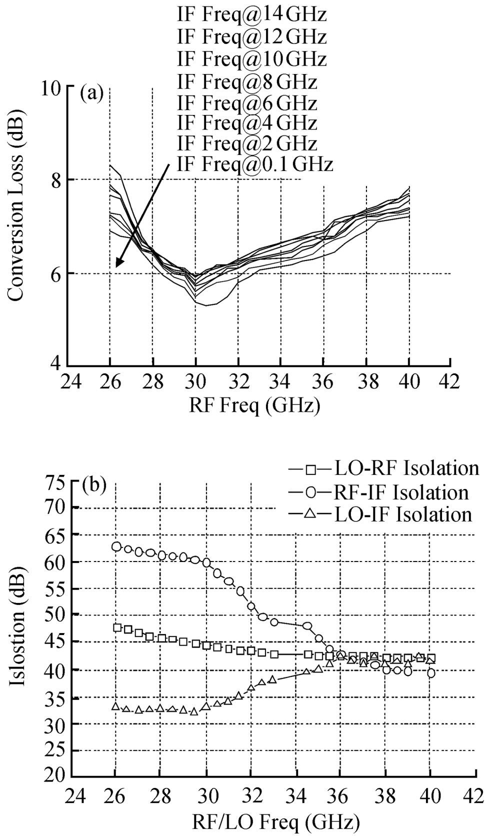

Fig. 6. (a) Simulated conversion loss. (b) Simulated LO-RF/RF-IF/LO-IF isolations.

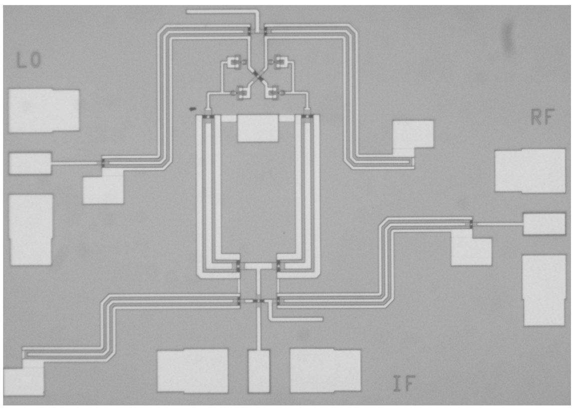

Fig. 7. Die photograph of the DBM.

HEMT (pHEMT) process is used to demonstrate the design procedure. This MMIC process employs a hybrid lithographic approach using direct-write electron beam lithography for the submicrometer gate definition and optical lithography for the other steps. Other passive components, including a thin-film resistor, metal–insulator–metal capacitors, spiral inductors, and air bridges, are all available. There are two metal layers available in this process. The wafer is thinned to 4 mil for the gold planting of the backside, and reactive ion etching via-holes are used for dc grounding. The minimum conductor width and spacing are both 5 μm. The diode is realized by connecting the drain and source pads of a pHEMT device to form the cathode. The cutoff frequency of the two-finger 15-

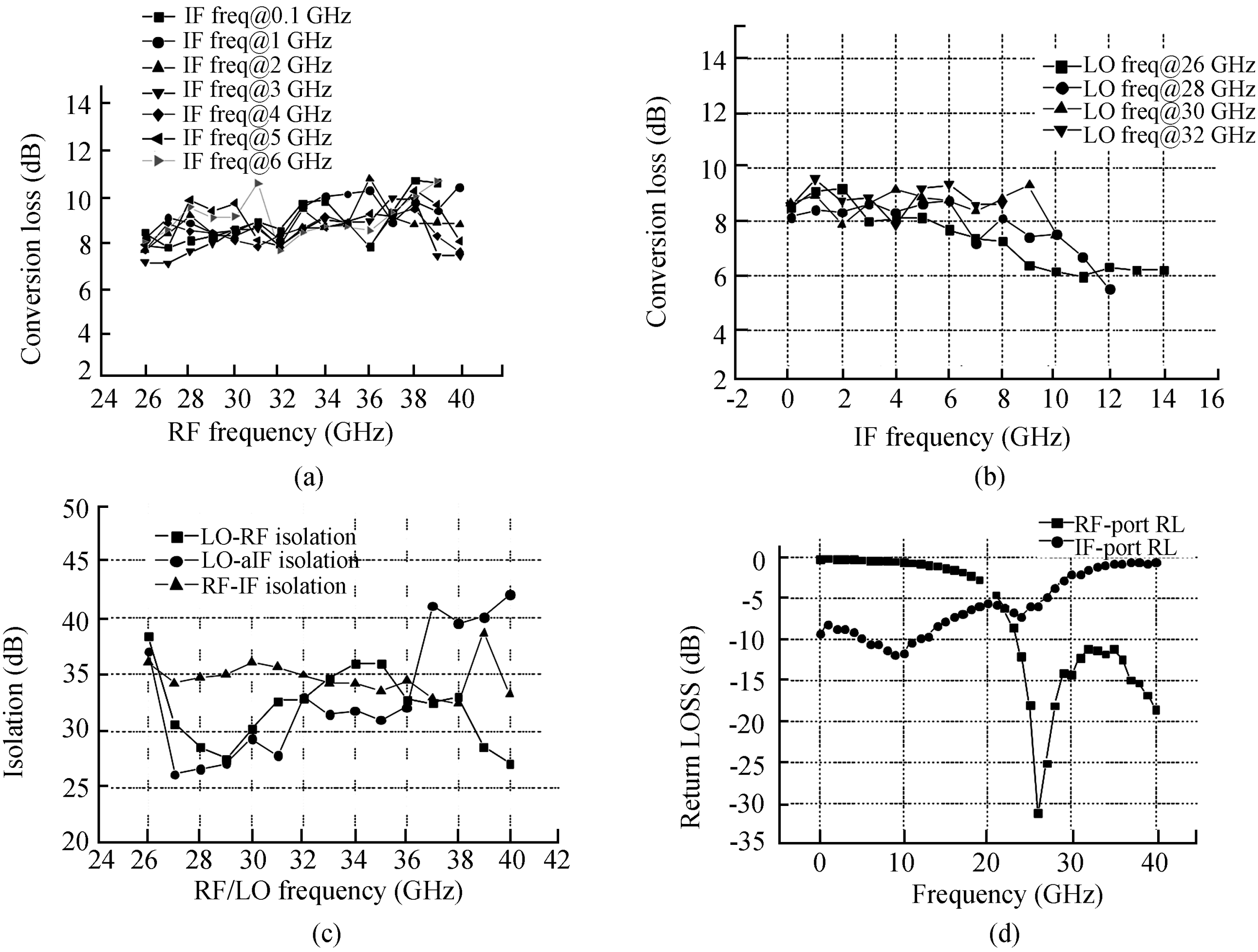

Fig. 8. (a) Conversion loss of the mixer as a function of RF frequency at an LO power of 13 dBm. (b) Conversion loss of the mixer as a function of IF frequency at an LO power of 13 dBm, RF = IF + LO. (c) LO-RF, LO-IF, RF-IF isolation of the mixer as a function of frequency with an LO power level of 13 dBm. (d) Return loss of RF port and IF port with an LO power level of 13 dBm at 26 GHz.

μm Schottky diode is approximately 381 GHz. A photograph of the fabricated doubly balanced ring mixer is shown in Fig. 7. The chip dimension was reduced to 1.2×0.8 mm.

5. Mixer performance

The fabricated MMIC mixer was attached on carrier plates for testing. The signal measurements were provided by a coplanar GSG on-wafer probe measurement system based on an HP8564E spectrum analyzer. The losses of the probes and cables were also calibrated by a PNA E8364A network analyzer.

The measurements are performed with the power level of LO at 13 dBm. Figure 8(a) shows the measured conversion loss of the mixer as a function of RF frequency. The conversion loss is 7.1 to 10.7 dB from 26 to 40 GHz with the IF fixed at 0.1–6 GHz. The losses in the baluns cause the conversion loss to increase with RF frequency. Figure 8(b) shows the conversion loss of the mixer as a function of IF frequency at a fixed LO frequency of 26–32 GHz with RF = IF + LO. The conversion loss is 5.5 to 9.6 dB. When the IF frequency increases, conversion loss decreases rapidly due to the decrease of LO frequency. Figure 8(c) shows the measured LO-to-RF, LO-to-IF and RF-to-IF isolations as functions of RF/LO frequency from 26 to 40 GHz. The LO-to-IF isolation is higher than 26 dB from 26 to 40 GHz, the LO-to-RF isolation is higher than 26 dB over the same frequency, and the RF-to-IF isolation is high than 32 dB during the whole bandwidth. The RF-port and IF-port return loss is presented in Fig. 8(d). The RF-port return loss is less than –10 dB from 26 to 40 GHz, and the LO-port return loss is less than –8 dB from 0 to 14 GHz.

6. Conclusions

A novel configuration consisting of two four-fold compensated baluns has been demonstrated to achieve a high-performance planar monolithic ring mixer with a wide bandwidth, small chip size, and compact IF extraction. The chip dimension for the fabricated monolithic mixer using 0.15 μm GaAs PHEMT processes can be much less than 1.2×0.8 mm^2. As the measured results show, the conversion loss is 5.5 to 10.7 dB from 26 to 40 GHz for IF bandwidth from dc to 14 GHz. The LO-to-IF isolation and LO-to-RF isolation is higher than 26 dB from 26 to 40 GHz;, the RF-port return loss is less than –11 dB and IF-port return loss is less than –8 dB.

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