Design of a monolithic millimeter-wave doubly-balanced mixer in GaAs

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Abstract: This paper presents the design of a 26–40 GHz monolithic doubly-balanced mixer for high-speed wireless communication. A modified Marchand balun is used to expand the bandwidth. A coupled line of the U section improves the port to port isolation and provides the IF-output port. The mixer was simulated and fabricated in 0.15-μm GaAs PHEMT technology; the measurement results agree well with the simulation results. The mixer achieves low conversion loss of 5.9 to 8.6 dB and high isolation over a 26–40 GHz RF/LO bandwidth and a DC-14 GHz IF bandwidth.

Key words: mixer; MMIC; millimeter-wave; balun; GaAs

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1. Introduction

In recent years, interest in monolithic millimeter-wave integrated circuits for Ka-bands has been increasing for high-speed data transfer systems. In these systems, microwave mixers are an important component and affect the whole system's performance. They provide primary frequency conversion from the radio-frequency band to the intermediate-frequency band in all sorts of transceivers. Doubly-balanced mixers (DBM) are usually the desirable mixer because of their superior suppression of spurious mixing products and good port-to-port isolation[1].

Two commonly used topologies for doubly-balanced mixers are ring and star configurations, and most of them are realized by using baluns at the radio frequency (RF) and local oscillation (LO) ports. In the past, the development of broadband monolithic mixers has been hampered by the lack of high-performance, broadband balun designs suitable for monolithic applications[2]. Many new topologies for millimeter-wave mixers have been proposed and devoted to high performance. In order to reduce size, a doubly-balanced mixer utilized Lange couplers with new phase relationships[3]. The Marchand balun was modified to a multiple coupled line ring type to reduce the chip size[4], however, this will cause the conversion loss and isolations to deteriorate. A star mixer used the Marchand balun and coplanar waveguide (CPW) to provide a simple topology with gate–drain-connected PHEMT diode[5].

In this paper, we develop a doubly-balanced mixer in the 26–40 GHz RF/LO range and DC-14 GHz IF by using a modified Marchand balun and ring diode structure. In the balanced circuit topology, baluns play a key role in driving diodes for mixing as well as the impedance match between diodes and input port impedance. In order to pursue good performance at such high frequency, we do not use a folded or spiral balun which was depicted in Ref. [6]; two improved Marchand baluns are designed for the mixer, i.e. a three-conductor coupled line balun for the LO port and a balun compensated with capacitances for the RF port. This mixer offers a low conversion loss of 5.9–8.6 dB and high isolations over a 26 to 40 GHz RF/LO bandwidth and a DC-14 GHz IF bandwidth.

2. Balun design

According to the requirement of the mixer, the balun should be broadband and have good balances. The Marchand balun is suitable for a broadband balun. It is composed of two quarter wavelength coupled transmission lines, and each section has one terminal grounded. The performance of baluns depends on their even and odd mode impedances, and in most cases, the even mode impedance should be as high as possible, but the Marchand balun has less sensitivity to low even mode impedance[7].

The balance of the balun is very important to the mixer and will affect its bandwidth and conversion loss. Since the phase velocities of even and odd modes are unequal for planar microstripe baluns, the magnitude and phase of the output signals are unbalanced. To compensate the phase velocity inequality in the microstripe balun, we use capacitive compensation technology to improve the performance of the Marchand balun. The proposed enhanced Marchand balun, as shown in Fig. 1, comprises two coupled line sections in cascade with two capacitances at the output ports. With the addition of the lumped capacitances, the electrical length of the coupler can be made to be equal for the even and odd modes at the designed frequency. Since the center frequency of this design is 33 GHz, the values of the compensated capacitances are so small and can be substituted by distributed capacitances such as open-circuited stubs.

For symmetrical coupled lines, the Marchand balun can be analyzed and designed as even and odd modes[8, 9]. The characteristic impedance Z_L of the coupled line is given by

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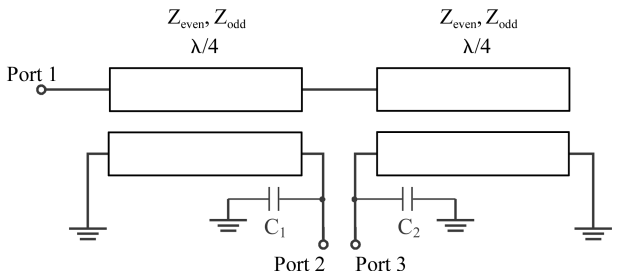

Fig. 1. Schematic of the proposed capacitive compensated Marchand balun.

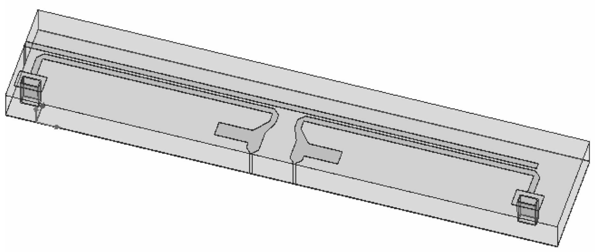

Fig. 2. 3D structure of the compensated Marchand balun.

$$Z_L = \sqrt{Z_{even} Z_{odd}}, \tag{1}$$

where Z_{even} and Z_{odd} are the even and odd mode impedances of the coupled lines. The coupling coefficient K can be written as

$$K = \frac{Z_{even} - Z_{odd}}{Z_{even} + Z_{odd}}. \tag{2}$$

The coupling coefficient K increases when Z_{even}/Z_{odd} increases. Since a higher coupling coefficient results in wider bandwidth of the Marchand balun[10], it is necessary to increase the ratio Z_{even}/Z_{odd} to a high value. The design procedure of Marchand balun is summarized as follows.

(1) Calculate the even and odd mode impedances for each coupled sections for different W and S;

(2) Calculate the quarter wavelength of the desired center frequency;

(3) Optimize the balun in terms of the structure's physical dimensions by fine-tuning the above calculated dimensions using EM simulators.

The simulation was done by using full wave electromagnetic simulator Ansoft HFSS and Agilent ADS. The Marchand balun was compensated by two open-circuited stubs at the output ports; we initially used the coupled line models in ADS simulator to predict the performance, and then used an EM simulator to improve the accuracy of the simulation and allow final optimization of the balun dimensions. The 3D structure of the balun was drawn by HFSS and shown in Fig. 2. Two open-circuited stubs can be equivalent to the compensated capacitances for their length being less than N_4, where λ is the wavelength of the signal. Figure 3 shows the insertion loss and phase balance of the proposed Marchand balun.

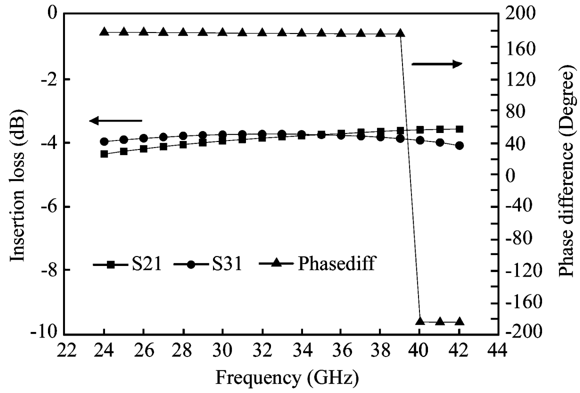

Fig. 3. Insertion loss and phase difference of the balun.

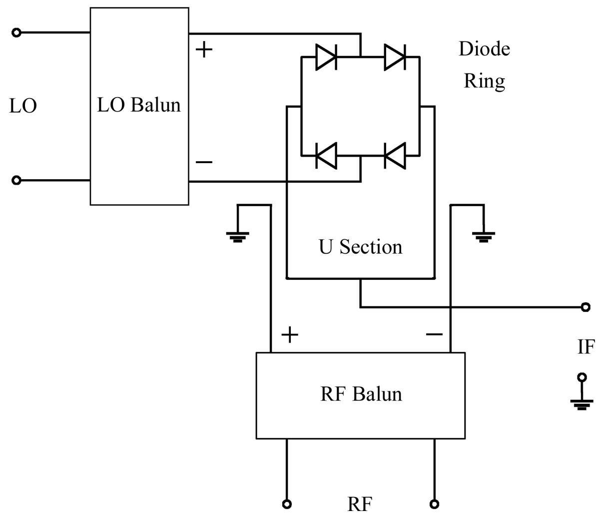

Fig. 4. Basic structure of the mixer.

3. Mixer design

The doubly-balanced ring mixer was designed with four diodes in a ring configuration, two Marchand baluns at the RF and LO ports, and an additional coupled-line of U section at the IF port. Figure 4 illustrates the basic structure of the mixer.

A proper LO power level is a necessary condition for the mixer to get the best performance. By using ADS and 0.15 μm GaAs process design kits (PDK) of the WIN Semiconductor, we simulate the circuit by sweeping LO power from 8 to 15 dBm and get a series of curves for the conversion loss of the mixer; finally a LO power level of 13 dBm was decided according to these curves.

In this design, the coupled-line of the U section provides additional even-mode rejection and improves the balance of the balun, and thus improves the port to port isolation and even order spurious response rejection of the mixer. The IF signal can be extracted from the center point of the U section. The U section's odd-mode impedance is

$$Z_{0O} = \sqrt{\frac{Z_s Z_L}{8}}, \tag{3}$$

where Z_s is the output impedance of the Marchand balun, and Z_L is the load impedance. Since the impedance of the diode varies with the frequency, it is hard to achieve matching between the diodes and U section in such a broad bandwidth

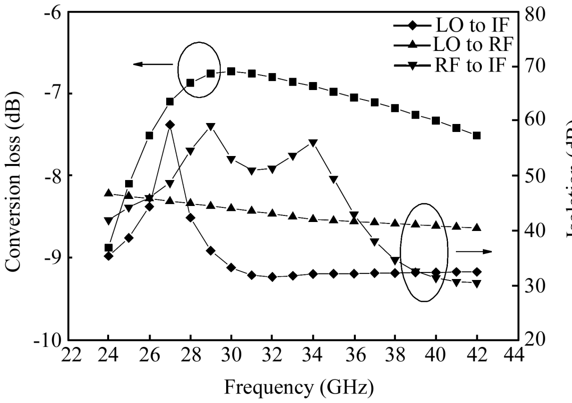

Fig. 5. Simulated conversion loss and isolations.

range from 26 to 40 GHz. In general, this problem can be ameliorated by optimizing the whole circuit by using the EM simulator and the circuit simulator together.

The designs of the LO balun and the RF balun are somewhat different; for coupled lines, the coupling coefficient between two lines can be increased by decreasing the spacing between the lines. However, the minimum line spacing in the implementation of the circuits limits the coupling coefficients of the planar two-conductor coupled lines; to resolve this problem, we use three-conductor coupled lines to realize the LO balun. Since the RF balun is close to the IF port, the isolation between the RF and IF ports will decrease as the coupling coefficient increases; there should be a tradeoff between isolation and bandwidth of the mixer. Through EM simulation, we found that the isolation between the RF and IF ports would decrease quickly towards to the high frequency band if using a three-conductor coupled line to realize the RF balun, while the conversion loss improved little; so it is better for the RF balun to be implemented by two-conductor coupled lines with compensated capacitances. Ideally the sections of Marchand balun are one-quarter wavelength long, but in practice the balun is often made shorter than this because it has parasitic capacitances at the end of each section.

The balun was designed for 26 to 40 GHz wideband mixer applications. Figure 5 shows the simulated conversion loss and isolations of the mixer as a function of RF frequency. From Fig. 5, the simulated insertion loss is less than 4.2 dB from 26 to 40 GHz. The magnitude imbalance is less than 0.5 dB and the phase imbalance is less than 4° from a 180° phase difference.

The design of the mixer is to establish models for the RF balun and the LO balun first, by using an electromagnetic simulator, and the S parameters of the baluns can be derived for the models. The large signal model for the Schottky diode is provided by the process design kit (PDK) of the WIN Semiconductor which can be used in Agilent ADS. These individual components are combined in a harmonic balance simulator to optimize the performance of the mixer.

The power level of LO is 13 dBm and the conversion loss is less than 7.5 dB from 26 to 40 GHz with the IF fixed at 8 GHz. The LO to RF isolation is higher than 40 dB from 26 to 40 GHz, and the LO to IF and RF to IF isolations are higher

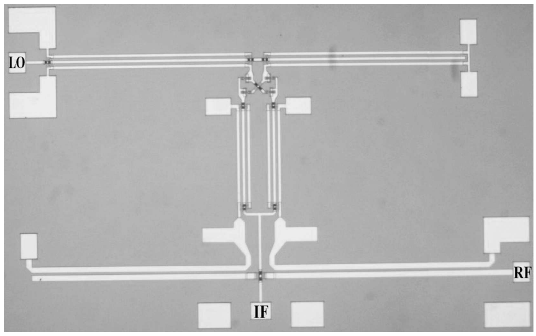

Fig. 6. Chip photograph of the mixer.

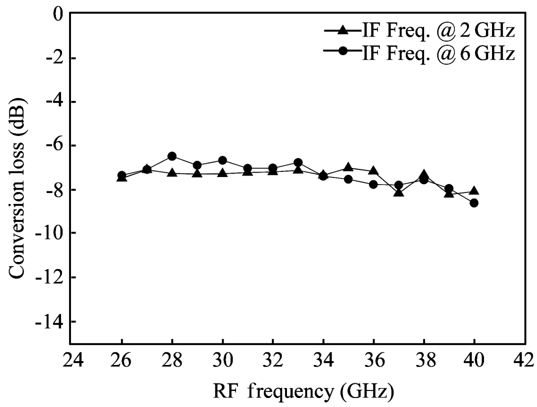

Fig. 7. Measured conversion loss of the mixer as a function of RF frequency.

than 30 dB over the same frequency range.

4. Experiment

The mixer was fabricated on the PHEMT MMIC process offered by the WIN Semiconductor in Taiwan. The diode was realized by connecting the drain and source of an HEMT device to form the cathode, and the gate length of the PHEMT was 0.15 μm with a gate width of 10 μm. The substrate was thinned down to 100-μm-thick. A chip photograph of the millimeter wave doubly-balanced mixer is shown in Fig. 6, and the chip size is 2×1.2 mm^2. The IF signal line comes straight out of the U section and crosses through the center of the RF balun with an air-bridge; this can not only save area but also keep the symmetry of the circuit.

The mixer was measured via on-wafer probing through ground-signal-ground RF probes. We used an Agilent E8257D PSG analog signal generator as the LO source, and a Rohde & Schwarz MP04 signal generator as the RF source; the IF output signal was measured by an Agilent E4440A spectrum analyzer. The insertion losses of the probes and cables were calibrated by an Agilent PNA E8363E network analyzer. The measurements were performed with the power level of LO at 13 dBm. Figure 7 shows the measured conversion loss of the mixer as a function of RF frequency. The conversion loss is 6.5 to 8.6 dB from 26 to 40 GHz with the IF fixed at 2 and 6 GHz, respectively. As RF frequency increases, the conversion loss increases slightly due to the loss in the baluns. Figure 8 shows the conversion loss of the mixer as a function of IF frequency at a fixed LO frequency of 26 GHz. The measured conversion

Table 1. Performance summary of doubly-balanced mixers.

Ref.	RF frequency (GHz)	Conversion loss (dB)	LO power (dBm)	IF bandwidth (GHz)	Chip size (mm^2)
[2]	18–40	6–9	17	DC-10	6.5
[3]	27–37	9–12	15	DC-3.5	1.15
[4]	16–40	8–13	14	1–5	1
[11]	26–38	5.4–10.7	12	DC-10	2.5
This work	26–40	5.9–8.6	13	DC-14	2.4

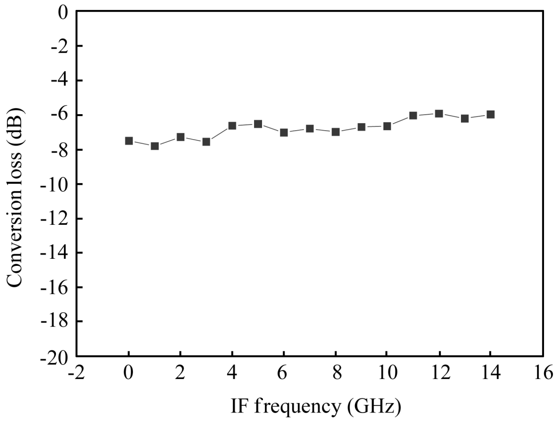

Fig. 8. Measured conversion loss of the mixer as a function of IF frequency.

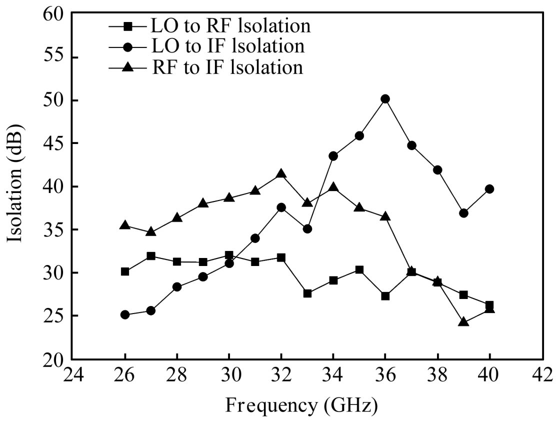

Fig. 9. Isolation of the mixer at the 13 dBm LO level, at 1 GHz IF frequency.

loss is 5.9 to 8 dB in an IF frequency range of DC to 14 GHz. Figure 9 shows the measured LO-to-RF, LO-to-IF and RF-to-IF isolations as functions of RF/LO frequency from 26 to 40 GH. The LO-to-RF isolation is higher than 26 dB from 26 to 40 GHz, and the LO-to-IF isolation is higher than 25 dB, and is greater than 30 dB above 30 GHz. The RF-to-IF isolation is higher than 24 dB over the same frequency range, and is greater than 30 dB from 26 to 37 GHz.

5. Conclusion

In this paper, we presented the design of a broadband doubly-balanced mixer with an operation frequency range from 26 to 40 GHz. A modified Marchand balun with compensated capacitances was proposed to improve the bandwidth and a design procedure for the Marchand balun has been presented. By using the coupled line of the U section between diodes and the RF balun, the even mode rejection and port to port isolation are improved. A comparison of the doubly-balanced mixer with previously reported work is summarized in Table 1. Maas *et al.*[2] reported a broad bandwidth and low conversion loss mixer in 1998; however, it has large dimensions and a high LO power level. The mixers designed by Lai *et al.*[3] and Chuang *et al.*[4] have small sizes, but the conversion loss is high. The proposed mixer has a low conversion loss and the widest IF bandwidth among the reported mixers.

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