Progress In Electromagnetics Research, Vol. 115, 289–301, 2011

DESIGN OF A MICROSTRIP BALANCED MIXER FOR SATELLITE COMMUNICATION

J. Guo, Z. Xu, C. Qian, and W. Dou

State Key Laboratory of Millimeter Waves
Southeast University, Nanjing, Jiangsu 210096, China

Abstract—The design and measured results of a compact, low cost, low conversion loss microstrip single balanced Schottky diodes mixer is proposed. This mixer is designed for Ka-band satellite transponder simulator to convert the 30 GHz radio-frequency (RF) signal down to the 20 GHz intermediate-frequency (IF) signal with 9.8 GHz local oscillator (LO) frequency. This design takes full advantage of the frequency relationship of the RF, IF and LO, which is 3 : 2 : 1. A microstrip rat-race ring is designed at the LO frequency, which also functions as a 180-degree hybrid coupler at the RF frequency by its intrinsic multi-band characteristic. The amplitude and phase balance at both LO and RF frequency are analyzed, which guarantee the state-of-art performance of this single balanced mixer. The multi-function open/short stubs and a lowpass filter (LPF) with bonding wires across the rat-race ring are optimized to realize this low conversion loss mixer. The measured results show that the conversion loss is less than 9 dB at the IF frequency from 20.0 to 21.6 GHz, and the power of the second harmonic of LO is -45 dBm with $+6.5$ dBm LO drive power. The 3rd order inter-modulation products (IMD3) could be lower than -50 dBc with LO power higher than $+7.8$ dBm at the input RF power of -15 dBm.

1. INTRODUCTION

The satellite transponder is a communication relay in the orbit. Various transponder configurations have been adopted, such as single-conversion transponder [1], double-conversion transponder and transponder with downconverter, onboard process and upconverter [2]. The single-conversion transponder has the advantages of smaller size

Received 21 February 2011, Accepted 31 March 2011, Scheduled 1 April 2011
Corresponding author: Jian Guo (james@seu.edu.cn).

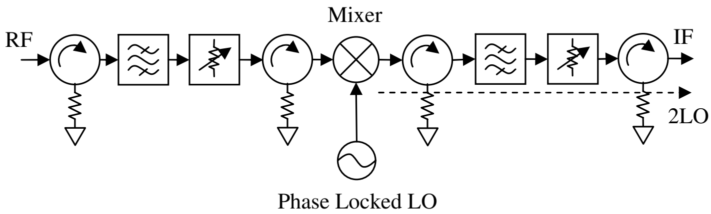

Figure 1. Typical diagram of the transponder simulator.

and less weight [3], which directly converts the received RF signal down to the IF signal and transmits it to the earth stations. The satellite transponder simulator, also known as test translator, is a module with basic functions of the transponder for the preliminary test of the RF and baseband units of the earth station. The typical diagram of the transponder simulator is shown in Fig. 1, which includes circulators, bandpass filters, a down-conversion mixer and adjustable attenuators.

The Ka-band single-conversion transponder simulator is designed to convert the 30 GHz RF signal (frequency f_{RF}) down to the 20 GHz one (frequency f_{IF}) with a 9.8 GHz LO frequency (frequency f_{LO}). In this case, the f_{LO} is lower than both the f_{RF} and f_{IF}, so the harmonics of the LO signal (especially the second harmonic at 19.6 GHz) and other modulation components between the RF signal and the LO signal are produced as spurious signals very close to or even falling into the IF frequency band [4]. The key parameters of this transponder including the rejection of second harmonic of LO (lower than -35 dBm), in-band spurious (lower than -60 dBc), amplitude response (± 1 dB), IMD3 (-50 dBc minimum at -15 dBm RF power), phase noise and so on. The spurious rejection and IMD3 mostly depend on the performance of the mixer. In order to improve isolation and suppress these spurious signals, the balanced drain mixer [4], balanced MMIC Schottky barrier diode mixer [3, 5, 6], resistive source-degenerated mixer [7], antiparallel diode pair harmonic mixer [1] and balanced resistive PHEMT mixer [8] have been proposed for the designs of the mixers. Schottky barrier diode is famous for its low noise and high cut-off frequency, and thus the diode pair or quad is often adopted for compact balanced MMIC mixer design utilizing broadband baluns such as Lange couplers, spiral baluns [3, 5], Marchand baluns and some others [9]. While in microstrip hybrid integrated mixer design, the input balun for the RF and LO could be realized by conventional 90-degree hybrid coupler and 180-degree rat-race ring [10–12], however restricted to low IF frequency mixer design [13].

In this paper, we present the design and performance of a microstrip single balanced Schottky diode mixer for the Ka-band transponder simulator. The design method has been briefly introduced in the earlier work [14]. A miscrostrip rat-race ring is constructed at the 9.8 GHz LO frequency, which also satisfies the amplitude and phase requirements at 30 GHz RF frequency. The matching open/short stubs are used to improve the conversion efficiency and the spurious rejection of the mixer, and an output lowpass filter with bonding wires across the hybrid ring is used to tap the IF out and to suppress some other spurious. High barrier Schottky diodes (0.7 V) are adopted to achieve better linearity at a given input RF level. By this way, this design ensures the state-of-art performance of the microstrip hybrid integrated single balanced mixer covering the 29.8 to 31.4 GHz RF and 20 to 21.6 GHz IF. A comparison of this mixer to previous work is also given. The design method could also be used in the mixer design for the single conversion transponder in the orbit.

2. CIRCUITS DESCRIPTION

This paper begins with an introduction to the topology of a single diode mixer in order to explain the design of the diode input and output matching circuits.

2.1. Design of the Single Diode Mixer

The single diode mixer designed for the Ka-band satellite transponder simulator is illustrated in Fig. 2.

This mixer consists of two open/shorted stubs and a single diode. The low pass filter at LO arm and the bandpass filter (BPF) at RF

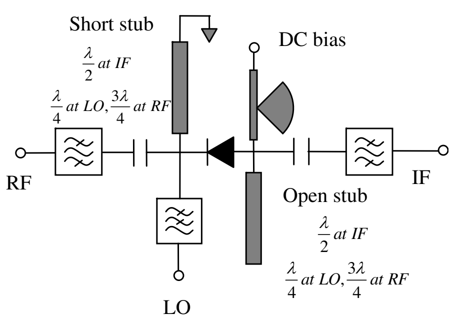

Figure 2. Schematic of the single diode mixer for Ka-band satellite transponder simulator(λ is one wavelength).

arm are used to prevent these two from leaking on each other. The output bandpass filter is used to suppress the spurious signals.

The open stub connected to the cathode of the diode has a length of a quarter wavelength at LO frequency. The functions of the open stub are as follows.

1) This open stub introduces a short at LO frequency and causes a reflection of LO component at the IF side. This way we suppress the LO odd harmonics at the IF side.
2) This open stub introduces a short at RF frequency and causes a reflection of RF component at the IF side because the RF frequency is three times that of the LO frequency. This way we suppress the RF harmonics at the IF side.
3) This open stub presents appropriate reactive terminations for the important idler frequencies which are about the odd harmonics that of the f_{LO}, such as f_{LO}, $f_{RF} - 2f_{LO}$ and so on.
4) This open stub presents an open at IF frequency because the IF frequency is two times that of the LO frequency.

The short stub connected to the anode of the diode has a length of a half wavelength at IF frequency, and the functions of the short stub are as follows.

1) This short stub introduces a short at IF frequency and causes a reflection of IF component at the IF side. This way we suppress the IF odd harmonics at the RF and LO side.
2) This short stub introduces a open at RF frequency without reflecting the RF signal because the RF frequency is one and a half times that of the IF frequency.
3) This short stub introduces a open at LO frequency without reflecting the LO signal because the LO frequency is half of the IF frequency.
4) This short stub presents appropriate reactive terminations for the important idler frequency: the even harmonics of f_{LO}, $2f_{RF} - 2f_{LO}$, $f_{RF} + f_{LO}$ and so on.

In all, the open and short stubs not only provide the short terminals for RF, LO and IF, but also function as reactive terminations for some of the idler frequencies, and thus called "multi-function stubs". However, the even harmonics of LO and RF, and the combination of them are not rejected by these stubs, which results in poor spurious rejection.

2.2. Topology of the Single Balanced Mixer

In order to improve the spurious rejection and the isolations between the three ports of the single diode mixer, a single balanced mixer is designed based on the single diode mixer, the schematic of which is shown in Fig. 3.

The schematic of single balanced mixer is similar to the single diode mixer except that the input network is constructed by the 180 hybrid coupler instead of the filter diplexer. The hybrid coupler needs not to be broadband to cover the RF and LO frequency because the RF frequency is three times the frequency of LO, and then the rat-race ring can be designed at LO frequency, which guarantees the amplitude and phase characteristics requirement at RF frequency too. The amplitude and phase balance of the rat-race ring is further analyzed in the following section. As shown in Fig. 2, the LO signal is applied to port 1, so the LO voltage has 180 degrees phase difference at the input of the two diodes. However the two diodes are reversed, then the LO signal is in-phase to the diodes. Similarly, the RF signal is out-of-phase to the diodes. Two short stubs and two open stubs are added at the inputs and the outputs of the diodes. The principles of how this stubs work are similar to the single diode mixer described above. The layout of this mixer is shown in Fig. 4. A lowpass filter is added at the LO arm to suppress the spurious signal from the LO source, and not a necessary part of the mixer. In order to save space, the diodes pair and the open/short stubs are placed inside the rat-race ring. The open/short stubs are further curved for the limited space inside the rat-race ring.

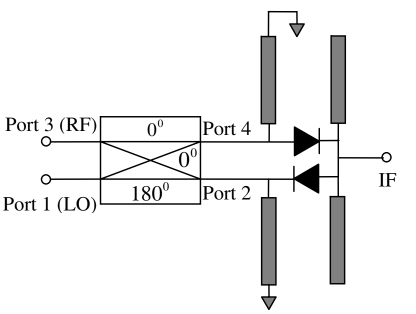

Figure 3. Schematic of the single balanced mixer.

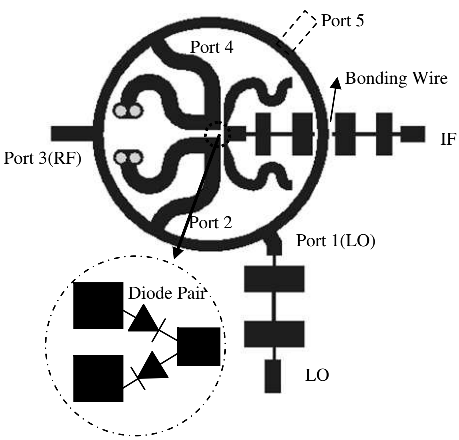

Figure 4. Layout of the single balanced mixer.

2.3. Design of the Rat-race Ring Coupler

The mixer is constructed on the Rogers® RT/Duroid 5880 with relative permittivity 2.2 and thickness 0.254 mm. The rat-race ring is designed at 9.8 GHz LO frequency, the radius of which is about 5 mm. The performances of the single balanced mixer depend on the amplitude and phase balance at the LO and RF frequencies. The S parameter of the rat-race ring as shown in Fig. 3 is defined as follow

$$S_{mn} = |S_{mn}|\, e^{-j\varphi_{mn}} \qquad m,\ n = 1, 2, 3, 4 \tag{1}$$

At LO frequency the expected amplitude difference between $|S_{21}|$ and $|S_{41}|$ is 0 dB and the expected phase difference between φ_{21} and φ_{41} is 180°. At RF frequency, the expected amplitude difference between $|S_{23}|$ and $|S_{43}|$ is 0 dB and the expected phase difference between φ_{23} and φ_{43} is 0°. The amplitude unbalance (AU) and phase unbalance (PU) in this paper are defined as

$$AU_{mni} = |S_{mi}| - |S_{ni}| \qquad m,\ n = 2, 4,\ i = 1, 3 \tag{2}$$

$$PU_{mni} = \varphi_{mi} - \varphi_{ni} \qquad m,\ n = 2, 4,\ i = 1, 3 \tag{3}$$

The simulated results of the amplitude and phase characteristics are shown in Fig. 5 and Fig. 6. The amplitude unbalance AU_{241} is less than 0.1 dB at port 1 (LO) at 9.8 GHz, and AU_{243} is less than 0.25 dB at port 3 (RF) at frequencies from 29.8 to 31.4 GHz. The phase unbalance PU_{241} is 182° at port 1 (LO) at 9.8 GHz, and PU_{243} is −3° to 7° at port 3 (RF) at frequencies from 29.8 to 31.4 GHz. Based on the simulated results, the amplitude and phase characteristics of the rat-race ring at both LO and RF frequencies could guarantee the performance of the single balanced mixer, which is further proved by the simulated isolation of the rat-race ring as shown in Fig. 7. The LO port and the

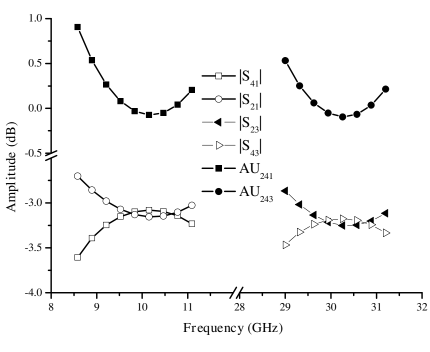

Figure 5. Amplitude unbalance of the rat-race ring.

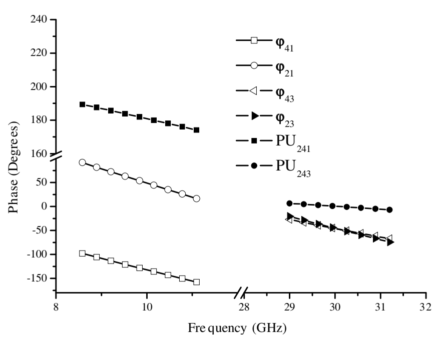

Figure 6. Phase unbalance of the rat-race ring.

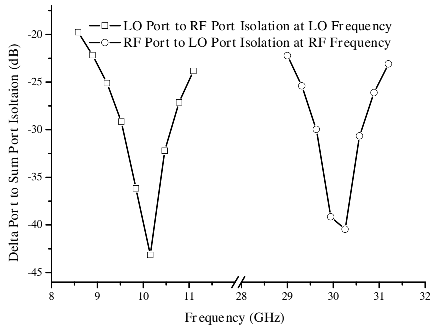

Figure 7. LO port to RF port and RF port to LO port isolation.

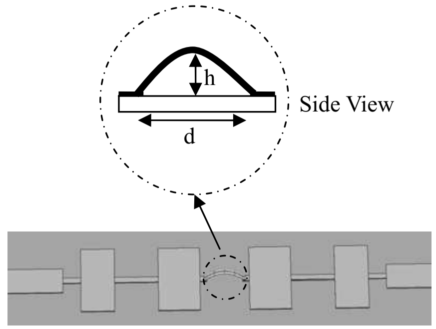

Figure 8. Model of the lowpass filter with bonding wires.

RF port are mutually isolated, so the LO/RF isolation of the single balanced mixer is usually as good as the rat-race ring itself [13].

2.4. Design of the Lowpass Filter for Tapping the IF Signal Out of the Single Balanced Mixer

When the Schottky diodes are placed inside the rat-race ring, there are generally two ways to tap the IF signal out, from some point of the rat-race ring or from a quarter wave radial stub at the diodes output by a small wire or a zero ohm resistor across the ring coupler. However, these two methods are suitable for relatively low IF frequency mixer. For the first one, there is indeed a point of the rat-race ring isolated from both the RF and LO, which is illustrated in Fig. 3 as port 5, which is 120° from both LO and RF ports. At this point, the isolations of LO (port 1) and RF (port 3) to port 5 at LO frequency are the same as LO to RF isolation at both LO and RF frequencies, which expected to be more than 20 dB. However the IF signals produced by the diodes from port 2 and port 4 are not combined in phase at port 5, which will degrade the conversion loss. For the second one, the radial stub can hardly function as a quarter wavelength stub at both RF and LO frequencies, and the small wire or resistor tapping the IF signal out will introduce spurious inductance at such a high IF frequency which will deteriorate the conversion loss. A new way proposed here for 20 GHz IF signal tapping out via a lowpass filter with bonding wires across the rat-race ring as illustrated in Fig. 4.

The high-low step impedance lowpass filter [15] with one half inside the rat-race ring and another half outside is designed by modifying a normal step-impedance lowpass filter. These two halves are connected by two parallel bonding wires acting as a high impedance microstrip line. One port of the filter is tapped at the common end of the diodes, while the other port is the IF output port. The middle high impedance microstrip line of the conventional step-impedance lowpass filter acting as an inductance is substituted by the bonding wires. The model of the lowpass filter is shown in Fig. 8. The distance of the two halves is fixed at 0.8 mm for the bonding wires crossing the 0.5 mm width ring and the diameter of the bonding wire is 0.0508 mm. In order to evaluate the impact of the bonding tolerance on the performance of this lowpass filter, the simulations are carried out with the bonding height "h" varying from 0.1 mm to 0.3 mm, the results of which are shown in Fig. 9. The return loss of this filter becomes a little worse with larger "h", but still good enough for this mixer application.

2.5. Simulation of the Mixer

GaAs flip chip Schottky diodes DMK2783 fabricated by Skyworks® are adopted. This low parasitic flip chip configuration diodes are suit for high frequency (20 to 100 GHz) application. The SPICE model provided by the manufacture could be used for the simulation of this mixer. First, the rat-race ring, the open/short stubs and the lowpass filter are simulated using Ansoft HFSS®, and then the S parameters of each are exported to Agilent Advanced Design System® to do a co-simulation together with the diode SPICE model. Some parameters of the rat-race ring and other components may need to be adjusted to achieve the optimal performance. The simulated results are shown in part 3 together with the measured results.

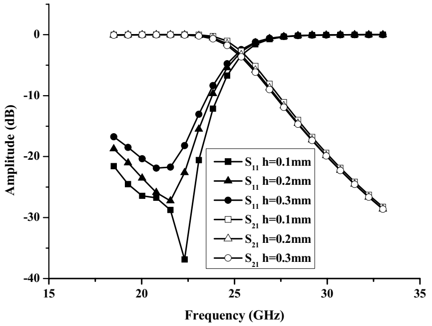

Figure 9. Simulated results of the lowpass filter.

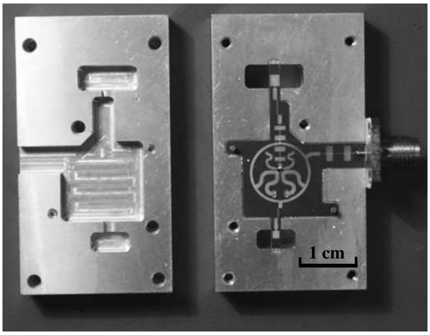

Figure 10. Photo of the single balanced mixer.

2.6. Spurious Signals Rejection

The spurious signals, such as harmonics and other mixed spurs, are inevitable in the mixer design. And the spurious rejection capability is also a key figure of merit of the mixer design. For Ka band transponder application, the second harmonic of f_{LO} is 19.6 GHz, which is very close to f_{IF}. From the simulated results, the power of second harmonic of f_{LO} of single diode mixer is larger than -10 dBm, and is vital to the system performance. However, from the simulated results of this proposed single balanced mixer, this spurious could be suppressed to about -50 dBm, and is reasonable for the transponder application. Even lower spurious power could be achieved by a doubly balanced mixer.

The measured results of the spurious signals' level are shown in part 3, and also the discussion.

3. PROTOTYPES AND RESULTS

The single balanced mixer prototype is designed using WR-28 rectangular waveguide flange for RF input, WR-42 for IF output and a SMA connector for LO injection. The waveguide flanges are used here just for the test of the mixer, and not needed when the mixer is integrated with other microstrip circuits. The diodes are mounted with silver epoxy alloy on the substrate, and the wedge wire bonding is performed by West bond 7476E. The final constructed prototype is illustrated in Fig. 10. The mixer with rat-race ring and filters size 2.1×1.7 cm, and 5×2.7 cm including the fixture with waveguide flanges.

The measured frequency response is shown in Fig. 11, which agrees well with the simulated result. The 3 dB bandwidth is about 3 GHz. The conversion loss is less than 9 dB with the RF frequency from 29.8 GHz to 31.4 GHz. Fig. 12 shows the power of second harmonic of LO. The measured result of the single balanced mixer agrees well with the simulated one, and is 40 dB lower than the simulated results of the single diode mixer with 6.5 dBm LO drive level. Other spurious signal are not critical as they are either relatively far away from the IF signal or low enough to be neglected. The isolation between LO and RF and the isolation between LO and IF of this single balanced mixer could not been measured in this situation because the cut-off frequencies of WR-28 and WR-42 waveguides are higher than the LO frequency, which supposed to be better than 20 dB from the simulated results.

The simulated and measured results of conversion loss of this mixer at +5 dBm and +7 dBm drive level are shown in Fig. 13. The conversion loss for +5 dBm LO is flat at RF power below -15 dBm, and

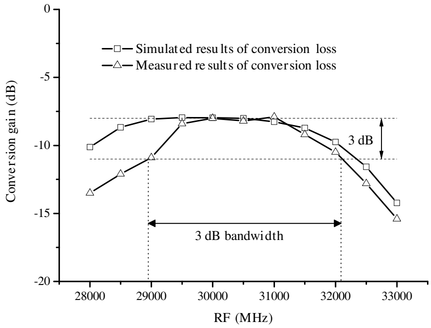

Figure 11. Frequency response of the single balanced mixer with 6.5 dBm LO power.

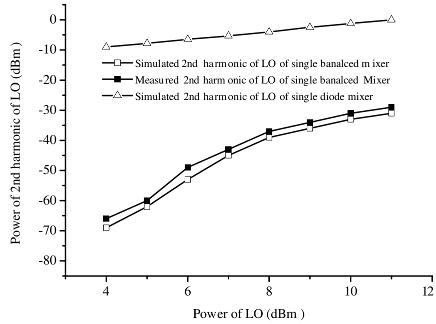

Figure 12. Power of second harmonic of LO measured at the IF port.

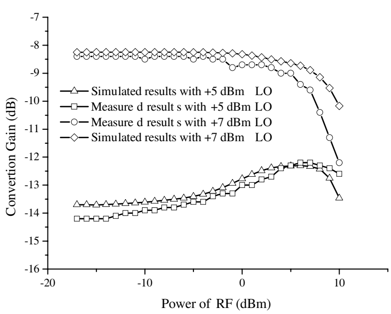

Figure 13. Power of RF vs. conversion gain at +5 and +7 dBm drive level at 30.2 GHz RF frequency.

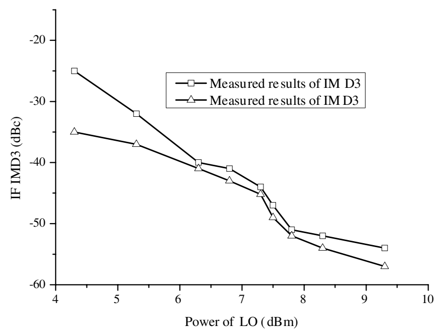

Figure 14. IF IMD3 vs. LO power with −15 dBm RF power at 30.2 GHz.

gradually becomes higher until +5 dBm RF level, and then gets lower. This is because the mixer is driven by both the RF and LO power at low LO power. However the conversion loss for +7 dBm LO is fairly flat at the RF power below 0 dBm, and then gets compressed at higher RF power, which is the normal phenomenon for nonlinear devices. From these simulated and measured results we can see that low LO power could lead to poor linearity, so in order to get better linearity, higher LO power should be used. Because the 1 dB compression point could not be measured at low LO power, the IMD3 is used here to characterize the linearity. The measured and simulated output IF IMD3 are shown in Fig. 14, and the measured IMD3 is a little larger

Table 1. Comparison of this work to the previous ones.

Reference	Circuits type	RF frequency (GHz)	IF frequency (GHz)	LO drive lever (dBm)	Conversion Gain (dB)	Spurious (dBm)
[1]	HIC	28.395 ∼ 29.015	15.595 ∼ 19.215		−11	
[3]	MMIC	30.6 ∼ 31	20.8 ∼ 21.2	13	−7.8 ∼ −7.5	−20 (LO-to-RF)
[4]	HIC	17.8 ∼ 18.4	12.3 ∼ 12.9	4	−26	−40 (3LO-to-RF)
[5]	MMIC	18 ∼ 32	DC ∼ 8	11	−9 ∼ −7	−30 (LO-to-RF)
[8]	MMIC	6.725 ∼ 7.025	4.5 ∼ 4.8	0 ∼ 2	12	−48 (2LO-to-RF)
[16]	MMIC	9 ∼ 31	DC ∼ 2	9.7	−9 ∼ −12	−20 (LO-to-RF) −27 (2LO-to-RF)
This work	HIC	29.8 ∼ 31.4	20 ∼ 21.6	6.5	−9 ∼ −8	−45 (2LO-to-RF)

than the simulated one. In order to get −50 dBc IMD3 at the RF power of −15 dBm, the drive LO power should be higher than +7.8 dBm.

The comparison of the proposed mixer to previous work is shown in Table 1.

4. CONCLUSION

This paper presents a novel way to design hybrid integrated mixers for Ka-band satellite transponder simulator to convert the 30 GHz RF signal down to the 20 GHz IF signal with 9.8 GHz LO frequency. The design of the microstrip single balanced mixer takes full advantage of the frequency relationship of the RF, IF and LO, which is about 3 : 2 : 1. First, the rat-race ring coupler is designed at the LO frequency, which also functions as a 180-degree hybrid coupler at the RF frequency. Second, the diode input and output matching circuits are also designed based on the frequency relationship. Third, a lowpass filter with bonding wires across the ring is used to tap the IF signal out from the inside ring. The measured results show that the conversion loss is less than 9 dB in 1.6 GHz bandwidth, and the 3 dB bandwidth is from about 29 GHz to 32 GHz RF frequency. The measured spurious power of second harmonic of LO is −45 dBm with 6.5 dBm LO drive level, and even lower spurious power could be achieved by a doubly balanced mixer. The IMD3 could be lower than −50 dBc with LO power higher than +7.8 dBm at the input RF power of −15 dBm.

Based on the measured results and the analysis above, the designed single balanced mixer is qualified for the application in the Ka-band satellite communication transponder simulator.

REFERENCES

1. Mizuno, H. and H. Kato, "30 GHz band low noise receiver for 30/20 GHz single-conversion transponder," *IEEE Journal on Selected Areas in Communication*, Vol. 1, No. 4, September 1983.
2. Elbert, B. R., *The Satellite Communication Applications Handbook*, 2nd edition, 81–82, Artech House, Boston, London, 2004.
3. Ryu, K.-K., D.-P. Jang, M.-Q. Lee, I.-B. Yom, and S.-P. Lee, "Design of double-balanced MMIC mixer for Ka-band satellite communications," *Microwave and Optical Technology Letters*, Vol. 34, No. 6, Sep. 20, 2002.
4. Kenji, I. and K. Kawakami, "A drain mixer with low spuriousness for satellite transponders," *Electronics and Communications in Japan*, Part 2, Vol. 80, No. 12, 1997.
5. Trantanella, C. J., "Ultra-small MMIC mixers for K- and Ka-band communication," *IEEE MTT-S Digest*, 2000.
6. Lai, Y.-A., S.-H. Hung, C.-N. Chen, and Y.-H. Wang, "A miniature millimeter-wave monolithic star mixer with simple IF extraction circuit," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 17–18, 2433–2440, 2009.
7. Wei, H. C., R. M. Weng, and S. Y. Li, "A broadband high linearity and isolation down-conversion mixer for wimax applications," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 11–12, 1555–1565, 2009.
8. Bhattacharya, A., M. Bhavsar, J. Thakkar, S. M. Srivastava, and V. K. Garg, "Advanced high performance MMICs for satellite transponder," *APMC 2005 Proceedings*, 2005.
9. Jafari, E., F. Hodjatkashani, and R. Rezaiesarlak, "A wideband compact planar balun for UHF DTV applications," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 14–15, 2047–2053, 2009.
10. Monti, G., F. Congedo, and L. Tarricone, "On the use of a rat-

race coupler in the design of a 180° phase shifter," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 8–9, 1201–1210, 2009.

11. Wang, J., J. Ni, S. Zhao, and Y.-X. Guo, "Compact microstrip ring branch-line coupler with harmonic suppression," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 16, 2119–2126, 2009.
12. Hammou, D., E. Moldovan, and S. O. Tatu, "Modeling and analysis of a modified V-band MHMIC six-port circuit," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 10, 1419–1427, 2010.
13. Mass, S. A., *Microwave Mixers*, 2nd edition. Artech House, London, 1993.
14. Guo, J., Z. Xu, C. Qian, and W. Dou, "A novel design of single balanced mixer for Ka-band satellite transponder simulator," *APMC 2009 Proceedings*, 2009.
15. Hong, J. S. and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, John Wiley & Sons, Inc., New York, 2001.
16. Bao, M., H. Jacobsson, L. Aspemyr, G. Carchon, and X. Sun, "A 9–31-GHz subharmonic passive mixer in 90-nm CMOS technology," *IEEE Journal of Solid-state Circuits*, Vol. 41, No. 10, October 2006.