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A W-Band High Isolation Single-Balanced Mixer in GaN HEMT Technology

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Abstract—A W-band high isolation single-balanced mixer using a 0.1-µm GaN high-electron mobility transistor process is proposed in this paper. The diode is biased near the threshold voltage to reduce drive level, and the needed LO power is only 3 dBm. Moreover, the reasonable diode layout and phase compensation structure are used in the proposed mixer to enhance the LO-to-RF isolation. The measured results of the proposed mixer demonstrate a single-sideband conversion loss of 9–10.6 dB and a LO-RF isolation of 40 dB from 75 to 110 GHz with 7 dBm LO power. Moreover, a DC-to-18 GHz IF bandwidth is achieved with the LO frequency fixed at 110 GHz. The 1 dB compression point of the proposed mixer is 11 dBm with 16 dBm LO power. The measurement results indicate that GaN mixer has great potential for W-band transceiver system applications.

1. INTRODUCTION

Thanks to its high power-density and high breakdown levels, Gallium-Nitride (GaN) semiconductor technology is well known for power amplifier and switch applications. Also, GaN technology has been widely used for low noise amplifier (LNA) applications owing to its good low noise performance [1] and high input-power handling capability, which could eliminate the limiter before the LNA in the receiver. Nowadays, GaN has become a promising technology to realize a fully integrated transceiver chain in a single technology [2–4]. Recently, GaN technology is trending to replace gallium arsenide (GaAs) in transceiver front-end circuitry in the favor of high robustness at high frequency with large operating power. As a key component of transceiver front-end circuitry, a good performance mixer circuit is highly desirable for modern wireless applications. Therefore, it will be interesting to investigate a GaN-based mixer which is important to realize fully GaN-based transceiver front-end in the future. To the authors' best knowledge, there are a few GaN-based mixers have been reported [5–9], and among these, only one is for W-band, which is a double-balanced resistive mixer, featuring a 5 GHz bandwidth for the IF signal and a conversion loss 12 dB. However, this mixer requires up to 24 dBm LO power [8].

This study proposes a W-band high isolation single balanced mixer in 0.1 µm GaN HEMT technology. The measured results show that the single-sideband (SSB) conversion loss is less than 10.6 dB, and the LO-to-RF isolation is better than 33 dB over the W-band from 75 to 110 GHz at 7 dBm LO power. A DC-to-18 GHz IF bandwidth is achieved with the LO frequency fixed at 110 GHz.

2. MIXER DESIGN

The schematic of the proposed mixer is shown in Fig. 1. It consists of a LO balun, two diodes, a power divider, an IF low pass filter, and bias circuits. In this design, two diodes devices constitute the core of the mixer. The size of diodes has a significant influence on both the conversion loss and the bandwidth

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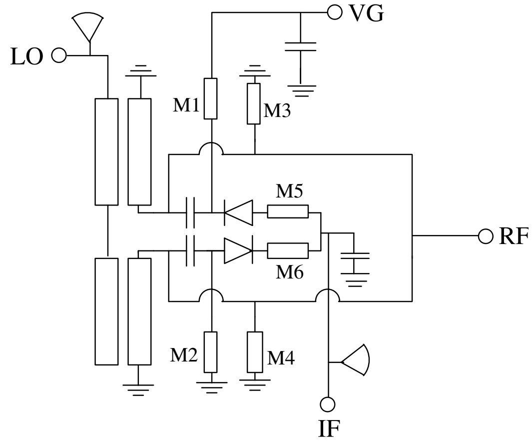


Figure 1. Schematic of the proposed single-balanced mixer.

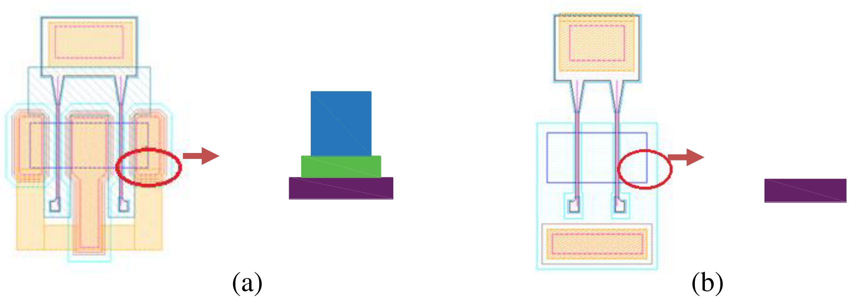


Figure 2. The layout of diodes in (a) three metal layers, (b) single metal layer.

of the mixer, which is $2 \times 10\,\mu\mathrm{m}$ in this design. The diode is realized by connecting the drain and source of an HEMT device to form the cathode. Usually, the GaN HEMT consists of three metal layers in the drain and source as shown in Fig. 2(a), providing a better power handling capacity for the design of power amplifier. However, the HEMT with only one metal layer in the drain and source which is illustrated in Fig. 2(b) can also be used for the design of mixer. The comparison of simulated results of electromagnetic coupling between the diodes pairs with different layouts is depicted in the Fig. 3. The simulated results reveal that the electromagnetic coupling between the antiparallel diodes pair is proportional to the thickness of the metal. Ideally, the pair of difference LO signals will be eliminated at the common node of the two diodes, but in practice the LO signals cannot be eliminated completely due to the electromagnetic coupling between the two diodes, which will reduce the LO-RF isolation. Therefore, the drain and the source of the HEMT in this design only contain one layer of metal to improve the LO-RF isolation.

The electrical behavior of the proposed diode can be modeled by the equivalent circuit model shown in Fig. 4. L_s and C_p account for the parasitic inductance and parasitic capacitance. R_s consists of two parts, source/drain resistances and gate metal resistance. R_j represents the channel resistance. C_j refers to the capacitance between the Schottky contact and the channel. Those element parameters of the equivalent circuit were extracted from the measured S-parameters.

The required drive level can be reduced if the diode is biased toward the threshold voltage. The bias voltage VG is set at $-3.2\,\mathrm{V}$ in this design, which is provided by a quarter wave length line of the LO centre frequency. DC blocking capacitors have been included between the LO balun and the diodes.

The input unbalanced LO signal is divided by the balun into a pair of balanced signals with equal amplitude but 180° out of phase, and the pair of difference signals are fed to the diodes. The Marchand balun, which is suitable for a broadband balun, has been chosen in this design. The balance of the balun has a significant impact on the bandwidth and isolation of the mixer. Since the phase velocities

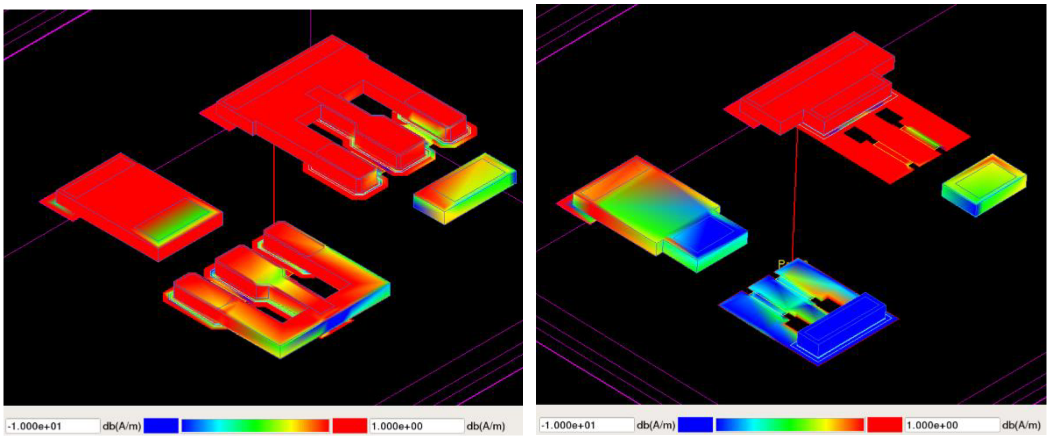


Figure 3. Comparison of simulated electromagnetic coupling between diodes pairs in different layouts, (a) HEMT with the drain and source consists of three metal layers, (b) HEMT with the drain and source consists of single metal layer.

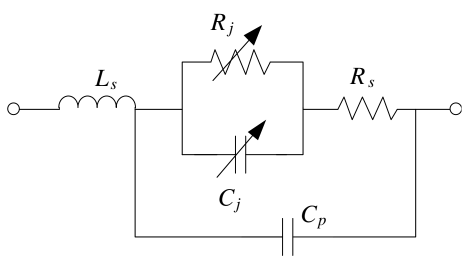


Figure 4. Equivalent circuits model of the proposed diode.

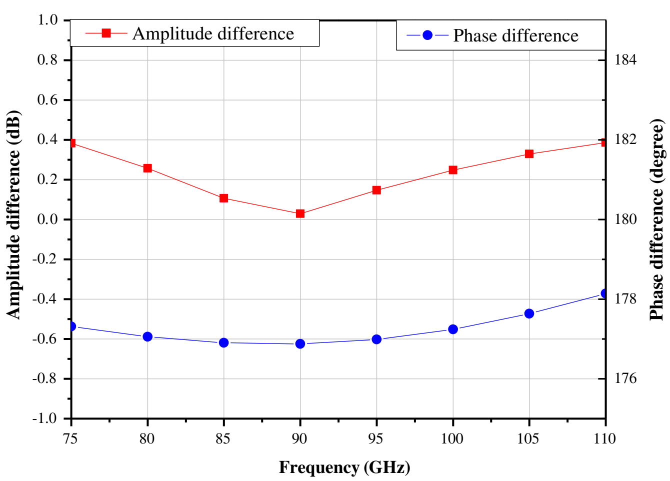


Figure 5. EM simulated, amplitude and phase difference of LO balun.

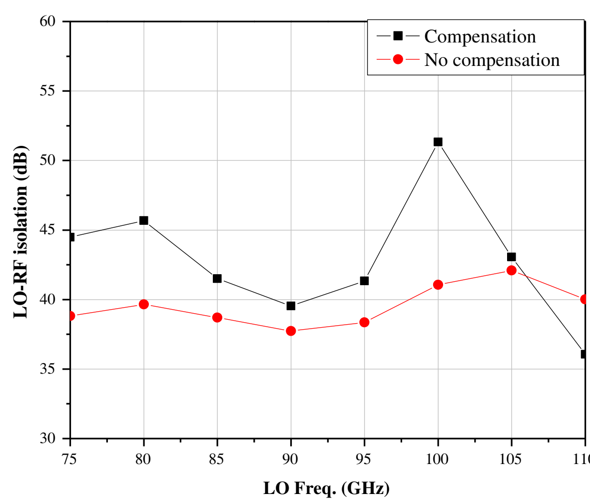
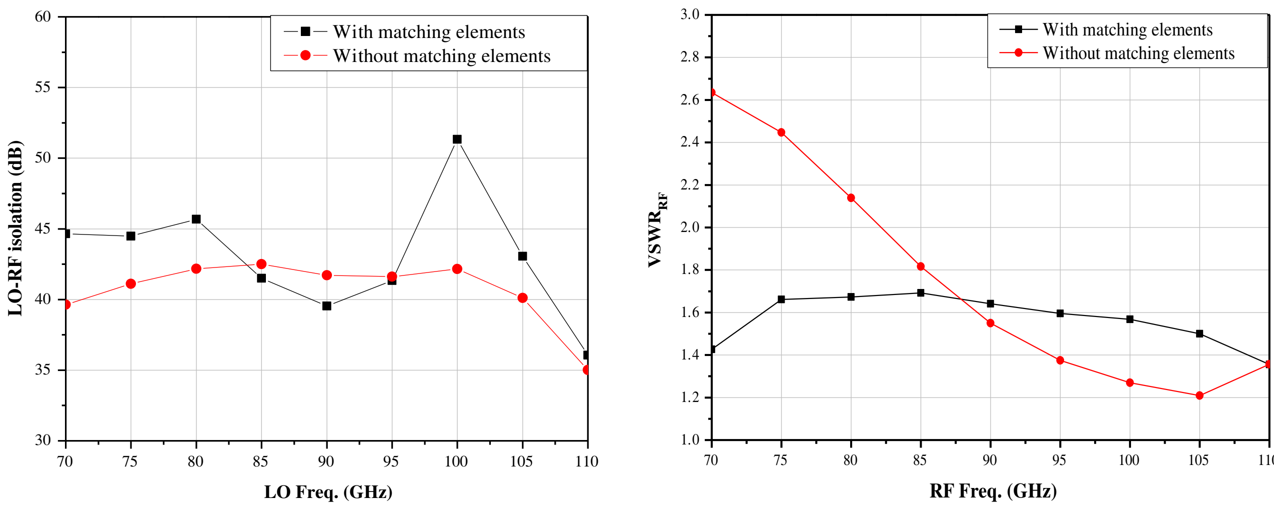


Figure 6. Comparison of the simulated LO-to-RF isolation with/without phase compensation.

of even and odd modes are unequal for planar microstripe baluns, the magnitude and phase of the output signals are unbalanced [10]. Fig. 5 shows the amplitude and phase difference predicted by the EM simulation of the LO balun. The amplitude imbalance is $< 0.4\,\text{dB}$, and the phase difference is

< 3.3° across the W-band. The microstrip line M5 is designed to have a different length from M6 to compensate the phase velocity inequality. The optimized structure improves the isolation between LO to RF port, as shown in Fig. 6.

The microstrip lines M3, M4 are simultaneously matching elements and provide a frequency correction, which improve the RF VSWR and LO-to-RF isolation, as shown in Fig. 7. The input RF signal is also split into a pair of equal amplitude in-phase output signals through the power divider. The IF port is designed with a low-pass filter, which suppresses LO and RF signal at the IF port.



(a) (b)

Figure 7. Simulated mixer performance with/without matching elements of (a) LO-to-RF isolation, (b) RF VSWR.

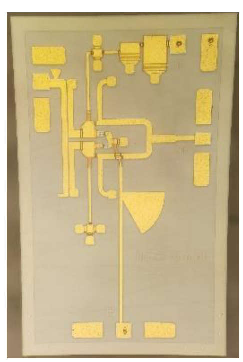


Figure 8. Chip photo of the mixer.

The circuit design described above was simulated by Keysight Advanced Design System (ADS). The entire passive layout simulation has been performed and optimized by a 2.5D planar EM-simulator (Momentum). The chip microphotography is presented in Fig. 8, and the chip area with the dicing street is 1030 µm × 1600 µm.

3. FABRICATION AND MEASUREMENT

The mixer was fabricated using the 0.1 µm GaN HEMT MMIC process. Electron-beam lithography has been used to produce a 100 µm T-shaped gate on the AlGaN/GaN HEMT structure with ultrahigh aluminum content. The metal organic chemical vapor deposition (MOCVD) was employed to prepare the AlGaN/GaN HEMT material structure with ultrahigh Al content on 100 mm semi-insulated SiC substrates. The detailed process used for W-band AlGaN/GaN HEMT MMIC fabrication has been described in [11].

The comparison of conversion loss between simulated and measured results is shown in Fig. 9. The results show that the measured results have a great agreement with the simulated ones. The conversion loss is below 10.6 dB from 75 GHz to 110 GHz at a fixed IF frequency of 1 GHz, $P_{LO} = 7$ dBm and VG $= -3.2$ V. It should be pointed out that the measured performance of the mixer should also be valid for a frequency below 75 GHz, due to the bandwidth limitation of the LO power amplifier. At the fixed LO frequency of 110 GHz, a conversion loss of 10–13 dB has been achieved when the IF is below 18 GHz. This indicates that the IF bandwidth is DC-18 GHz.

Figure 10(a) shows the conversion loss of the mixer with the LO levels of 3 dBm, 5 dBm, 7 dBm, and 9 dBm, respectively. The conversion loss is 8.7 to 11 dB from 75 to 110 GHz. The results reveal that the LO power of 3 dBm is enough to drive the mixer, because the conversion loss is almost saturated

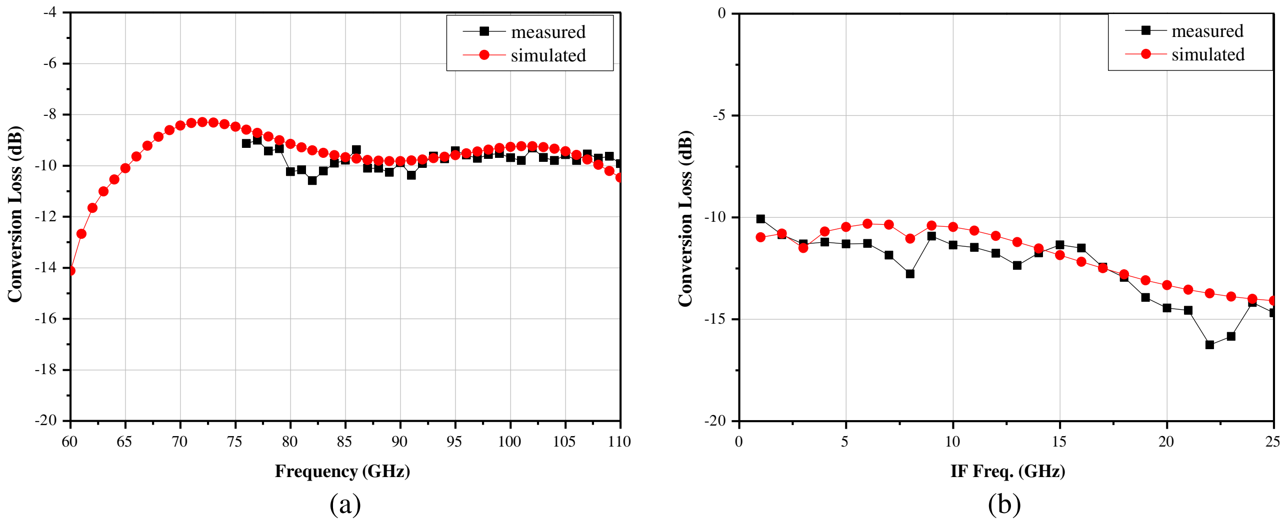


Figure 9. Comparison of conversion loss between simulated results and measured results, (a) versus RF frequency, (b) versus IF frequency.

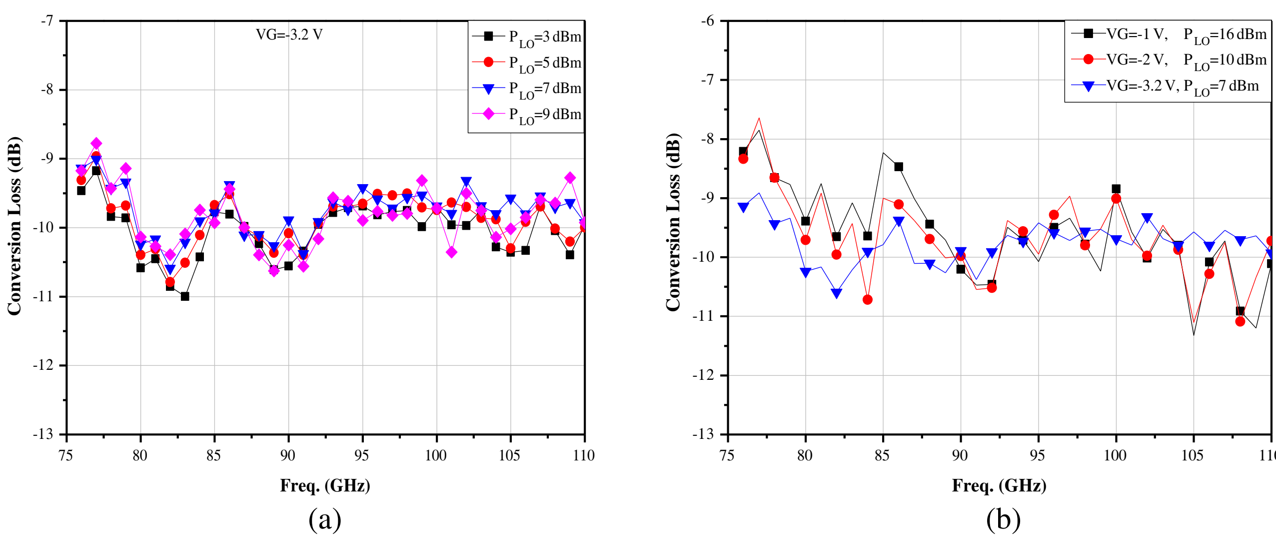


Figure 10. Measured results of conversion loss, (a) at different LO power, (b) at different LO power and VG.

with this LO level. Fig. 10(b) shows the conversion loss with a bias voltage VG of −1 V, −2 V, and −3.2 V, respectively. In order to drive the mixer with these bias voltages, P_{LO} is provided with 16 dBm, 10 dBm, and 7 dBm, respectively. The conversion loss is 7.7 to 11.2 dB from 75 to 110 GHz at different VGs.

The effect of diode layout is shown in Fig. 11(a). The LO-RF isolation is measured at a fixed IF frequency of 1 GHz, LO power of 7 dBm, and VG = −3.2 V. It can be seen that LO-RF isolation of the mixer with single metal layer diodes is 10 dB better than the mixer with three metal layers diodes. The LO-RF isolation of the mixer with single metal layer diodes is about 40 dB and better than 33 dB over the overall W-band. The measured results of LO-RF isolation at different LO powers and VGs are presented in Fig. 11(b). The LO-RF isolation of the mixer is better than 32 dB at different LO powers and VGs.

The RF input power at 1 dB gain compression is presented in Fig. 12. In the 75–110 GHz frequency band, $P_{1\,\mathrm{dB}}$ of the mixer is about 11 dBm at a fixed IF frequency of 1 GHz, P_{LO} = 16 dBm and VG

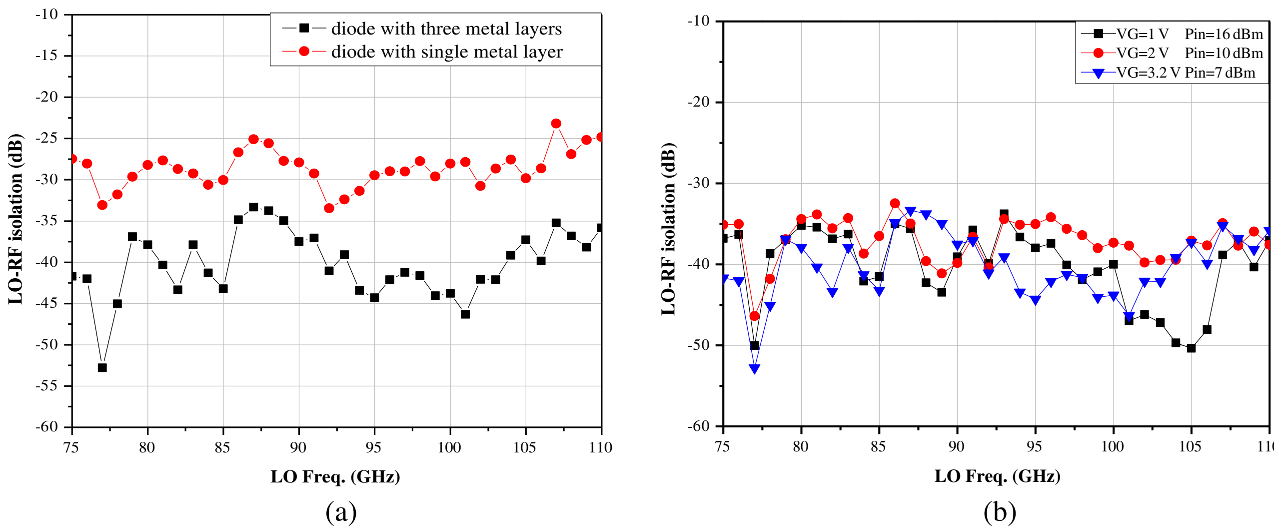


Figure 11. Measured LO-RF isolation, (a) with different diodes, (b) at different LO power and VG.

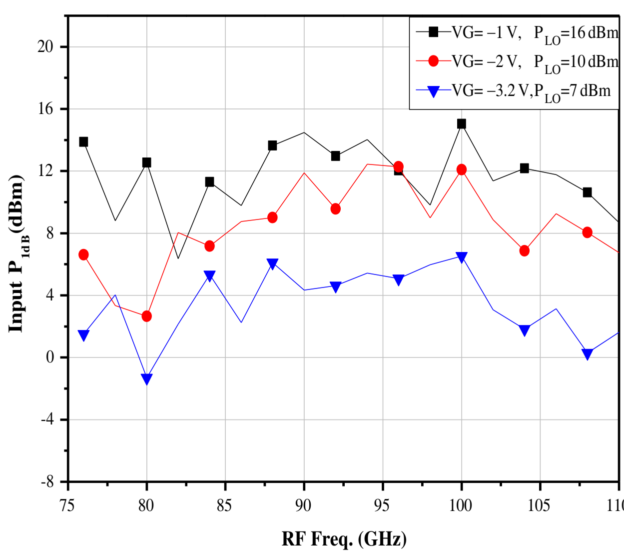


Figure 12. Measured result of input $P_{1\,\mathrm{dB}}$ at different LO power and VG.

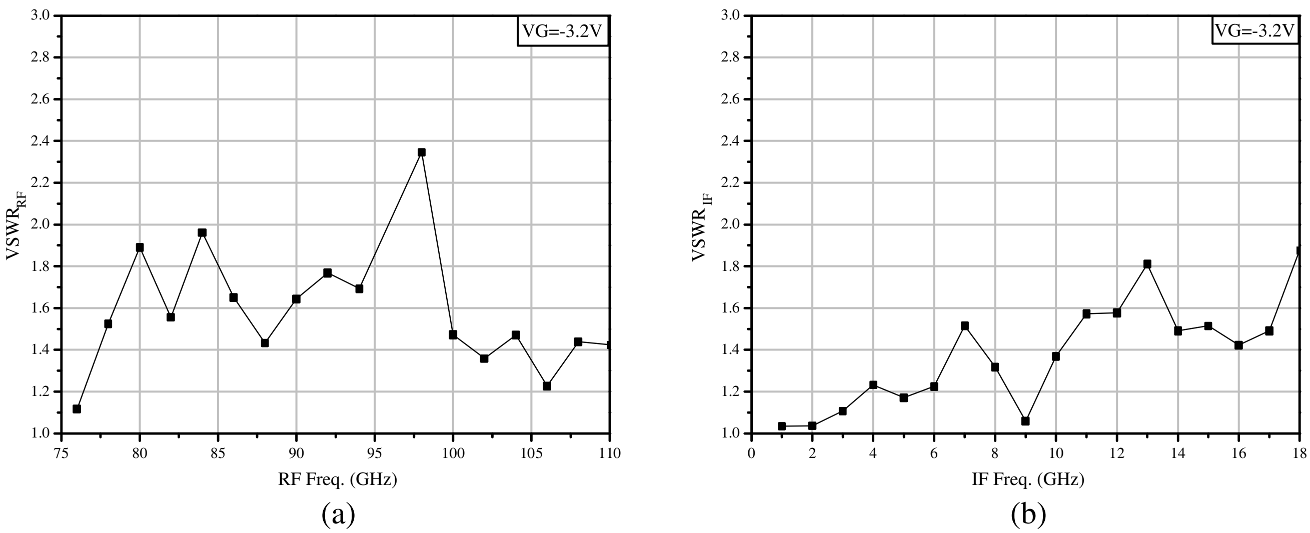


Figure 13. Measured RF and IF VSWR of the proposed mixer, (a) RF VSWR, (b) IF VSWR.

= −1 V. $P_{1\,\mathrm{dB}}$ has been significantly benefited from the bias and LO-level, which has improved about 8 dB compared to VG = −3.2 V and P_{LO} = 7 dBm. This is a consequence of enhancing the usable linearity range of the mixer. Therefore, when the mixer is applied in the system, the bias and LO power can be changed according to the linearity requirements of the system to avoid wasting power consumption. Fig. 13(a) shows the VSWR at the RF ports of the mixer circuit from 75 to 110 GHz. The RF VSWR was measured with the IF fixed at 1 GHz and the LO input power of 7 dBm. Fig. 13(b) shows the VSWR at the IF ports of the mixer circuit from DC to 18 GHz. The IF VSWR was measured with the LO fixed at 110 GHz and the LO input power of 7 dBm.

The performance comparison between the proposed design and other reported mixers with similar operating frequencies is listed in Table 1. Among these listed results, the proposed mixer demonstrates a wide bandwidth, good LO-RF isolation, low conversion loss with good flatness, as well as high $P_{1\,\mathrm{dB}}$. Moreover, the needed LO power is only 3 dBm, which is lower than all the listed works. The good performances of the proposed mixer demonstrate that GaN mixer has good potential for W-band transceiver system applications.

Table 1. Performance comparison between the propsed design and other products.

Ref.	Process	Conversion Loss (dB)	RF Freq. (GHz)	IF Freq. (GHz)	LO Power (dBm)	LO-RF Isolation (dB)	$P_{1\,\mathrm{dB}}$ (dBm)
[12]	GaAs pHEMT	4.7–17	75–105	DC-21	11	15	/
[13]	InP HEMT	≤ 12	75–107	1	8	27	> 5
[14]	GaAs pHEMT	10–14	78–114	DC-18	10	20.5@LO, 42@2LO	/
[8]	GaN HEMT	11–15	74–94	0.5–5	24	> 45	12@84 GHz, 15@94 GHz
This work	GaN HEMT	9–10.6	75–110	DC-18	3–16	40	> 10 @84–108 GHz, $P_{LO} = 16$ dBm

4. CONCLUSION

In this paper, a wideband high isolation single-balanced mixer has been successfully developed using a 0.1 μm GaN HEMT process. The diodes are biased to reduce LO drive power to 3 dBm. Moreover, the reasonable diode layout and phase compensation structure are used in the proposed mixer to enhance the LO-to-RF isolation. In addition, the mixer exhibits other good performances such as low conversion loss, high P1dB, and wide bandwidth. The excellent measurement results indicate that GaN mixer has great potential for W-band transceiver system applications.

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