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# A 220-GHz Third-Harmonic Mixer Based on Balanced Structure and Hybrid Transmission Line

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**ABSTRACT** This paper proposes a novel 220-GHz third-harmonic mixer, which using a waveguide-fin-coplanar waveguide-microstrip line hybrid transmission line as the carrier circuit, based on the balanced structure and the co-directional diode pair. The hybrid transmission line is designed to allow the mixing signals to be input in the correct direction in order to achieve the third-harmonic mixing. Then, high isolation between the radio-frequency (RF) port and the local oscillator (LO) port is performed through the mode orthogonality of the balanced structure. The metal slots on the fin line are used as the matching network for the RF signal to enable the RF signal into the diode pair with low loss. The experimental test results show that the conversion loss of the third-harmonic mixer is better than 18.5 dB in the range of 210–230 GHz and has a tiny fluctuation in the broad range of intermediate frequency (IF).

**INDEX TERMS** Terahertz, hybrid transmission line, odd harmonics mixer, balanced structure.

## I. INTRODUCTION

In recent years, with the continuous improvement of application requirements, terahertz technology has become an emerging interdisciplinary research hotspot due to advantages in communications, radar, security, electronic countermeasures, astronomical observation and other applications [1]–[4]. Terahertz radar, communication, and radiometer systems are important applications of terahertz technology and have immense research value. In these terahertz systems, mixer, as an indispensable component, plays a vital role in the performance of the systems [4]–[6]. Especially in the case of absence of terahertz low noise amplifier, the impact of the mixer on the system is more significant due to its role as the first stage of the receiver system [5], [6]. Besides, because of the difficulty in fabricating terahertz oscillator sources, harmonic mixers that can reduce local oscillation frequency are widely used to make the LO power requirements more readily complied with [7]–[12]. At present, the researches of terahertz harmonic mixers mostly focus on even harmonic mixer, for which, an appropriative parallel diode pair is developed to realize the stable and straightforward design of even harmonic mixing circuits [10]–[13]. However, this also limits the application of some special structures in harmonic mixing circuits, such as balanced structure, fin line, etc. But, since the fundamental diode connection mode of odd harmonic mixing circuit is different from that of even harmonic mixing circuit, [7], [14]–[18], these special structures can be used in odd harmonic mixing circuit to obtain better performance, and smaller size, higher isolation. The research of odd harmonic mixer not only enriches the study of terahertz harmonic mixer but also provides a new construction method for terahertz communication and radar systems.

In this paper, a third-harmonic mixer using a hybrid transmission line and the balanced structure is proposed. The hybrid transmission line, which is composed of rectangular waveguide, fin line, coplanar waveguide and microstrip lines, controls the input direction of the RF and LO signals. A co-loading of RF signals and a reverse loading of LO signals on the co-directional series diodes (DBES105A) is achieved to output odd mixing components and suppress even

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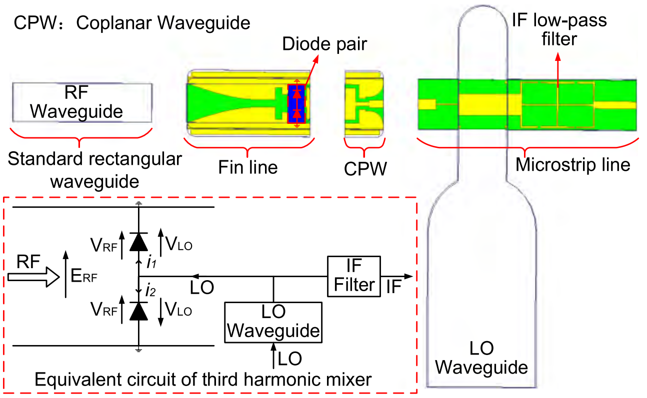


**FIGURE 1.** The longitudinal section and equivalent circuit of the proposed third-harmonic mixer.

harmonic components. The Fin line and the coplanar waveguide compose a balanced structure, which has a high isolation characteristic due to the orthogonality of transmission modes at both ends. Due to this high isolation characteristic the LO low-pass filter in traditional mixers [9]–[11], [14]–[18] is no longer needed, which can reduce the size of the whole circuit and internal transmission loss. The RF signal matching network is realized by etching metal slots on the fin line that can perform impedance changes. The LO signal matching network is composed of multi-section high-low impedance lines running through the coplanar waveguide and microstrip transmission line. Besides, the improved split-ring resonator structure [19] is adopted for the IF low-pass filter in order to decrease the overall size of the circuit.

## II. MIXER DESIGN

The longitudinal section of the third-harmonic mixer is depicted in Figure 1. It consists of waveguide-fin-coplanar waveguide-microstrip hybrid transmission line, LO waveguide-to-stripline transition, planar Schottky diode pair(DBES105A), IF low-pass filter, as well as the RF and LO matching networks. The LO input rectangular waveguide performs impedance matching by decreasing the height (narrow side) to achieve a wide-band, low-loss transition structure. The waveguide-to-stripline transition structure with both-end conducting is used to realize the integrated design of the LO input and IF output, which makes the layout of the third harmonic mixing circuit more reasonable. As described by the equivalent circuit in Figure 1, the RF signal inputs from the standard rectangular waveguide to the fin line and then concentrates in the EH1 mode near the diodes, and feeds into the diodes by direct induction. Due to the co-directional configuration of the diodes, the RF signal forms a co-directional feeding, and it is clear that the LO signal can be fed reversely into the two diodes. So that the mixing circuit will output odd harmonic component and suppress even harmonic component.

### A. THE SPECIAL STRUCTURE IN MIXER

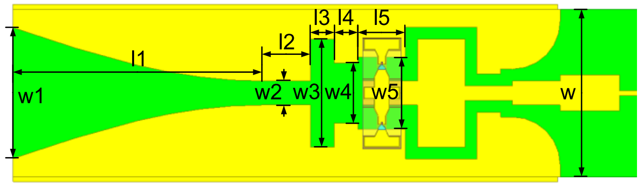


**FIGURE 2.** The settings of the RF signal matching network using the metal slots on unilateral fin line, where quartz substrate width w=0.7mm; w1=0.546mm, w2=0.1mm, w3=0.45mm, w4=0.25mm w5=0.3mm, l1=1.05mm, l2=0.2mm, l3=0.1mm, l4=0.1mm, l5=0.2mm. And the gradient function of the fin line is a cosine function.

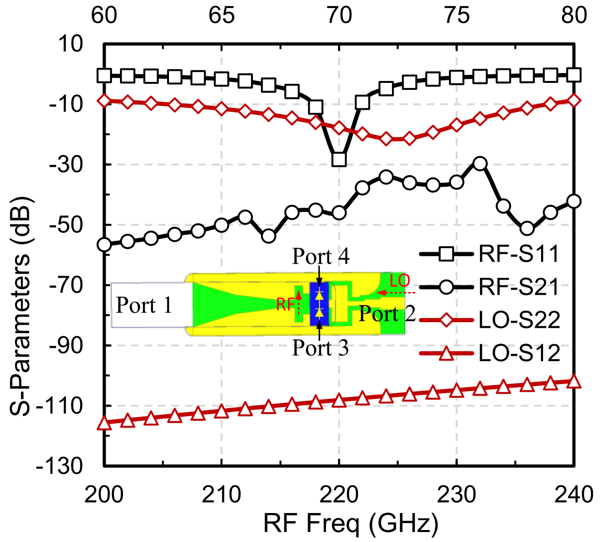


**FIGURE 3.** Configuration and simulation S parameters of the balanced structure showing its high isolation characteristic.

In mixing circuit, the unilateral fin line is adopted as the final structure and the diode pair is longitudinally placed on the unilateral fin line. The metal slots matching impedance were etched on the unilateral fin line in order to match the diode pair for the RF signal, as shown in Figure 2. And the LO signal was matched by the multi-section high-low impedance lines running through the coplanar waveguide and microstrip line. Besides, a gradual transformation from the coplanar waveguide to microstrip line was realized by chamfering the ground metal.

The RF rectangular waveguide (WR-4.3), the fin line, the coplanar waveguide, and the microstrip line compose a high isolation balanced structure, in which the signal is transmitted in HE1 mode in the waveguide and the fin line, meanwhile quasi-TEM mode in the coplanar waveguide and the microstrip line. There is orthogonal isolation between the two signals due to electric field directions being perpendicular to each other. Therefore, the two ends of the balanced structure have a very high isolation characteristic, as described in Figure 3. This high isolation characteristic can realize the isolation between the RF port and the LO port, so the RF low-pass filter needed in traditional mixing circuit can be removed to reduce the size of the whole circuit and the internal transmission loss. Besides, the IF low pass filter is designed with the improved split-ring resonator structure that

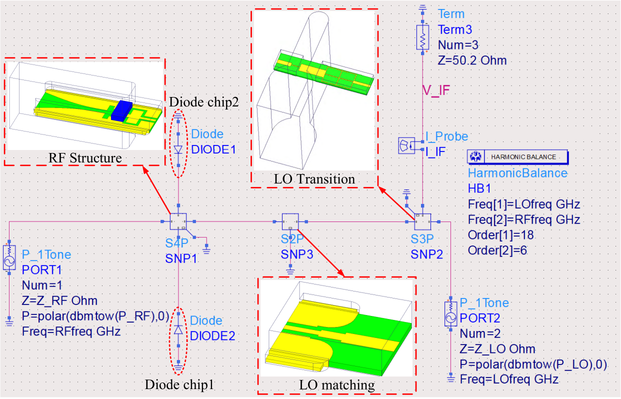


**FIGURE 4.** **Overall simulation schematic diagram of the third-harmonic mixer. In which, HFSS simulation results of each part were converted into SNP files, these results were then imported into the ADS by S-parameter matrix data for co-simulation.**

has a small transverse dimension to cut down the aspect ratio of the quartz substrate.

### B. SIMULATION OF THE THIRD-HARMONIC MIXER

The simulation analysis method combining "field" and "road" was adopted to design the third-harmonic mixer, in which the "field" represents the characteristics of the linear structures whose electric field characteristics are simulated in High Frequency Software Simulator (HFSS) by establishing a 1:1 model. The "road" represents the characteristics of nonlinear structures. These features will be simulated in Advanced Design System (ADS) using the ideal nonlinear models and SPICE parameters. The 3D model of the third-harmonic mixer was built, and the ports were set according to Figure 4. Then the mixing circuit was optimized with the harmonic balance analysis in HFSS and ADS. In particular, in the 3D model of the Schottky diode pair, each diode port was defined as a 2-D micro-coaxial that takes as inner boundary the circular anode and as outer boundary a 2-D circular defined by the circular anode outer edge plus a gap equal to the thickness of the epitaxial layer. An integration line between the outer and inner boundary of the port was used to set the right polarity of the diodes when performing subsequent nonlinear and linear circuit simulations. This polarity needed to be emphasized when connecting the resulting parameter file extracted from the EM simulation to nonlinear electrical model of the diode for a correct synthesis of the circuit and determination of the third-harmonic mixer performance.

## III. FABRICATION AND MEASUREMENTS

The third-harmonic mixer circuits were patterned with lithography sputtering process on a 50um quartz substrate, and the precision of the conductor strip was less than 1$\mu$m. The split-blocks of the mixer were milled directly on the copper bar along waveguide E plane. Photograph of the final circuits inside the packing block is shown in Figure 5, and the copper cavity was gilded. On the copper block, two side grooves with a width of 0.1 mm were dug along the fin line in order to make the fin line thoroughly grounded using silver glue. The quartz substrate was fixed on the groove of the cavity with the silver glue. A 10um gap between the quartz substrate and the cavity wall was retained in advance for easy processing and manual assembly. And four square metal blocks with a side length of 15um were placed on the edge of the quartz substrate as the positioning pieces. They can realize the positioning of the quartz circuit in the packing block during manual assembly, and do not affect the circuit performance due to the small size and the far away from the central microstrip line metal. In addition, the quartz circuit was connected with a K connector through a 50 ohm microstrip line based on Rogers RT/duroid 5880. The width of the microstrip line used in the IF low pass filter design was 20$\mu$m.

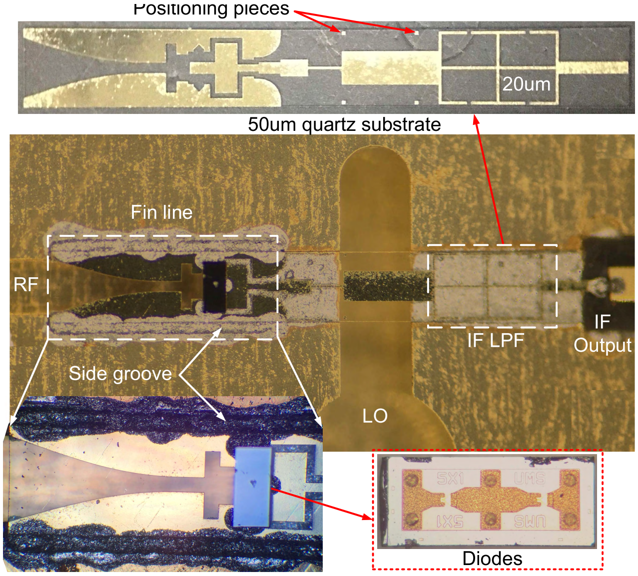


**FIGURE 5.** **The Photograph of the manufactured quartz circuits and the assembled mixer block.**

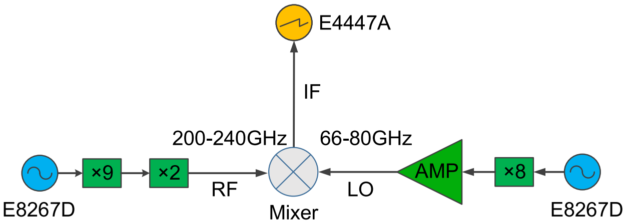
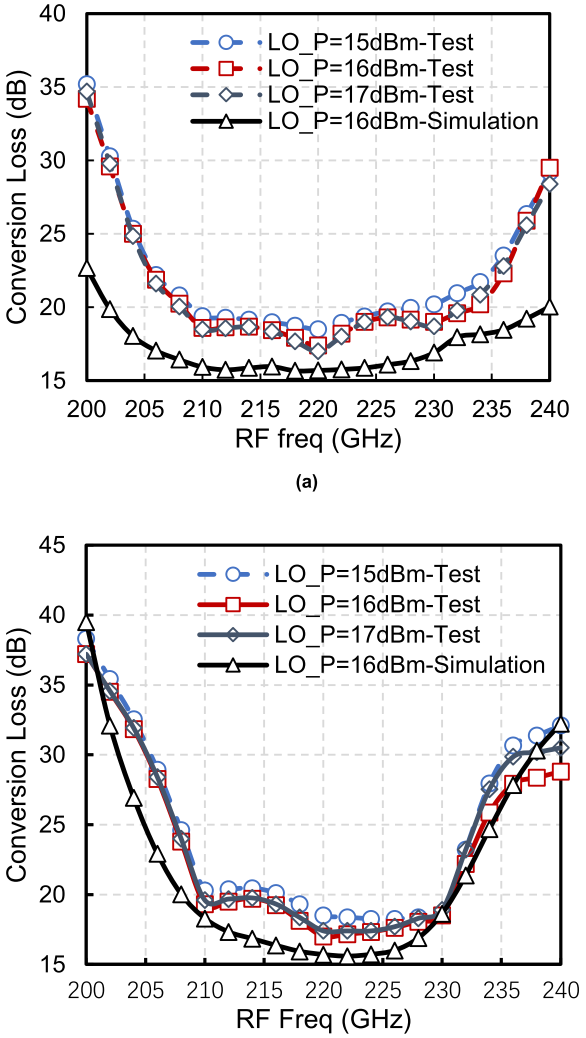


**FIGURE 6.** **The setup of mixer conversion loss test platform.**

The measurement setup consists of two signal generators, which are Agilent Technologies E8267D (250KHz - 43.5GHz, ±0.01Hz), a spectrum analyzer, which is Agilent Technologies E4447A (3Hz - 42.98GHz, ±2Hz), an 18X chain frequency chain for RF signal, an 8X chain frequency chain and an amplifier for LO signal, as shown in Figure 6. The LO output part, which can provide a signal with a power level of 10 - 20dBm among the frequency range of 66 - 80GHz, was built up with a signal generator, an eight frequency multiplier, and an amplifier. Furthermore, the RF source module can generate a signal with the power level of $-10$dBm in the frequency range of 200 – 240 GHz.



(a)

(b)

**FIGURE 7.** **Simulated and test results: (a) The CL varies with different LO power levels and RF frequencies when IF frequency' is fixed to 1 GHz, and (b) The CL varies with different LO power levels and RF frequencies at fixed LO frequency of 73 GHz.**

The third-harmonic mixer was driven by different LO frequencies and powers, and the conversion losses were shown in Figure 7. The mixer performance presented slight differences when the input LO power varied, showing a similar curve trend from 15 to 17mW. For this range of LO powers, the CL values ranged from 17 to 20 dB and between 210 - 230 GHz. The best results were obtained at the LO power of 16mW. In order to verify the conversion loss characteristics of the third-harmonic mixer when the IF frequency changed, the conversion loss at a fixed LO frequency of 73 GHz was tested. As shown in Figure 7 (b), the conversion loss of the mixer had a variation of less than 2dB when the IF frequency rose from 0 to 11 GHz. And, the mixer had the same bandwidth of 20GHz when the IF frequency was fixed or the LO frequency was fixed. Also, there was a good agreement between simulation and measurement, as described in Figure 7.

**TABLE 1.** **Summary of measured performances to the reported similar odd harmonic mixer.**

| Ref. | RFfreq (GHz) | Harmonic number | CL*(dB) |
|---|---|---|---|
| [8] | 1905 - 2060 | 3 | 27 - 35 |
| [16] | 220-325 | odd(⩾5) | 39-51 |
| [17] | 500-750 | 5 | 27@650GHZ |
| **This work** | **210-230** | **3** | **17-18.5** |

Table 1 shows the measured performance comparison between the proposed third-harmonic mixer and the similar state-of-the-art odd-harmonic mixers in solid-state terahertz circuits. It demonstrates that the proposed third-harmonic mixer has a low conversion loss. Although this performance is far from the performance of the existing sub-harmonic mixers, it enriches the study of terahertz harmonic mixer and provides a new approach for the design of terahertz harmonic mixer.

## IV. CONCLUSION

In this paper, an effective design approach for a third-harmonic mixer is presented and validated. A hybrid transmission line composed of the rectangular waveguide, fin line, coplanar waveguide, and the microstrip line is used to form odd harmonic mixing circuits due to its electric field direction and high isolation characteristics. According to the basic principle of mixers, the measurement setup for measuring conversion loss is built. The measured results show that the mixer can operate at 210-230 GHz with a variable CL of 17-18.5 dB when LO power is about 16dBm. And the conversion loss has a variation of less than 2dB with the IF frequency from 0 to 11 GHz. Even though this performance is far from being comparable with that of the existing sub-harmonic mixers, they offer a new alternative mixing scheme for the terahertz system.

## REFERENCES

[1] I. Hosako *et al.*, "At the dawn of a new era in terahertz technology," *Proc. IEEE*, vol. 95, no. 8, pp. 1611–1623, Aug. 2007.
[2] R. Appleby and H. B. Wallace, "Standoff detection of weapons and contraband in the 100 GHz to 1 THz region," *IEEE Trans. Antennas Propag.*, vol. 55, no. 11, pp. 2944–2956, Nov. 2007.
[3] P. H. Siegel, "THz instruments for space," *IEEE Trans. Antennas Propag.*, vol. 55, no. 11, pp. 2957–2965, Nov. 2007.
[4] T. Kleine-Ostmann and T. Nagatsuma, "A review on terahertz communications research," *J. Infr. Millim. THz Waves*, vol. 32, no. 2, pp. 143–171, Feb. 2011.
[5] E. Schlecht *et al.*, "Schottky diode based 1.2 THz receivers operating at room-temperature and below for planetary atmospheric sounding," *IEEE Trans. THz Sci. Technol.*, vol. 4, no. 6, pp. 661–669, Nov. 2014.
[6] J. Treuttel *et al.*, "A 520-620-GHz schottky receiver front-end for planetary science and remote sensing with 1070 K-1500 K DSB noise temperature at room temperature," *IEEE Trans. THz Sci. Technol.*, vol. 6, no. 1, pp. 148–155, Jan. 2016.
[7] D.-Z. Ding and J.-P. Xu, "Low conversion loss full E-band seventh-harmonic mixer with compact filter," *Electron. Lett.*, vol. 50, no. 7, pp. 526–528, Mar. 2014.
[8] B. T. Bulcha *et al.*, "Design and characterization of 1.8-3.2 THz schottky-based harmonic mixers," *IEEE Trans. THz Sci. Technol.*, vol. 6, no. 5, pp. 737–746, Sep. 2016.

[9] E. Schlecht, J. Gill, R. Dengler, R. Lin, R. Tsang, and I. Mehdi, "A unique 520-590 GHz biased subharmonically-pumped schottky mixer," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 12, pp. 879–881, Dec. 2007.

[10] J. Deng, Q. Lu, D. Jia, Y. Yang, and Z. Zhu, "Wideband fourth-harmonic mixer operated at 325-500 GHz," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 3, pp. 242–244, Mar. 2018.

[11] B. Thomas, A. Maestrini, and G. Beaudin, "A low-noise fixed-tuned 300-360-GHz sub-harmonic mixer using planar Schottky diodes," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 12, pp. 865–867, Dec. 2005.

[12] A. Y. Tang, "Modeling of terahertz planar Schottky diode," M.S. thesis, Licentiate Eng., Chalmers Univ. Technol., Gothenburg, Sweden, 2011.

[13] I. Mehdi, J. V. Siles, C. Lee, and E. Schlecht, "THz diode technology: Status, prospects, and applications," *Proc. IEEE*, vol. 105, no. 6, pp. 990–1007, Jun. 2017.

[14] M. Cohn, J. E. Degenford, and B. A. Newman, "Harmonic mixing with an antiparallel diode pair," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-23, no. 8, pp. 667–673, Aug. 1975.

[15] J. Guo, J. Xu, Y. Chen, and C. Qian, "Design of a millimeter-wave third-harmonic mixer using substrate integrated waveguide balun," *IEICE Electron. Express*, vol. 14, no. 21, pp. 1–7, Oct. 2017.

[16] X. Dai and W. Zhu, "Design of a 220-325 GHz odd harmonic mixer," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, vol. 4, May 2012, pp. 1–3.

[17] V. S. Mottonen and A. V. Raisanen, "General-purpose fifth-harmonic waveguide mixer for 500-700 GHz," in *Proc. 34th Eur. Microw. Conf.*, Oct. 2004, pp. 1145–1147.

[18] Y. Huang, W. Hui, and B. Alderman, "A W band third-harmonic mixer using planar Schottky diodes," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, Chengdu, China, May 2018, pp. 1–3.

[19] D. F. Ji, B. Zhang, J. L. Wang, D. Xing, Y. Fan, and X. D. Chen, "Wide stopband millimeter/terahertz lowpass filter using improved split ring resonator," *J. Electromagn. Waves Appl.*, vol. 32, no. 5, pp. 579–590, Nov. 2017.

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