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A 200-240 GHz Sub-Harmonic Mixer Based on Half-Subdivision and Half-Global Design Method

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ABSTRACT For the terahertz harmonic mixer, a design model based on Half-Subdivision and Half-Global Design Method (HS-HGDM) with a single functional unit is proposed. The single functional unit circuit of the mixer, such as LO or IF Low Pass Filter (LPF), is designed by Subdivision Design Method (SDM), and the rest circuits of the mixer are designed by Global Design Method (GDM). The harmonic mixer based on this model is characterized by simple circuit structure, low conversion loss, small circuit size and high stability. In this paper, an improved Compact Suspended Micro-strip Resonators (CSMRs) filter is developed for the IF part of sub-harmonic mixer. The remaining circuits consist of some basic transmission units, such as the High-Z Low-Z impedance Transmission Lines (H-Z L-Z TLs) applied for main circuit, and full/reduced height WR4.3/WR8 applied for providing RF/LO signal. In RF frequency range 200-240 GHz, a Single Sideband (SSB) conversion loss of 7.36±0.76 dB operating at IF frequency 1.8 GHz, and a Double Sideband (DSB) noise temperature below 1034 K with the LO power of 2-5 mW and the LO frequency of 107 GHz were achieved. This broadband sub-harmonic mixer operates at room temperature, which makes it applicable to sub-millimeter wave or terahertz wireless communication systems and imaging inspection systems.

INDEX TERMS Terahertz sub-harmonic mixer, CSMRs filter, wireless communication systems.

I. INTRODUCTION

At present, the solid-state sub-millimeter wave and terahertz technologies, such as frequency multiplication, detection, mixing, power amplification and combiner based on various types of diodes and transistors [1]–[6], are moving toward higher operating frequency bands, higher output power and newer materials [7], [8]. Due to the lack of high power and stable radiation sources operating at higher frequency, the mixing technology has received rising popularity for the design of sub-millimeter wave or terahertz system. For example, the harmonic mixers with Schottky Barrier Diodes (SBDs) [9]–[11], Hot Electron Bolometer [12], [13] and Super-conductor Insulator Super-conductor [14], [15] have been extensively applied in the conversion of high frequency to relatively low frequency for the purpose of signal amplification and measurement. Especially when the RF operating frequency band of the mixer reaches in excess of 1 THz, high order harmonics are usually involved to facilitate the LO signal, the related measurement and application conditions to be realized [16]–[18]. At present, harmonic mixers based on the SDM, the GDM and the HS-HGDM have been commonly applied to the sub-millimeter wave or terahertz wireless communication systems and imaging inspection systems [19]–[23].

Among those methods, the terahertz harmonic mixer based on the SDM is known as the most common one, as shown in Fig. 1. At first, it requires the design of some passive functional units, such as LO LPF, IF LPF and the likes [24]–[28]. In addition, those passive functional units can be directly applied for other sub-terahertz circuits. Then, the completed RF part (the blue box) and the completed LO part (the green box) are designed to achieve their specific performance, respectively. At last, the RF part, diode and the LO part are connected and matched through a number of Suspended Micro-Strips (SMS). At this time, the impedance matching

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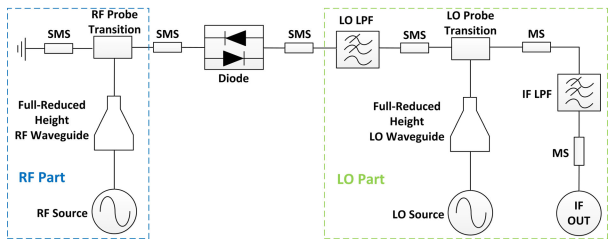

FIGURE 1. The simple model of terahertz harmonic mixer based on the SDM.

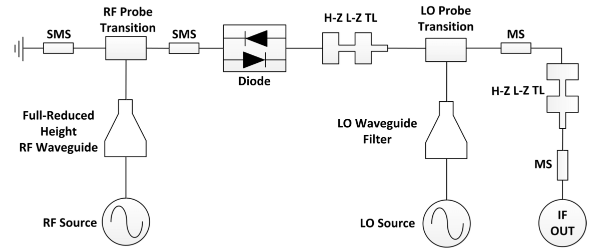

FIGURE 2. The simple model of terahertz harmonic mixer based on the GDM.

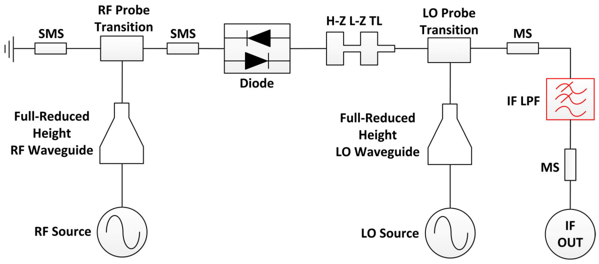

FIGURE 3. The simple model of terahertz harmonic mixer based on the HS-HGDM with a single functional unit.

variables of the whole circuit are reliant on the numbers of SMS. It would make the circuit structure complicated and cause the circuit size to increase. Therefore, the operating frequency band of the mixer based on the SDM is narrow in most cases. Moreover, once the expected performances of the mixer fail to be achieved, there is a necessity for all of the functional units and the RF part and the LO part to be re-designed. For example, [26] presented a 211-226 GHz sub-harmonic mixer using a high-low impedance filter applied for LO LPF and a CSMRs filter applied for IF LPF. The SSB conversion loss is 5.9-12 dB for the mixer, which has a 14 GHz operation bandwidth and a 8.908 mm circuit size. Also, this mixer has a narrow frequency band and poor flatness. In [27], a 290–310 GHz sub-harmonic mixer with the RF waveguide filter, the LO filter and the IF filter is reported. The measured SSB conversion loss is 9-10 dB, and the DSB noise temperature is 1000-1500 K with the operation bandwidth of merely 20 GHz. The mixer shows a complex structure, and a further improvement is necessary for the effective operating frequency band.

In addition to the mixer designed by the SDM with functional unit circuits, another approach to the design of the harmonic mixer is the GDM, consisting of some basic circuit units and treating the SSB conversion loss as the optimization goal. Those basic circuit units mainly include H-Z L-Z TLs, full/reduced height rectangular waveguides and others, as described in our previous work [29]–[31]. The simple model of sub-terahertz harmonic mixer based on the GDM is illustrated in Fig. 2. As there are a large number of optimization variables and massive optimization space, such mixers demonstrate such characteristics as simple structure, small size and wide working frequency band. Nevertheless, the GDM requires repeated iterations by performing field simulation and circuit simulation until the desired results are achieved, which is time consuming in the design process and leads to a poor stability in actual operation. Though the GDM can be used commonly, the specific design circuit for every mixer is unique and incapable to be applied to other circuits straightaway. For example, [30] referred to a 220 GHz sub-harmonic mixer based on the GDM. In the RF frequency 198-238 GHz, this mixer has achieved a SSB conversion loss of 6.35-10 dB operating at 110 GHz and a substrate size of 5.365 mm. The problem lies in a large flatness shown by that measured SSB conversion losses, and a deviation from the simulation results with LO non-central frequencies.

At present, there is one approach to designing the mixer that combines the SDM and the GDM, which is the HS-HGDM. It can be seen on "Design of 220GHz Sub-harmonic Mixer Based on Planar Schottky diode" from Gaojian Liu's M.S. thesis in 2017 and "Research on Terahertz Frequency-Multiplied Technology Based on Schottky Diodes" from Chengkai Wu's M.S. thesis in 2018. On the one hand, some of the LPF filters are designed for parts of harmonic mixer based on the SDM. On the other hand, the H-Z L-Z TLs and the full/reduced height Standard Rectangular Waveguide (SRW) are applied for others circuits of the harmonic mixer based on the GDM. The HS-HGDM involves more optimization variables and more optimization space compared to the SDM. Due to the addition of functional units, the performance of harmonic mixer designed by the HS-HGDM is consistent when compared with that of GDM. With similar LO LPF and IF LPF structures to [26], [32] introduced a 220 GHz sub-harmonic mixer premised on the HS-HGDM with double LPFs. This mixer achieved a SSB conversion loss of 9 dB and a DSB noise temperature of 500-1500 K at 208-229 GHz.

In this paper, a model for designing terahertz harmonic mixers based on the HS-HGDM with a single functional unit is introduced in section II. In section III, a 200-240 GHz sub-harmonic mixer based on this method proposed by us is designed, and an improved CSMRs is applied for IF part. In section IV, the results of sub-harmonic mixer are presented, including simulated and measured SSB conversion loss, DSB noise temperature, the linearity and S11. In section V, the analysis of 220 GHz sub-harmonic mixers is conducted by applying different methods. The conclusion is drawn in Section VI.

II. METHOD

In general, the harmonic mixer with specific performances is obtained by combining the circuit model designed by

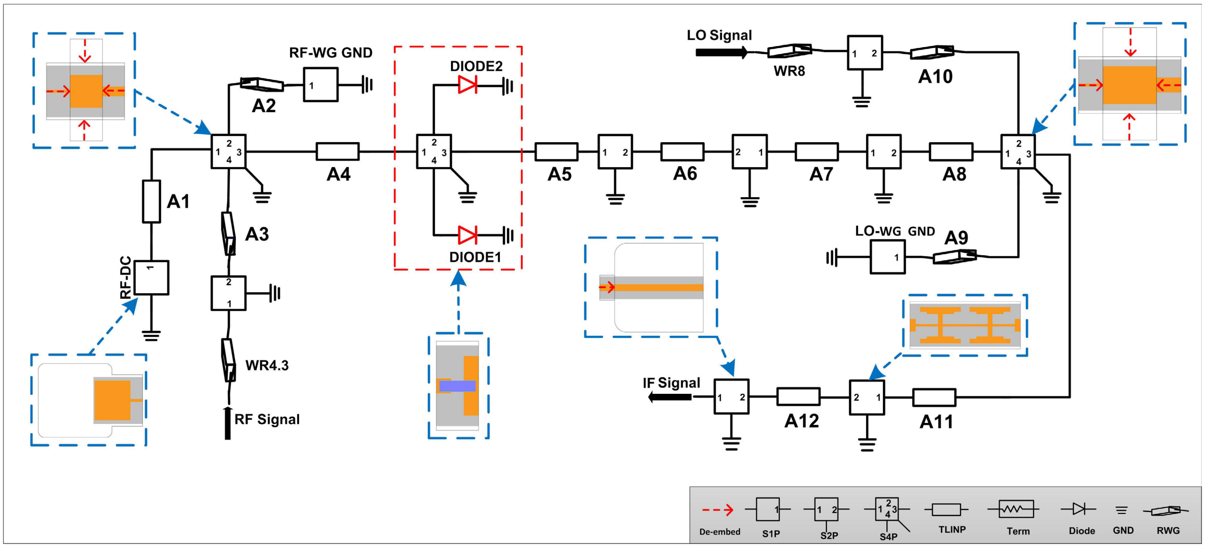

FIGURE 4. The circuit model of 220 GHz broadband sub-harmonic mixer based on the HS-HGDM with an IF LPF.

Advanced Design System and the field model designed by High Frequency Structure Simulator. According to the harmonic mixers designed by the SDM, the GDM and the HS-HGDM with double function units [19]–[32], it can be found out that the HS-HGDM with a single function unit is able to be realized. The design process of the mixer can be referenced in [30].

A simple model for the design of terahertz harmonic mixer by the HS-HGDM with a single functional unit is illustrated in Fig. 3. The IF output part is very important to the whole mixer. Therefore, a LPF filter intended to pass the IF signal is applied to the IF part of the harmonic mixer. The remaining circuits of the mixer, including RF part and LO part, consist of some basic transmission units, such as H-Z L-Z TLs and full/reduced height waveguide.

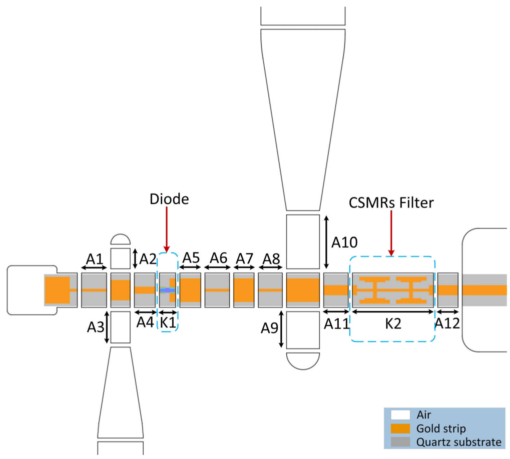

FIGURE 5. The field model of 220 GHz broadband sub-harmonic mixer based on the HS-HGDM with an IF LPF.

III. DESIGN

A. THE 200-240 GHZ SUB-HARMONIC MIXER BASED ON THE HS-HGDM WITH A SINGLE LPF

In order for further introduction and validation of the model, a sub-terahertz sub-harmonic mixer is designed based on Fig. 3, which covers the range from 200 to 240 GHz. The circuit model and the field model of this sub-harmonic mixer are shown in Fig. 4 and Fig. 5, respectively. The mixer is comprised of the continuous basic circuit units and the discontinuous basic circuit units. The former includes the suspended micro-strip transmission line, micro-strip transmission line and full/reduced height WR4.3/WR8. The latter includes a DC grounded in RF port, the RF/LO probe transition, the RF/LO reduced waveguide transition, the shorted circuit end of RF/LO reduced waveguide, SBDs flipped on quart-glass substrate, suspended micro-strip high-low impedance step structure, micro-strip high-low impedance step structure, an improved CSMRs filter and IF output. The details about the diode and the basic circuit units can refer to [30], [31].

The full height WR4.3 and a reduced height WR4.3 coupled to a quartz suspended micro-strip probe are applied to generate the RF signal. The full height WR8 and a reduced height WR8 coupled to a quartz micro-strip probe are involved to generate the LO signal. The CSMRs filter is intended for IF part with the performances of passing the IF signal and blocking the RF/LO signal. The K connector is employed to output the IF signal, and the IF port is terminated in 50 Ω.

In addition to the improved CSMRs filter (specific stated in ***B***), 220 GHz sub-harmonic mixer involves 12 variables, as shown in Fig. 5. Based on the field model of 220 GHz broadband sub-harmonic mixer, its corresponding circuit model is designed as illustrated in Fig. 4. After repeated design and simulation of the mixer field model and circuit model, the mixer 3-D illustration and dimensions are finalized as shown in Fig. 6 and Table 1, respectively.

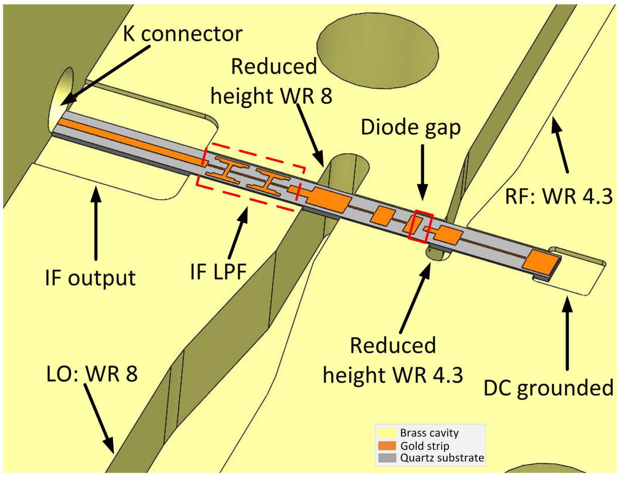

FIGURE 6. The 3-D illustration of 220 GHz broadband sub-harmonic mixer.

TABLE 1. Dimensions of 220 GHz sub-harmonic mixer (mm).

A1	0.62	A7	0.18
A2	0.1	A8	0.29
A3	0.09	A9	0.4
A4	0.07	A10	0.77
A5	0.05	A11	0.18
A6	0.17	A12	0.05

Initially, in order to validate the effectiveness of the HS-HGDM with a single functional unit, two sub-terahertz sub-harmonic mixers with different RF grounded structures are designed, both of which achieve an excellent performance. For one mixer, the RF end of the substrate and the cavity are connected by three gold wires. For the other mixer, the holes are punched at the RF end of the substrate and are filled with the silver epoxy. In comparison to the former, the latter minimizes manual assembly errors and avoids the additional losses. However, due to the small circuit size of the terahertz band and the brittleness of the quartz substrate, it is challenging to ensure the integrity of the substrate in the process of fabricating the holes. Therefore, the former mixer structure with jumping gold wires at the end of the RF ends up being chosen.

B. THE IF LPF

Concerning 220 GHz sub-harmonic mixer, the IF LPF based on quartz micro-strip is applied to pass the IF signal (0-50 GHz), and to block the LO signal (100-120 GHz) and RF signal (200-240 GHz) propagation into the IF channel. In this work, a symmetrical improved CSMRs is proposed, as illustrated in Fig. 7. The performance and dimension of the CSMRs are indicated in Fig. 8 and Table 2, respectively. The S21 of the CSMRs is better than −0.25 dB from frequency between 0 and 50 GHz, and the S11 is greater than −20 dB. The out-of-band suppression of the CSMRs is below −19 dB

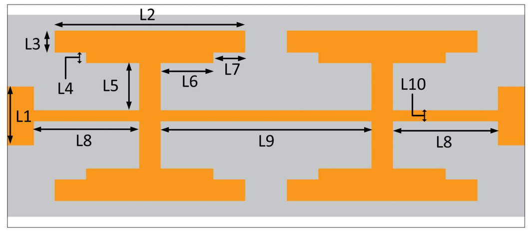

FIGURE 7. Design of IF LPF: CSMRs.

TABLE 2. Dimensions of CSMRs (mm).

L1	0.11	L6	0.1
L2	0.36	L7	0.06
L3	0.04	L8	0.2
L4	0.02	L9	0.4
L5	0.09	L10	0.02

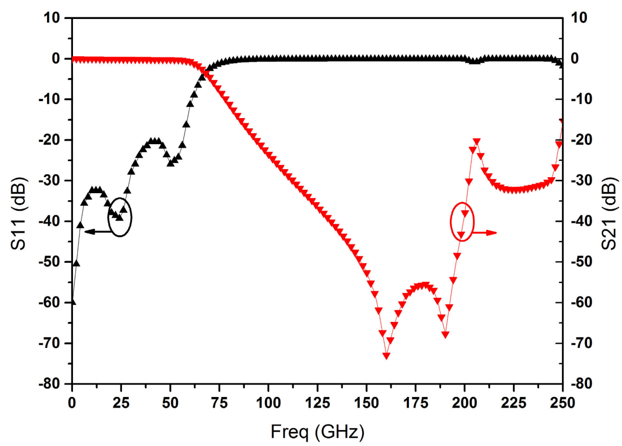

FIGURE 8. The S11 and S21 of the CSMRs.

from frequency 92 GHz to 248 GHz. It is worth noting that the improved CSMRs exhibits such characteristics as low pass-band insertion loss, high stop-band rejection, wide stop-band and small size. It is capable of enabling the IF signal to pass and the RF/LO signal to block.

C. THE OTHER PARTS

In addition to the structures of 220 GHz sub-harmonic mixer referred to above, more details on other parts, such as RF probe-to-waveguide, LO probe-to-waveguide and the high-low impedance transition of LO part, are presented in Fig. 9. The two ends of the RF probe-to-waveguide and H-Z L-Z TLs of LO part adopt suspended micro-strip structure. In respect of the LO probe-to-waveguide, the suspended micro-strip structure is applied to one end of connection with H-Z L-Z TLs, while the micro-strip structure is adopted for the other end close to the IF part.

D. THE FABRICATION

With regard to the main circuit of the sub-harmonic mixer, a quartz substrate with the length of 5.33 mm is designed.

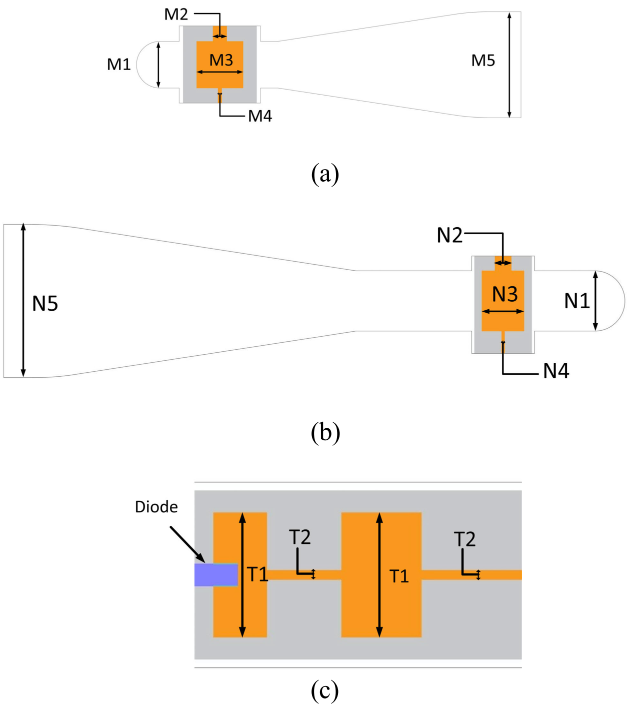

FIGURE 9. (a) The RF probe-to-waveguide, (b) the LO probe-to-waveguide and (c) the H-Z L-Z TLs of LO part.

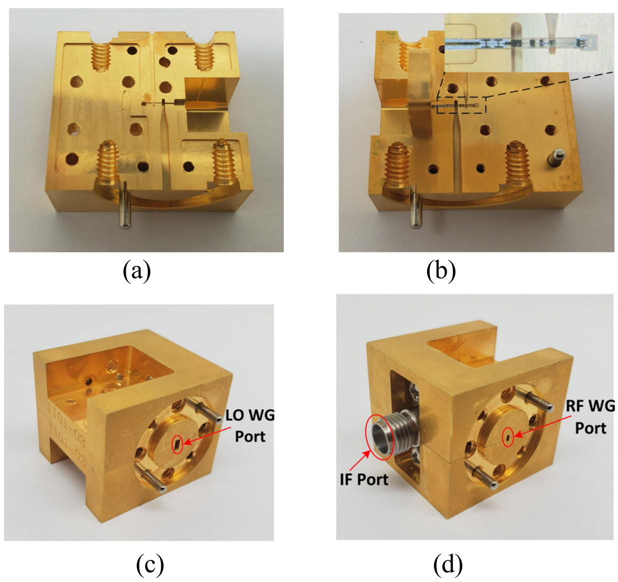

FIGURE 10. The 220 GHz mixer: (a) The upper cavity, (b) the down cavity, (c) the view of LO Port and (d) the view of RF port and IF port.

A gold conductor is electroplated on the surface of the quartz substrate. Fig. 10 illustrates the fabricated and the assembled cavities of 220 GHz sub-harmonic mixer.

IV. MEASUREMENT AND RESULTS

In order to validate the accuracy of the HS-HGDM with the single functional unit, the performances of 220 GHz sub-harmonic mixer are subject to assessment with consideration given to the simulated and measured SSB conversion loss, DSB noise temperature,linearity and S11. The similar mixer measurement process is detailed in [31]. Furthermore, a comparison is performed between this 220 GHz sub-harmonic mixer and other 220 GHz sub-harmonic mixers designed by taking different methods.

TABLE 3. The summary of SSB conversion losses.

Fixed LO Freq (GHz)	104	111	115
RF Freq (GHz)	198-230	201-238	208-238
Simulated CL (dB)	7.4-8.13	7.14-8.67	7.2-8.2
Simulated CL average (dB)	7.64	7.5	7.4
Measured CL (dB)	6.83-8.53	6.63-9.38	6.96-8.93
Measured CL average (dB)	7.85	8.14	8.23

A. THE SSB CONVERSION LOSSES WITH FIXED LO FREQUENCIES

The simulated and measured SSB conversion losses of the mixer are obtained by sweeping the RF frequency to maintain the LO frequencies (104 GHz, 111 GHz and 115 GHz), as illustrated in Fig. 11. When the LO frequency is maintained at 111 GHz with the LO driven power of 3 mW and the RF power of 0.15 mW, the conversion loss was simulated to be 7.9±0.76 dB and measured to be 8±1.38 dB across the RF frequency range from 201 to 238 GHz.

The summary of the SSB conversion losses with LO frequencies is indicated in Table 3, and it can be discovered that the measured results are consistent with the simulation ones. The difference of average value between the simulated and measured SSB conversion loss is lower than 0.83 dB. The fluctuation of the measured SSB conversion loss is insignificant, and the max fluctuation is less than ±1.38 dB.

B. THE SSB CONVERSION LOSSES WITH FIXED IF FREQUENCIES

The simulated and measured SSB conversion losses of the 220 GHz sub-harmonic mixer are determined by sweeping the RF frequency at multiple fixed IF frequencies, which are 1.8 GHz, 3.6 GHz and 5.2 GHz, respectively. Those data are plotted in Fig. 12, and the measured results conform to the simulated ones. As for the RF frequency ranging from 200 to 240 GHz, the simulated SSB conversion loss is 6.88-7.86 dB, and the measured results with IF frequencies are lower than 8.6 dB overall. It can be noticed that the IF output of the mixer is consistent in the low frequency range. The summary made of those conversion losses is indicated in Table 4.

C. THE DSB NOISE TEMPERATURE OF MIXER VERSUS THE LO POWERS, FIXED IF FREQUENCIES

In respect of the LO frequency fixed at 107 GHz, the measured DSB noise temperatures of the measurement system

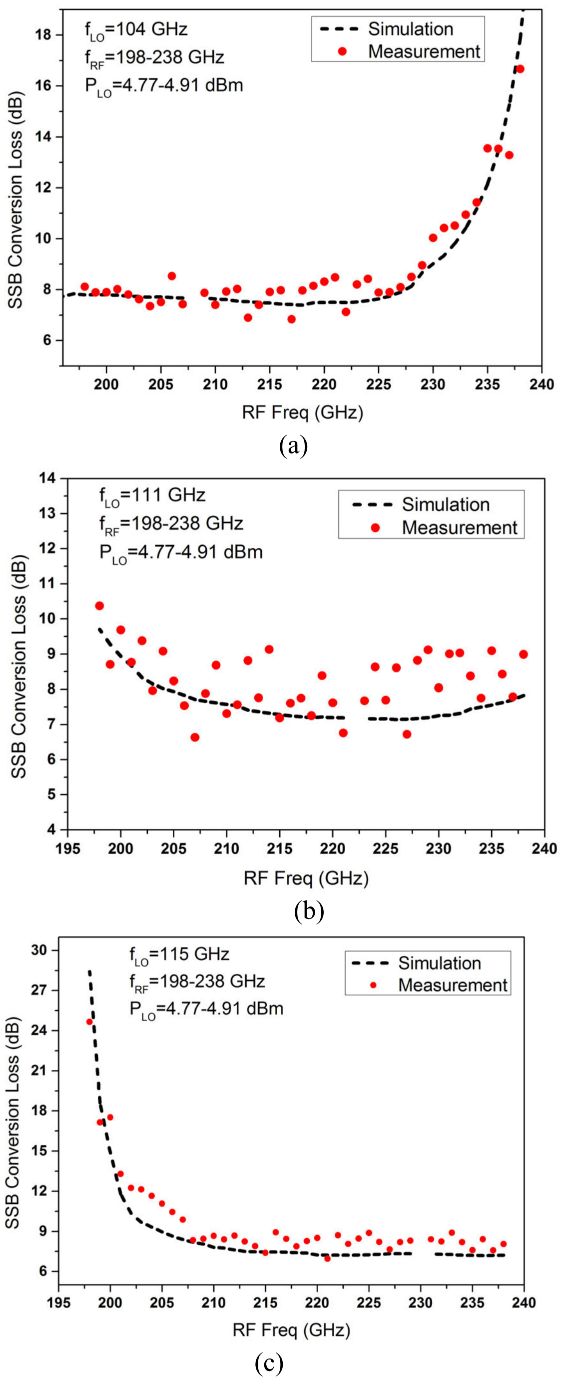

FIGURE 11. The simulated and measured SSB conversion losses of 220 GHz sub-harmonic mixer versus the RF frequency, LO frequencies are maintained at: (a) 104 GHz, (b) 111 GHz and (c) 115 GHz.

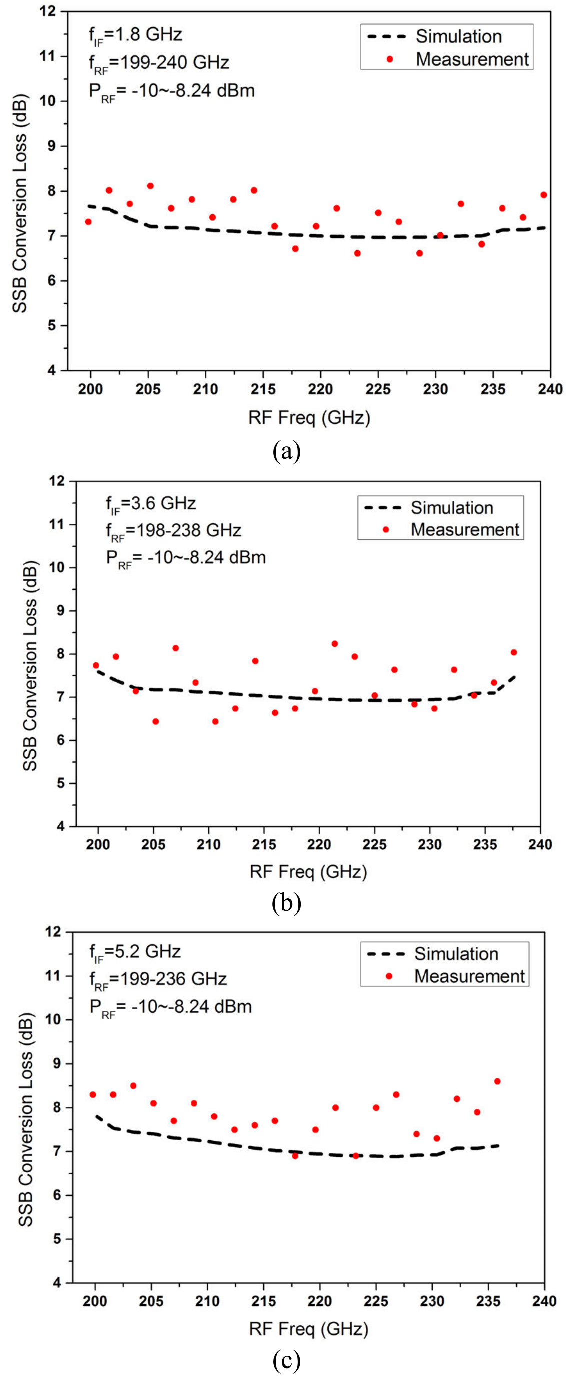

FIGURE 12. The simulated and measured SSB conversion losses of 220 GHz sub-harmonic mixer versus the RF frequency, IF frequencies are maintained at: (a) 1.8 GHz, (b) 3.6 GHz and (c) 5.2 GHz.

and mixer versus the LO powers are indicated in Fig. 13. When the sub-harmonic mixer operates at the fixed IF frequencies (1.83 GHz and 2.75 GHz), the DSB noise temperature of the measurement system ranges from 763 K to 1137 K, and the DSB noise temperature of the mixer is lower than 1034 K with the LO power of 2-5 mW. The minimum DSB noise temperature is 688 K at the IF frequency 1.83 GHz, with the LO power being 2 mW.

D. THE IF OUTPUT POWER VERSUS THE RF INPUT POWER

In order to describe the linearity of the 220 GHz sub-harmonic mixer, the measured IF output power versus the RF input power is illustrated in Fig. 14. The LO frequency is maintained at 110 GHz with the LO power of 3 mW and the RF frequency of 217 GHz. The P_{1dB} of the IF output power is −9.1 dBm with the RF input power of −0.6 dBm. When the RF input power rises to 3 dBm, the IF output power is saturated at −8.1 dBm.

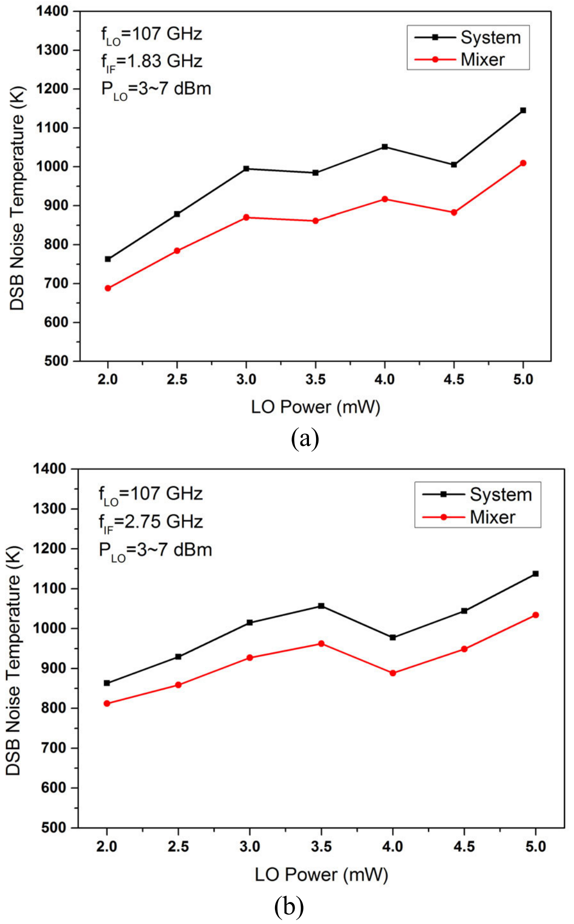

FIGURE 13. **The DSB noise temperatures of the measurement system and mixer versus the LO power, IF frequencies are maintained at: (a) 1.83 GHz and (b) 2.75 GHz.**

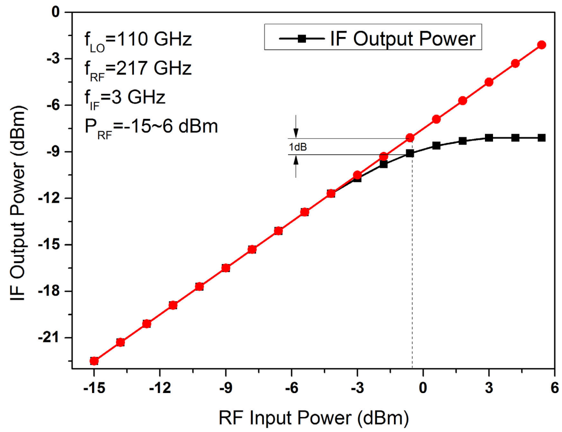

FIGURE 14. **The IF output power versus the RF input power, IF frequency is 3 GHz.**

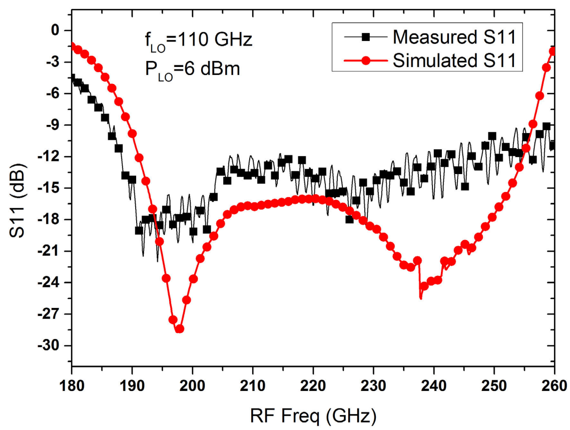

FIGURE 15. **The S11 of the 220 GHz sub-harmonic mixer.**

TABLE 4. **The summary of SSB conversion losses.**

Fixed IF Freq (GHz)	1.8	3.6	5.2
Simulated RF Freq(GHz)	200-240	200-238	200-236
Simulated CL (dB)	6.96-7.67	6.93-7.62	6.88-7.86
Simulated CL average (dB)	7.13	7.1	7.14
Measured CL(dB)	6.61-8.12	6.44-8.24	6.89-8.6
Measured CL average (dB)	7.44	7.31	7.84

E. THE S11 OF THE SUB-HARMONIC MIXER

In the RF frequency range from 192 to 249 GHz, the simulated S11 of the 220 GHz sub-harmonic mixer is lower than −13.8 dB and the measured S11 is lower than −10 dB, as indicated by Fig. 15. This sub-harmonic mixer achieves an excellent return loss in the RF port.

V. ANALYSIS

The 220 GHz sub-harmonic mixer based on the HS-HGDM with a single functional unit has demonstrated an excellent performance in terms of SSB conversion loss, DSB noise temperature, linearity and S11. In [31], it has demonstrated that a 220 GHz sub-harmonic mixer designed by the GDM achieves a superior performance on the circuit size, conversion loss and DSB noise temperature of the mixer compared to the mixers designed by the SDM. Therefore, in this paper, just some of the details about the comparison between the HS-HGDM and the GDM are shown in Fig. 16.

When LO frequencies are maintained at non-central frequencies, 104 GHz and 115 GHz, the problems of the mixer designed by the GDM [31] include a deviation of the measured SSB conversion loss from the simulation results, and a relatively large flatness. The sub-harmonic mixer designed by the HS-HGDM with a single functional unit has achieved an excellent consistency in the simulation and measurement of the SSB conversion loss. Meanwhile, the fluctuation is significant.

As revealed by a further analysis, the core of the mixer designed by the GDM is that all transmission lines and rectangular waveguides with varying impedances are taken as the optimization variables, and the SSB conversion loss is treated as the final optimization goal. Despite the mixer based on the GDM that possesses a simple structure and demonstrates a superior performance to the SDM, it discounts the

TABLE 5. The comparison of 220 GHz sub-harmonic mixers.

RF Freq (GHz)	SSB Conversion Loss (dB)	LO Power (mW)	Circuit Size (mm)	Noise Temperature (K)	Method	Reference
210-219.8	min: 11.4	10	10.97	min:1500	SDM	[25]
211-226	5.9-12	5	8.908	-	SDM	[26]
198-238	6.35-10	3.1	5.365	692-924	GDM	[30]
199-238	7.84-12.4	3.1	5.232	580-1058	GDM	[31]
208-229	6.3-9	4.3	10.81	500-1500	HS-HGDM (double LPFs)	[32]
200-240	**6.61-8.12**	**3**	**5.33**	**688-1034**	**HS-HGDM (single LPF)**	**This paper**

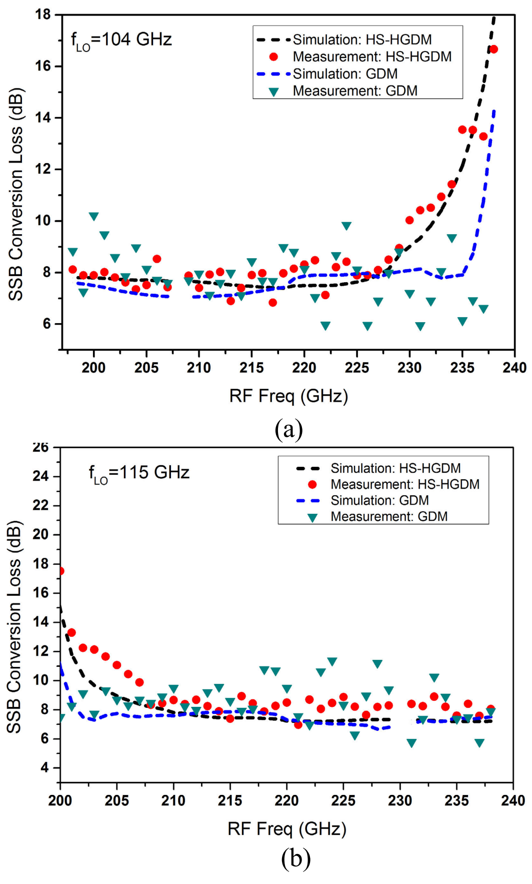

FIGURE 16. The comparisons of the simulated and measured SSB conversion losses of 220 GHz sub-harmonic mixer based on the HS-HGDM and the GDM, LO frequencies are: (a) 104 GHz and (b) 115 GHz.

performance of some internal circuits. In addition, the mixer operates at terahertz frequencies, which causes the gap to be widened between simulation and measurement results. The comparison performed of the 220 GHz sub-harmonic mixers based on the HS-HGDM with single LPF/double LPFs, the GDM and the SDM is indicated in Table 5.

In comparison to the 220 GHz sub-harmonic mixers designed by the SDM [25]–[27], the mixer designed by the HS-HGDM exhibits such advantages as simple circuit structure, low conversion loss and low DSB noise temperature. And relative to the 220 GHz sub-harmonic mixers designed by the GDM [31], the mixer designed by the HS-HGDM with a single LPF is effective in reducing the flatness of SSB conversion loss.

VI. CONCLUSION

In this paper, the design, fabrication, measurement and analysis of the 200-240 GHz sub-harmonic mixer using the HS-HGDM with a single functional unit are discussed in detail. It consists of an improved CSMRs filter and variety of basic transmission units, such as the H-Z L-Z TLs and full/reduced height WR4.3/WR8. This 220 GHz sub-harmonic mixer is characterized by SSB conversion loss, DSB noise temperature, linearity and S11, all of which indicates an excellent performance. When IF frequency is maintained at 1.8 GHz, the measured SSB conversion loss is measured to be 6.61-8.12 dB across the RF frequency range from 200 to 240 GHz. In comparison to the harmonic mixers designed by the SDM, the GDM and HS-HGDM with double LPFs, the harmonic mixer based on the HS-HGDM with a single LPF demonstrates various advantages, including simple circuit structure, low conversion loss, small circuit size and high stability.

REFERENCES

[1] B. Thomas, J. Gill, A. Maestrini, C. Lee, R. Lin, S. Sin, A. Peralta, and I. Mehdi, "An integrated 520–600 GHz GHz sub-harmonic mixer and tripler combination based on GaAs MMIC membrane planar Schottky diodes," in *Proc. 35th Int. Conf. Infr., Millim., THz. Waves*, Sep. 2010, pp. 1–2

[2] M. H. Eissa, A. Awny, M. Ko, K. Schmalz, M. Elkhouly, A. Malignaggi, A. C. Ulusoy, and D. Kissinger, "A 220–275 GHz direct-conversion receiver in 130-nm SiGe:C BiCMOS technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 7, pp. 675–677, Jul. 2017.

[3] M. Urteaga, Z. Griffith, M. Seo, J. Hacker, and M. J. W. Rodwell, "InP HBT technologies for THz integrated circuits," *Proc. IEEE*, vol. 105, no. 6, pp. 1051–1067, Jun. 2017.

[4] T. Shivan, N. Weimann, M. Hossain, D. Stoppel, S. Boppel, O. Ostinelli, R. Doerner, C. R. Bolognesi, V. Krozer, and W. Heinrich, "A highly efficient ultrawideband traveling-wave amplifier in InP DHBT technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 11, pp. 1029–1031, Nov. 2018.

[5] D. Yoon, J. Kim, J. Yun, M. Kaynak, B. Tillack, and J.-S. Rieh, "300-GHz direct and heterodyne active imagers based on 0.13-μm SiGe HBT technology," *IEEE Trans. THz Sci. Technol.*, vol. 7, no. 5, pp. 536–545, Sep. 2017.

[6] J. Kim, D. Yoon, J. Yun, K. Song, M. Kaynak, B. Tillack, and J.-S. Rieh, "Three-dimensional terahertz tomography with transistor-based signal source and detector circuits operating near 300 GHz," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 5, pp. 482–491, Sep. 2018.

[7] S. H. Zainud-Deen, A. M. Mabrouk, and H. A. Malhat, "Frequency tunable graphene metamaterial reflectarray for terahertz applications," *J. Eng.*, vol. 2018, no. 9, pp. 753–761, Sep. 2018.

[8] M. Bonmann, M. Asad, X. X. Yang, A. Generalov, A. Vorobiev, L. Banszerus, C. Stampfer, M. Otto, D. Neumaier, and J. Stake, "Graphene field-effect transistors with high extrinsic F_T and F_{max}," *IEEE Electron Device Lett.*, vol. 40, no. 1, pp. 131–134, Nov. 2019.

[9] T. Bryllert, V. Drakinskiy, K. B. Cooper, and J. Stake, "Integrated 200–240-GHz FMCW radar transceiver module," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 10, pp. 3808–3815, Oct. 2013.

[10] K. Dahlberg, T. Kiuru, J. Mallat, T. Narhi, and A. V. Raisanen, "Mixer-based characterization of millimeter-wave and terahertz single-anode and antiparallel Schottky diodes," *IEEE Trans. THz Sci. Technol.*, vol. 4, no. 5, pp. 552–559, Sep. 2014.

[11] X. Qu, Y. Zhang, and W. Zhao, "Design of 330–340 GHz 4th harmonic mixer using planar Schottky diodes," in *Proc. IEEE Int. Conf. Commun. Problem-Solving (ICCP)*, Oct. 2015, pp. 1–3.

[12] A. Kawakami, H. Shimakage, J. Horikawa, M. Hyodo, S. Saito, S. Tanaka, and Y. Uzawa, "Design and fabrication for the construction of MIR HEB mixers," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 2300105.

[13] S. Krause, D. Meledin, V. Desmaris, A. Pavolotsky, H. Rashid, and V. Belitsky, "Noise and IF gain bandwidth of a balanced waveguide NbN/GaN hot electron bolometer mixer operating at 1.3 THz," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 3, pp. 365–371, May 2018.

[14] Y. Uzawa, M. Kroug, T. Kojima, K. Makise, A. Gonzalez, S. Saito, Y. Fujii, K. Kaneko, H. Terai, and Z. Wang, "Design of terahertz SIS mixers using nb/aln/nb junctions integrated with all-NbTiN tuning circuits," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, Jun. 2017.

[15] S. Montazeri, P. K. Grimes, C.-Y.-E. Tong, and J. C. Bardin, "A wide-band high-gain compact SIS receiver utilizing a 300-μW SiGe IF LNA," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1–5, Jun. 2017.

[16] A. Danylov, N. R. Erickson, A. Light, and J. Waldman, "Phase locking of 2.324 and 2.959 terahertz quantum cascade lasers using a Schottky diode harmonic mixer," *Opt Lett*, vol. 40, no. 21, pp. 5090–5092, 2015.

[17] B. T. Bulcha, J. L. Hesler, V. Drakinskiy, J. Stake, A. Valavanis, P. Dean, L. H. Li, N. S. Barker, "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.

[18] Q. Zhong, W. Choi, and K. O. Kenneth, "Terahertz RF front-end employing even-order subharmonic MOS symmetric varactor mixers in 65-NM CMOS for hydration measurements at 560 GHz," in *Proc. IEEE Symp. VLSI Circuits*, Jun. 2018, pp. 1–2.

[19] K. Takano, S. Hara, K. Katayama, S. Amakawa, T. Yoshida, and M. Fujishima, "Quintic mixer: A subharmonic up-conversion mixer for THz transmitter supporting complex digital modulation," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–3.

[20] R. A. Hadi, Y. Zhao, Y. Li, Y. Du, C. Curwen, M. K. Lo, B. S. Williams, and M.-C.-F. Chang, "Multi-spectral terahertz interferometric imaging based on a monolithic retroactive silicon chip," in *Proc. IEEE Int. Conf. Microw., Antennas, Commun. Electron. Syst. (COMCAS)*, Nov. 2017, pp. 1–4.

[21] A. Mostajeran, S. M. Naghavi, M. Emadi, S. Samala, B. P. Ginsburg, M. Aseeri, and E. Afshari, "A high-resolution 220-GHz ultra-wideband fully integrated ISAR imaging system," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 1, pp. 429–442, Jan. 2019.

[22] P. Rodriguez-Vazquez, J. Grzyb, N. Sarmah, B. Heinemann, and U. R. Pfeiffer, "Towards 100 Gbps: A fully electronic 90 Gbps one meter wireless link at 230 GHz," in *Proc. 15th Eur. Radar Conf. (EuRAD)*, Sep. 2018, pp. 1–4.

[23] J. Jun, A. Jianfei, H. Yue, M. Li, T. Yao-ling, C. Peng, and H. Hai-long, "A imaging system based on two bands RF mixer and output multiplier in one stage at 340 GHz and 170 GHz," in *Proc. 43rd Int. Conf. Infr., Millim., Terahertz Waves (IRMMW-THz)*, Sep. 2018, pp. 1–2.

[24] Z. Chen, B. Zhang, Y. Fan, and X. Yang, "Design of up/down converters with subharmonic pump for wireless communication at 220 GHz," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, vol. 2, May 2012, pp. 1–4.

[25] I. Maestrojuan, I. Palacios, A. Rebollo, D. Etayo, J. Teniente, I. Ederra, and R. Gonzalo, "Development of a sub-harmonic mixer working at 220 GHz," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Sep. 2011, pp. 77–80.

[26] Y. Zhang, W. Zhao, Y. Wang, T. Ren, and Y. Chen, "A 220 GHz subharmonic mixer based on Schottky diodes with an accurate terahertz diode model," *Microw. Opt. Technol. Lett.*, vol. 58, no. 10, pp. 2311–2316, Oct. 2016.

[27] C. Guo, X. Shang, M. J. Lancaster, J. Xu, J. Powell, H. Wang, K. Parow-Souchon, M. Henry, C. Viegas, B. Alderman, and P. G. Huggard, "A 290–310 GHz single sideband mixer with integrated waveguide filters," *IEEE Trans. THz Sci. Technol.*, vol. 8, no. 4, pp. 446–454, Jul. 2018.

[28] C. Wang, Y. He, B. Lu, J. Jiang, L. Miao, X.-J. Deng, Y.-Z. Xiong, and J. Zhang, "Robust sub-harmonic mixer at 340 GHz using intrinsic resonances of hammer-head filter and improved diode model," *J. Infr. Milli. THz Waves*, vol. 38, no. 11, pp. 1397–1415, Nov. 2017.

[29] J. Cui, Y. Zhang, D. Xia, X. Liu, C. Wu, and R. Xu, "Design of a 220 GHz broadband sub-harmonic mixer based on global circuit simulation method," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, May 2018, pp. 1–3.

[30] J. Cui, Y. Zhang, D. Xia, Y. Xu, F. Xiao, B. Yan, and R. Xu, "A 220 GHz broadband sub-harmonic mixer based on global design method," *IEEE Access*, vol. 7, pp. 30067–30078, 2019.

[31] J. Cui, Y. Zhang, X. Liu, Y. Li, and C. Wu, "Design of 199 to 238 GHz broadband subharmonic mixer combining two-stage reduced matching technology with global design method," *Int. J. Numer. Model.*, p. e2581, Mar. 2019.

[32] L. Gaojian, L. Jun, X. Hui, Z. Xiaoyang, L. Shuantao, and Y. Hongxi, "Design of a 220 GHz subharmonic mixer based on plannar Schottky diode," in *Proc. IEEE Asia–Pacific Microw. Conf. (APMC)*, Nov. 2017, pp. 418–421.

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