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Analysis of Welding Pad for Terahertz Hybrid Integrated Mixer

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ABSTRACT In this paper, the influence of the silver glue on circuit performance and the reasons for its formation are analyzed in a terahertz hybrid integrated mixer. A validation analysis was carried out in the 600 - 700 GHz band with the aid of simulation software. Then a terahertz hybrid integrated mixing circuit with large pads was proposed in order to reduce the influence of the silver glue. Through the comparison of simulation results, it can be seen that after using large pads, the silver glue used for connection mainly concentrated on pads, which cannot have a significant impact on the matching of the circuits. The use of large pads also to a certain extent eliminates the resonance effect caused by silver glue. A terahertz hybrid integrated mixer with large pads was processed, assembled and tested. The test results show that the conversion loss is less than 14 dB under an RF frequency of 600 - 667 GHz. The experiments prove good consistency between measured and predicted conversion loss of the mixer using large pads. The difference between the measured and predicted conversion loss is only within 1.8 dB.

INDEX TERMS Terahertz, hybrid integrated, harmonics mixer, solid state.

I. INTRODUCTION

Terahertz wave has great application prospects due to a series of unique advantages. Especially its unique advantage in communication [1], imaging [2], and detection [3], [4] has made terahertz wave a focus of research. With the expansion of spectrum utilization and the development of terahertz technology, terahertz mixers which can shift the received high-frequency terahertz signal to the low-frequency band for digital signal processing have attracted increasing attention and research [5], [6]. The solid-state terahertz harmonic mixer has been favored by scholars because of its ability to work at room temperature, the small size, easiness of fabrication, and wide application [5]–[7]. As the terahertz band is an extension of the millimeter-wave band, solid-state terahertz mixers have some similarities with solid-state millimeter-wave mixers in design methods and ideas [7]–[10]. Furthermore, the planar Schottky barrier diode is used as the core device because it is structurally stable, easy to integrate, can work at room temperature, and has a high cut-off frequency [11]–[13], making it a suitable candidate for a terahertz mixer that can work stably at room temperature.

Terahertz mixers are usually divided into hybrid integrated mixers [7]–[10], [14]–[17] and monolithic integrated mixers [18]–[21] based on the degree of circuit integration and different methods of diode assembly. The hybrid integrated mixers were first used in the terahertz band [7], [8], [16]. In this technology, the diodes are separated and need to be manually assembled [7], [14], so the alignment of the diodes to the passive circuit is poor and uncertain. In monolithic integrated mixers, the Schottky diodes and the passive circuit are integrated into the same substrate through integration technology, eliminating the manual assembly process of the diodes [18]–[21], thereby improving the alignment accuracy of diodes. However, the monolithic integrated mixers have a high technical threshold, complex fabrication process, and high cost. Therefore, the hybrid integrated mixer is still a good choice to design a terahertz band mixer because of its

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advantages of simple process, low cost, easiness of assembly and obtaining diodes. However, poor diode alignment accuracy and the silver glue used for fixing will change the matching networks, which will lead to a deterioration of the performance of an assembled mixer. This deterioration will result in a difference between test results and prediction, which in serious cases will lead to the failure of mixer design. This phenomenon is particularly prominent in the high-frequency band. So, it is necessary to study the basic reason for the influence of silver glue, and on this basis, to study the methods to reduce the influence of silver glue and expand the frequency band of hybrid integrated mixer application.

In this paper, based on the processing and assembly process of a terahertz hybrid integrated mixer, the influence of the silver glue for pasting separated Schottky diode on circuit performance is analyzed. A traditional terahertz hybrid integrated mixing circuit working in 600-700 GHz is designed and modeled in the High Frequency Structure Simulator (HFSS) software. The silver glue introduced in the assembly process is then modeled according to the actual irregular physical shape. Furthermore, the influence of the size of the silver glue on circuit performance is analyzed. The analysis shows that in the traditional hybrid integrated mixing circuit, the silver glue will change the matching between the diode and the passive circuit, which will affect the performance of the assembled mixer. This effect mainly comes from the metal cover formed by the silver glue and the resonance caused by its volume formation. Since the minimum size of silver glue coverage area formed by the manual assembly is fixed, the influence of silver glue on mixer performance will be more obvious in the high frequency band. Based on the main reason that silver glue affects the performance of the mixing circuit, in this paper, a terahertz mixer with large pads is designed to reduce the influence of silver glue. The feasibility of the scheme is verified by simulation and experiment.

II. MIXER DESIGN

The basic topology [7] of the solid-state terahertz harmonic mixer is shown in Figure 1. It consists of radio frequency (RF) and local oscillator (LO) transitions, the Schottky diodes, intermediate frequency(IF) and LO low-pass filters, as well as matching networks. In terahertz hybrid integrated mixers, the diode pair is separated and needs to be pasted on the transmission line using flip-chip technology [7], [14], as described in the setup of the diode pair in Figure 1. In this paper, a mixing circuit working at 600-700 GHz is studied as an example, in which the RF and LO signals are fed by standard rectangular waveguide WR-1.5 and WR-2.2 respectively. Note that the load-carrying transmission line used in the terahertz mixer is a quartz microstrip line or suspended microstrip line with a substrate thickness of 50 um, substrate width of 220 um, substrate length of 1714 um, conductor thickness of 2 um, substrate dielectric constant of 3.81. A 50-ohm impedance line is used to output the IF signal. In addition, an RF transition with shorted ground [22] is also used in the

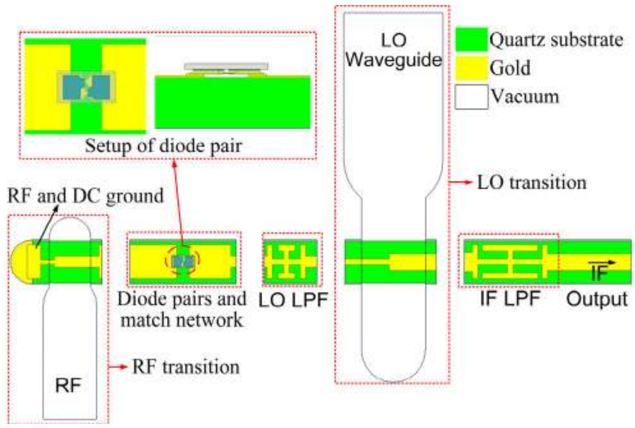

FIGURE 1. Longitudinal section and diode pair setup of terahertz hybrid integrated harmonic mixer.

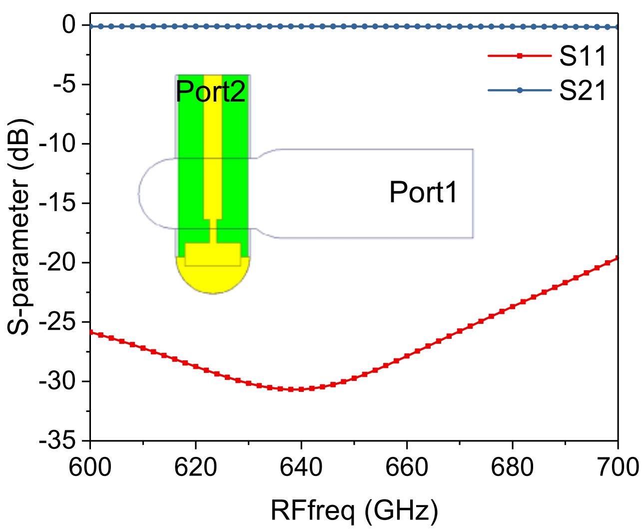

FIGURE 2. S-parameter simulation results and model structure of the RF waveguide transition.

hybrid integrated mixing circuit, so that the Schottky diode can complete the DC circuit through the RF transition. Thus, the grounding structure on the side of the shielding cavity in the traditional structure is removed, which reduces processing and assembly difficulty of the high-frequency mixing circuit.

As shown in Figure 2, the simulated S11 of RF transition with the shorted ground is below −20 dB, the transition loss (−S21) between two ports is better than 0.18 dB. These prove that the RF signal can be well input from the RF waveguide through the RF transition. During the design and optimization of the LO waveguide transition, it is necessary to consider a transmission or isolation between different ports in different frequency bands, so LO waveguide transition, LO and IF low-pass filters need to be integrated as an LO diplexer for optimization, as shown in Figure 3. The optimized LO diplexer performance is also shown in Figure 3. The simulated S11 for the LO path is below −25 dB for 300-350 GHz with a loss from port 1 to port 2 of less than 0.3 dB. The isolation between port 1 and 3 is better than 30 dB. For the IF path of 0.1-30 GHz, the S11 is better than −15 dB, the insertion

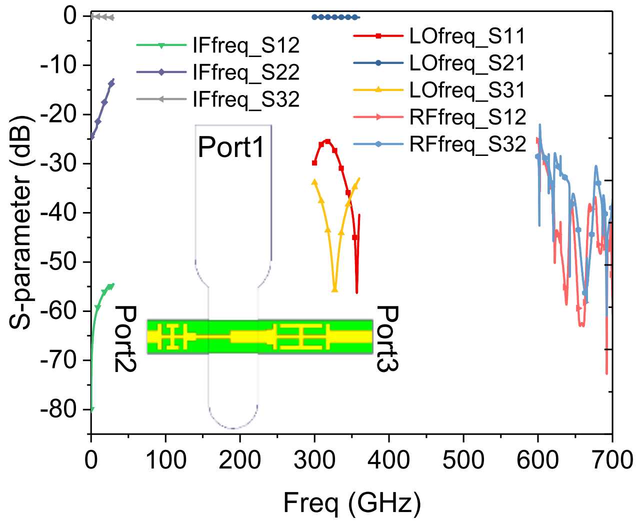

FIGURE 3. S-parameter simulation results and model structure of the LO diplexer.

loss(−S32) from port 2 to 3 is less than 0.4 dB. For the RF path, the isolations between port 2 and port 1, 3 are both better than 20 dB.

A. SIZE ANALYSIS OF SILVER GLUE

In the hybrid integrated mixing circuit, the Schottky diode is separated from the passive circuit. Therefore, after processing the passive circuit, it is necessary to bond the Schottky diode pair to the passive circuit with the conductive adhesives (silver glue) [7], [9]. This process is usually implemented by flip-chip technology. In this process, the silver glue is first applied to the two contact positions of the Schottky diode pair and the passive circuit, forming two small silver glue stacks. Then the two pads of the Schottky diode pair are respectively contacted with the silver glue piles and the Schottky diode pair is put in the right position. The mixing circuit is then heated and cooled to harden the silver glue. The silver glue will form a metal area covering the substrate, which ensures that the Schottky diode firmly adheres to the passive circuit. In a low-frequency band, because the size of the metal strip line contacted with the Schottky diode is relatively large, the metal area formed by the silver glue will not cover the metal strip line completely, the influence of the silver glue on the mixing circuit is relatively small. As the frequency increases, the size of the metal strip line connected with the Schottky diode decreases gradually. When the working frequency reaches the terahertz band, the metal strip line will be completely covered by silver glue due to its small size. As silver glue is a conductive material, its coverage area will change the size of the metal strip line, thus changing the predicted matching of the Schottky diode, resulting in a deterioration of the performance of the assembled mixer. As frequency increases, the effect of the silver glue on metal strip line will be more obvious, and the deterioration of performance will be more serious. Similarly, with increasing frequency, the size of the shielding cavity used in the mixing circuit also becomes smaller and smaller, so that the size ratio of the irregular metal bodies formed by silver glue to shielding cavity gets larger and larger. This makes silver glue have more and more influence on the electric field transmission, distribution and the mode of electric field transmission in the shielding cavity, even causes high-frequency resonances. In addition, the uncertainties of the manually applied silver glue will make the performance of the mixer full of uncertainties. Therefore, silver glue should be fully considered in the design of a hybrid integrated mixer in the terahertz band to minimize its influence and ensure uniformity of the design.

In the process of manual assembly, silver glue is applied using a metal rod. The minimum coverage area formed by the silver glue will depend on the diameter of the metal rod. At present, the minimum diameter of the metal rod that can be manually operated is 0.1 mm, so the diameter of the coverage area formed by silver glue is at least 0.1 mm. As shown by a literature review [9], [14]–[16] and the assembled circuit, the silver glue coverage area in the assembled hybrid integrated mixer is usually greater than 0.11 mm. In addition, it can be seen from the assembled mixing circuit that the silver glue has a certain thickness, which is 15 - 25 um depending on the assembly experience. Since silver glue is pasted before heating and cooling, it will form an irregular cone on the substrate after being applied. At the same time, because of the fluidity of paste silver glue, the metal coverage formed by silver glue will be distributed in an elliptical shape and have irregular edges.

B. THE INFLUENCE OF SILVER GLUE ON MIXER PERFORMANCE

In order to analyze the influence of silver glue on the mixing circuit, we first optimized a mixing circuit using the traditional design method without considering the silver glue, as described in Figure 4. Then, according to the actual situation of manual assembly and the shape analysis of the silver glue, the shape of the silver glue stack was simulated by using an elliptical cylinder with a thickness of 10 um and a cone frustum with a thickness of 20 um. The elliptical cylinder was used to simulate the metal coverage of silver glue, and the cone frustum was used to simulate the slope information of silver glue. Some holes were subtracted from the edge of the elliptical cylinder to simulate the irregular edges of the actual silver glue. The physical parameters of the silver glue EPO-TEK® H20-HC were established in HFSS, whose bulk conductivity is $1.25*10^7$ siemens/m [23], the relative permittivity is 1, the relative permeability was 0.99998, the mass density is 10500 kg/m^3. The Schottky diode pair was mounted between two silver glue stacks. In the coverage area formed by silver glue, the maximum size perpendicular to the microstrip line was defined as W, and the maximum size parallel to the microstrip line was defined as L, as shown in Figure 4.

In a mixing circuit using the traditional design method, the performance of the mixer would deteriorate after assembly with silver glue, and resonance points would appear in the high-frequency part of the band making the fre-

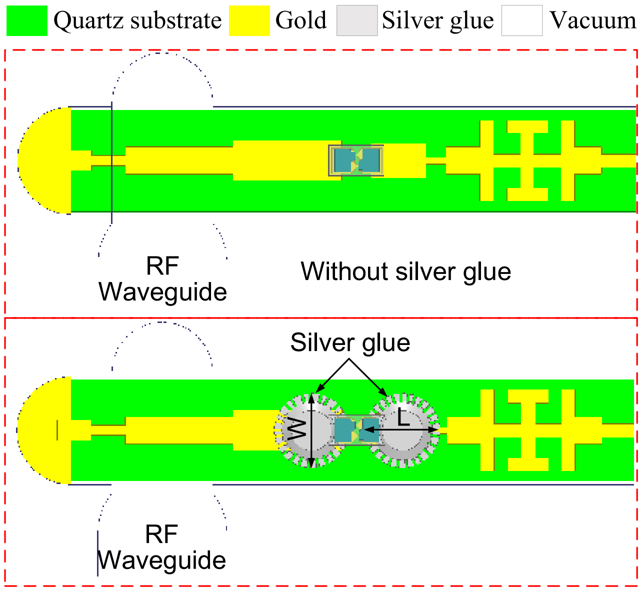

FIGURE 4. **Simulation model of the silver glue application in traditional hybrid integrated mixing circuit. Where the quartz substrate is with a dielectric constant of 3.81, loss tangent of 0.003 [24], the mass density of 2500 kg/m^3.**

quency conversion loss fluctuate dramatically, as depicted in Figure 5. As W increases, the conversion loss of the mixing circuit will further deteriorate sharply and change more dramatically in the low-frequency band. Compared with W, the conversion loss will change the same when L increases, but the trend of deterioration is relatively slow. The main reason for this deterioration is that the coverage area formed by silver glue changes the size (the length and width) of the strip line connected with the Schottky diode due to metal characteristics of the silver glue. This change in size results in a mismatch of the Schottky diode. In the silver glue coverage area, W changes the width of the strip line, so when W increases, the conversion loss of the mixing circuit should gradually increase from a smaller value, which is consistent with the trend shown in Figure 5 (a). L changes the length of the strip line after increasing the width, the conversion loss should begin to change from a larger value, which is also consistent with the description in Figure 5 (b). The changes of width will directly lead to the changes of characteristic impedance of the strip transmission line. So when the width of strip line changes, the changes in frequency conversion loss should be more drastic. This is still consistent with what is shown in Figure 5. Figure 5 also illustrated that the bandwidth of the mixing circuit will become narrower as the coverage area of silver glue increases. In addition, the appearance of a high-frequency resonance point is mostly from the volume of silver glue, which occupies certain space in the shielding cavity, causing resonance and high-order modes.

C. ANALYSIS OF THE TERAHERTZ MIXER WITH LARGE PADS

According to the analysis in the previous section, in the traditional terahertz hybrid integrated mixing circuit, the coverage

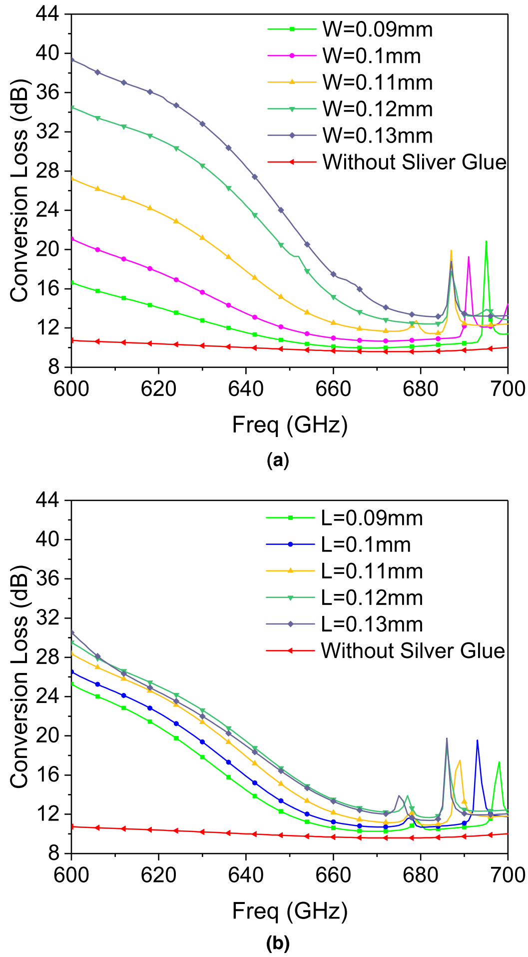

FIGURE 5. **Simulation of the influence of silver glue size change on mixing circuit performance: (a) when L = 0.11 mm, W changes, (b) when W = 0.11 mm, L changes.**

area formed by the silver glue used for the manual assembly will cause a mismatch of the Schottky diode, resulting in the deterioration of the performance. More importantly, the performance of the assembled mixer is unstable due to the uncertainty of the manual application of the silver glue (the coverage area, shape, and thickness of the silver glue cannot be accurately controlled). This is more obvious in high-frequency bands. Therefore, reducing the influence of the silver glue on the assembled circuit is an important problem to be solved in the design of the high-frequency terahertz hybrid integrated mixer. In this paper, based on the main reason due to which silver glue affecting the performance of the mixing circuit, larger pads were used. The silver glue is then all applied on the pre-designed pads in order to reduce the influence of silver glue on the Schottky diode matching after assembly, as shown in Figure 6. Then, the matching network of the Schottky diode is optimized based on large pads. Although the performance of the mixing circuit with larger pads would become worse (the most obvious feature being the narrowing of working bandwidth), this change is acceptable compared with the uncertainty introduced by the silver glue. When large pads are used, all silver glue can be

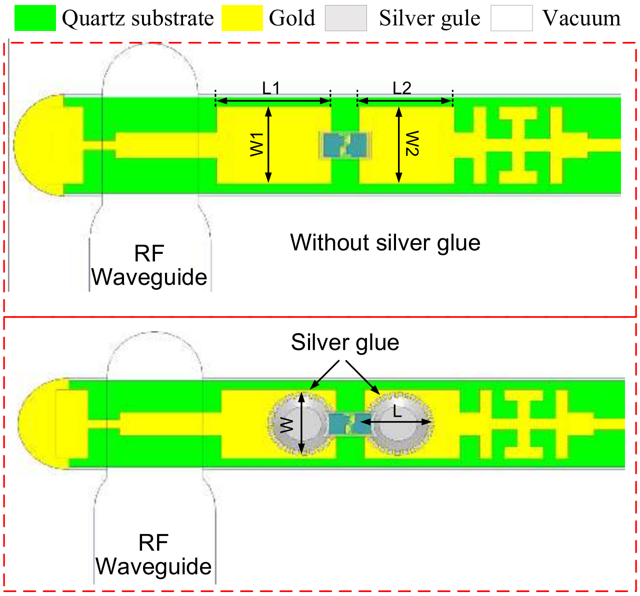

FIGURE 6. **Simulation model of traditional hybrid integrated mixer using large pads. Where the size of two large pads is W1 = W2 = 0.12 mm, L1 = 0.18 mm, L2 = 0.15 mm.**

applied to the prepared pads, the metal coverage area formed by the silver glue will not change the size of the strip line, so its effect on the matching network will be minimized. The simulation results in Figure 7 show that there is only a small change in the conversion loss as the size of the silver glue coverage changes, which indicates that large pads can reduce the effect of the silver glue on the diode matching. The use of large pads also eliminated the high-frequency resonance caused by the silver glue to a certain extent. In addition, the conversion loss will have a small increase after applying the silver glue, which is the loss caused by the thickness of the silver glue.

D. RETURN LOSS OF THE TERAHERTZ MIXER WITH LARGE PADS

The return loss of the input and output of harmonic mixing circuits can be simulated and calculated using the ''circulator'' in the Advanced Design System (ADS). The simulated return loss of RF and LO ports in the terahertz mixer with large pads are depicted in Figure 8. The simulated RF return loss has a best value of 30 dB at 637 GHz and is below 8 dB from 600 - 661 GHz, which is consistent with the trend of conversion loss. The RF return loss simulation results demonstrates the mixing circuit with large pads works well in terms of impedance matching. LO return loss is better than 9 dB for the LO path of 300-350 GHz, which demonstrates LO signal can be fed into the mixer. The impedance matching of the IF output port is characterized using the Keysight VNA VA 40. A 0.1–30 GHz signal is directly applied to the IF port. The simulated and measured results are shown in Figure 9. The measured responses agree well with the simulation. The measured return loss is better than 10 dB in the frequency

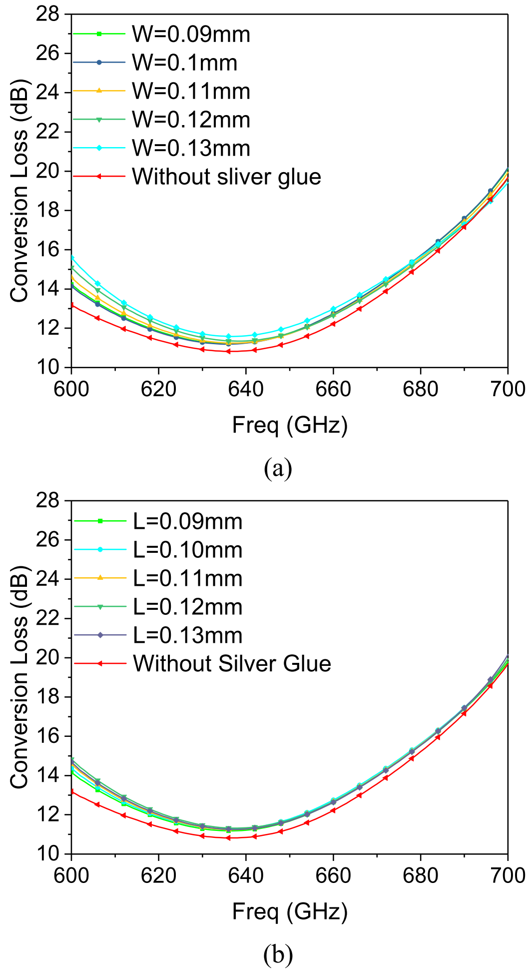

FIGURE 7. **Influence of silver glue size change on mixing circuit performance when large pads are used: (a) when L = 0.11 mm, W changes, (b) when W = 0.11 mm, L changes.**

range of 0.1-30 GHz, which indicates the mixer has a wide IF bandwidth.

III. FABRICATION AND MEASUREMENTS

The strip line on the 50 um quartz substrate used in the hybrid integrated mixer is fabricated by mask lithography and etching technology, and the precision of the conductor strip is less than 1μm. The shielding cavity is composed of two split blocks, which are milled directly on the copper block by a diamond cutter, as shown in Figure 10. The copper block is divided into top and bottom cavities at the center of the wide side of two standard rectangular waveguides. Four protruding tables are designed on the four corners of the upper cavity in order to make the top and bottom cavities more easily fixed and assembled. In the last section of IF signal output, a 50 ohm microstrip line on a 0.127 mm Rogers RT/Duroid 5880 substrate is used to connect the quartz substrate and the K connector.

The prepared quartz substrate is fixed in the copper block with silver glue to form a microstrip or suspended microstrip line with a limited shielding cavity, as shown in Figure 11.

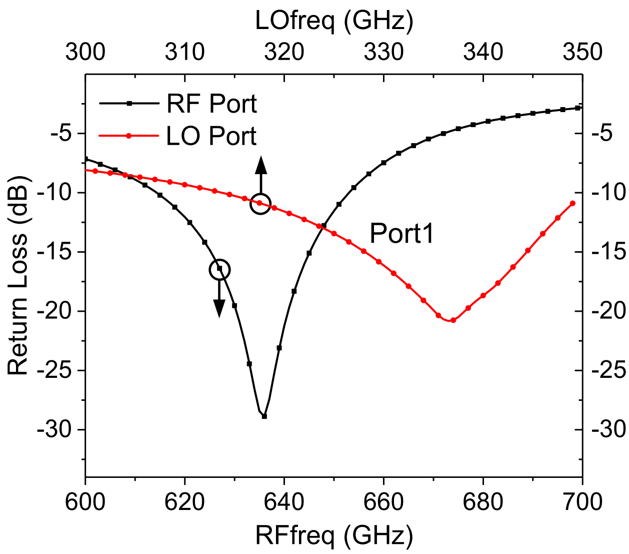

FIGURE 8. Simulated return loss of LO and RF input port.

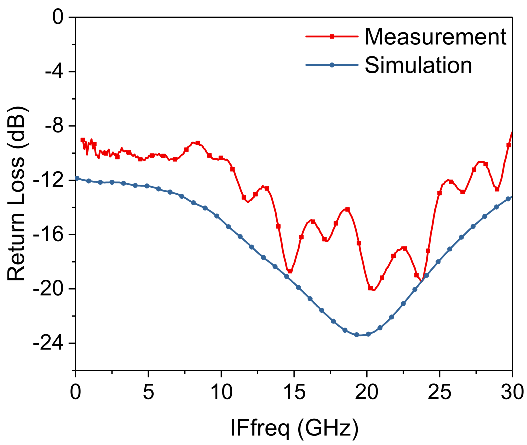

FIGURE 9. Simulated and measured return loss of IF output port.

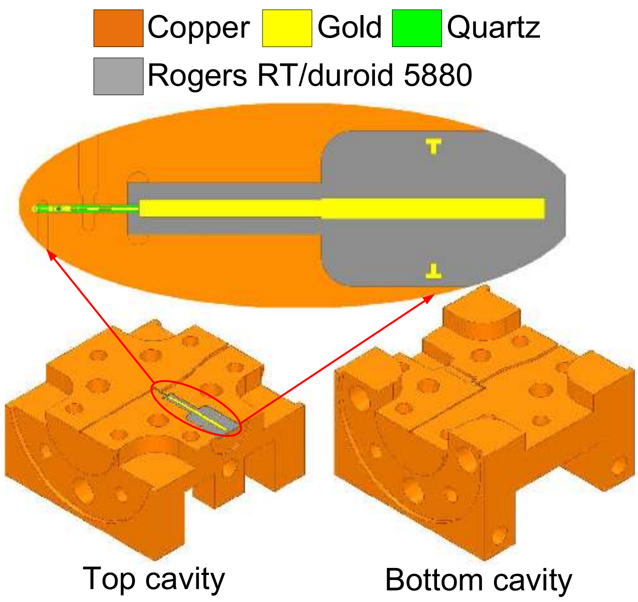

FIGURE 10. The 3D model of top and bottom cavities, and the top view of the overall circuit. Where the mixer module has an overall volume of 20 mm × 20 mm × 20 mm.

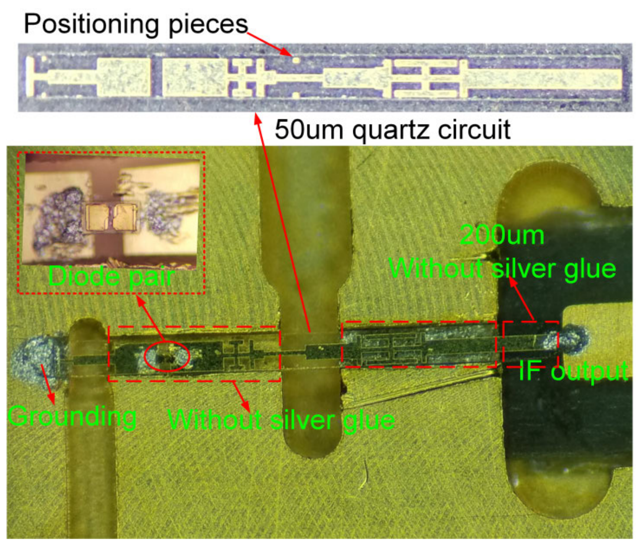

FIGURE 11. The Photograph of the manufactured quartz circuits and the assembled mixer block.

In RF transition ground and IF output parts of the assembled mixer, the microstrip transmission line is used and the silver glue is adopted to fix the quartz substrate on the bottom. While, in the Schottky diode and matching network parts, the suspended microstrip transmission line is used. Silver glue is not used underneath these parts to reduce the deterioration caused by the assembly. Four rectangular metal blocks were placed in advance on the edge of the quartz substrate as positioning pieces. They can realize the positioning of the quartz substrate in the copper block during manual assembly, and do not affect the circuit performance due to the small size and the distance from the central strip line metal. These metal blocks can also be used as circuit identification marks by processing different quantities and positions. In the assembly of the mixing circuit, the quartz substrate exceeds the groove by 200 um at the connection with the Rogers RT/duroid 5880 substrate. In this part, the silver glue will not be applied to the bottom of quartz substrate to prevent short circuit. In addition, note that the silver glue applied for RF transition grounding almost completely covers the whole width of the quartz substrate, so it is necessary to use wide metal tabs for grounding wire.

According to the basic principle of the harmonic mixer and the definition formula of the single sideband (SSB) conversion loss, it is necessary to set up the LO and RF signal inputs and test the IF signal output power. The measurement setup consists of two signal generators Agilent Technologies E8267D (250KHz - 43.5 GHz, ±0.01Hz), a spectrum analyzer Agilent Technologies E4447A (3Hz-42.98 GHz, ±2Hz), a 54X frequency chain for RF signal, an 18X frequency chain for LO signal, as shown in Figure 12. The RF output part is built up with the signal generator,

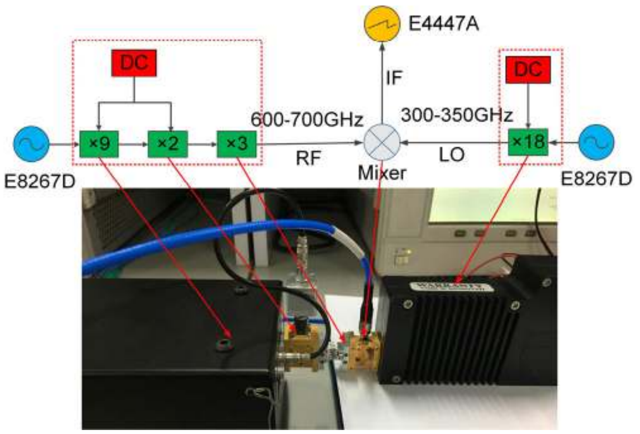

FIGURE 12. Setup and photograph of the measurement platform of the conversion loss.

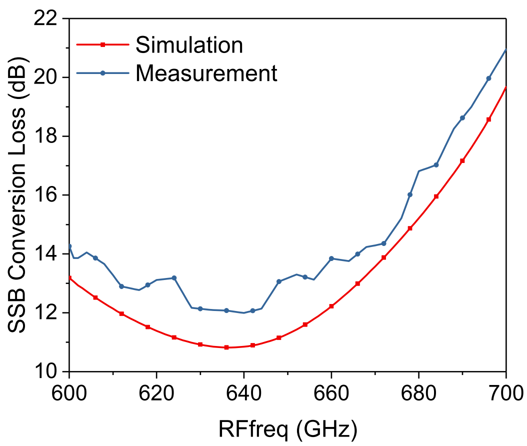

FIGURE 13. Comparison between simulated and measured the SSB conversion loss when the IF frequency is fixed to 2 GHz.

a 54 frequency multiplier (including a 9X frequency multiplier, a frequency tripler, and a frequency doubler). The RF frequency chain module can output a signal with a power level of −20 dBm to −10 dBm in the frequency range of 600-700 GHz. The detailed structure of the source module can also be found in Figure 12. Following the setup presented in Figure 12, the conversion loss of the proposed hybrid integrated mixer can be measured.

Figure 13 shows the simulated and measured SSB conversion loss of the hybrid integrated mixer with large pads. It can be observed that the measured conversion loss is better than 14 dB in the RF frequency range of 600-667 GHz, and reaches its minimum value of 12 dB at 640 GHz. Furthermore, the trend between the experiment results and simulation results has good consistency. The difference between conversion loss and the predicted value is only within 1.8 dB.

In order to verify IF bandwidth characteristics of the mixer, the conversion loss at the fixed LO frequency is simulated and tested as shown in Figure 14. Combined with the trend of conversion loss in Figure 13, it can be seen that the mixer has a wide IF bandwidth (the IF bandwidth is 30GHz). In the

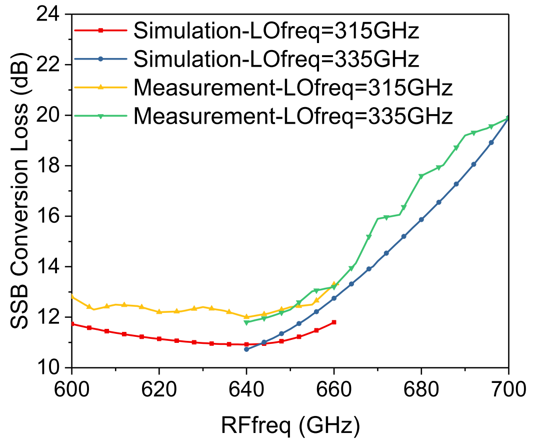

FIGURE 14. Comparison between simulated and measured the SSB conversion loss when the LO frequency are fixed to 315 GHz and 335 GHz.

TABLE 1. Summary of measured performances to the reported similar terahertz hybrid integrated mixers.

Ref.	RF(GHz)	CL(dB)	Dif.[a](dB)
[9]	638-713	8.2 – 11.2 (DSB)	1.6 ~ 5.0
[10]	665-715	13.1-16 (DSB)	3 ~ 4
[14]	433-451	14-17 (SSB)	> 6
[15]	664	11 (DSB)	> 2.5
[17]	380-430	10 – 15 (SSB)	> 2.9
This work	**600-667**	**12 – 14 (SSB)**	**< 1.8**

[a]The Difference between measured conversion loss and the predicted value. CL is the abbreviation of conversion loss.

whole RF band of 600-700 GHz, the conversion loss of the fixed LO frequency shows the same trend as that of the fixed IF frequency. Again there is good consistency between prediction and measurement at two the fixed LO frequency.

Table 1 summaries the comparison between the performances of published terahertz hybrid integrated mixers and this work. Note that the Double Side Band (DSB) conversion loss is theoretically half of the SSB conversion loss (for the DSB conversion loss, the working signal has two signal sidebands; for the SSB conversion loss, the working signal has only one signal sideband). It can be seen that the measured results of those terahertz hybrid integrated mixers all have the differences from the prediction results. The comparison shows that the terahertz hybrid integrated mixer with large pads has a smaller difference between the measured and predicted conversion loss. This validates the correctness of our analysis.

IV. CONCLUSION

This paper firstly analyzed the influence of silver glue on the hybrid integrated mixing circuit. Then, the main reasons for this influence were studied and verified by simulations at 600-700 GHz. The influence of silver glue on the mixing circuit mainly comes from its metal coverage area and volume. Since the minimum coverage area formed by silver glue in the process of manual assembly is fixed, the higher the frequency band, the greater the impact of the silver glue on the circuit. Considering the main reason for the deterioration of the mixing circuit after assembly, a large-pad design was introduced in the terahertz hybrid integrated mixing circuit in order to reduce the impact of silver glue. The rationality of the large pad design was verified by simulation. Finally, a terahertz hybrid integrated mixer at 600 – 700 GHz with large pads was processed. The experiments show that the measured conversion loss is in good agreement with the predicted value, and there was only a difference of less than 1.8 dB.

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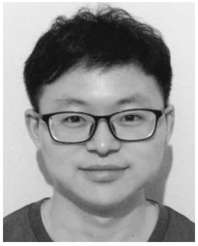

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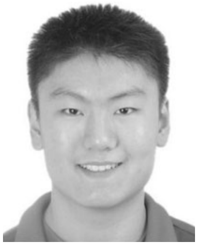

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