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Development of High Power 220 GHz Frequency Triplers Based on Schottky Diodes

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ABSTRACT In this paper, the development of two high power 220 GHz frequency triplers is proposed. The GaAs Schottky diodes with six nodes are applied to realize high efficiency 220 GHz tripler, while the application of GaN Schottky diodes with eight nodes is another attempt to improve power handling of the 220 GHz tripler. To reduce thermal effect of high power multipliers, the AlN substrates with high thermal conductivity are applied to provide better heat dissipation at the diode areas. A combination of electrical and thermal model of the Schottky diodes is established while the optimization of 220 GHz triplers are realized with 3D electromagnetic (EM) simulation and harmonic balanced simulation. Good agreement is achieved between the simulated results based on electro-thermal model and measured performances of the triplers. At room temperature, peak efficiency of the tripler based on GaAs Schottky diodes is 17.8%, while the maximum output of the tripler is 38.2 mW with 300 mW input power. As for the 220 GHz GaN Schottky diode tripler, measured results show that the maximum power handling is beyond 400 mW. The peak efficiency and maximum output are 4.7% and 18.4 mW, respectively. The proposed methods of developing high power multipliers can be applied in higher frequency band in the future.

INDEX TERMS Submillimeter wave, frequency tripler, high power, Schottky diodes, electro-thermal model.

I. INTRODUCTION

A considerable number of submillimeter wave and terahertz (THz) applications such as radio astronomy, earth observation, remote sensing, communication and imaging applications have brought increasing demands and researches of stable and high output signal sources [1], [2]. In the past few decades, the development of multiplier-based solid state electronic sources, quantum cascade lasers (QCLs), backward-wave oscillators (BWOs), high-electron mobility transistor (HEMT), heterojuction bipolar transistor (HBT), etc. offers multiple approaches to generate THz signals [2]–[6]. However, many of these useful technologies have their limitations. Some are inherently limited to pulsed operation; others are limited in low output power or the requirement for cryogenic cooling. The size, cost, lifetime and complexity should also be concerned in the practical application of these technologies. Among others, the solid state multiplying sources are preferred in THz band due to their compact size and the ability to generate continuous wave signal [6], [7].

In recently years, great progress has been achieved in the researches of solid state sources based on planar Schottky diodes. Multipliers based on Schottky diodes are able to realized good output and high efficiency with frequency up to 2.7 THz [8], [9]. Although heterostructure barrier varactors (HBV) is also a promising option to realize THz multipliers [10], [12], it only generates odd harmonics of the input signal due to their internal symmetry. Meanwhile the multipliers based on HBV have lower efficiency compared with their counterparts based on Schottky diodes. Nowadays, THz doublers and triplers based on Schottky diodes are more commonly used for their better performances referring to output power, efficiency and bandwidth [6], [7], [13]–[15]. The development of solid state sources based on Schottky diodes has greatly contributed to the progress in emerging areas such as high-speed wireless communication and security imaging systems [17]–[22].

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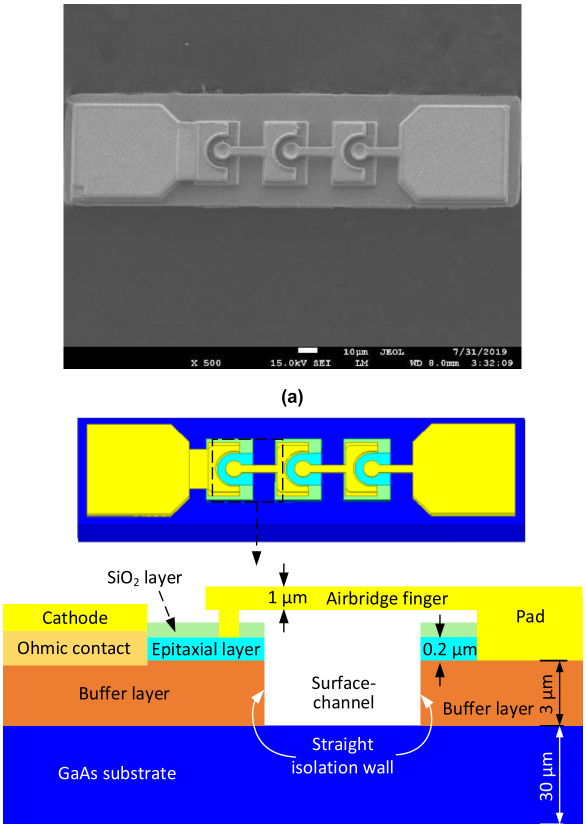
As THz applications move up to 1 THz, many stages of multiplication are required as the fundamental input signal are often in the millimeter wave frequency band, where significant driving power (watt-level) is accessible [23]. Therefore, as the first stage of the multiplier chains, the multipliers working within submillimeter wave range are required to increase power handling while guaranteeing high efficiency and output power at the same time.

There are two main strategies of increasing power handing of multipliers based on Schottky diodes. One is improving power handling of the applied Schottky diodes. Another is applying power-combining techniques [24]–[26]. Meanwhile, an essential concern of high power submillimeter wave and THz multipliers is heat dissipation, especially at anode area of the Schottky diodes. Excessive heat generated around the Schottky junctions due to high driving power and limited conversion rate will degrade diode performances or even disable the diodes. An effective solution is applying Schottky diodes with more anodes to distribute input power. Using circuit substrates with high thermal conductivity is another method to overcome the thermal issues [27]–[29].

Traditional designing procedures of THz multipliers only consider the electrical model of nonlinear devices. However, in order to accurately analyze and optimize the performances of high power multipliers, the thermal characteristics of Schottky diodes should be taken in to consideration. Over the last ten years, the introduction of self-consistent electro-thermal model of Schottky diode multipliers has improved the designing procedures by analyzing the internal temperature distributions and offering useful information for circuit reliability and optimization [30]–[32]. The simulated performances based on electro-thermal exhibit better agreement with the measured results in previous researches [29], [30]. Meanwhile, according to the researches in [29], the flip chip diodes mounted on high thermal conductive substrate exhibit better thermal behaviors compared membrane integrated diodes or substrateless configuration. Therefore, the flip chip Schottky diodes are chosen to realize 220 GHz high power triplers.

In this paper, two 220 GHz triplers are developed based on proposed GaAs Schottky diodes and GaN Schottky diodes. The GaAs diodes manufactured by Hebei Semiconductor Research Institute are used to realize high efficiency while the GaN diodes with high break down voltage are applied to achieve high output by improving power handling of the tripler. In order to reduce performance degradation brought by thermal effects at the diode areas, the AlN substrates with superior thermal conductivity are used. Based on the simulation and optimization utilizing electro-thermal model of Schottky diodes, both 220 GHz triplers realize state-of–art performances. The output power can be further improved by optimizing diode parameters and applying powering combining in the future. Meanwhile, the measured performances agree well with the simulated results based on electro-thermal model, which validates the analyzing methods introduced in this paper.



(a)

(b)

FIGURE 1. **(a) SEM photograph of the GaAs diode chip manufactured by Hebei Semiconductor Research Institute (b) 3D model and cross section view of the proposed GaAs Schottky diode.**

II. SCHOTTKY DIODES FOR 220 GHz TRIPLERS

THz Schottky diodes are greatly developed because of the need for compact, broadband coherent sources in the THz range. Multipliers based on Schottky diodes have been preferred in THz systems due to compact size, low DC consumption, good performances at room temperature, etc. With appropriate embedding impedances at each harmonic frequency, the Schottky diodes are able to generate desired output power with good efficiency. In recent years, the GaAs Schottky diodes are most commonly used to realize high efficiency multipliers at THz frequency range. A great challenge for high power GaAs Schottky diode multipliers is low power capacity of the diodes. GaN Schottky diodes with higher breakdown voltage are good options to improve power handling of THz multipliers [33]–[35]. In this paper, two types of Schottky diodes are introduced and utilized to realize high power 220 GHz triplers.

A. GaAs SCHOTTKY DIODE

As the key component of the multipliers, the Schottky diodes decide the integral performances of the circuits. In this paper, the applied GaAs Schottky diodes shown in Fig. 1(a) are developed by University of Electronic Science and Technology of China (UESTC) and Hebei Semiconductor Research Institute. 3D electromagnetic (EM) model and cross section

TABLE 1. Electrical parameters of the applied GaAs Schottky diode (per anode).

Number of anodes	Breakdown voltage (V_{br})	Zero bias junction capacitance (C_{j0})	Series resistance (R_s)	Ideal factor(n)
3	-7.5 V	32 fF	5 Ω	1.3

view are shown in Fig. 1(b). Main parameters and dimensions of the diode chip are optimized to realize best performances of the 220 GHz tripler. The fabrication processes of the proposed GaAs diodes include the following steps:

1) Deposition of the GaAs layers. The GaAs layers including a 0.2 μm thick epitaxial layer and a 3 μm thick highly doped n+ GaAs layer are grown on the diode substrate with metal-organic chemical vapor deposition (MOCVD). In this design, the doping density of the epitaxial layer and highly doped n+ GaAs layer are 2×10^{17} cm^{-3} and 5×10^{18} cm^{-3}, respectively. Then, a thin SiO_2 layer is deposited and etched to provide passivation.
2) Etching the surface channel and formation of the ohmic contact. The straight isolation walls, which lead to lower parasitic capacitances [36], are realized with drying etching process. Circular anode wells are etched by standard lithography and reactive ion etching. The ohmic contacts are formed by electron-beam (e-beam) evaporated Ti/ Al/Ni/ Au metallization. In this design, the anode diameter is 5.4 μm.
3) Formation of airbridge finger and cathode pad. The airbridge finger is formed by electroplating process. Then, the Schottky contact and the anode pad are connected.
4) Thinning the diode substrate. The GaAs substrate is thinned from backside using grinding machine. The substrate thickness of the GaAs Schottky diode is 30 μm.

Based on these processes, the GaAs Schottky diodes with overall dimensions of 240 μm × 60 μm × 35 μm are manufactured. Extracted from previous measurements, main parameters of the proposed GaAs diodes are shown in Table 1.

B. GaN SCHOTTKY DIODE

GaN is a promising material to realize high power operation due to its wider band-gap (3.44 eV) compared with GaAs (1.42 eV), which leads to high breakdown voltage. Although GaN Schottky diodes have high series resistance due to low mobility of GaN, their power handling is higher compared with GaAs diodes [33]–[35].

There are two methods to improve power handling of the diode chip. One option is increasing the number of anodes, which is limited by the dimensions of the diode chip for corresponding frequency band. There are four anodes on the proposed GaN diode chip. Another is improving the breakdown voltage of the diode. Applying epitaxial layer with lower doping density can achieve this goal, but it will also lead to higher series resistances of the diode, which could deteriorate the efficiency of the tripler. In this design, an optimized doping density of 4×10^{17} cm^{-3} is applied for the 0.3 μm thick epitaxial (n- GaN) layer. The doping density and thickness of the highly doped n+ GaN layer are 5×10^{18} cm^{-3} and 3 μm, respectively. The diameter of the Schottky anodes formed on the epitaxial layer is 3.2 μm. SiC substrate with high thermal conductivity is utilized to provide better heat sink of the diode chip.

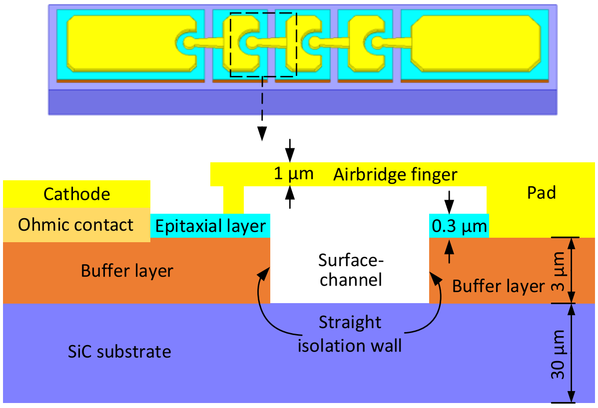


FIGURE 2. 3D model and cross section view of the proposed GaN Schottky diode.

TABLE 2. Electrical parameters of the applied GaN Schottky diode (per anode).

Number of anodes	Breakdown voltage (V_{br})	Zero bias junction capacitance (C_{j0})	Series resistance (R_s)	Ideal factor (n)
4	-22.6 V	12.6 fF	20 Ω	1.5

3D model and cross section view of the proposed GaN Schottky diode with overall dimensions of 255 μm × 65 μm × 35 μm are shown in Fig. 2. The GaN Schottky diodes are manufactured using similar process of GaAs diodes. Electrical parameters of the GaN Schottky diodes are calculated with previous junction measurement and shown in Table 2. The breakdown voltage (V_{br}) of GaN diode is -22.6 V, which is more than triple of breakdown voltage (V_{br}) of the GaAs diode. Higher breakdown voltage and more anodes indicate that the proposed GaN Schottky diode can handle more input power in the development of 220 GHz triplers. Apart from that, the cut off frequency of GaN Schottky diodes is lower compared with GaAs diodes due to low mobility of GaN. Therefore, a lower zero bias junction capacitance is applied for the proposed GaN diode to improve the cut off frequency.

III. CIRCUIT DESIGN

A. CONFIGURATION OF THE 220 GHz SCHOTTKY DIODE TRIPLERS

For submillimeter wave and THz triplers, the configurations based on anti-parallel or anti-series connected Schottky diodes have been proposed and demonstrated in the past few decades. In this paper, the anti-series configuration introduced in [37] is applied to realize 220 GHz high efficiency triplers. Topology of the 220 GHz tripler based on GaAs

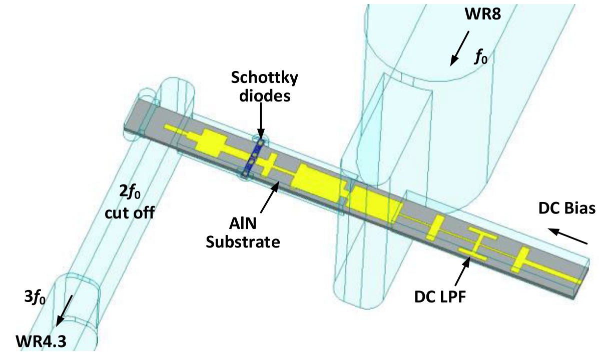


FIGURE 3. Configuration of the proposed 220 GHz triplers based on Schottky diodes.

Schottky diodes is shown in Fig. 3. Two discrete diode chips are mounted on the circuit with silver epoxy in a flip-chip configuration while outer pads of the diodes are directly soldered to the waveguide block. Aluminum Nitride (AlN) with good thermal conduction is used as the material of the tripler substrate to provide rapid heat sink. The substrate with dimensions of 5.5 mm × 0.4 mm × 0.05 mm is suspended in an enclosed channel across the input and output waveguides (WR8 and WR4.3, respectively). The DC low pass filter is utilized to provide DC bias and prevent input signal leaking from this port. Although the GaAs diodes arranged in a balanced configuration, this structure can provide an improved thermal path for heat flow from the diodes to the metal waveguide block [37]. An improvement of the tripler configuration proposed in this paper is that the whole tripler circuit is developed on one substrate, which is beneficial for the fabrication process.

The topology of the GaN Schottky diode tripler is very similar with the GaAs diode tripler. It applies identical external structures including input and output waveguide-microstrip transitions, DC LPF and so on. The matching networks are reoptimized to realize best performances of the GaN Schottky diode tripler. The dimensions of the AlN substrate are 5.48 mm × 0.42 mm × 0.05 mm. To achieve optimum performances of the 220 GHz tripler, the electro-thermal models of the Schottky diodes are established, while the simulated performances are carried out with a combination of EM simulation and harmonic balance simulation.

B. THERMAL CHARACTERIZATION

Thermal analysis has become important in the development of Schottky diode-based circuits for high power applications. To realize high output power multipliers, the power handling and efficiency need to be guaranteed. An important concern is the degraded performances or even damage to the diode brought by excessive self-heating in the diode area. This concern is especially crucial for THz Schottky diode, which features smaller sizes of the anodes and chip geometry. In order to quantify the self-heating level at the Schottky junction and improve the design procedure of the circuits, the electro-thermal model was proposed [30]. The model provides useful information including temperature-dependent material parameters and internal temperature distribution, which greatly contributes to accurate analysis of the integral circuit.

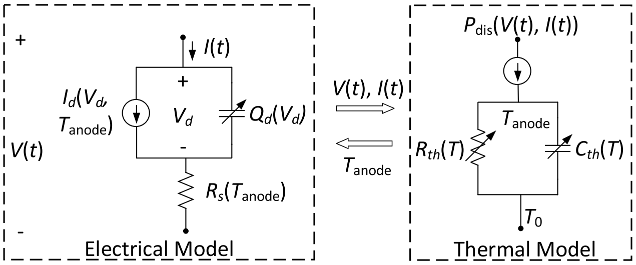
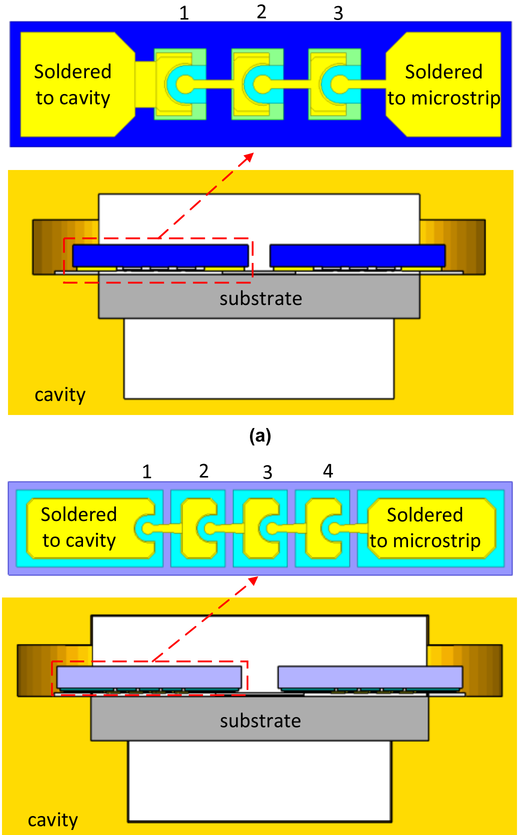


FIGURE 4. Electro-thermal model of single diode [30].



(a)

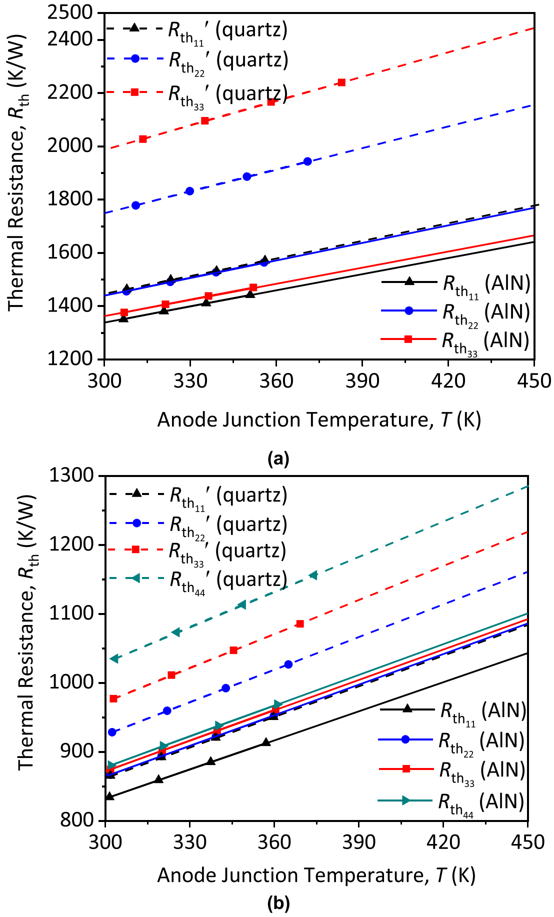
(b)

FIGURE 5. Cross section views of (a) GaAs Schottky diodes and (b) GaN Schottky diodes mounted on different substrates in the tripler cavity.

1) SCHOTTKY DIODES ELECTRO-THERMAL MODEL

In this paper, the electro-thermal model is used to analyze the thermal characteristic and performances of 220 GHz high power tripler. As shown in Fig. 4, the electrical model provides the calculated dissipated power to the thermal model, while the thermal model complements the electrical model with the junction temperature. As shown in (1), the thermal resistance $R_{\mathrm{th}}(T_{\mathrm{anode}})$ is utilized to quantify the self-heating effect.

$$\Delta T = T_{\mathrm{anode}} - T_0 = R_{\mathrm{th}}\left(T_{\mathrm{anode}}\right) \times P_{\mathrm{dis}} \tag{1}$$



(a)

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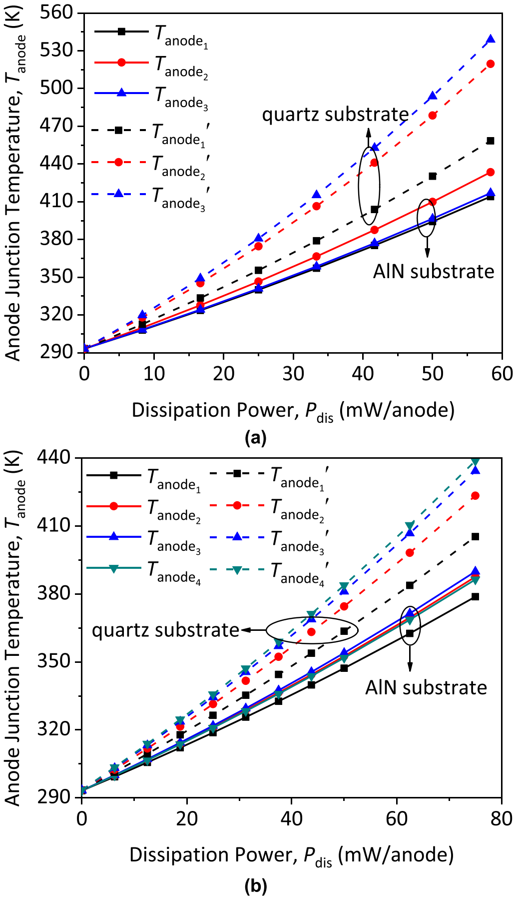
FIGURE 6. Temperature dependency of the main diagonal terms in the thermal resistance matrix calculated for (a) GaAs Schottky diodes and (b) GaN Schottky diodes mounted on different substrates. Markers show the temperatures acquired from the thermal simulations at dissipated power levels of 10, 20, 30 and 40 mW in the single heat source cases.



(a)

(b)

FIGURE 7. Anode temperature of (a) GaAs Schottky diode and (b) GaN Schottky diode mounted on different substrates. (T_{anode} and T_{anode}' represent anode temperature with AlN substrate and quartz substrate, respectively) Equal dissipation power is assumed at each anode of the diodes.

where P_{dis} represents the dissipated power at the anode, T_0 and ΔT are ambient temperature and temperature rise brought the dissipated power, respectively.

For Schottky diodes with n anodes, the elements in $n \times n$ thermal resistance matrix $R_{\text{th}}(T_{\text{anode}})$ can be calculated with (2). For anode i, $R_{th_{ij}}$ (T_i) represents the anode temperature rise (ΔT_i) brought by dissipated power in anode j, while no power is dissipated in the rest of anodes.

$$R_{\text{th}ij}(T_{\text{anode}_i}) = \frac{T_{\text{anode}_i} - T_0}{P_{\text{dis}_j}}\bigg|_{P_{\text{dis}_k}=0,k\neq j} \qquad (2)$$

In this multi-anode thermal model, the self-induced thermal resistances ($R_{th_{ii}}$ (T_i)) in each anode and thermal interaction between different anodes ($R_{th_{ij}}$ (T_i)) are both considered.

2) THERMAL ANALYSIS OF THE 220 GHz TRIPLERS

The thermal model of the tripler is established using CST MPHYSICS STUDIO. To research the self-heating effect of the Schottky diodes, the thermal characteristics of the diodes pair using AlN substrate are compared with the ones using quartz substrate. The quartz substrate is more commonly used to realize THz multiplier in the past, however, it features much lower thermal conductivity (1.4 W/(m· K)) compared with AlN substrate (160 W/(m· K)). The cross section view of the flip chip GaAs Schottky diodes mounted on the substrate is shown in Fig. 5 (a). Due to the symmetry structure, the thermal matrix can be simplified to a 3 × 3 matrix. By applying heat source with particular power at one single anode, the temperature rise of each anode of the diode chip can be obtained. The thermal resistance elements, calculated as a function of power dissipation level, are then analyzed as a function of anode temperature. All the simulations and calculations in this paper are carried out with ambient temperature T_0 =20 °C (293 K). Fig. 6(a) shows the main element $R_{th_{ii}}$ (with corresponding anode position shown in Fig. 5(a)) of the thermal resistance matrixes calculated for GaAs Schottky diodes mounted on different substrates. It shows that the flip chip Schottky diodes on AlN substrate have lower thermal resistances, which lead to lower temperature rise at each anode.

The cross section view of flip chip configuration of GaN Schottky diodes is shown in Fig. 5 (b). The anodes from diode chips mounted on AlN substrate features lower thermal

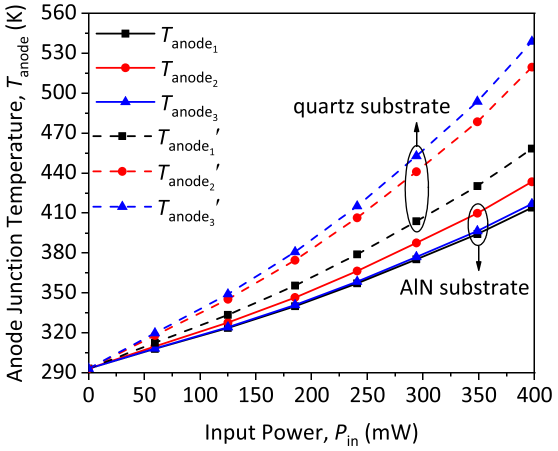


FIGURE 8. **Estimated anode temperature of GaAs Schottky diode as a function of RF input power.**

resistances as shown in Fig. 6(b). Meanwhile, the thermal resistances of GaN diodes are much lower than GaAs diodes. This is brought by SiC substrate of GaN diodes with high thermal conductivity, which offers more rapid heat sink and lower temperature rise to the diode chips.

To calculate the temperature rise at each anode of Schottky diode, it's assumed that the heat generated by the diodes is equally dissipated at each anode [30]. Figure 7 shows the anode temperature of different Schottky diodes and different substrates with equal dissipated power at each anode. These results can either calculated with thermal resistance matrixes using (1) or simulated by EM software CST.

According to the simulated results in Fig. 7, lower temperature rise is achieved with AlN substrates for both diode chips. Compared with GaAs diodes, GaN diodes feature lower temperature rise at each anode. These comparisons validate the importance of applying high thermal conductivity material for both diode substrates and circuit substrate in the development of high power multipliers. Based on these simulated results, the integral performances of 220 GHz tripler can be carried out.

C. HARMONIC BALANCE SIMULATION BASED ON ELECTRO-THERMAL MODEL

The integral circuits of 220 GHz triplers are simulated and optimized with a combination of EM simulation and harmonic balance simulation. Each part of the tripler in Fig. 3 is optimized in 3D EM model software ANSYS. The output waveguide with reduced height is cut-off at second harmonic of the input signal. 3D models of the applied Schottky diodes are built in ANSYS to consider the parasitic elements of the diode package. The S-parameters of each part of 220 GHz triplers are simulated and packaged as touchtone files, while the harmonic balance simulations are carried out with nonlinear simulation software ADS from Keysight. The optimum embedding impedances of corresponding harmonics of the Schottky diodes are calculated with simulation based on load-pull techniques. Then, the matching networks are optimized to realized best performances of the tripler.

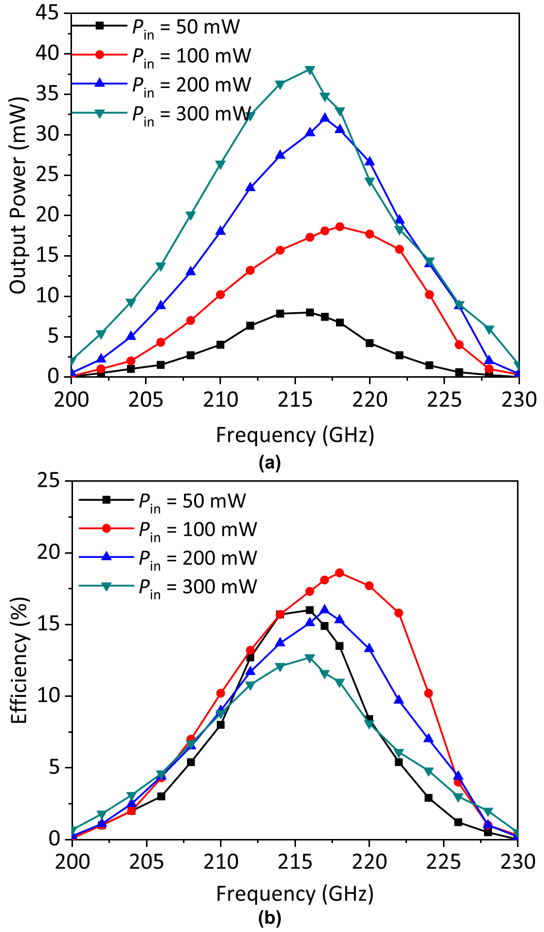


FIGURE 9. **Simulated performances of the 220 GHz GaAs diode tripler using electro-thermal model.**

In order to accurately simulate the performances of the triplers, the anode temperature with particular input power should be obtained. The triplers are firstly simulated and optimized with only electrical model. Based on simulated output power and efficiency of the 220 GHz triplers, the dissipated power with particular input power is obtained. Then, the relation between the input power and temperature rise at each anode can be obtained as illustrated in the previous part. With the calculated anode temperature and electro-thermal model, more accurate simulated results of the 220 GHz triplers are carried out.

1) SIMULATED PERFORMANCES OF THE 220 GHz TRIPLER BASED ON GaAs DIODES

The 220 GHz tripler using GaAs diodes is optimized with a combination of EM simulation and harmonic balance simulation. With aforementioned methods, the anode junction temperatures are estimated as a function of the RF input power as shown in Fig. 8. In the process of harmonic balance simulation, the matching networks are optimized while the bias voltage is tuned to realize optimum performances of the tripler. The simulated output power and efficiency of the proposed tripler are shown in Fig. 9. Peak efficiency of 18.4%

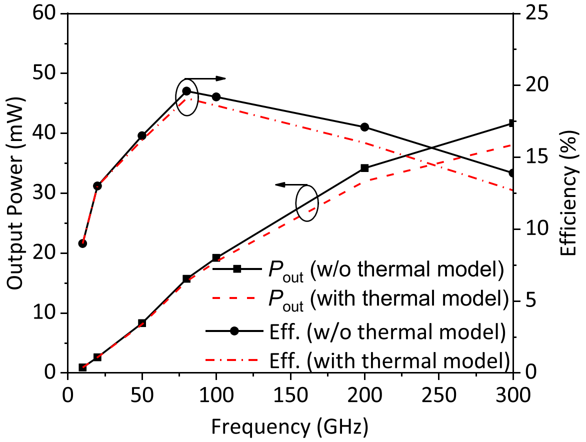


FIGURE 10. Comparison of the simulated performances with and without thermal model.

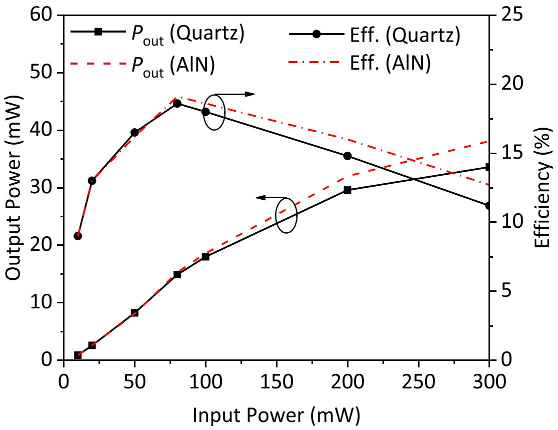


FIGURE 11. Comparison of the simulated performances of 220 GHz GaAs diode tripler based on different substrate.

is realized with input power of 100 mW and optimum bias voltage of −7 V. Figure 10 shows the simulated results of the 220 GHz tripler with and without thermal model. The comparison shows that the thermal effect is negligible for lower input power (< 50 mW). There is no significant difference in the simulation results with and without the thermal model. For input power beyond 50 mW, the results based on electro-thermal model are worse compared with the ones simulated without thermal model.

Meanwhile, to validate the thermal effects, the simulated performances the 220 GHz tripler based on quartz substrate are compared with the proposed 220 GHz tripler using AlN substrate. Simulated results in Fig. 11 reveal that the 220 GHz tripler based on AlN substrate has better performances, which validates the importance of applying high thermal conductive substrates for high power THz multipliers.

2) SIMULATED PERFORMANCES OF 220 GHz TRIPLER BASED ON GaN DIODES

According to the analysis in the Section II, the GaN Schottky diode features much higher breakdown voltage and lower thermal resistances. Estimated node temperature of the proposed GaN Schottky diode is also calculated with different RF input power and shown in Fig. 12. Compared with the anode temperature of GaAs diode in Fig. 8, the GaN diode exhibits lower anode temperature with same input power. These characteristics enable the GaN diodes to operating higher input power. Meanwhile, higher series resistance of GaN diodes will lead to lower efficiency of the multipliers.

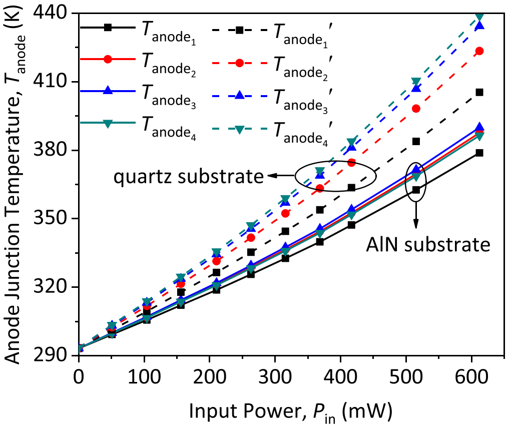


FIGURE 12. Estimated node temperature of GaN Schottky diode as a function of RF input power.

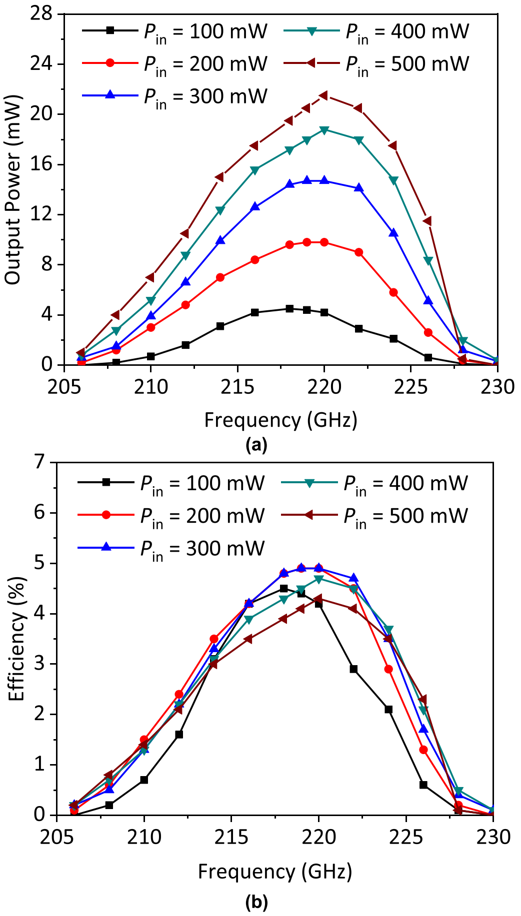


FIGURE 13. Simulated performances of 220 GHz GaN diode tripler using electro-thermal model.

The 220 GHz GaN diode tripler applies identical structures including input and output waveguide-microstrip transitions,

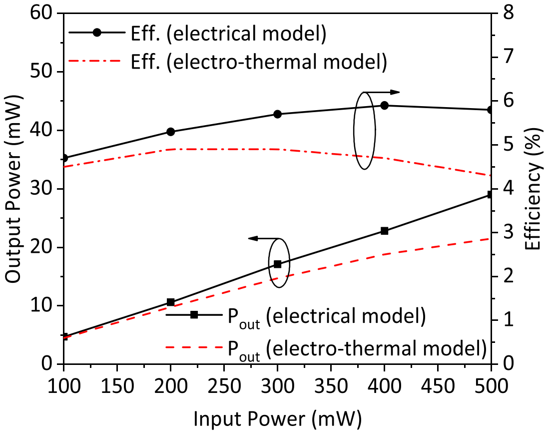


FIGURE 14. Comparison of the simulated performances of 220 GHz GaN diode tripler with and without thermal model.

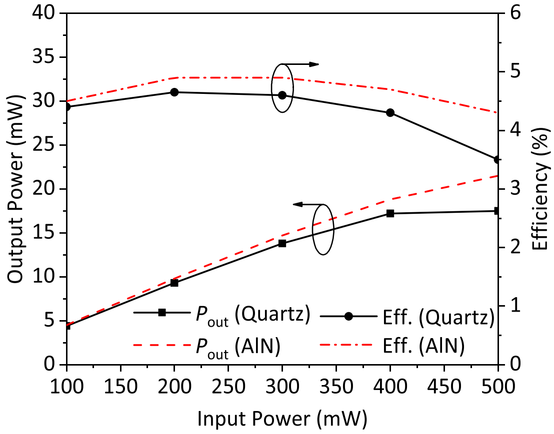


FIGURE 15. Comparison of the simulated performances of 220 GHz GaN diode tripler based on different substrate.

DC LPF, while the matching networks are optimized to provide optimum embedding impedances to the GaN diodes. Simulated performances of the 220 GHz GaN diode tripler are shown in Fig. 13. Peak efficiency of this tripler is 4.9% with input power of 200 mW and optimum bias voltage of -11 V. Figure 14 shows the simulated results with and without thermal model, while the comparison of 220 GHz triplers utilizing different substrate is shown in Fig. 15. It shows that the application of substrates with high thermal conductivity can improve efficiency of the triplers. Meanwhile, it also contributes to the improvement of power handling of the triplers by providing better heat sink at the diode areas, which prevents the tripler from burning out due to excessive heat at the Schottky junction.

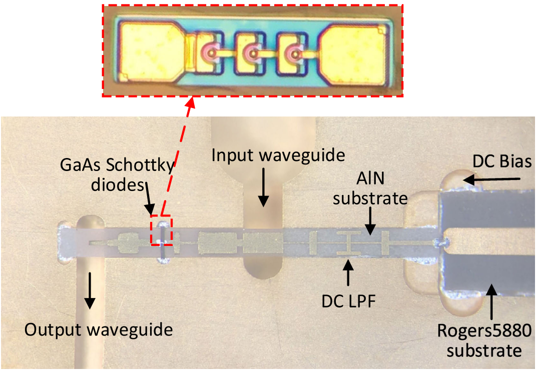


FIGURE 16. Photograph of the 220 GHz GaAs diode tripler mounted on lower half of the split metal block.

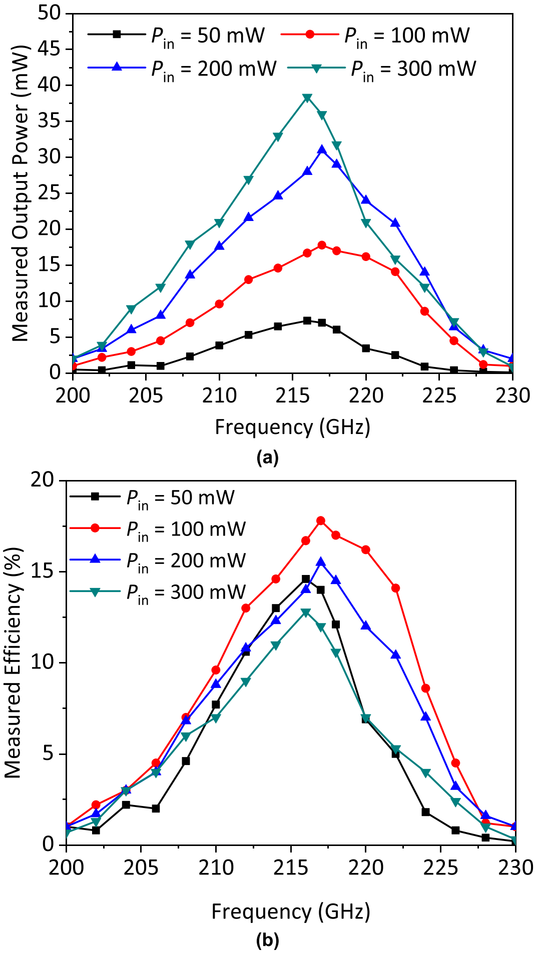


FIGURE 17. Measured ouput power and efficiency of the proposed 220 GHz tripler based on GaAs Schottky diodes.

IV. MEASUREMENT AND COMPARISON

Based on the aforementioned analyses and optimization techniques, the two triplers are fabricated and measured separately. The 220 GHz tripler circuit based on GaAs Schottky diodes mounted on lower half of the block is shown in Fig. 16. Test platform includes a × 8 multiplier chain, an E band amplifier and VDI's PM4 power meter. The performances of the GaAs diodes tripler with different input power are illustrated in Fig. 17. The maximum input power is 300 mW, as the 220 GHz tripler burned out when the input power was tuned to 350 mW. Peak efficiency of 17.8% is achieved with 100 mW input power and bias voltage of -7.4 V. The maximum output power is 38.2 mW at 217 GHz when 300 mW input power and -9.4 V bias voltage are applied. A comparison of the circuit measured performances, simulated results with and without thermal model, is shown in Fig. 18.

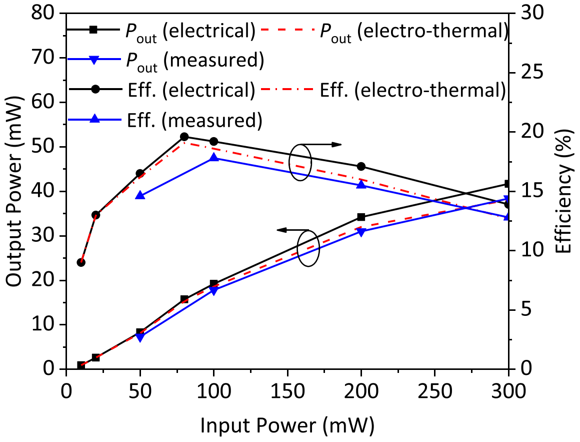


FIGURE 18. Comparison between the simulated and measured performances of the proposed 220 GHz tripler based on GaAs Schottky diodes.

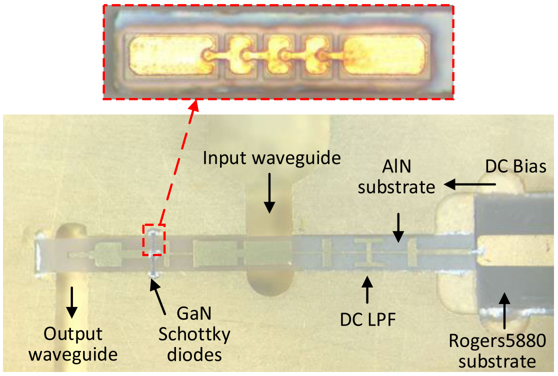


FIGURE 19. Photograph of the 220 GHz GaN diode tripler mounted on the half of the split metal block.

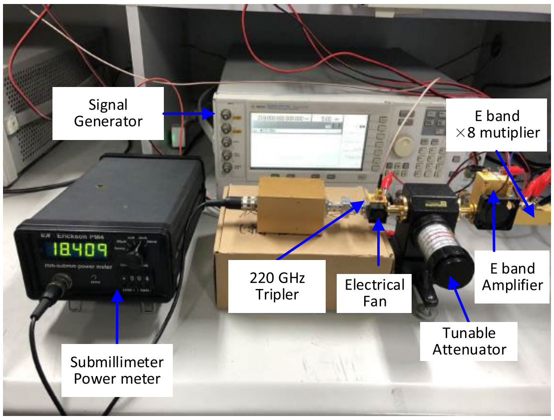
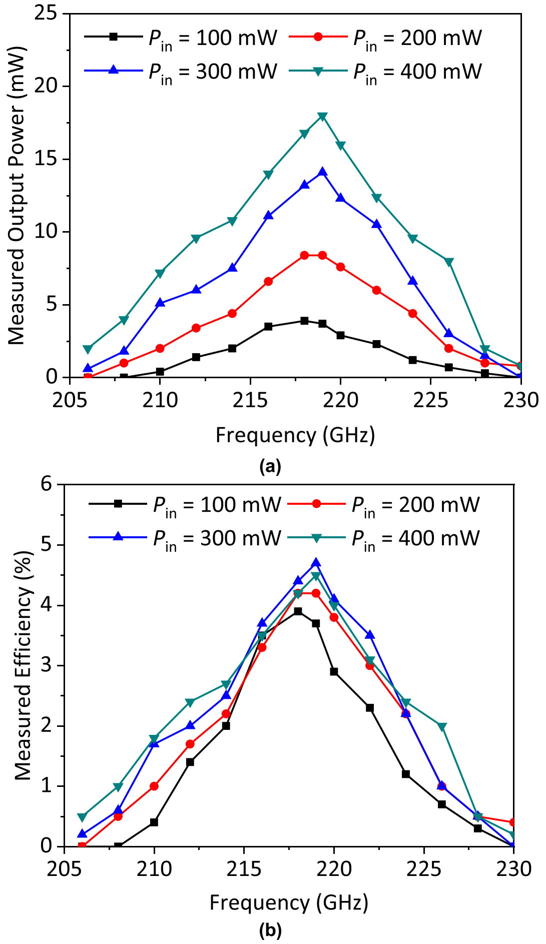


FIGURE 20. Test platform of the 220 GHz tripler.

It reveals that a better agreement is achieved by taking into consideration of the thermal effect and applying electro-thermal, especially with high input power (> 100 mW).

Another 220 GHz tripler based on GaN Schottky diodes was also fabricated as shown in Fig. 19. The measured results were carried out with test platform shown in Fig. 20. Due to the experimental limitation, the maximum input power for the proposed tripler is 400 mW. The measured output power and efficiency are shown in Fig. 21. Peak efficiency is 4.7% with 200 mW input power and −10.6 V bias voltage. With 400 mW input power and bias voltage of −13.8 V, the maximum output power is 18.4 mW at 219 GHz. Good agreement between the measurement and electro-thermal simulation results in Fig. 22 once again validates the important role of thermal management in the analysis of high power multipliers. Without considering thermal effect, the expected peak efficiency is realized with 400 mW input power. However, due to significant thermal effect brought by high input power, the tripler efficiency is reduced and the peak efficiency is achieved with 300 mW input power, which agree with the measured results.



(a)

(b)

FIGURE 21. Measured ouput power and efficiency of the proposed 220 GHz tripler based on GaN Schottky diodes.

The performances of the proposed two 220 GHz triplers are compared with previously researches in the similar frequency band. As shown in Table 3, the majority of these triplers are based on GaAs Schottky diodes due to higher efficiency and easier process. In this paper, the proposed 220 GHz tripler utilized self-developed GaAs Schottky diodes to realize higher efficiency and output power. As illustrated in Section II, the application of AlN substrate with higher thermal conductivity also contributes to the improvement of efficiency and power handling of the tripler.

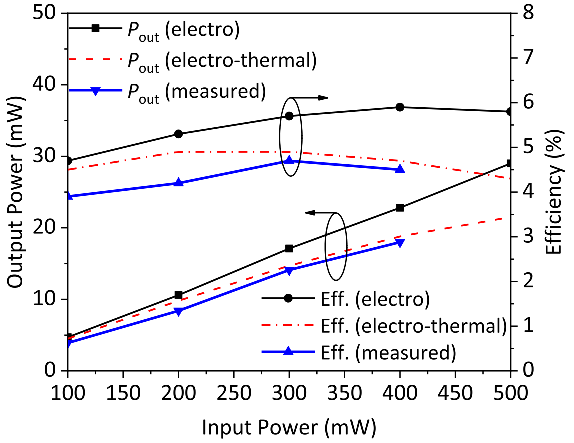


FIGURE 22. **Comparison between the simulated and measured performances of the proposed 220 GHz tripler based on GaN Schottky diodes.**

TABLE 3. **Summary of the performances of published triplers in the similar frequency range.**

Ref.	Frequency (GHz)	Sim. PE	Meas. PE	Meas. MOP (mW)	Diode technology
[35]	205 - 225	3%	1.9%	17.5	GaN SBD
[37]	200 - 230	NI	16%	23	GaAs SBD
[38]	216 - 232	8%	5%	6.3	GaAs SBD
[39]	211 - 226	NI	7.3%	17	GaAs SBD
[40]	240 - 290	NI	4.3%	35.1	HBV
This work-1	**200 - 230**	**18.4%**	**17.8%**	**38.2**	**GaAs SBD**
This work-2	**205 - 230**	**4.9%**	**4.7%**	**18.4**	**GaN SBD**

PE: Peak efficiency, MOP: Maximum output power, NI: Not indicated, SBD: Schottky barrier diode.

The technology of GaN Schottky diodes provides another good method to realize high power submillimeter wave multipliers. Although the high series resistances will bring low efficiency to the multipliers, the power handling of the diodes is promising. Maximum input power of the proposed 220 GHz tripler based on GaN Schottky diodes is beyond 400 mW. The burn out power will be examined in the near future using more powerful millimeter wave amplifiers in the future. To the author's knowledge, the proposed 220 GHz tripler exhibits state-of-art performances in terms of bandwidth, efficiency, and output power, compared with previously reported triplers based on GaN Schottky diodes. The electrical and dimensional parameters of the GaN Schottky diodes can be further optimized to improve the performances of 220 GHz tripler. The application of HBV diodes is another method to realize high power multipliers with high power handing. Peak efficiency of the proposed GaN diode tripler is comparable with efficiency of the HBV diode tripler in [40]. However, the HBV diodes can only be utilized to develop odd harmonic multipliers. The GaN Schottky diodes have more potential in the development of multipliers using odd or even harmonics in the future.

The researches in this paper also validate the importance of thermal management in the analysis of high power multipliers at submillimeter wave and terahertz band. With accurate electro-thermal models of Schottky diodes, the simulated performances of the triplers are more consistent with measured results compared with previous researches in Table 3. Therefore, the electro-thermal model is essential in the circuit analysis and optimization for high power applications.

V. CONCLUSION

Two 220 GHz frequency tripler based on planar Schottky diodes are proposed in this paper. The tripler based on GaAs Schottky diodes features high efficiency, while the GaN diode tripler realizes considerable output with higher power handling. AlN substrates with high thermal conductivity are applied for both triplers to reduce performance degradation brought by excessive heat at the Schottky junction. The simulation and optimization of the triplers are carried out with electro-thermal models of Schottky diodes. According to the analyses in this paper, a better agreement is achieved between simulated and measured performances by taking thermal effects into consideration, especially when high input power is applied.

Measured results show that peak efficiency and maximum output power of the 220 GHz GaAs diode tripler are 17.8% and 38.2 mW, respectively. The maximum input power of this tripler is 300 mW. As for the tripler based on GaN Schottky diodes, the maximum input power is beyond 400 mW. Peak efficiency of this tripler is 4.7%, while the maximum output power is 18.4 mW. The high power 220 GHz triplers can perform as fundamental stages in THz multiplier chains, while the analyzing and optimizing methods in this paper can be utilized to realize multipliers at higher frequency band in the future.

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