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0.68 THz and 1.00 THz triplers based on discrete Schottky diodes and quartz glass

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Abstract: This paper introduces two designs of balanced frequency triplers in 0.68 THz and 1.00 THz bands. The proposed triplers are based on discrete antiparallel Schottky diodes and quartz glass instead of terahertz integrated circuit. The merits of this work are attributed to the improvement of the diode model, the thinned quartz glass film and the machining accuracy of the waveguide. The improved LEC diode model considers not only the current-voltage (*I/V*) and capacitance-voltage (*C/V*) but also plasma resonance and skin effect. The quartz glass film is thinned to 15um and can be used for up to 1.2 THz. The machining accuracy of the waveguide is (±3) μm for terahertz applications with channel size 60 μm. The measurement shows a peak output power above 160 μW and 60 μW for the 0.68 THz and 1.00 THz triplers, respectively. Moreover, the efficiencies of the 0.68 THz and 1.00 THz triplers are around 1% and 0.6% correspondingly. The output frequency bandwidths are both more than 10%.

Key words: terahertz, balance tripler, Schottky diode, LEC model, antiparallel diodes, quartz glass
PACS: 07.57.Hm, 85.30.De, 85.30.Kk, 84.30.Vn, 42.70.Ce

基于分立器件和石英基片的0.68 THz和1.00 THz三倍频器

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摘要:介绍了基于反向平衡式二极管和石英基片完成,而非集成电路的0.68 THz和1.00 THz频段平衡式三倍频.此项工作提高了二极管等效电路模型,该二极管模型不仅包括*I/V*和*C/V*,同时还加入了等离子体共振和趋肤效应,将薄膜电路减薄至15 μm,机械加工精度提高至3 μm内,使工作频率提高至1.2 THz.通过场路协同仿真,利用高精度太赫兹装配工艺,最终实现工作频率为0.68 THz和倍频效率为1 %的三倍频器,工作频率为1.00 THz和倍频效率为0.6 %的三倍频器,输出相对带宽均大于10 %.

关键词:太赫兹;平衡式三倍频;肖特基二极管;LEC模型;反向平衡二极管;石英基片

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Introduction

Terahertz spectrum has numerous applications in medicine identifications, astronomy, security, Earth's thermosphere, ionosphere measurement systems, and telecommunications[1-3]. The terahertz source is very important for these applications[4-5]. Certain integrated sources are based on InP HEMT[6] and SiGe HBT[7]. Other solid-state devices including resonant tunneling diodes (RTDs)[8] and heterostructure barrier varactors

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(HBVs)[9], for generating terahertz radiation have also been published. Compared with other high-frequency sources, Schottky diode based frequency multipliers maintain excellent signal quality, tunability, and stability simultaneously. Therefore, they are widely used as a local oscillator for ground-based radio astronomical receivers and vector network analyzer (VNA) frequency extenders[10]; their output power is less than 1 mW at around 1.00 THz band and the bandwidth is less 10%[11].

There are two ways to realize the Schottky diode-based circuits, THz-MICs, and THz-DCs (discrete circuits). THz-MIC is the main technical solution over 500 GHz, while the THz-discrete circuit is more popular below 300 GHz. THz-MICs ease chip assembly with an increase in cost, and the circuit based on discrete diodes, with design flexibility, is much cheaper. However, it demands good fault-tolerance circuit design and high assembly accuracy.

In this work, two frequency triplers are designed based on a discrete circuit, and the analysis on improved diode model, thinned quartz glass film, metal waveguide, and especially assembly process are demonstrated. It is proved that the discrete circuit and LEC model can be used up to 1.00 THz.

In this paper, several parts including modeling Schottky diodes, analysis of circuit theory, circuit's topology design and simulation, measurement of the modules, and conclusions, are organized sequence.

1 Modeling Schottky diodes

Schottky diode model is very important for circuit design. There are mainly five kinds of models in the literature, including LEC model, drift-diffusion (DD) model, Hydro-energy transport (HD) model, Monte Carlo (MC) model and Quantum Kinetic model [12].

The tripler uses one discrete Schottky diode chip, with two junctions in antiparallel. The main parameters of the diodes are extracted from the *I-V* and *C-V* curves. The model includes two parts: 3D model with coaxial probe shown in Fig. 1(a) and nonlinear LEC junction model shown in Fig. 1(b). Nonlinear LEC junction model includes Schottky diode junction, undepleted epi-layer, and GaAs N+ substrate. The main parameters of the Schottky diode junction are presented in Table 1. The values of the parts include epi-layer, N+ substrate, and Ohmic contact. They can be calculated from the material parameters and device size[13].

Table 1 Two varistor diodes in anti-parallel configuration
表 1 反向平行结构变阻二极管参数

V_b/V	I_{sat}/A	R_s/Ω	n	C_{j0}/fF	C_{edge}/fF
0.69	9.11e−15	28	1.12	1.0	0.3

The simulation model in the circuit comprises of two parts: nonlinear junction and 3D EM model. The 3D EM simulation software (like Ansys HFSS) exports the SNP file. The SNP file and nonlinear junctions in the HB simulation software (like ADS) make the final circuit model. Figures 2-3 show comparison of simulation and model results.

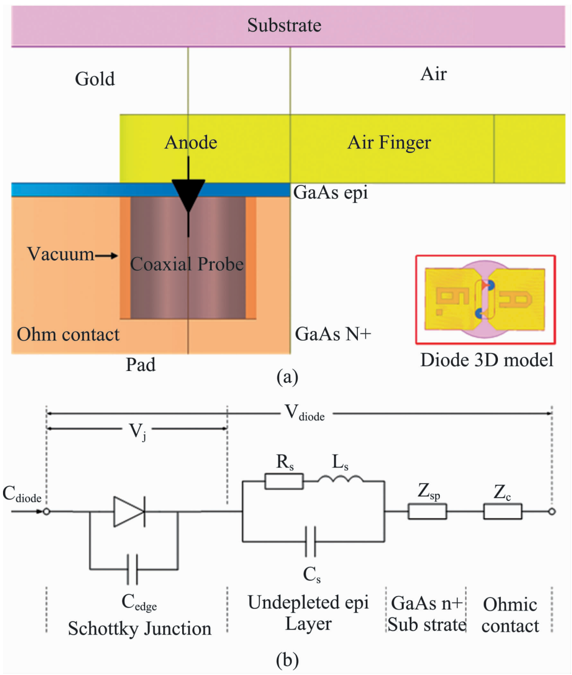

Fig. 1 (a) Structure of Schottky junction and the coaxial probe,(b) lumped model for single Schottky junction from *I/V*, *C/V*, and high frequency behavior
图 1 (a)二极管结区结构和同轴探针,(b)具有 *I-V*,*C-V* 和高频效应的集总模型

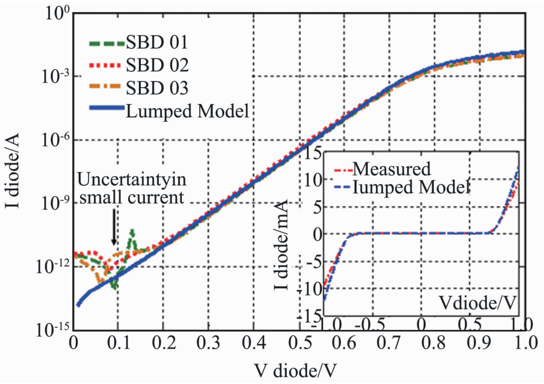

Fig. 2 Simulation and testing curve of *I-V*
图 2 二极管模型 *I-V* 仿真和测试对比

The diode parameters extracted from the measured *I-V* and *C-V* curve are junction capacitance C_{j0}, series resistance R_S, saturated current I_{sat}, ideality factor n, barrier height V_j, and reverse breakdown voltage V_{bv}. As shown in Fig. 1(a), a coaxial probe is inserted in the 3D model to replace the nonlinear Schottky junction as described in Ref. [11]. The Schottky lumped element model shown in Fig. 1 (b) considers plasma resonance, skin effect, leakage effect, and undepleted epi layer effect[13].

2 Analysis of circuit theory

2.1 Theory of the balanced tripler

Figure 4 shows the balanced tripler circuit based on

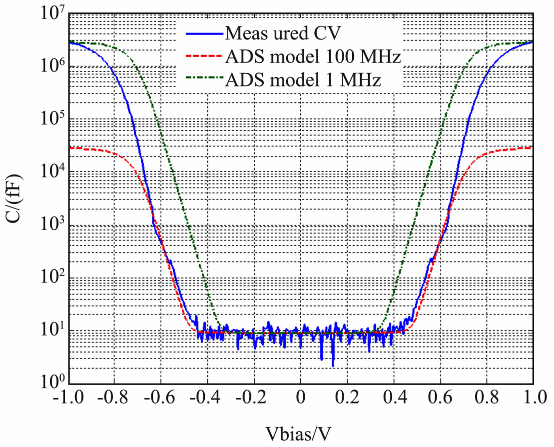

Fig. 3 Simulation and testing curve of *C-V*
图 3 二极管模型 *C-V* 仿真和测试对比

the anti-parallel diodes. The two diodes are placed between the input and output ports. In Fig. 4, V_{in}, V_{out}, i_{in}, and i_{out} represent the voltage and instantaneous current of the input and output signal respectively, where i_1 is the instantaneous current flowing through the diodes.

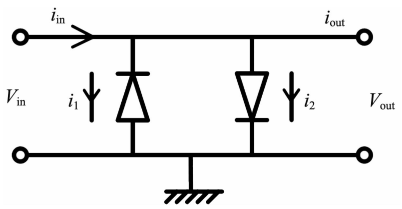

Fig. 4 The balanced frequency tripler circuit
图 4 平衡式三倍频电路结构

The current-voltage (*I/V*) characteristic of the Schottky barrier junctions is shown by Eq. 1.

$$\begin{aligned} i_1 &= I_s[e^{\alpha V_{in}} - 1] \\ i_2 &= -I_s[e^{-\alpha V_{in}} - 1] \end{aligned} \quad , \qquad (1)$$

where I_s is the reversed saturation current; $\alpha = q/nkT$, and n is the ideality factor, a parameter that accounts the junction non-ideality. k is Boltzmann constant, T means the diode working temperature and q is an electrical charge. Then, the output current can be derived as Eq. 2.

$$i_{out} = i_1 + i_2 \quad . \qquad (2)$$

According to the analysis in Ref. [17], the output current can be expressed as Eq. 3.

$$i_{out} = 4I_s[I_1 \alpha V_s \cos\omega_s t + I_3 \alpha V_s \cos 3\omega_s t + \cdots] \quad ,(3)$$

where ω_s is the fundamental frequency and I_n means amplitude value of n-th harmonic signal. V_s is the value of input single. As Eq. 3 shows, the output currents contain only the odd harmonics, including fundamental.

2.2 Theoretical simulation of tripler

The efficiency of a Schottky varistor frequency tripler is determined by the diode non-linearity driven power, input power, diode biasing voltage, and the embedding impedances at the fundamental and harmonic frequencies. In the ideal resistive mode, the tripler efficiency remains below 6% ($\eta_{max} = n^{-2}$). In reality, the efficiency of the frequency multipliers declines rapidly with increasing output frequency and the multiplication factor. It is necessary to use harmonic tools to simulate the balanced tripler for an effective circuit structure. Figure 5 shows the theoretical simulation diagram, the BPFs (band pass filters) control the output harmonics frequency, and the terms control the impedance matching of corresponding harmonics. The simulation shows that there are no 2^{nd} or 4^{th} harmonic frequencies. Theoretical efficiency component of the thripler is up to 2.5% in 0.68 THz bands, and 1.7% in 1.00 THz bands. The simulation results are show in Figs. 9 and 11.

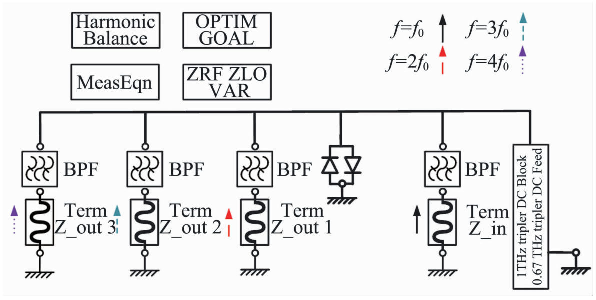

Fig. 5 Theoretical simulation diagram in the HB simulator
图 5 在谐波平衡仿真工具中理论仿真框图

3 Topology design and simulation

In 1990, Erickson established some successful architectures for both doublers and triplers, including the main topology of the balanced circuit and unbalanced circuit. Many works of literature have reported such architectures [13-16]. In this work, both the triplers employ the balanced architecture, using antiparallel Schottky diodes and quartz glass film. The design steps are diode modeling, theoretical simulation, separate simulation and global simulation in sequence. The parameters of diode models and impedances are optimized to achieve the design goal in an iterative procedure.

Three different tools are used for the design. In the beginning, physics-based models are constructed to calculate optimum diode properties based on the desired operating conditions (i. e., doping, epi-layer thickness, material). Then harmonic balance (HB) tools (such as Agilent ADS) calculate next embedding impedances. Finally, the complete the physical design is verified by a 3D EM simulation (such as Ansys HFSS).

Figure 6 shows the final physical design of the 0.68 THz and 1.00 THz triplers. The structures of the two triplers are almost similar, including input probe, input filter, diode placement, output probe, and match tuning network. Whether the two triplers are grounded is the main difference. If the 1.00 THz tripler is grounded, the ratio of length to width of will be too long. In fact, the ungrounded structure is acceptable and has little influence on the circuit.

4 Measurements

The measured results of the designed triplers are shown in this session.

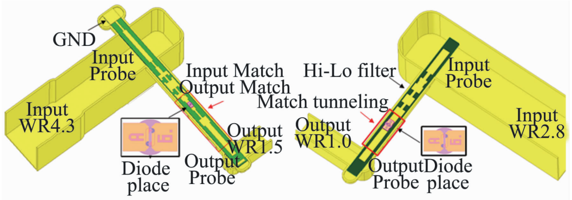

Fig. 6 The tripler design at frequency of 0.68 THz and 1.00 THz tripler, (a) 0.68 THz tripler, (b) 1.00 THz tripler
图 6 0.68 THz 和 1.00 THzs 三倍频器设计,(a) 0.68 THz,(b) 1.00 THz

4.1 The 0.68 THz tripler measurements

For the 0.68 THz tripler, the measurement platform is shown in Fig. 7. Here, our multiplier chain serves as the driver in 220 GHz. The output power of the 0.68 THz tripler is measured by VDI-Erickson PM4 through a WR1.5 to WR10 convertor.

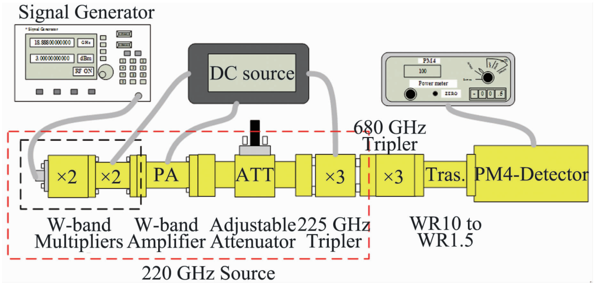

Fig. 7 0.68 THz tripler measurement platform
图 7 0.68 THz 三倍频测试平台

Figure 8 shows the details of quartz-glass circuit used in the 0.68 THz tripler module. The thickness of quartz-glass substrate is about ~15 μm. The circuit includes five parts: WR1.5 output probe, match-tuning network, hammerhead low pass filter, WR4.3 input probe, and GND. The size of the quartz substrate is 2.428 mm × 0.145 mm × 0.015 mm, and the precision of machining is about (±0.003) mm.

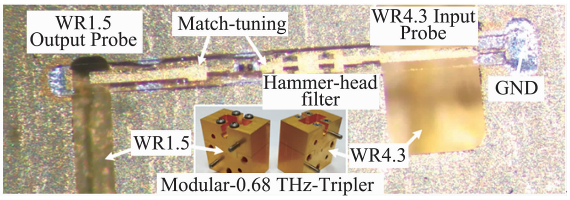

Fig. 8 Photograph of quartz circuit and entire modular of 0.68 THz tripler
图 8 0.68 THz 三倍频石英电路和全模块图

Figure 9 shows the test results where the efficiency is 0.95% to 1.30%. The out power is between 100 μW and 160 μW when the driver power is varied from 10 to 12 mW in 220 GHz bands, and the simulation results matches the test results well.

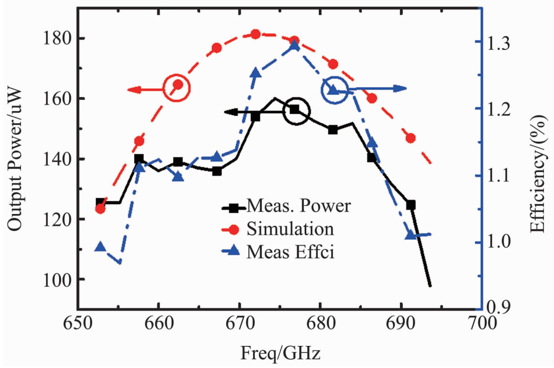

Fig. 9 The results of the 0.68 THz tripler with 10 ~ 12 mW at 220 GHz, including simulation output power, measured output power and measured efficiency
图 9 在 200 GHz 频段 10 ~ 12 mW 驱动条件下,仿真和测试得到 0.68 THz 三倍频器输出功率

4.2 The 1.00 THz tripler measurements

For the 1.00 THz tripler, the measurement platform is very similar to the one in Fig. 7. The 340 GHz multiplier chain serves as driver source. The output power is measured by VDI-Erickson PM4 through a WR1.0 to WR10 convertor. Fig. 10 shows the detail of quartz-glass circuit in the 1.00 THz tripler module. The thickness of quartz-glass substrate is about 15 um, including four parts: WR1.0 output probe, match-tuning network, Hi-Lo low pass filter, and WR2.8 input probe. The size of quartz substrate is 1.091 mm × 0.075 mm × 0.015 mm. And the precision of machining is about (±0.003) mm.

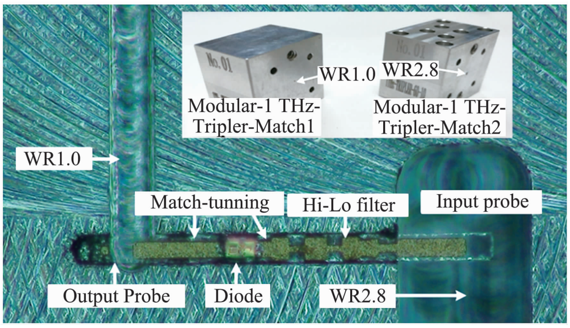

Fig. 10 Photograph of quartz circuit and entire modular of 1.00 THz tripler
图 10 1.00 THz 三倍频石英电路和全模块图

Figure 11 shows the test and simulation results. The test output power is between 10 μW and 60 μW when the driver power is varied from 5 mW to 12 mW around 340 GHz band. There are two kinds of 1.00 THz tripler circuits, which are named tripler-match1 and triper-match2. They are very similar to each other. The length of match tuning in the tripler-match1 is longer than tripler-match2. The structure of the match tuning is shown in Fig. 6(b) with the same microstrip line width in matching. The triper-match1 means the length of input and output match line is 60 μm and 10 μm respectively. The triper-match2 means the length of input and output match line is 30 μm and 12 μm respectively.

The differences between the simulation and measurement are mainly due to the deviation of machining, quartz substrate, diode high frequency model, and the assembling mismatches. On the other hand, the transmission loss model of the aluminum metal cavity and the suspended microstrip line at high frequency is inaccurate and difficult to be measured. In general, the reasonable gap between simulation and measurement is within 6dB when the frequency is up to 1.00 THz. As long as the above deviation is improved, it is possible that the measurement will be closer to the simulation.

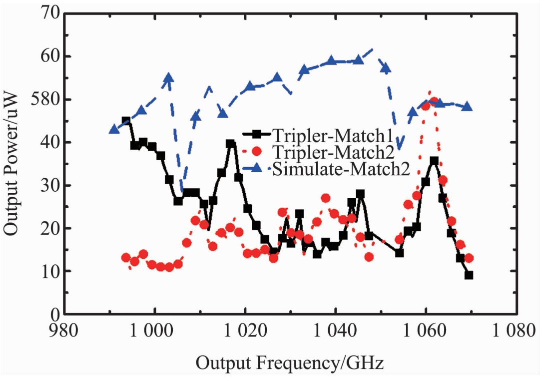

Fig. 11 The results of 1.00 THz tripler with 10 ~ 12 mW at the 340 GHz band, including one kind of circuit's simulation output power, two kinds circuits of measured output power

图 11 1.00 THz 三倍频器在 340 GHz 频段内 10 ~ 12 mW 驱动条件下测试得到输出功率

5 Conclusions

This paper proposes the design and fabrication of two frequency triplers at 0.68 THz and 1.00 THz bands basing on discrete Schottky diodes and quartz glass. Triplers around 0.68 THz and 1.00 THz bands have been investigated and the state of the arts in table 2. There is few papers or products in these bands and not too many research institutes around the world have studied in the relevant frequency bands, such as JPL and VDI. The measured results prove that the 0.68 THz frequency tripler can work at 0.65 ~ 0.69 THz and achieve a maximal output power of 160 μW. The maximal efficiency is up to 1.3%. The 1.00 THz frequency tripler can work at 0.99 ~ 1.07 THz, and achieve a maximal output power of ~ 60 μW. The efficiency is up to 0.6%. The 1.00 THz tripler is able to deliver higher output power and wider bandwidth if the driving source provides higher power and wider bandwidth. Discrete circuit technology and TMICs can both be used in the frequency multiplier source up to 1.1 THz. Furthermore, discrete circuit technology is much more flexible and cheaper.

Table 2 Compare with similar works

表 2 类似频段三倍频工作比较

Year	Output Freq.	Form	Output	Effic.	Ref.
1989	720 ~ 880 GHz tripler	TMIC	110 μW	1.7%	[18]
2004	1 178 GHz tripler	TMIC	0.17 μW	0.9%	[19]
2001	1 126 GHz tripler	TMIC	80 μW	0.9%	[20-21]
2017	325 ~ 500 GHz tripler	TMIC	100 μW	2%	[22]
2018	1 000 GHz tripler	TMIC	250 μW	–	[23]
2018	660 GHz tripler	–	1mW	1.7%	[23]
2018	650 ~ 700 GHz tripler	Discrete	100 μW Peak > 200μW	1%	This work
2018	990 ~ 1 070 GHz tripler	Discrete	10 μW Peak > 60μW	0.6%	This work

Acknowledgments

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