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335 GHz unbalanced Schottky diode frequency tripler

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Abstract: Based on the hybrid integration method, a 335 GHz unbalanced frequency tripler is designed with a symmetrical tapered gradient line matching structure. Under the condition of ensuring single-mode transmission, the matching structure can not only fix the diode position, but also increase the matching effect, and thus solve the problem of narrow 3dB bandwidth for high-frequency band multiplier. The measured results show that the output power of the frequency tripler is all greater than 5 mW in the frequency range of 330-356 GHz. The maximum output power even reaches 11. 2 mW at a driving power of 220 mW. The solid-state terahertz local oscillator, as the core device, can drive the 670 GHz sub-harmonic mixer in the superheterodyne receiver.

Key words: local oscillator, symmetrical tapered gradient line, terahertz, unbalanced tripler

335 GHz非平衡式肖特基二极管三倍频器

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摘要：基于混合集成的方式，采用对称锥形渐变线匹配结构设计了335 GHz非平衡式三倍频器。在保证单模传输的条件下，该匹配结构不仅能够固定二极管位置，而且可以增大匹配效果，解决了高频段倍频器3 dB带宽较窄的问题。实测结果表明，该倍频器在330~356 GHz频率范围内输出功率均大于5 mW。驱动功率为220 mW时，有最高输出功率11.2 mW，由它作为核心器件组成的固态太赫兹本振源，能够驱动超外差接收机中670 GHz二次谐波混频器。

关 键 词：本振源；对称锥形渐变线；太赫兹；非平衡式三倍频器

中图分类号：TN771 **文献标识码：**A

Introduction

Terahertz (THz) technology have broad application prospects in radio astronomy, biomedicine, national defense, aerospace and other fields [1-4]. With the in-depth application of meteorological satellites, the detection frequency is constantly rising [5-6]. Frequencies above 600 GHz are essential for meteorological detection for terahertz remote sensing. As for terahertz sources, the solid-state electronics is the typical method that can work at room temperature. Frequency multipliers based on Schottky diodes have gradually become the core devices in local oscillator chains in the terahertz band, and play a crucial role in various submillimeter wave systems [7-10]. Therefore, to solve the problem of subharmonic mixer in the front-end of terahertz meteorological detection in the frequency band near 670 GHz, the core device in the 335 GHz local oscillator source is studied. The adjacent

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frequency band has been studied by some scholars. A 260–340 GHz frequency tripler with the efficiency in the range 1.5%–7.5% under a 100 mW input power is presented in Ref. [11]. A 340 GHz frequency tripler with the output power is 0.3–0.821 mW in the range 333–354 GHz is designed in Ref. [12]. A 330 GHz frequency tripler is designed in Ref. [13]. Measurement results show the output power is 0.1–0.26 mW in the frequency range 302–336 GHz. A 300 GHz monolithic integrated frequency tripler is fabricated in Ref. [14]. The peak output power of this tripler is 0.451 mW under a 20 mW input power. A 315–340 GHz frequency tripler is designed in Ref. [15], which exhibits a maximum of 7.08 mW output power with a peak of 8.1% conversion efficiency.

In this paper, a 335 GHz unbalanced frequency tripler was designed and implemented based on the varactor diode. Through the analysis and design of the input and output circuit, the short circuit of the unnecessary harmonic idle circuit was realized. The tapered line structure was applied to the diode matching circuit, which not only facilitates the assembly of the diode, but also broadens the working bandwidth to a certain extent and reduces the power loss. The designed frequency tripler was manufactured, assembled and tested, and the superiority over the gradient line matching structure is verified.

1 Tripler design

The 335 GHz frequency tripler consists of input/output circuit, diode unit circuit and matching circuit. The design of each part is described below.

1.1 Input/output circuit

The input part is composed of a DC bias filter, a low-pass filter and an input waveguide-to-suspended microstrip transition to form a three-port network. To widen the bandwidth, two sections of reduced-width waveguide are added. The DC filter and lowpass filter are designed with a compact resonant cell structure. The value of the ground capacitance is greatly reduced by forming a fringe capacitance from the microstrip to the metal wall. By adjusting the value of the equivalent inductance, the size of the resonator is adjusted. At this point, the value of the equivalent capacitance also changes, and then affect the filter rejection degree. The output structure also adopts the probe coupling method. The quasi-TEM mode of the microstrip line is converted into the TE10 mode of the waveguide, and the coupling bandwidth is increased by reducing the broad side of the output waveguide.

1.2 Matching circuit

When the order of step matching structure increases to infinity and the length of each section is infinitely shortened, the discrete section can be replaced by a continuously tapering transmission line, and it has a shorter total length than the former in the same working bandwidth. Therefore, to further increase the output power and 3 dB bandwidth, a hyperbolic taper gradient line structure is adopted in the matching circuit design of 335 GHz frequency tripler. The matching part inserted between the two transmission lines with impedance Z_1 and Z_2 is represented by a gradient line of length l. The left half of its structure is shown in Fig. 1, and the range of these terminal lines is assumed to be uncertain for convenience.

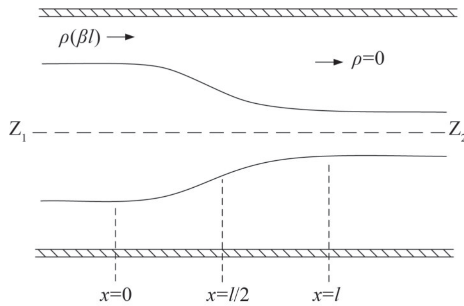

Fig. 1 Hyperbolic tapered transmission line structure
图1 双曲锥形传输线结构

A wave traveling from the transmitting end to the receiving end of the tapered non-uniform line undergoes continuous reflections as it travels outward along the portion. These reflections are the result of continuous variations and are directed towards the transmitter. When the wave reaches the receiving end, it encounters an impedance match. Therefore, without any further reflection, it will enter the distant uniform line. Following the convention of dealing with RF transmission line problems, it is assumed that the line is lossless and that the nominal propagation factor is a purely imaginary number, independent of position. That is, $\gamma = j\beta$, β is the phase shift constant.

Since the tapered asymptote is in symmetric form, the nominal characteristic impedance Z varies with the hyperbolic tangent on the cross section. When the wave propagates along a uniform line, according to the research results of Herbert J. scholars, the reflection coefficient expression is obtained as [16]: $\rho = \frac{a \ln \frac{Z_2}{Z_1}}{4l \tanh \frac{a}{2}} \int_0^l \operatorname{sech}^2 a\left(\frac{x}{l} - \frac{1}{2}\right) \cdot e^{-2j\beta l(x/l - 1/2)} dx$. The value of $|\rho|$ obtained from this expression is normalized and displayed as a function of l/λ, with the length of the matched portion expressed in wavelengths, as shown by the hyperbolic tapered structure curve in Fig. 2. It can be seen that fluctuations like in the Chebyshev curve do not exist in the hyperbolic cone structure. At the same length, the tapered gradient line can achieve the smallest reflection for a given length. Conversely, it requires the shortest length of transformation segment for a given reflection [17]. Therefore, compared with the traditional step matching structure, the symmetric tapered matching structure can ensure a relatively wide frequency band while reducing the length of the substrate, thus reducing the power loss and achieving the purpose of increasing the output power. This structure is applied to the design of the diode cell about the 335 GHz frequency tripler, as shown in Fig. 2. The internal transmission line of the diode cell is similar to a hyperbolic tapered tapering line structure, which can increase the matching effect while fixing the diode position.

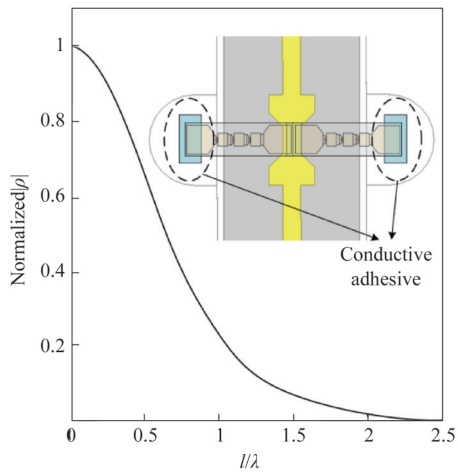

Fig. 2 Variation of $|\rho|$ with l/λ for Hyperbolic structure and 335 GHz frequency tripler diode unit
图2 双曲线结构中$|\rho|$随l/λ的变化以及335 GHz三倍频器二极管单元

1.3 Circuit Topology

The design of this frequency tripler adopts the method of combining field and circuit. The frequency multiplier efficiency and output power are taken as the optimization goals, and considering bandwidth for comprehensive consideration. Combine the actual processing capacity and control its range and accuracy at the same time. Finally, the complete circuit is established to calculate the full wave electromagnetic field. The complete model of the frequency tripler is shown in Fig. 3. It mainly consists of the following parts: ①DC bias filter, ②input waveguide short circuit, ③reduced-width input waveguide, ④suspended microstrip-to-waveguide probe transition structure, ⑤low-pass filter, ⑥matching circuit, ⑦diode cell, ⑧reduced-width-height output waveguide, ⑨output waveguide short circuit.

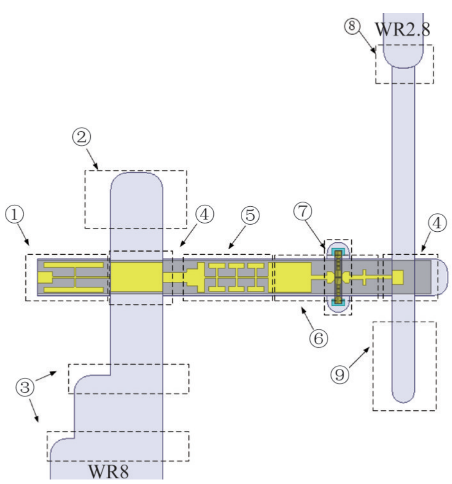

Fig. 3 Architecture of 335 GHz frequency tripler
图3 335 GHz三倍频器结构

The fundamental wave signal is input through the standard WR8 waveguide in TE10 mode, and converted into a quasi-TEM wave by the input waveguide-suspended microstrip E-probe, then the third harmonic signal is output by the WR2.8 waveguide. In order to facilitate assembly, the suspended microstrip transmission line is made into a "step" form. The Schottky varactor diodes are flip-mounted on the 30 μm thick quartz substrate, which is welded with the frequency tripler cavity through a conductive adhesive. The simulation results are shown in Fig. 4. When the driving power is 200 mW and the bias voltage is 12.7 V, the output power in the 329-343.5 GHz band is greater than 30 mW with the maximum value of 39.03 mW.

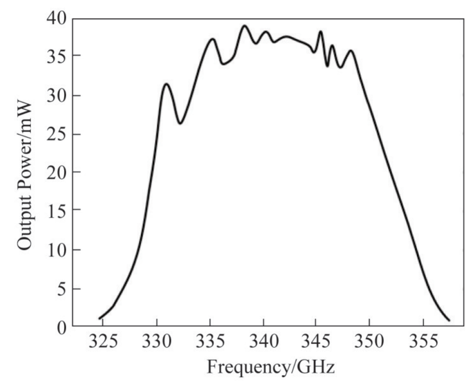

Fig. 4 335 GHz frequency tripler simulation result
图4 335 GHz三倍频器仿真结果

2 Result and discussion

2.1 Assembly

The physical diagram, internal structure and test environment of the 335 GHz frequency tripler are shown in Fig. 5. The dimensions of frequency tripler modules are made of gold-plated oxygen-free copper, 19.1 mm long, 12.2 mm wide and 20.2 mm high. The pre-driver source of the frequency doubler is the F-band frequency source, which is the signal generated by the signal source (Keysight E8257D) through the frequency sextupler expansion module, and then the output signal is obtained after two stages of power amplification. The SMA (Sub-Miniature-A) was connected to the main transmission circuit via gold wire bonding, and the DC source was connected to the SMA port to provide bias voltage for the frequency tripler. The output power was measured by a PM-5 power meter.

2.2 Measurement

The test results of the tripler are shown in Fig. 6. Figure 6 (a) shows the curve of output power variation with frequency and input power, which is greater than 5 mW in the frequency range of 330-356 GHz. The maximum output power is 11.2 mW at a driving power of 220 mW.

With a fixed bias voltage of -6 V, the efficiency variation curve with input power at 349.5 GHz is shown in

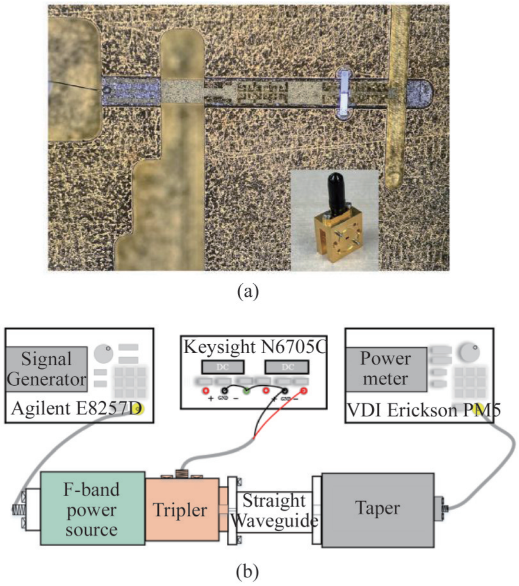

Fig. 5 Assembly and test environment of 335 GHz frequency tripler, (a) entire modules, (b) measurement platform
图5 335 GHz三倍频器装配及测试环境,(a)整体模块,(b)测试平台

Fig. 6(b). The efficiency increases with the input power until it reaches a maximum value of 5.25%. As the input power continues to increase, the efficiency decreases, which is consistent with the theoretical analysis.

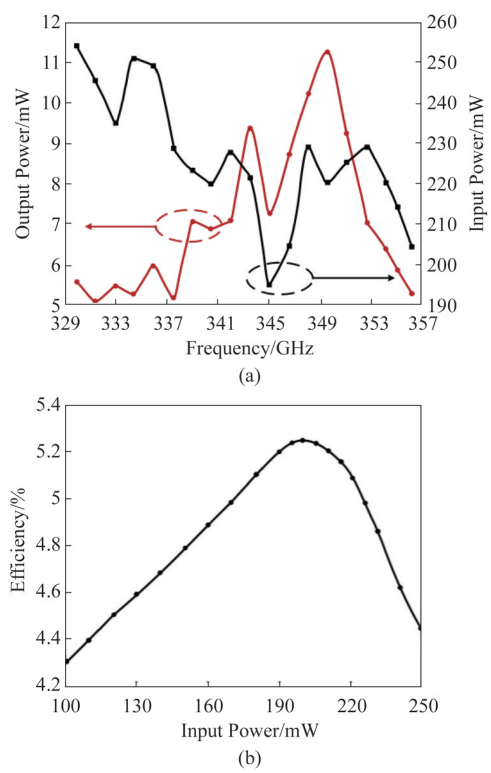

Fig. 6 Test results of 335 GHz local oscillator based on frequency triple technology, (a) output power *vs.* frequency, (b) efficiency *vs.* input power at 349.5 GHz
图6 基于三倍频技术的335 GHz本振源测试结果,(a)输出功率与频率关系,(b) 349.5 GHz频点处倍频效率与输入功率关系

In this paper, a hybrid integrated frequency tripler is studied. This approach is easier to implement than the integrated circuit, and the cost is relatively low. It can be seen that there are deviations between the test results and simulation results, which are due to the following reason: When the diode operates at high frequency, the value of the series resistance R_s and zero bias junction capacitance will change due to the increase in temperature. As one of the important parasitic parameters of the diode, its influence on the overall performance of the frequency multiplier cannot be ignored. In order to verify the correctness of the designed frequency multiplier, the W-band driving power is fixed at 23 dBm, the fixed value of C_{j0} is 43 fF, and the value of R_s varies between 4 and 8 Ω. The simulation results of changing the R_s value in the circuit are shown in Fig. 7(a). The simulation found that the output power increased with the decrease of R_s, while the operating bandwidth of the frequency tripler increased slightly. The value of R_s is fixed at 43 Ω, and the value of C_{j0} varies between 39 fF and 47 fF, the curve of output power with C_{j0} is shown in Fig. 7(b). The simulation reveals that the overall performance of the frequency triplexer deteriorates with the change of C_{j0}.

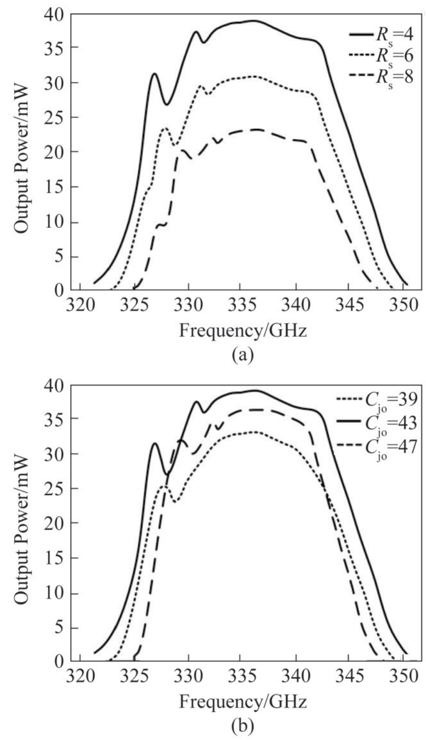

Fig.7 Relationship between output power and parasitic parameters, (a) output power *vs.* R_s, (b) output power *vs.* C_{j0}
图7 输出功率与寄生参数关系,(a)输出功率与R_s关系,(b)输出功率与C_{j0}关系

Therefore, correcting the value of the important parasitic parameter in the diode model will improve the overall performance degradation of the multiplier caused by it.

3 Conclusion

A frequency tripler is designed in the form of hybrid integration based on a 30 μm thick quartz substrate. From the theoretical analysis, a frequency multiplier design method based on a symmetric conical asymptotic matching structure is proposed, and the 335 GHz tripler is fabricated, assembled and tested. The measured output power of the frequency tripler is greater than 5 mW at 330−356 GHz, and the peak output power is 11.2 mW at 349.5 GHz under the 220 mW input power. The measured results verify that the design can increase the matching effect while fixing the diode position. At higher frequency bands, the effects of assembly accuracy on multiplier performance are issues that need to be addressed in future terahertz device designs and will be solved in monolithic design.

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