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Theoretical and experimental study of a 0.85-THz tunable folded waveguide regenerative-feedback vacuum-electronics oscillator

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Abstract: A tunable feedback oscillator for 850 GHz terahertz wave imaging system is proposed. The use of a folded waveguide as the slow-wave structure permits the superior performance together with the capability of UV-LIGA process. The comparison of dispersion character of FWG designed and optimized using eigenmode solver in CST Microwave Studio, respectively applied in regenerative feedback oscillator and traveling wave tube shows the key factor of tunable frequency centered at 850 GHz. Additionally, a feedback circuit including T-joint structure with lossy metal is simulated and the design, including SWS and feedback circuit, is verified by 3-D particle-in-cell simulations. On varying the beam voltage, the frequency-adjustable oscillation changes from a stale single-frequency state at the beginning to multi-frequency spectra, demonstrating more than 200 mW output power.

Key words: regenerative feedback oscillator, terahertz, folded waveguide, PIC solver

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0.85 THz 可调谐式折叠波导再生反馈真空电子学振荡器的理论及实验研究

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摘要:提出了一种适用于850 GHz太赫兹波成像系统的可调谐再生反馈振荡器。使用UV-LIGA微加工工艺制作慢波结构,可满足折叠波导在太赫兹频段的尺寸需求。使用CST微波工作室对折叠波导色散特性进行设计,同时针对于行波管和再生反馈振荡器中折叠波导的结构,阐明了影响频率调谐的因素。此外,对带衰减的反馈回路进行仿真模拟,并使用三维粒子模拟验证了整体设计。改变电子注电压可实现振荡频率可调,振荡从单频状态逐渐变为多频状态,整体输出功率均大于200 mW。

关 键 词:再生反馈振荡器;太赫兹;折叠波导;PIC模拟

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Introduction

In recent years, many research institutions are devoted to the research of high-frequency terahertz devices and their applications, and the research on terahertz radiation sources has become the basis of all researches. As a kind of terahertz radiation source, regenerative feedback oscillator (ROF) connects the input port and output port of TWT amplifier through the lossy feedback circuit with a coupling output port. Stable electromagnetic output signal can be obtained by amplifying the electronic noise of random phase. Regenerative feedback oscillator has many advantages, such as small size, low manufacturing cost compared with other kind of terahertz sources such as the free electron laser (FEL) and backward wave oscillator (BWO). It has been listed as the primary research content of high-frequency terahertz devices by domestic and foreign research institutions. In 2004, a 65 MW, 560 GHz regenerative feedback oscillator was designed and simulated by the University of Wisconsin Madison, United States Air Force Research Institute and Navy Laboratory[1]. In 2007, Northrop Grumann developed a regenerative feedback oscillator sample tube by using folded waveguide TWT for the first time. An output

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power of 16.3 mW can be obtained at the central frequency of 638 GHz with the beam voltage of 9.44 kV, and the current of 0.9 mA[2]. In 2009, Beijing Vacuum Electronic Technology Research Institute completed the optimization design of a regenerative feedback oscillator in the 560 GHz frequency range. The output power is 95 mw centered at 559.63 GHz with an electronic efficiency of 0.45%[3]. Gao Peng of University of Electronic Science and technology simulated 560 GHz regenerative feedback oscillator in his doctoral dissertation in 2010, and carried out regenerative feedback oscillation experiment using a 5 GHz helix TWT, demonstrating the feasibility of regenerative feedback oscillator of TWT[4]. Recently, Peking University proposed a scheme of regenerated amplification of terahertz spoof surface plasmon radiation via loading a Fabry-Perot (F-P) cavity on a grating interaction circuit[5], where THz wave experienced multiple back-and-forth regenerated amplifications to obviously improve the device efficiency.

In this paper, the theory of regenerative feedback oscillation is introduced. Then a comparison of FWGs applied in both TWT and RFO is demonstrated. The overall structure including SWS and feedback circuit is designed and optimized by CST simulation software, and the scheme design is verified by the simulation results.

1 Theory of regenerative feedback oscillation

Regenerative feedback oscillator is proposed on the basis of TWT amplifier by adding a feedback circuit with T-joint structure between input and output ports which is shown in Fig. 1. A phase-random electron beam noise is used as the signal source and a stable output signal is demonstrated by multiple-selective amplification in the interaction structure of TWT amplifier through the energy exchange between electromagnetic wave and electron beam.

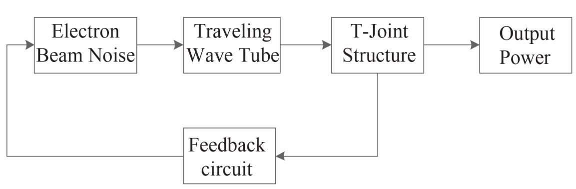

Fig. 1 Operating principle of RFO
图1 再生反馈振荡器工作原理

There are three conditions for the establishment of regenerative feedback oscillation including synchronization condition, amplitude condition and phase condition. The synchronization condition needs the electron beam to keep a synchronous phase velocity with the electromagnetic wave spreading in the SWS. By calculating the dispersion and coupling impedance of SWS, the size of FWG which conforms to the synchronization condition can be obtained. The dispersion character is given by[6]

$$\omega^2 = \omega_c^2 + c^2\left(\frac{p}{\pi p/2 + h}\right)^2\left(\beta_n - \frac{(2n+1)\pi}{p}\right)^2, \quad (1)$$

Amplitude condition is given by[6]

$$\eta_f \cdot G \geqslant A_{loss} \quad , (2)$$

where η_f indicates feedback factor determined by feedback circuit with T-joint structure while G indicates the gain of SWS. A_{loss} indicates the total loss of electromagnetic wave propagating in the whole circuit. G is given by[6]

$$G = A + BCN \quad , (3)$$

where

$$\begin{cases} A = 20\lg\dfrac{1}{3} = -9.54 \\ B = 20\lg e^{\sqrt{3}\pi} = 47.3 \\ N = \dfrac{\beta_e z}{2\pi} = \dfrac{\beta_e l}{2\pi} \\ C = \sqrt[3]{\dfrac{I_0 K_c}{4V_0}} \end{cases} \quad , (4)$$

where I_0 and V_0 indicates beam current and beam voltage. K_c is the coupling impedance of SWS which can be written as[7]

$$K_n = Z_n\frac{1}{(\beta_n p)^2}\left(\frac{\sin\beta_n p/2}{\beta_n p/2}\right)^2 \cdot \frac{1}{I_0^2(k_{cn} rc)} \quad . (5)$$

Amplitude condition suggests that the gain of the SWS should be greater than the loss in the feedback loop, otherwise, no signal will transmit to the input port through the feedback loop, which means the RFO can't start the oscillation.

Phase condition means that the phase shift of electromagnetic signal after passing through SWS, feedback circuit and T-joint should be a positive integral multiple of 2π, otherwise the signal of each cycle cannot be superposed. The phase condition for realizing single frequency oscillation is shown below[6]:

$$\beta L + \beta_b L_b = 2N\pi \; N = (1,2,\cdots) \quad . (6)$$

The parameters of β, β_b and L, L_b are phase constants and lengths in the folded waveguide and feedback circuit respectively. Different from the beam feedback circuit of BWO, The feedback circuit of RFO is a rectangular waveguide located outside SWS. Therefore, there are numerous electromagnetic waves near the center frequency point that can conform to the phase conditions. The target frequency electromagnetic wave can be obtained by selecting the electromagnetic wave through the synchronous condition of SWS.

The core component of the regenerative feedback oscillator is slow wave structure and feedback circuit with attenuation. The dispersion and coupling impedance characteristics of slow wave structure directly determine the synchronization conditions in the regenerative feedback oscillation theory. Both SWS and feedback circuit determine the amplitude conditions and phase conditions.

2 Design of SWS in RFO

Due to the wavelength-scale law of vacuum electronic devices, the fabrication and assembly of a traditional vacuum electronic device in the THz band encounter unavoidable challenges. The slow wave structure with working frequency higher than 0.5 THz is generally processed by UV-LIGA or deep reactive ion etching (DRIE) technology[8]. The applicable SWS types are folded waveguide, double rectangular waveguide grating SWS, corrugated rectangular waveguide and other planar structures. FWG has an advantages of good heat dissipation and large power capacity, which is widely used in the vacuum devices such as TWT amplifier, BWO, stop band oscillator, etc. Therefore, the folded waveguide SWS is selected to design the SWS of RFO in this paper. A single period folded waveguide SWS model is established in the CST Microwave Studio which is shown in Fig. 2. The parameter a respects for the size of waveguide broadside while b respects for waveguide narrow side. The parameter h is the length of straight waveguide, p is half period length of the module, and r_c respects for half edge of electronic channel.

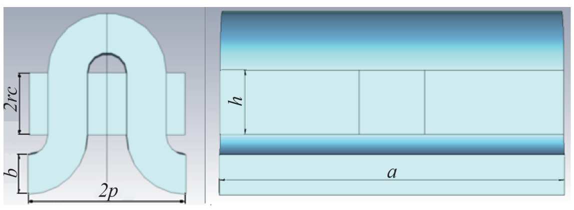

Fig. 2 Folded waveguide module
图2 折叠波导模型

Although the RFO is designed on the basis of TWT with the folded waveguide SWS, the design for dispersion characteristics of the folded waveguide is the opposite. As a broadband amplifier, TWT aims to achieve power amplification in a wide frequency range, so the dispersion of the SWS is relatively flat and it is synchronized with the electron beam voltage in a broadband. However, if the slow wave structure of TWT is directly applied to the RFO, there will be many signals oscillated from different frequencies in the synchronous bandwidth meeting the oscillation conditions at the same time. As a result, the signal spectrum excited by FRO is not pure enough to be used as a power source and the change of beam voltage has a great influence on the oscillation frequency which means the oscillation frequencies are extremely a few. According to the law that the frequency is step-tune with the variation of beam voltage[2], the SWS of RFO needs to have a steep dispersion characteristics. A large number of oscillation signals working at different frequencies with a pure spectrum are generated on varying the beam voltage.

Table 1 shows the SWS design dimensions of 850 GHz TWT and RFO respectively. Figure 3 shows the relatively flat dispersion curve of the TWT SWS, which is synchronized with beam voltage in the 800~850 GHz broadband. According to the previous report, only two frequency points centered at 801.7 GHz and 811.1 GHz can generate oscillation signals when the structure is directly applied to RFO[12]. Figures 4-5 show the dispersion and interaction impedance of the SWS in RFO. The normalized phase velocity v_p/c decreases rapidly from 0.2378 to 0.2706, the corresponding synchronous voltage varies from 15.1 kV to 11.7 kV. And the interaction impedance is over 3.435 Ω. The structure with steep dispersion can make the resonant frequency of the RFO have a large tuning range with the variation of beam voltage.

Table 1 Dimension parameter of FWG in TWT and RFO
表1 行波管与再生反馈振荡器中折叠波导尺寸参数

parameter	a	b	h	p	r_c
value of TWT(/mm)	0.210	0.025	0.040	0.050	0.020
value of RFO(/mm)	0.185	0.022	0.036	0.044	0.018

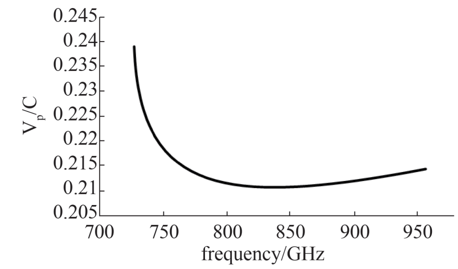

Fig. 3 Dispersion curve of TWT
图3 行波管慢波结构色散曲线

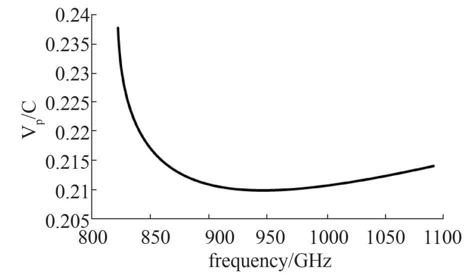

Fig. 4 Dispersion curve of RFO
图4 再生反馈振荡器慢波结构色散曲线

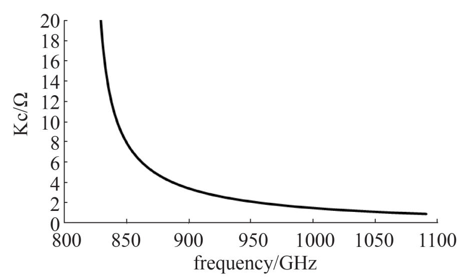

Fig. 5 Interaction impedance of RFO
图5 再生反馈振荡器慢波结构耦合阻抗

3 Design of 850 GHz oscillator

The preliminary design is simulated with Rowe three-dimensional large signal software[9]. The length of slow wave structure is 6.6 mm with a saturated output power of 616 mw shown in Fig. 6, and the small signal gain is 17. 89 dB. The loss introduced by metal materials is not considered in this software. The formula for calculating the equivalent conductivity of high-frequency metal is given by Hammerstad and Bekkadal through data fitting[10]. HB formula is given as

$$\sigma_c = \frac{\sigma}{\left\{1 + \frac{2}{\pi}\arctan\left[1.4\left(\frac{h}{s}\right)^2\right]\right\}^2} \quad , \quad (7)$$

where skin depth $s = \sqrt{2/\omega\mu\sigma}$, h respects for surface roughness while σ respects for DC conductivity. The surface roughness of copper produced by UV-LIGA process is 30~100 nm[11], and the equivalent conductivity of 850 GHz copper is calculated to be 3×10^7 S/m when the value is 50 nm. A SWS module is built in CST PIC solver. A saturated output power of 332. 76 mW is produced centered at 850 GHz with a lossy metal background of 3×10^7 S/m shown in Fig. 7.

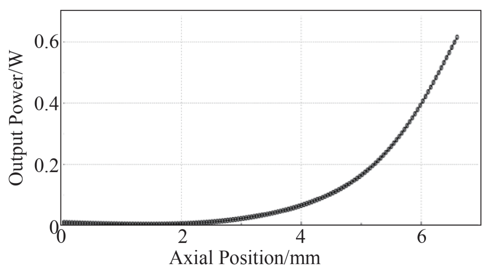

Fig. 6 Output power of interaction structure in three-dimensional large signal software
图6 三维大信号软件中互作用结构输出功率

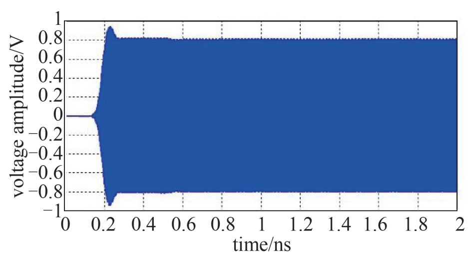

Fig. 7 Output power in PIC
图7 PIC模块中互作用结构输出功率

The length of the feedback circuit is 6. 6mm whose metal conductivity is set as 3×10^7 S/m. The T-joint is a standard E-T joint whose size is 0. 185×0. 022 mm. The model of feedback circuit and T-joint is established in CST Microwave Studio shown in Fig. 8. Port 1 is connected to the SWS. After passing through the T-joint, half of the power transmits to the output port which is Port 2, while the other part of power enters the SWS again after the transmission along feedback circuit and proceed beam-wave interaction. The S parameter is shown in Fig. 9. The overall attenuation of the feedback circuit including the loss of T-joint is -11. 23 dB , which is less than the small signal gain of the SWS. As a result, the design meets the amplitude condition of the regenerative feedback oscillator.

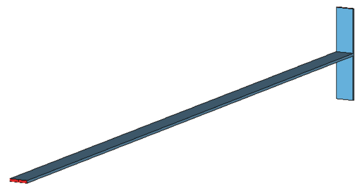

Fig. 8 CST module of feedback circuit and T-joint
图8 反馈回路与T型结构模型

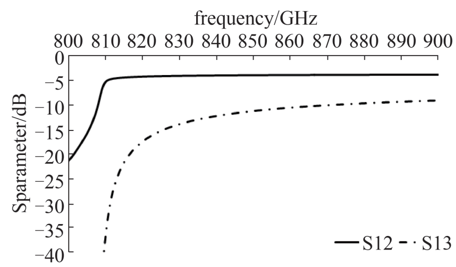

Fig. 9 S parameter
图9 S参数

4 PIC Simulation of feedback oscillator

According to the oscillator preliminarily designed, 3D model is built in the PIC module of CST particle studio. The electron is transmitted from the cathode on the left to the collector on the right. In Fig. 10, the electron beam is clustered in the second half of the SWS to realize the energy exchange between beam and electromagnetic wave. The conductivity of 0. 8 THz oxygen-free copper material is set to 3×10^7 S/m. The SWS has 75 periods with an electron beam whose current is 5 mA. The synchronous voltage varies from 11. 7 kV to 12. 9 kV. The permanent magnetic field is 0. 8 T.

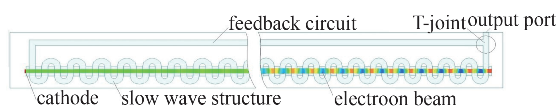

Fig. 10 Model of regenerative feedback oscillator
图10 再生反馈振荡器模型图

For operation at 841. 09 GHz, a power of 334 mW is demonstrated with a 12. 9kV electron beam through the FWG circuit shown in Figure 11. As shown in Fig. 12, the frequency spectrum of the oscillation signal is pure, which means the RFO works in the single frequency oscillation state.

The output power and oscillation frequency are shown in Table 2. With the decrease of beam voltage, the oscillation frequency of the RFO increases gradually and is observed to step-tune shown in Fig. 13. With the decrease of beam voltage, the distance between oscillation frequency bands is gradually reduced, and the voltage range of maintaining the same oscillation frequency is gradually increased. There is a corresponding relationship between the normalized phase velocity and the beam

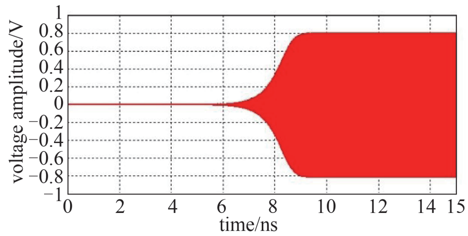

Fig. 11 Output power with synchronous voltage of 12. 9 kV
图 11 同步电压为 12. 9 kV 时输出功率

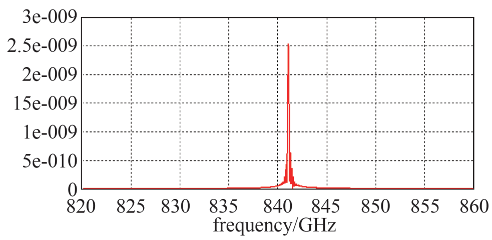

Fig. 12 FFT spectrum analysis with voltage of 12. 9 kV
图 12 同步电压为 12. 9 kV 时快速傅里叶频谱分析

voltage. With the decrease of the normalized phase velocity, the dispersion curve tends to be gentle.

When beam voltage varies from 12. 9 kV to 12. 2 kV, the RFO operates at single frequency state. A power of 237 mW is demonstrated at 867. 64 GHz with the beam voltage of 12. 2 kV, which is the last single frequency working state. Figure 14 shows the output power of 214 mW centered at 871. 95 GHz with the beam voltage of 12. 1 kV. As shown in Fig. 15, there are small spikes in the outer envelope of the power amplitude curve because of the signals oscillated at other frequencies. There are two small signals generated at the distance of 5. 23 GHz between the two sides of the center frequency of 871. 95 GHz.

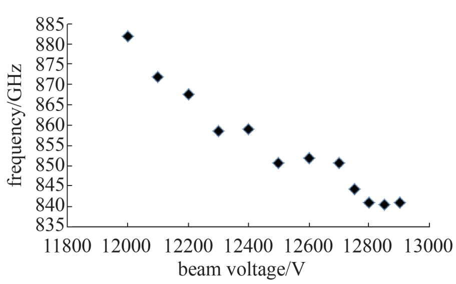

Fig. 13 The tuning effect of beam voltage on frequency
图 13 电子注电压对频率的调谐作用

When the beam voltage is adjusted to 11. 7 kV, the SWS works in the target working range of TWT, and the beam voltage synchronizes with the dispersion curve in a

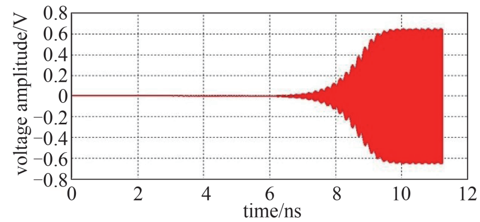

Fig. 14 Output power with synchronous voltage of 12. 1 kV
图 14 同步电压为 12. 1 kV 时输出功率

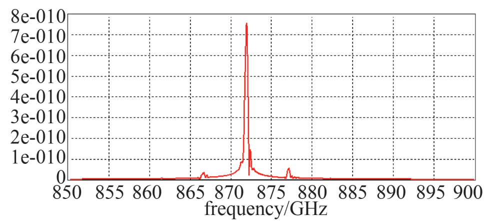

Fig. 15 FFT spectrum analysis with voltage of 12. 1 kV
图 15 同步电压为 12. 1 kV 时快速傅里叶频谱分析

large frequency range, so the frequency spectrum of oscillation signal is chaotic, as shown in Fig. 16.

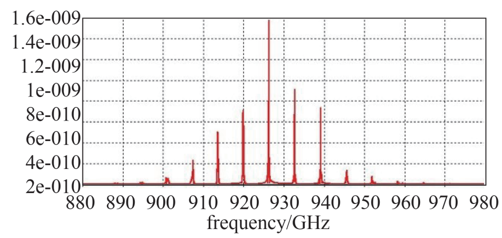

Fig. 16 FFT spectrum analysis with voltage of 11. 7 kV
图 16 11. 7 kV 同步电压快速傅里叶频谱分析

5 UV-LIGA micro-fabrication

UV-LIGA is the process method of re-electroforming by ultraviolet exposure. This method use copper block with good surface roughness and flatness after grinding and polishing as substrate. The photoresist film is obtained on the substrate by UV exposure of thick SU-8 photoresist, and then the surface without photoresist on the substrate is treated and electroplated to produce the folded waveguide SWS. The advantage of this process is that solid pure copper structure can be obtained. The disadvantage is that the copper material is relatively soft, so the thick copper substrate required considering the stress of electroforming process leads to the difficulty whirl coating. At the same time, it is very challenging to obtain a high precision depth width ratio thick photoresist film with good side wall perpendicularity.

The experiment of using UV-LIGA to develop folded

Table 2 The tuning effect of beam voltage on output power and frequency
表 2 电子注电压对输出功率及频率的调谐作用

Voltage(/V)	12000	12100	12200	12300	12400	12500	12600	12700	12750	12850	12900
Output power(/mW)	133	214	237	220	223	233	217. 8	250	195. 9	302. 6	334
Frequency (/GHz)	882	871. 95	867. 64	858. 56	859	850. 86	852. 04	850. 86	844. 33	840. 61	841. 09

waveguide is in progress in BVERI. Figure 17 shows a scanning electron microscope image of the photoresist film structure. Figure 18 shows the folded waveguides on the substrate after electroplating and polishing. Although the good surface roughness realize the minimized losses with high conductivity copper walls, it remains necessary to develop precision welding technology to keep two circuit halves in a better relative position.

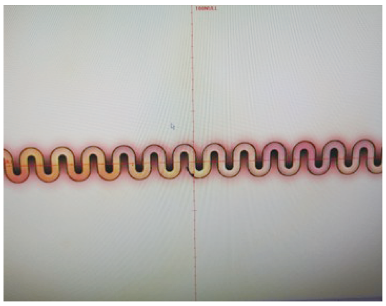

Fig. 17 Photoresist film structure
图17 光刻胶膜结构

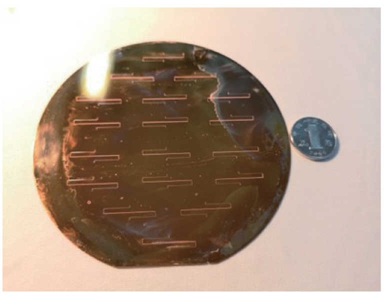

Fig. 18 Folded waveguide electroplated on substrate
图18 衬底上电铸出的折叠波导结构

5 Conclusions

In this paper, theoretical study about a 0.85 THz tunable folded waveguide regenerative feedback vacuum-electronics oscillator is carried out. Firstly, the cold characteristics of the FWG are analyzed, and the structure size parameters are determined according to UV-LIGA fabrication process. Then, the interaction structure is designed and simulated using PIC module in CST particle studio. The simulation result shows that a RFO operates between 841.09 and 882 GHz is proposed with more than 200 mW output power. The recent experimental results of UV-LIGA are introduced. The following experimental development of the 0.85 THz tunable power source work is going to be carried out.

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